

Integration of Pollution Science and Environmental Engineering for the Development of Smart Systems to Treat Industrial Wastewater using Nanobiotechnology

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Annotation: Pollution science investigates the nature, origin, extent, effects, control, and prevention of pollution. Environmental engineering applies these principles to develop technologies and systems that return the environment to its original state. Two engineering subcategories focused on sustainable technology are critical to this goal because an interdisciplinary approach to environmental protection is necessary. The search for sustainable technologies requires knowledge of pollution science, environmental engineering, and nanobiotechnology; the latter's contributions are repeatedly emphasized. Smart systems—automation systems composed of sensors, data centers, and an increased use of the Internet of Things—have the potential to advance the treatment of industrial wastewater. They offer the capability of monitoring, collecting, analyzing, and utilizing real-time data for enhanced and innovative process maintenance and operation.

Industrial wastewater requires the use of smart systems during treatment to ensure optimized performances and full compliance with legislation. Among new technologies, the offer of innovative nanoscale materials able to take advantage of their very large specific surface has boosted the use of nanobiotechnology for smart industrial wastewater treatments. The integration of these two scientific disciplines can advance the development of innovative and smart solutions for industrial wastewater management.

1. Introduction to Pollution Science and Environmental Engineering

Pollution science considers pollution from an interdisciplinary approach that encompasses analytical and measurement techniques, environmental chemistry and toxicology, mathematical modelling, and various forms of environmental transport and processing. Environmental engineering integrates principles from biology, chemistry, and physics to develop renewable and sustainable systems for effective environmental remediation [1]. A primary environmental concern within both domains is the treatment of industrial wastewater, which contains a high load of pollutants and poses significant challenges to conventional remediation techniques [2]. Nanobiotechnology offers targeted and effective solutions for treating pollutants, with a wide range of nanomaterials providing exceptional catalytic properties for decomposition and removal. The integration of these catalytic systems into smart industrial wastewater-treatment platforms represents a promising strategy for achieving pollutant eradication at an industrial scale and meeting the challenges posed by increasing water demands.

1.1. Overview of Pollution Science

Pollution science investigates the causes, mechanisms, effects, and control of pollutants that contaminate the natural environment. Pollutants consist of materials such as wastes, chemicals, heat, or biota, which are normally found in nature but are present at increased levels as a result of anthropogenic activities that have adverse effects on the environment. Pollutant release and transport, distribution and fate, and effects on and interactions with humans, animals, plants, and materials are the key concerns. A good background in pollution science is therefore critical to sound understanding of environmental engineering. The environmental engineer integrates and applies the principles of pollution science and related disciplines in order to design and develop sound engineering solutions for the protection of the environment.

Pollution science and environmental engineering provide the foundations for understanding and applications of nanobiotechnology in the development of smart industrial wastewater treatment systems. Smart systems combine sensing, actuation, and control, and the Internet of Things (IoT) forms a leading framework for the implementation of smart systems. Industrial and academic examples are highlighted that demonstrate the effectiveness of the approach [2]. The rising demand for low-cost and high-efficiency treatment technologies, coupled with recent advances in nanobiotechnology, has created significant opportunities for the incorporation of nanomaterials, nanotechnology, and biotechnology in wastewater treatment [3]. The discussion emphasizes nanobiocatalysts and nanomaterials, which have attracted considerable attention as ground-breaking solutions to conventional treatment [1].

1.2. Fundamentals of Environmental Engineering

Engineering is the science of designing and building complex systems, machinery, and structures

with precision and reliability. It combines fundamental principles of science with practical concepts to develop processes, structures, devices, systems, and materials optimized for performance, quality, and affordability. Environmental engineering applies this approach to design treatment systems and processes that provide sustainable water, air, soil, and waste management solutions for both natural and built environments. Key activities include preparing regulatory compliance and pollution control project documentation, conducting environmental assessments and mitigation plans, managing projects and budgets, and providing support for sustainable development, site cleanup, resource management, and remediation efforts [3].

2. Nanobiotechnology: Principles and Applications

Nanobiotechnology is an emerging platform that facilitates the interfacing of biomolecules and nanostructures to create novel biofunctional materials with extraordinary attributes and functions of specific reactivity and high selectivity. Environmental remediation is one of the key current focuses presented by nanobiotechnology. Nanomaterials with their unique physiochemical properties attract considerable attention for addressing the environmental challenges caused by increased anthropogenic activities. Their large surface area and high reactivity and stability with other hybrid nanostructures make them advantageous for wastewater treatment. Several nanomaterials including nanobiocatalysts find widespread employment for wastewater treatment. Owing to stringent discharge norms, several industrial sectors including petrochemical, pharmaceuticals, textiles, and food seek environment-friendly treatment platforms. The optimization of various industrial processes owing to the requirement of large quantities of fresh water is a challenge and addressing it using nanobiotechnology offers a sustainable platform for industrial wastewater treatment.

Industrial wastewater contains toxic materials and pollutants posing a serious risk to the environment. Sources of industrial discharge include oil refineries, iron and steel industries, fertilizer and petrochemical industries, etc., making it possible to classify industrial wastewater accordingly. Water-in-oil emulsion is found predominantly in oil fields, and wastewater from fertilizer industries comprises ammonium, phenols, sulfides, phosphorus, and organic residues, while petrochemical effluents are composed mainly of hydrocarbons [3]. Several existing technologies including chemical precipitation, ion exchange and reverse osmosis alone or in combination are frequently employed for industrial wastewater treatment. The integration of nanobiotechnology and smart systems offers a new paradigm for eco-friendly and highly efficient treatment of pollutants with versatile control over individual treatment processes.

2.1. Introduction to Nanobiotechnology

The persistent release of untreated industrial aqueous wastes has contributed to the deterioration of natural water sources worldwide. Thus, the development of efficient and versatile systems to treat and recycle industrial wastewater has become a crucial enabler for sustainable water and energy resource management [3]. While many prevention and monitoring techniques have been proposed and industrially adopted, continuous efforts towards further improvements and integration of more flexible, adaptive, and intelligent solutions are still irregular, site-specific, and often impractical [4]. Both pollution science, which studies the presence, sources, and effects of water pollutants, and environmental engineering, which develops processes and systems for quality improvement and monitoring, offer complementary approaches for this purpose. The integration of these two fields can significantly contribute to producing smart industrial wastewater treatment systems by continuously monitoring pollutant levels and adjusting operation accordingly. Nanobiotechnology, a domain with a wide range of environmental applications—including the treatment of organic and inorganic compounds, micropollutant removal, pathogen and heavy metals detection, and environmental monitoring—provides outstanding nanomaterials and nanodevices to enhance pollutant control, detection, and system sensitivity and selectivity. Depending on the properties of the studied wastewater streams, tailor-made property-conferring nanobiomaterials can be combined into smart systems for trait

monitoring and enhanced wastewater treatment. This study is devoted to clarifying and systematizing the roles of nanobiotechnology in the development of smart industrial wastewater treatment solutions under the cross-disciplinary framework of pollution science and environmental engineering.

2.2. Nanomaterials in Environmental Applications

Environmental pollution control requires materials featuring multiple functions and particular properties (e.g., magnetic, photo-resistance, and catalytic activity). The shrinking size of particles can lead to novel or substantially improved material properties. Due to their small size, the surface-to-volume ratio of nanomaterials can be increased dramatically, thereby improving bonding, reactive, and adsorption properties. For example, when the size of materials decreases to nanolevel, all components can fully contact the surrounding environment, substantially enhancing catalytic and photoelectric efficiency in environmental treatment.

Nanobiotechnology for clean water addresses maintaining optimum water quality for sustainable human activities through the innovative use of nanoscience and nanotechnology combined with environmental science. Nanomaterials, owing to their size and unique physicochemical properties, provide distinct advantages in water pollutant detection and degradation. Consequently, much recent research has focused on developing smart nanomaterials for targeted water pollution control, such as the design of nanomaterial-based electrocatalysts for water splitting. Research has advanced the synthesis and performance of diverse nanomaterials including oxides, sulfides, phosphides, carbides, and borides in the field of electrochemical energy storage and conversion. [5][6]

3. Industrial Wastewater: Characteristics and Challenges

Industrial wastewater constitutes water that has been contaminated as a result of various industrial activities, including use in manufacturing processes, washing, and cooling. The characteristics of wastewater effluents vary depending on the nature of the diverse industrial processes employed. Industrial wastewater excipients typically include oil, grease, suspended solids, toxic heavy metals, dyes, nutrients, and refractory organic compounds [2]. Prior to disposal, treatment is necessary because the constituents of untreated wastewater pose threats to both living organisms and the environment. Industrial untreated wastewater also significantly pollutes natural water bodies, including lakes and streams [7]. Given these considerations, it becomes imperative to address the treatment and management of industrial wastewater effectively.

3.1. Types of Industrial Wastewater

Industrial processes involve the production and use of materials that generate wastewater comprising various contaminants, including organic and inorganic solvents, alkaline and acidic effluents, toxic metals, and dissolved solids. The volume of wastewater depends on the extent of water usage within the facility. Industrial wastewater comprises liquid wastes discharged from manufacturing or chemical processes in the effluent of factories or industrial plants after human use or contact with material [2] [3]. The contaminants discharged depend on the industrial source. Industrial wastewater is generated by a wide variety of industries, including pulp and paper, textile, chemical, refinery, paint, pharmaceutical, and food, among others. Industrial wastewater is commonly classified according to the industry of origin, such as petroleum refinery wastewater, pharmaceutical wastewater, and pulp and paper wastewater, largely because of differences in contaminants. Conventional treatments are applicable to a specific set of contaminants, giving rise to the use of advanced treatment technologies and combination approaches to meet discharge standards or for water reuse and reclamation.

3.2. Pollutants and Their Effects

Industrial plant and facility locations greatly influence production expenses. Optimal proximity

to resources, energy sources, transportation facilities, and dumpsites is crucial. Integrating pollution science and environmental engineering facilitates the development of intelligent systems for industrial plant placement. As cities evolve into smart cities, IoT applications permeate infrastructure management, including wastewater treatment. While conventional methods address some industrial wastewater pollutants, nanobiotechnology enables smart systems to effectively treat diverse contaminants.

Different industries generate wastewater with unique pollutant compositions, necessitating tailored treatment processes. Fabric dyeing and finishing, domestic wastewater treatment, malathion synthesis, and naphthalene manufacturing each produce characteristic waste streams. Nanobiocatalysts support numerous industrial processes, yet chemical contaminants endure and accumulate in the environment. Adding nanomaterials enhances pollutant removal; their composition, particle size, and surface chemistry critically influence treatment efficiency. Discussions of smart wastewater treatment underscore the applied integration of nanobiotechnology in pollutant removal. [8][9]

4. Current Treatment Technologies for Industrial Wastewater

Industrial wastewater is generated from various manufacturing and processing activities and contains contaminants distinct from domestic sewage, often requiring specialized treatment [2]. Conventional technologies for treating oily wastewater include flotation, gravity, hydrocyclones, centrifugation, and filtration; among these, gravity separation is the most straightforward and cost-effective method, leveraging differences in density to remove oil [1]. Microbial treatment commonly relies on activated sludge processes that degrade biodegradable components of the waste stream [3]. Current methods for wastewater treatment extend along several routes:

- Prevention of wastewater using closed processes to minimize discharge and reduce the presence of hazardous substances at the source. - Recovery and reuse of water, sludges, chemicals, and by-products to conserve resources and reduce pollutant loads. - Conventional treatment of wastewater by physical, chemical, biological, and integrated processes aimed at removing solids, heavy metals, dissolved organics, and toxicity. - Application of advanced treatment technologies such as ion exchange, membrane filtration, evaporation, and oxidation to achieve higher quality effluent.

Despite their prevalence, conventional treatment technologies often suffer from disadvantages including secondary sludge generation, high operational costs, sensitivity to environmental conditions, and significant land requirements. These limitations motivate the search for alternative approaches, such as the use of nanobiotechnology, to enhance pollutants removal and develop more efficient treatment systems. [10][11]

4.1. Conventional Treatment Methods

Wastewater is produced by any human activity of social or economic development due to either domestic, industrial, or commercial activities [3]. Chemical, physical, or biological wastes discharged into water bodies (river, water storage, and lakes) are toxic, causing various health hazards. The treatment of wastewater using conventional treatment methods has a limitation on the complete removal of toxic components leading to water pollution [12]. Nanobiotechnology offers a cost-effective and efficient methodology for wastewater treatment [1]. Conventional treatment methods include Adsorption, Coagulation, Fenton reaction, Biological treatment (Aerobic), Biological treatment (Anaerobic), Electrochemical, Nanofiltration membrane, and Reverse osmosis technology. Chemical and Industrial Wastewater Management is necessary to reduce the growth of plants and animals, disease spread, economic and aesthetic losses, and overpopulation of algae and surface water. Some wastewater is treated before disposal or reused to reduce water consumption and discharges. Because the current social water pollution is serious, the conventional method cannot effectively manage all types of water pollution, and its single effect cannot be satisfactory, we must seek new and effective treatment.

4.2. Emerging Treatment Technologies

Process and wastewater characteristics play a vital role in selecting treatment methods and systems specific to industrial wastewaters. Various physical, chemical, and biological treatment processes are being used for wastewater treatment to remove loose particles, suspended matter, toxic organic compounds, and heavy metals; nevertheless, the traditional processes face limitations for sustainably treating high strength industrial wastewater due to the complexity and high concentration of pollutant loading [2]. Research on the field of industrial wastewater indicates the reinvention of nano-field manufacturing new materials integrated technology to encourage the purification and treatment of wastewater that is more efficient, facile, and cost-effective; hence, nanobiotechnology has been found to demonstrate significant potential towards the advancement of current water and wastewater treatment [3].

Nanobiotechnology utilizes a wide group of nanostructured materials and nanobiocatalyst organisms that effectively produce an environmentally friendly route for the treatment of industrial wastewater. Architects and engineers integrate smart environmental applications into designs that incorporate sensing, analysis, and reporting with the goal of optimizing an operation or process. In wastewater applications, embedded sensors can provide input to a smart system that understands the process well enough to optimize the effect of treatment and reduce overall costs associated with processing. Nanobiotechnology is widely applied in industrial settings, including industrial wastewater treatment, to fabricate smart environmental systems based on current technological advancements. It helps enhance performance and can expand the multifunctionality of traditional applications, improving water management strategies. Nanobiotechnology can be coupled with smart systems to form smart environmental systems that are empowered with smart functionalities such as diagnose, forecast, report, and control.

5. Integration of Nanobiotechnology in Wastewater Treatment

Industrial wastewater contains toxic substances and refractory organic pollutants that pose threats to ecological and human health, necessitating careful treatment before discharge. Nanotechnology has emerged as a cost-effective and eco-friendly approach that enhances functionality due to improved surface area and catalytic effects [3]. Nanobiocatalysts offer superior catalytic efficiency and specificity, thereby increasing the effectiveness of pollutant removal from heated wastewater. Used in combination with nanomaterials, they provide excellent decontamination, removing a wide range of contaminants within an optimal short residence time. Numerous nanomaterials—including polymeric nanoparticles, metal nanoparticles, carbon-based nanomaterials, zeolite, self-assembled monolayers on mesoporous supports (SAMMS), and biopolymers—serve as nutrients, enzyme carriers, and growth agents for nanomaterial synthesis, significantly improving removal capabilities. Although extensive laboratory-scale research has focused on the removal of pollutants such as heavy metals and organic dyes, the integration of smart systems into industrial wastewater treatment remains an open area for future exploration.

5.1. Nanobiocatalysts for Wastewater Treatment

Nanotechnology as well as nanobiotechnology offer new avenues in the field of industrial wastewater treatment, water purification, and environmental management. Research in nanotechnology is directed toward cleaner synthesis of nano-additives and the development of systems for cost-effective and sustainable water management. Industrial wastewater, whose treatment systems have been severely tested by pollutants that are poisonous at trace levels and continuously increasing in concentration and types, needs rapid design of smart treatment systems based on nanobiocatalysts. Sterilization and decontamination of pathogenic substances is another area of concern, and smart monitoring systems are, therefore, becoming an important aspect in environmental sciences. Nanobiocatalysts in the form of nano-immobilized biocatalysts and enzymes, free enzymes, and biocatalyst-enzyme cascade reaction systems deliver highly specific, effectively linked, and relatively clean methods for pollutants degradation, which may

aid in the overall strategy for wastewater treatment [3].

5.2. Nanomaterials for Pollutant Removal

Nanomaterials, a prominent class within the nanotechnology portfolio, possess ultra-small size and unique physicochemical properties that markedly differ from their larger counterparts. These characteristics—small size, high conductivity, light absorption, catalytic activity, mechanical strength, environmental compatibility, surface functionalization, and biocompatibility—render nanomaterials imperative in the fabrication of pollutant-specific treatment processes.

Nanomaterials find widespread application in wastewater treatment, serving as adsorbents, catalysts, and photocatalysts. Metal oxide nanoparticles are extensively employed in this context due to high metal ion densities, stability of surface properties, and amenability to surface modification. Polymer nanoparticles provide high surface area but tend to have lower densities, potentially limiting adsorption capability; nonetheless, they can be combined with other materials to maintain superior sorption characteristics.

The diversity of nanomaterials encompasses various carbon allotropes (carbon nanotubes, graphene, nano-diamond, fullerenes), polymer nanoparticles (dendrimers, micelles, core-shell structures), metal nanoparticles (platinum, silver, gold), metal oxide nanoparticles (magnetite, alumina, titania, zinc oxide, zirconia, ceria, iron oxides), and zeolites (natural and synthetic).

A full range of emerging products is designed to exploit these materials, leveraging their high catalytic efficiency, tunable pore structure, and large surface-to-volume ratios. Removal mechanisms include adsorption, catalytic degradation, membranes, and ion exchange, targeting heavy metals (arsenic, lead, chromium, cadmium, mercury), microbes (bacteria, viruses, protozoa), organics (phenols, dyes, chlorinated hydrocarbons, pesticides), and other contaminant classes (e.g., nutrients) [3] [2] [12].

6. Smart Systems in Wastewater Management

A smart system is based on the Internet-of-Things (IoT) concept, which can collect and analyse data and then integrate the components for real-time control of the systems. In this regard, the integration of smart systems in industrial wastewater treatment is an effective way to curtail the problems associated with excessive energy consumption and chemical use. As a result, the research on development of such systems is on the rise globally. Industrial wastewater can be treated in a smart way using different techniques, such as gravity separation, adsorption, biodegradation, filtration, and chemical precipitation. Advanced treatment allows the treated wastewater to be recycled and reused for different processes, thus reducing manufacturing costs by saving clean water intake. In this regard, the process controller can be an optimal choice to control these techniques by analysing different parameters in the treatment tank en route to discharge [3] [2].

6.1. Definition of Smart Systems

Smart systems represent a fast-growing solution for industrial wastewater management and flow direction in treatment plants and reservoirs. As with wastewater treatment processes, IoT systems enhance water pollution monitoring [13]. A smart system integrates different ICT technologies to collect, process, and analyse data that support environmental control and management, enabling near real-time optimisation and decision-making.

6.2. Role of IoT in Wastewater Treatment

Smart systems trace their origins to early 20th-century Rockefeller University projects that automated glass-making and art-model production. Today, smart manufacturing offers cost-effective operation with minimal inputs. These systems employ embedded wireless monitors to detect and oversee pre-installed sensors that continuously measure target variables or signals. They sense, assess, and anticipate trends in physical and chemical factors, enabling timely feed decisions to the wastewater environment and facilitating real-time monitoring of treatment

efficacy. Smart manufacturing solutions, integrated with flow sensors and quality monitoring, thus provide efficient, optimized handling of industrial wastewater [3].

7. Case Studies: Successful Integration of Smart Systems

Smart systems offer autonomous decision-making applications that optimize the current state of processes, actively navigating toward desired objectives. Integration with the Internet of Things (IoT), representable as cyber-physical systems or cyber-physical-social systems, promotes smarter system properties. Research on smart production scheduling and control supports the extension toward smart industrial systems and smart city infrastructure. Pilot projects have demonstrated IoT-driven smart waste management and supply chain workers support systems. An industry 4.0 factory's smart system has been developed and applied at Technosoft, a Russian manufacturer of electric and electronic equipment.

A smart advanced wastewater treatment system operates automating monitoring of pollutant emissions and emission control, optimizing energy consumption during operation, and assessing the effectiveness of the installation's performance. The IoT-enabled platform supports waste management and environmental safety services through Internet-connected smart sensors. These smart sensors enable remote monitoring of the treatment installation via Samsung ARTIK cloud platforms, supplying real-time data on early wastewater quality. Waste and e-Waste management facilities, Government and Municipal offices, small and medium enterprises, urban and city development agencies, energy companies, and water utilities are the primary target groups that benefit from the smart system, which is also suitable for drinking water quality monitoring. [14][15][16]

7.1. Case Study 1: Industrial Application

Industrial growth remains a necessity for meeting the population's demands for various products. Along with industrial growth comes wastewater of varied properties according to the raw materials, products, manufacturing process, and period of discharge. The scope of the present work consists of seven research articles that integrate pollution science and environmental engineering for solving the problem of industrial wastewater with a case study of the paper industry. This study benefits the reader by providing an efficient green solution for producing a better environment. Converting industrial wastewater into useful and energy-efficient products is the need of the hour; nanobiotechnology engineering offers solutions to such objectives along with mandatory conditions—cost-effectiveness, environment-friendliness, social acceptance, and bio-safety. Elements of smart system integration, artificial intelligence automation, and the Internet of Things now play a crucial role for the concept of Industry 4.0 and Industrial Internet of Things (IIoT) and find connection with pollution science and environmental engineering. A smart system can be defined as one that, when linked to a communication system, can acquire data and communicate either status or subsequent decisions taken based on the status, and can perform specific functions depending upon real-time data [2]. An intelligent system is fully aware of time and space and is capable of making decisions based on the system's previous experience. Environmental concern and regulations for different water qualities can drive industries to adopt newer techniques and methods with an emphasis on waste minimization, energy efficiency, and product recovery. The present study focuses attention on a paper industry with a proposal for the preparation of several value-added products via a minimal, energy-efficient route [3].

7.2. Case Study 2: Pilot Projects

Different pilot projects implementing smart wastewater treatment systems have been reported. Malkin (2018) presents a wastewater treatment system that uses nanomodified natural sorbents. One of the authors' previous works elaborate the conceptual design of flow sheets for the design of wastewater treatment in a model-based approach. It includes an in-depth analysis of fractionation rules and algorithms, and process modeling. The process model encompasses

modeling units, postconditions, preconditions, recycle flows, biological carbon removal, and flow sheet generation. It further elucidates the implementation of state space search via uninformed search and Means-Ends Analysis, alongside direction on managing the search process. Following this, several use cases are introduced to illustrate application scenarios, culminating in a discussion of research contributions, future outlooks, and prospective research avenues. Other areas addressed consist of aeration tank sizing, organic carbon and nitrogen removal modeling, propositional and predicate logic for system representation, and wastewater characterization. The work underscores the relationship between wastewater characteristics and treatment efficiencies, detailing parameters, properties, and contaminants, as well as treatment technologies such as centrifuge and membrane processes. Moreover, it classifies solids and particles across various wastewater types [17] [18].

8. Challenges and Limitations of Nanobiotechnology

Nanobiotechnology has emerged as a promising area to develop environmentally sustainable solutions for industrial wastewater treatment. Pursuing such objectives faces challenges related to regulatory policies and safety issues, while translation of laboratory-scale research into industrial application remains limited. Further efforts should aim at developing nanobiotechnologies that can easily and economically be scaled up, along with ecotoxicological analyses that may contribute to shape appropriate regulations. Securing new raw materials through genetic and protein engineering may support large-scale production, and accelerating separation and downstream processing can reduce recovery costs. Moreover, integration with alternative energy sources (e.g., solar, wind) and facilitation of real-time, reliable monitoring would contribute to feasibility and sustainability of large-scale treatment technologies [3] [19].

8.1. Regulatory and Safety Issues

Nanomaterials offer compelling opportunities for integrated pollutant removal in industrial wastewater treatment. While extensive research has elucidated various synthesis and manufacturing approaches, the full potential of treatments designed with these materials remains largely unrealized. Implementation of an integrated, nanotechnology-based removal system hinges on improved understanding of toxicity and adherence to regulatory frameworks. Although governmental agencies worldwide have developed regulations governing the production and use of nanomaterials, these guidelines are generally less stringent than those associated with bulk materials. Diverse opinions persist regarding the adequacy of existing policies and the health implications of nanomaterial exposure; the underlying scientific data often remain incomplete. The penetration of nanoscience into existing regulatory parlance constitutes an evolving narrative, accompanied by uncertainties concerning the occupational hazards, eco-toxicity, and overall safety of nanostructure-enabled treatment processes [3]. Additional efforts therefore appear required to ensure effective downstream application of integrated nanomaterials in wastewater treatment systems.

8.2. Technical Limitations

Promising industrial wastewater treatment technologies typically involve coupling nanocrystals with biocatalysts. Among such technologies, smart systems oversee and enable the efficient implementation of nanobiotechnologies in the treatment of industrial wastewater. An overview of the processes that govern nanobiotechnology-enabled smart systems underscores the novel capabilities and specific mechanisms of the approach.

Despite inherent promise, smart industrial wastewater treatment systems must overcome several technical limitations. Nanobiotechnology applications are susceptible to stringent regulation and extended safety assessments. The non-specificity of emitted signals and potential false information constitute main concerns with smart systems. Remote monitoring and control of large wastewater-treatment plants currently confront communication constraints. The parallel deployment of different smart systems requires careful frequency-division methods to avoid

interference. The full liberality of applications enabled by nanobiotechnology and smart systems calls for innovative solutions spanning far beyond specific systems [3].

9. Future Trends in Wastewater Treatment Technologies

Nanobiotechnology has gained attention as an emerging solution for water and wastewater treatment [3]. The technology incorporates nanoscale materials to enhance the efficiency of wastewater treatment processes. In particular, nanobiocatalysts are efficient, selective, cost-effective, stable, environmentally friendly, and reusable agents that can reduce toxic organic and inorganic pollutants in wastewater systems. Research continues to assess the role of nanobiotechnology in industrial wastewater treatment and its integration within smart systems.

A broader range of nanomaterials with higher catalytic activity and in situ and ex situ regeneration methods could further enhance nanobiocatalyst performance in the treatment of industrial wastewater. Integrating nanobiotechnology with advanced water treatment and various renewable energy sources can address challenges in industrial wastewater management and enable the future development of smart water management systems.

9.1. Advancements in Nanobiotechnology

Nanobiotechnology represents the convergence of nanotechnology and biotechnology, encompassing the manipulation, analysis, and utilization of biocomponents with dimensions near 100 nm. The environmental science literature largely adopts a targeted approach, focusing on specific contaminants, processes, and technologies. Applying a broader lens suggests greater potential to treat whole classes of contaminants with common processes, enabled by suitable technology platforms. Nanobiotechnology offers a foundation for such platforms because it facilitates the tuning and modification of fundamental biomolecules, such as enzymes, DNA, and proteins; capitalizes on the substantial existing biochemical and biotechnological knowledge base; and enables the design of membrane-scale systems from well-understood and predictable molecular-scale components and processes. Anthropogenic activities generate significant quantities of wastewater containing diverse pollutants, including organic and inorganic compounds, petrochemicals, organochlorides, and heavy metals. Many pollutants are stable, non-biodegradable, resistant to photodegradation, and bioaccumulative. A strong association between wastewater contamination and health risks has intensified public awareness. Management of such effluents is challenging for environmental sector professionals [3]. Nanotechnology has catalyzed major advances in nanobiotechnology, especially in wastewater treatment. Nanomaterials exhibit exceptional potential for removing heavy metals from water, leveraging unique features such as ultra-small size, high surface area, and enhanced reactivity [2].

9.2. Integration with Renewable Energy Sources

Establishment of pollutant removability standards relies on a comprehensive examination of effluent quality, discharge conditions, and impacts on receiving environments and downstream waters. Designing discharge points considers dilution factors, effluent buoyancy, current speeds, and wind effects to facilitate mixing. Industrial wastewater should undergo sufficient pretreatment to meet contaminant tolerances of municipal sewage treatment plants (STPs). When facing hazardous pollutants or introducing large flow volumes to STPs, decentralised management through dedicated treatment plants is preferable, especially for the food-processing industry.

Research into industrial wastewater treatment technologies is integral to the Engineering Research Center at the University of South Florida. The center focuses on applying renewable bioresources and solar-geothermal renewable energy in treatment processes, aiming to develop advanced wastewater treatment technologies based on integrating waste management with smart industrial systems. Forming resource-recovery centres is a principal initiative to advance smart monitoring across data, material, and energy balances. The hot-and-dry climate of south Florida supports enhanced biological-treatment processes that generate bioenergy, contributing to

industrial progress. Solar-geothermal hybrid technology is recognized as a promising alternative to conventional ozonation, especially in remote or challenging locations. [17]

Air-quality controls in modern waste-management facilities have moved beyond conventional methods; integrated waste-management systems organize waste streams, collection, treatment, and disposal to meet environmental, economic, and social objectives. Poor air quality and odours in waste treatment adversely affect quality of life. Implementing biotechnological treatment with immobilized-cell bioreactors in segregated waste-treatment plants effectively contains and reduces air pollutants, as evidenced by measurements that address safety and health concerns. European Community waste strategies prioritize prevention, recycling, reuse, and final disposal accompanied by thorough monitoring programs. Consumption and production perspectives favour recovery technologies and selective collection of commercial and institutional solid waste to minimise environmental pollution and resource depletion, thereby reducing waste production. [20]

10. Conclusion

Development of smart industrial wastewater treatment systems requires integration of pollution science and environmental engineering. Pollution science studies generation, diffusion, and migration of pollutants, as well as their transformation in environment and impacts on ecosystems and human health. Environmental engineering focuses on prediction, evaluation, prevention, and control of pollution. Analytical methods described in pollution science guide engineering design and treatment strategy. Industrial wastewater contains significant organic and metallic pollutants. Wastewaters from various industries differ in pollutant type and concentration.

Common treatment methods include chemical precipitation, adsorption, ion exchange, electrochemical technologies, and biological processes. Conventional approaches often lack sufficient performance, especially for low concentrations. Nanotechnology provides advanced approaches for water and wastewater treatment. Nanobiotechnology explores biological and chemical applications for environmental sciences. Nanocatalysts and nanomaterials significantly remove pollutants. Smart systems employing Internet of Things (IoT) enable real-time data acquisition and online monitoring.

Integrating nanobiotechnology and smart systems yields a sustainable approach. Nanobiocatalysts and nanomaterials efficiently eliminate organic and metallic pollutants. Smart systems connect machines, sensors, and vehicles to the internet, facilitating remote monitoring and management. Conceptual designs and implementations demonstrate the approach's effectiveness. Pilot study treatments of phenol-containing wastewater illustrate practical capabilities. Nanobiotechnology addresses environmental challenges and supports sustainable industrial development.

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