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Catalytical Degradation of Industrial Dyes using Biosynthesized Nanoparticles - Review

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ABSTRACT

The rapid growth of the textile industry has led to a surge in the release of industrial dyes, posing a severe environmental threat. An attempt was made in this review paper to explore the catalytical degradation of industrial dyes using biosynthesized nanoparticles as a promising avenue for sustainable remediation and to provide a thorough understanding of the advancements, challenges and potential applications of this innovative approach. The synthesis methods of biosynthesized nanoparticles were explained, highlighting the use of natural extracts and their inherent catalytic properties. A critical analysis of the catalytic degradation process was presented, examining the diverse range of industrial dyes targeted by biosynthesized nanoparticles. The factors influencing degradation efficiency, such as nanoparticle size, composition and the nature of the dye pollutants were investigated and the kinetics and mechanisms governing catalytic degradation were explored, shedding light on the intricacies of the reaction pathways. The environmental impact and sustainability of biosynthesized nanoparticles for dye degradation were thoroughly evaluated. Comparisons with conventional remediation methods were made, emphasizing the eco-friendly nature and potential scalability of this innovative approach. Moreover, challenges and future directions in this field were outlined to guide further research efforts.

Keywords: Degradation; Industrial dyes; Light sources; Nanoparticles; Pollutants.

1. INTRODUCTION

The Industrial Revolution, while propelling advancements in manufacturing and technology, has inadvertently given rise to environmental concerns, with the textile industry standing as a notable contributor to ecological challenges (Stengl *et al.* 2009). The widespread use of synthetic dyes in textile processes has led to the discharge of industrial effluents containing complex dye molecules, resulting in severe environmental pollution. Conventional treatment methods often fall short in providing sustainable and efficient solutions for the remediation of these persistent pollutants (Latha *et al.* 2017). In response to the global environmental crisis, the catalytical degradation of industrial dyes using biosynthesized nanoparticles has emerged as a cutting-edge and promising avenue for sustainable remediation (Demartis *et al.* 2021).

This review paper aims to comprehensively explore and consolidate the current state of knowledge regarding the catalytical degradation of industrial dyes, focusing on the innovative use of biosynthesized nanoparticles (Adams *et al.* 2006). The urgency of addressing industrial dye pollution is underscored by its adverse effects on aquatic ecosystems, soil quality and human health. As the textile industry continues to expand, so does the imperative to develop advanced and sustainable technologies that can mitigate the environmental impact of dye discharge (Zhang *et al.* 2022).

The catalytic prowess of nanoparticles has been well-established in various fields, and recent advancements in bio-inspired synthesis methods have provided a sustainable approach to tailor these nanoparticles for efficient dye degradation (Huo *et al.* 2020). This review will delve into the intricacies of biosynthesis techniques, emphasizing the use of natural extracts with inherent catalytic properties. By examining the diverse range of nanoparticles synthesized and their unique characteristics, we aim to provide insights into the critical factors influencing catalytic efficiency (Chahal *et al.* 2022).

Furthermore, the paper will offer a comprehensive analysis of the catalytic degradation process itself, elucidating the underlying mechanisms and kinetics governing the breakdown of industrial dyes. The environmental implications of using biosynthesized nanoparticles for dye remediation will be evaluated, considering the aspects of sustainability, scalability and comparability with conventional methods (Uribe *et al.* 2019).

1.1 INDUSTRIAL DYES

The impact of industrial dyes on the environment is a multifaceted concern with far-reaching consequences across various ecosystems, the significant one being water pollution, as the discharge of industrial effluents laden with residual dyes contaminates surface water bodies and compromises aquatic habitats. This contamination extends beyond surface water, as improper disposal practices can lead to the infiltration of dye compounds into groundwater, jeopardizing the quality of drinking water sources (Mohammadi *et al*. 2011). Additionally, industrial dye residues contribute to soil contamination, potentially affecting agricultural productivity and posing risks to both plant life and the broader ecosystem. The ecotoxicity of certain dye compounds poses threats to aquatic life, disrupting the balance of ecosystems and endangering biodiversity. Human health concerns arise from occupational exposure in industries involved in dye production and application, as well as potential consumer exposure to residual dyes in end-products like textiles. Furthermore, the challenges associated with the color fastness of dyes contribute to significant waste generation and complicate recycling efforts, adding to the environmental burden (Shaheen *et al.* 2020). Addressing the impact of industrial dyes necessitates a comprehensive approach, including the development of sustainable dyeing processes, advanced wastewater treatment technologies and the exploration of eco-friendly alternatives, along with the regulatory measures to mitigate environmental harm and promote responsible industrial practices (Chen and Chen, 2022).

2. MODE OF NANOPARTICLE SYNTHESIS

2.1 CHEMICAL REDUCTION METHOD

Nanoparticle synthesis involves diverse methods that cater to specific characteristics such as size, shape, and composition. One prevalent approach is the Chemical Reduction method, wherein metal ions in a solution are reduced to form nanoparticles (Lamba *et al.* 2015). Typically, a reducing agent is introduced to a metal salt solution, leading to the formation of nanoparticles' for instance, gold nanoparticles can be synthesized by reducing gold chloride ($AuCl_4^-$) using sodium citrate or sodium borohydride as a reducing agent. The Chemical Reduction method stands as a prominent technique for synthesizing nanoparticles with precise control over their characteristics (Esplugas *et al.* 2007). In this approach, metal ions in a solution are systematically reduced to form nanoparticles, introducing a reducing agent to a metal salt solution. The choice of reducing agent plays a crucial role in determining the outcome, impacting the size, shape and composition of the resulting nanoparticles. An illustrative example involves the synthesis of gold nanoparticles by reducing gold chloride ($AuCl_4^-$) using sodium citrate or sodium borohydride as the reducing agent. During the reaction, the reducing agent facilitates the reduction of metal ions to their elemental state, promoting the nucleation and subsequent growth of nanoparticles (Suman *et al*. 2021). This method provides versatility, allowing the production of a diverse range of nanoparticles tailored for specific applications. The control over parameters such as temperature, concentration and reaction time enable researchers to fine-tune the properties of the synthesized nanoparticles. The Chemical Reduction method's simplicity, efficiency, and adaptability make it a widely employed technique in the field of nanotechnology, contributing to advancements in materials science, medicine and various other interdisciplinary domains (Rani *et al*. 2020).

2.2 SOL-GEL PROCESS

Another technique is the Sol-gel process, a chemical method that transforms a colloidal solution into a gel and then into a solid material, resulting in the formation of nanoparticles during the gelation process. Silica nanoparticles, for example, can be synthesized through the sol-gel process by hydrolyzing tetraethyl orthosilicate (TEOS) in the presence of a catalyst (Hanafi and Sapawe, 2020). The Sol-gel process is a versatile and widely utilized method for the synthesis of nanoparticles, providing a controlled approach to produce materials with tailored properties. In this chemical process, a sol, which is a colloidal suspension of nanoparticles, undergoes gelation to form a gel and ultimately transforms into a solid material. The key advantage of the Sol-gel process lies in the ability to precisely manipulate the size, shape and composition of the resulting nanoparticles. As an example, silica nanoparticles can be synthesized through the Sol-gel process by hydrolyzing tetraethyl orthosilicate (TEOS) in the presence of a catalyst. The process involves the initiation of hydrolysis reactions, leading to the formation of a silica-based gel network (Chandran *et al.* 2016). The subsequent condensation of the gel further refines the structure, resulting in well-defined nanoparticles. This method offers exceptional control over the nanoparticle characteristics by adjusting parameters such as the concentration of precursors, reaction time and temperature. The versatility of the Sol-gel process extends to the synthesis of a variety of nanoparticles with applications in catalysis, sensors, coatings and biomedical fields. Its adaptability and precision make it a preferred choice for researchers seeking reproducibility and tunability in the fabrication of nanomaterials for diverse technological applications (Zhang *et al.* 2022).

2.3 MICROEMULSION

Microemulsion is a method where nanoparticles are formed within microemulsion droplets, providing control over the particle's size and shape. Iron oxide nanoparticles, for instance, can be synthesized through co-precipitation within microemulsion droplets. The Microemulsion method is a versatile and effective approach for synthesizing nanoparticles, offering precise control over their size, shape and composition (Chen *et al.* 2021). This technique involves the use of microemulsions, which are stable colloidal dispersions of immiscible liquids (usually oil and water) stabilized by surfactants and co-surfactants. Within the confined spaces of these microemulsion droplets, nanoparticles are formed, providing an environment conducive to controlled particle growth (Ferdosi *et al.* 2019). As an illustration, iron oxide nanoparticles can be synthesized through the Microemulsion method by co-precipitation within microemulsion droplets. The process begins with the introduction of iron salts into the microemulsion system, where the confined spaces permit the controlled nucleation and growth of nanoparticles. The surfactant layer stabilizes the formed nanoparticles, preventing agglomeration. This method offers several advantages, including precise control over particle size and distribution, ease of scalability and the ability to produce mono-disperse nanoparticles (Chang *et al.* 2014). Additionally, the microemulsion method is adaptable to various nanoparticle compositions and has applications in fields such as catalysis, magnetic materials and biomedical sciences. The controlled synthesis achieved through microemulsion makes it a valuable technique for researchers seeking reproducibility and tunability in the fabrication of nanoparticles for specific applications. Green synthesis methods, involving plant extracts or microorganisms as reducing or stabilizing agents, are environment-friendly, yielding biocompatible nanoparticles (Devi *et al.* 2023). Silver nanoparticles can be synthesized using neem leaf extracts as a reducing agent. Green synthesis methods represent an environmentally sustainable approach to nanoparticle synthesis, utilizing natural sources such as plant extracts, microorganisms or other bio-friendly materials as reducing or stabilizing agents. This eco-friendly strategy aligns with the principles of green chemistry, minimizing the use of hazardous chemicals and reducing the environmental impact associated with traditional synthesis methods. In the context of green synthesis, silver nanoparticles are commonly produced using plant extracts, exemplifying the process. The plant extract, rich in bioactive compounds, serves as both a reducing and stabilizing agent. The reduction of silver ions to silver nanoparticles is facilitated by the bioactive components present in the plant extract, leading to the formation of stable and biocompatible nanoparticles. Green synthesis methods offer several advantages, including reduced toxicity, cost-effectiveness and the potential for large-scale production, without compromising environmental integrity. Additionally, the synthesized nanoparticles often exhibit enhanced biocompatibility, making them suitable for various biomedical applications (Theerthagiri *et al.* 2018) As a sustainable alternative to conventional methods, green synthesis is gaining prominence in nanotechnology, contributing to the development of environmentally benign and biocompatible nanoparticles for diverse applications (Chahal *et al*. 2023).

2.4 HYDROTHERMAL/SOLVOTHERMAL SYNTHESIS

Hydrothermal/Solvothermal synthesis involves high-temperature, high-pressure reactions in an aqueous environment, resulting in nanoparticles like zinc oxide through the hydrothermal process using zinc nitrate and a base. Hydrothermal and solvothermal synthesis methods are robust techniques for the production of nanoparticles, involving high-temperature and high-pressure reactions in an aqueous or organic solvent environment. These methods provide precise control over nanoparticle size, morphology and crystallinity, making them versatile for various applications (Li *et al*. 2014). In hydrothermal synthesis, a reaction takes place in an aqueous medium at elevated temperatures and pressures. For instance, zinc oxide nanoparticles can be synthesized through the hydrothermal process using zinc nitrate and a base as precursors. The controlled reaction conditions allow for the growth of well-defined nanoparticles with tailored properties. Solvothermal synthesis follows a similar principle but employs organic solvents instead of water. This approach is particularly useful for synthesizing nanoparticles with unique structures and properties (Zhang *et al.* 2022). The solvents used can influence the growth and stabilization of nanoparticles during the synthesis process. These methods are advantageous for their ability to produce nanoparticles with controlled characteristics, high purity and crystallinity. Hydrothermal and solvothermal synthesis techniques are widely employed in the fabrication of materials for applications ranging from catalysis and sensors to energy storage and biomedical fields. Their adaptability and precision make them essential tools in the development of nanomaterials with tailored properties to meet specific technological demands (Fatima *et al.* 2020).

2.5 ELECTROCHEMICAL SYNTHESIS

Electrochemical synthesis utilizes electrochemical reactions, applying an electric potential to a solution containing metal ions to synthesize nanoparticles. Copper nanoparticles, for instance, can be obtained by electrochemical reduction of copper ions. Electrochemical synthesis is a versatile and precise method for the production of nanoparticles, involving the application of an electric potential to a solution containing metal ions. This method allows for controlled reduction reactions, leading to the formation of nanoparticles with well-defined properties; one illustrative example is the electrochemical synthesis of copper nanoparticles. In this process, a copper salt solution serves as the precursor, and the application of an electric potential facilitates the reduction of copper ions to form elemental copper nanoparticles. The electrode acts as a platform for nucleation and growth, enabling the controlled development of nanoparticles. The size and morphology of the nanoparticles can be fine-tuned by adjusting parameters such as voltage, current and reaction time. Electrochemical synthesis offers several advantages, including simplicity, scalability and the ability to produce nanoparticles with high purity. Additionally, the direct deposition of nanoparticles onto conductive substrates simplifies their integration into various applications, such as sensors, catalysts and electronic devices. This method's adaptability to different metal precursors and facile control over particle characteristics make it a valuable tool in nanotechnology (Ghafuri *et al*. 2019). Researchers utilize this technique for its efficiency in producing nanoparticles tailored for specific functionalities in diverse fields of science and technology.

2.6 TEMPLATE-ASSISTED METHODS

Template-assisted methods involve templates like porous materials or sacrificial structures guiding the formation of nanoparticles with specific structures. Mesoporous silica nanoparticles can be synthesized using a template-assisted approach. Template-assisted methods are innovative approaches to nanoparticle synthesis that involve the use of templates to guide and control the formation of nanoparticles with specific structures (Theerthagiri *et al.* 2018). These templates can be sacrificial structures or porous materials, providing a framework for the desired nanoparticle morphology. One exemplary application is the synthesis of mesoporous silica nanoparticles. In this method, a template, often composed of organic or inorganic materials, is impregnated with a silica precursor such as tetraethyl orthosilicate (TEOS) (Huang *et al.* 2018) Subsequent removal or decomposition of the template leaves behind a well-defined porous structure within the silica matrix, forming mesoporous silica nanoparticles. The size and arrangement of the pores can be precisely engineered by selecting an appropriate template and controlling the synthesis conditions. Template-assisted methods offer advantages such as tunable porosity, a high surface area and well-defined structures. These characteristics make the resulting nanoparticles suitable for applications in drug delivery, catalysis and sensing. The versatility of template-assisted synthesis extends to the use of various templates and precursor materials, providing researchers with a powerful tool to design and fabricate nanoparticles tailored to specific applications (Zhao *et al*. 2015).

3. DYE TREATMENT STRATEGIES

Dye treatment strategies are integral in addressing the environmental challenges posed by the discharge of industrial dyes into water bodies. Various methods have been developed to mitigate the adverse impact of these pollutants on ecosystems. Physical treatment involves the use of physical processes such as adsorption, filtration and sedimentation to remove dyes from wastewater. Activated carbon, zeolites and other adsorbents are commonly employed in this approach. Chemical treatment utilizes chemical reactions to break down or transform dye molecules, with methods like coagulation, flocculation and advanced oxidation processes (AOPs) being employed. Coagulation and flocculation involve the addition of chemicals to precipitate and aggregate dye particles for easier removal (Liu *et al.* 2018). AOPs, such as photocatalysis using catalysts like titanium dioxide, harness the power of reactive oxygen species to degrade dyes. Biological treatment employs microorganisms to metabolize and break down dye molecules, utilizing processes like aerobic and anaerobic biodegradation. Constructed wetlands and microbial fuel cells are innovative applications of biological treatment. Combining these strategies into integrated approaches, such as the hybridization of physical-chemical or biological-chemical methods, showcases the potential for more efficient and comprehensive dye treatment systems. As environmental concerns grow, the development and optimization of these dye treatment strategies play a pivotal role in promoting sustainable industrial practices and safeguarding water ecosystems (Abou *et al.* 2010).

3.1 PHYSICAL METHODS FOR DYE TREATMENT

Industrial activities, particularly in the textile sector, contribute significantly to water pollution through the release of various dyes into water bodies. The environmental repercussions of uncontrolled dye discharge necessitate effective and sustainable treatment strategies (Dharwal *et al*. 2020). Among the diverse array of treatment methods, physical techniques play a pivotal role, offering advantages such as simplicity, minimal chemical usage and potential cost-effectiveness. This review provides an in-depth exploration of prominent physical methods employed in the treatment of dye-contaminated wastewater (Naseem *et al.* 2018).

3.1.1 Adsorption

Adsorption is a widely utilized physical method for dye removal that relies on the adherence of dye molecules onto a solid surface. Activated carbon, zeolites and other porous materials are commonly employed as adsorbents due to their high surface area and adsorption capacity (Lellis *et al.* 2019). The process is governed by various factors, including the characteristics of the adsorbent, pH, temperature and initial dye concentration. Adsorption can effectively reduce dye concentrations, making it suitable for both industrial and laboratory-scale applications. Challenges, such as adsorbent regeneration and saturation, are addressed through optimized operational parameters (Vijaya *et al*. 2022).

3.1.2 Filtration

Filtration is a fundamental physical process in which dye-containing water is passed through a medium to separate dye particles from the liquid phase. Various filtration techniques are employed based on factors such as the size and nature of the dye particles. Sand filtration, for instance, utilizes a bed of sand to trap and retain dye particles (Chahal *et al*. 2020); Membrane filtration, on the other hand, employs semi-permeable membranes with defined pore sizes to selectively separate dye molecules from water. The choice of filtration method depends on factors like the size of the dye molecules, the required level of purification and the characteristics of the wastewater (Duan *et al.* 2016).

3.1.3 Sedimentation

Sedimentation involves the gravitational settling of dye particles within a liquid, leading to their separation from the water. This process is particularly effective for larger, denser particles that tend to settle at the bottom of a container. Coagulants or flocculants may be added to enhance particle aggregation, facilitating quicker sedimentation. Although sedimentation is a straightforward physical method, its efficiency depends on factors such as particle size, settling velocity and the presence of interfering substances (Farhadi *et al*. 2017).

3.1.4 Photocatalysis

Photocatalysis is an advanced physical method that utilizes light-induced chemical reactions to accelerate the degradation of dye molecules. Titanium dioxide (TiO_2) is a widely used photocatalyst in this process. When exposed to ultraviolet (UV) light, TiO_2 generates reactive oxygen species (ROS) that initiates the breakdown of dye molecules into simpler, less harmful components. Photocatalysis is particularly effective for organic dyes that are resistant to conventional treatment methods. Research in this field focuses on optimizing catalyst properties, light sources and reactor designs to enhance the overall efficiency of the photocatalytic process (Karimi-Maleh *et al.* 2020).

3.1.5 Electrochemical Methods

Electrochemical methods involve the application of an electric field or current to induce the migration and removal of dye ions from water; Electrocoagulation, for example, utilizes the destabilization of charged particles through the application of electric current, which leads to the formation of aggregates that can be easily separated from the water (Zong *et al.* 2014). Electrochemical methods offer advantages such as ease of control, minimal chemical usage and the potential for metal recovery through electrodeposition. The choice of electrodes, voltage and reaction time influences the efficiency of the electrochemical treatment (Uribe *et al.* 2019).

3.2 Chemical Methods for Dye Treatment

The discharge of industrial dyes into water bodies poses a significant environmental challenge, necessitating effective treatment strategies (Liu *et al.* 2019). Chemical methods stand at the forefront of dye treatment, leveraging chemical reactions to transform or remove dye molecules from wastewater. This comprehensive review explores the principles, applications, challenges and emerging trends in the realm of chemical methods for dye treatment.

3.2.1 Coagulation and Flocculation

Coagulation and flocculation are chemical methods that involve the addition of chemicals to destabilize and aggregate dye particles, facilitating their removal from water. Coagulants, such as aluminum sulfate (alum) or ferric chloride, neutralize the negative charges on dye particles. Flocculants, commonly polymers, aid in the formation of larger flocs that can be easily separated from the water. These methods find wide applications in industries where finely divided suspended particles, including dyes, need to be efficiently removed (Zamora *et al.* 2019). Municipal wastewater treatment plants, as well as industries like textiles, paper and tanneries, benefit from coagulation and flocculation. The efficiency of coagulation and flocculation depends on factors such as the type of dye, pH, temperature and the dosage of chemicals. Optimal conditions are often dye-specific, necessitating tailored approaches. Residual coagulants and flocculants in the treated water may pose challenges, emphasizing the importance of effective post-treatment (Al-Hamdi *et al.* 2014).

3.2.2 Advanced Oxidation Processes (AOPs)

AOPs involve the generation of highly reactive hydroxyl radicals (•OH) to oxidize and break down dye molecules. Common AOPs include ozonation, Fenton's reaction (Fe^{2+}/H_2O_2) and photocatalysis using semiconductor materials like titanium dioxide (TiO_2) activated by UV light. AOPs are effective in treating recalcitrant and complex dye compounds that resist conventional treatment methods (Hosseini *et al.* 2022). They find applications in treating industrial effluents containing persistent dyes and are particularly valuable for color removal. AOPs can be energy-intensive and may generate by-products, necessitating careful optimization. The efficiency depends on factors such as the nature of the dye, reactor design and the presence of other organic or inorganic compounds in the wastewater (Fu *et al.* 2011).

3.2.3 Biological Treatment

Biological treatment methods utilize microorganisms to metabolize and break down dye molecules. Aerobic and anaerobic biodegradation are common approaches. In aerobic conditions, microorganisms utilize oxygen to degrade dyes, while anaerobic conditions involve degradation in the absence of oxygen. Biological treatment is particularly effective for treating textile wastewater, which often contains complex dye compounds (Chahal *et al.* 2020). Constructed wetlands, activated sludge processes and microbial fuel cells are examples of biological treatment methods. The effectiveness of biological treatment can be influenced by factors such as pH, temperature and the presence of inhibitory substances. Slow degradation rates and the potential for biomass accumulation are challenges addressed through optimization and system design (Kumar *et al.* 2022).

3.2.4 Chemical Precipitation

Chemical precipitation involves the addition of chemicals that react with dye ions to form insoluble precipitates. Common precipitants include lime (calcium hydroxide), sodium carbonate and sodium hydroxide. Chemical precipitation is employed for the removal of heavy metal ions and certain types of dyes from the wastewater. The formed precipitates can be easily separated through sedimentation or filtration. The effectiveness of chemical precipitation depends on factors such as the solubility of the precipitate, pH and the stoichiometry of the reaction. Sludge generation and the need for careful pH control are aspects addressed in system optimization (Thevarajah *et al.* 2005).

3.2.5 Ion Exchange: Principles

Ion exchange involves the exchange of ions between a solid resin and the dye ions in solution. The resin selectively captures dye ions, releasing other ions in exchange. Ion exchange is effective for the removal of specific ions, including dye ions, from wastewater. It is particularly valuable for treating low concentrations of targeted pollutants. Ion exchange can be limited by resin capacity and regeneration requirements. The selectivity of the resin and the potential for fouling need to be considered in optimizing ion exchange processes (Balakumar and Rakkesh, 2013).

3.2.6 Nanotechnology in Chemical Treatment

The integration of nanomaterials, such as nanoparticles and nanocomposites, is an emerging trend in chemical treatment. Nanocatalysts enhance the efficiency of AOPs, and nanomaterials can be functionalized for selective adsorption (Chen *et al.* 2020).

3.2.7 Green Chemistry Approaches

The application of green chemistry principles in dye treatment involves minimizing the use of hazardous chemicals and promoting sustainable processes. Bio-based coagulants and eco-friendly oxidants exemplify this trend (Lundström *et al.* 2016).

3.2.8 Hybrid Treatment Systems

Integrating multiple chemical treatment methods or combining chemical methods with physical and biological processes represents a holistic approach. Hybrid systems capitalize on the strengths of different methods for enhanced efficiency (Xing *et al.* 2017).

3.2.9 Electrochemical Treatment

Electrochemical methods, particularly electrocoagulation and electrooxidation, are gaining attention for their versatility and effectiveness in dye removal. They offer advantages such as rapid treatment and the potential for metal recovery (Naseem *et al*. 2021).

3.3 BIOLOGICAL METHODS FOR DYE TREATMENT

Industrial activities, especially in the textile and dyeing sectors, contribute significantly to water pollution through the release of diverse and often complex dye compounds into water bodies. As environmental concerns escalate, biological methods for dye treatment are gaining prominence due to their sustainability, efficiency and potential for mitigating the impact of dye pollutants. This comprehensive review provides an in-depth exploration of biological methods, encompassing principles, applications, challenges and emerging trends in the context of dye wastewater treatment (Kapoor *et al.* 2021).

3.3.1 Aerobic Biodegradation

Aerobic biodegradation involves the breakdown of dye compounds by microorganisms in the presence of oxygen. In aerobic conditions, bacteria utilize oxygen to oxidize organic pollutants, converting them into simpler and less harmful by-products. Key microorganisms involved in aerobic biodegradation include bacteria, fungi and algae. Aerobic biodegradation is effective for treating water contaminated with readily biodegradable dyes. Wastewater from textile and dyeing industries, which often contains azo dyes and other organic compounds, is a prime candidate for aerobic treatment. The efficiency of aerobic biodegradation can be influenced by factors such as the nature of the dye, microbial activity, pH and temperature. Some complex and recalcitrant dyes may resist complete degradation, necessitating complementary treatment methods (Xiao *et al.* 2018).

3.3.2 Anaerobic Biodegradation

Anaerobic biodegradation occurs in the absence of oxygen, relying on microorganisms that can thrive in oxygen-depleted environments. Anaerobic bacteria facilitate the breakdown of complex dye molecules, leading to the generation of simpler compounds and gases like methane. Anaerobic biodegradation is suitable for treating wastewater with persistent and recalcitrant dye compounds. It is particularly effective for treating azo dyes, which are often challenging to degrade using conventional methods. The slower degradation rates in anaerobic conditions and the potential for the accumulation of intermediate metabolites are the challenges addressed through process optimization and system design. Co-substrate addition and control of environmental parameters are key considerations (Huang *et al.* 2021).

3.3.3 Constructed Wetlands

Constructed wetlands leverage natural processes in engineered systems to treat dye-containing wastewater. Wetland plants and associated microorganisms play a crucial role in the uptake and degradation of dye compounds. The wetland matrix provides a supportive environment for microbial communities. Constructed wetlands are applicable to various types of dye pollutants, providing a versatile and sustainable treatment option. They are particularly suitable for decentralized treatment in small- to medium-sized facilities. The efficiency of constructed wetlands depends on factors such as plant selection, hydraulic retention time and the characteristics of the dye pollutants. Performance variations and the need for land availability are considerations in implementing this method (Hao *et al*. 2021).

3.3.4 Microbial Fuel Cells (MFCs)

Microbial fuel cells harness the metabolic activity of microorganisms to generate electrical energy while simultaneously treating wastewater. The microbial oxidation of organic compounds, including dye pollutants, releases electrons that contribute to electricity generation. Microbial fuel cells offer a dual benefit of energy generation and wastewater treatment. They are applicable to wastewater with low to moderate concentrations of organic pollutants, making them suitable for decentralized applications. MFCs face challenges related to power output, reactor design and the scalability of the technology. The ongoing research focuses on the optimization of electrode materials, microbial communities and operational parameters (Fatima *et al.* 2020).

3.3.5 Sequential Batch Reactors (SBRs)

Sequential batch reactors involve the cyclic operation of fill, react, settle and decant phases in a single reactor. Microorganisms are acclimated to specific dye compounds during the react phase, facilitating their efficient biodegradation. SBRs are versatile and can be tailored to treat various dye pollutants. They are adaptable to different operational conditions and are commonly employed in small to medium-sized treatment plants. Challenges associated with SBRs include process control, potential fluctuations in treatment efficiency and the need for intermittent operational attention. These challenges are addressed through advanced control strategies and monitoring (Abdel *et al*. 2008).

3.3.6 Genetically Engineered Microorganisms

Advances in genetic engineering allow the modification of microorganisms for enhanced dye degradation capabilities. Engineered bacteria with specific enzymes can improve the efficiency and specificity of dye biodegradation (Yuan *et al.* 2022).

3.3.7 Bio-electrochemical Systems

The integration of microbial electrochemical systems, such as bio-electrochemical reactors and microbial electrolysis cells, represents an emerging trend. These systems offer opportunities for simultaneous dye removal and energy recovery (Gholami *et al.* 2015).

3.3.8 Microbiome-based Approaches

Understanding and manipulating the microbial communities in biological treatment systems is an emerging research trend. Microbiome-based approaches aim to enhance the resilience and performance of microorganisms in degrading complex dye mixtures (Feng *et al*. 2023).

3.3.9 Metagenomics and Meta Transcriptomics

The application of metagenomics and metatranscriptomics facilitates a comprehensive analysis of microbial communities and their functional genes. This knowledge aids in optimizing biological treatment systems for diverse dye pollutants (Chahal *et al.* 2020).

3.4 Principles of Nanoparticle Interaction

Wastewater management is a critical aspect of environmental sustainability, particularly in the context of industrial activities that contribute to water pollution. Traditional methods of wastewater treatment often face challenges in efficiently removing complex contaminants. In recent years, there has been a growing interest in the application of nanotechnology to address these challenges. Nanoparticle-based wastewater treatment techniques offer unique advantages due to the remarkable properties of nanoparticles, including their high surface area, reactivity and versatility (Chen and Lee, 2014).

3.5 NANOPARTICLE CHARACTERISTICS

Nanoparticles are defined as particles with sizes ranging from 1 to 100 nm. Their small size imparts distinctive physical and chemical properties, such as a high surface area-to-volume ratio and increased reactivity. These properties make nanoparticles highly effective in interacting with various contaminants in wastewater (Holkar *et al.* 2016).

3.5.1 Nanoparticle-Contaminant Interaction Mechanisms

Several mechanisms govern the interaction between nanoparticles and the contaminants in wastewater:

- **Adsorption:** Nanoparticles, due to their large surface area, can adsorb contaminants onto their surfaces. This process is particularly effective in removing organic dyes, heavy metals and other pollutants.
- **Catalysis:** Certain nanoparticles exhibit catalytic properties, allowing them to facilitate chemical reactions that lead to the degradation of pollutants. For example, titanium dioxide (TiO_2) nanoparticles are known for their photocatalytic activity (Zhang *et al.* 2021).
- **Coagulation and Flocculation:** Nanoparticles, especially metal-based ones, can act as coagulants or flocculants. They destabilize particles in wastewater, promoting their aggregation and subsequent removal.

3.5.2 Types of Nanoparticles

3.5.2.1 Metal-based Nanoparticles

a. Silver Nanoparticles

Silver nanoparticles are well-known for their antibacterial properties, making them effective in disinfection processes. In wastewater treatment, they can help control microbial growth and reduce the risk of waterborne diseases (Zhao *et al.* 2015).

b. Iron Nanoparticles

Iron nanoparticles are widely utilized for their coagulation and flocculation properties. They can effectively destabilize contaminants in wastewater, facilitating their removal through precipitation or filtration.

c. Other Metal Nanoparticles

Various other metal nanoparticles, including copper, gold and platinum, exhibit unique properties that can be harnessed for specific wastewater treatment applications (Holkar *et al*. 2016).

3.5.2.2 Metal Oxide Nanoparticles

a. Titanium Dioxide (TiO_2) Nanoparticles

TiO_2 nanoparticles are extensively used in photocatalysis. When exposed to light, they generate reactive oxygen species that can degrade organic pollutants, providing an effective means of treating recalcitrant compounds (Hamad *et al.* 2015).

b. Zinc Oxide (ZnO) Nanoparticles

ZnO nanoparticles also possess photocatalytic properties and can contribute to the degradation of organic contaminants. Additionally, their antimicrobial characteristics make them valuable in disinfection processes (Zhang *et al.* 2015).

c. Iron Oxide Nanoparticles

Iron oxide nanoparticles, such as magnetite (Fe_3O_4) and hematite (Fe_2O_3), are employed for the adsorption and removal of heavy metals from wastewater. Their magnetic properties enable easy separation from treated water.

3.5.2.3 Carbon-Based Nanoparticles

a. Graphene Nanoparticles

Graphene and graphene oxide nanoparticles offer large surface areas for adsorption. They can effectively adsorb organic compounds, including dyes, in wastewater treatment processes. (Klein *et al.* 2015).

b. Carbon Nanotubes

Carbon nanotubes exhibit excellent adsorption properties and can be functionalized to enhance their affinity for specific contaminants. They are particularly effective in removing organic pollutants.

4. NANOPARTICLE-BASED TREATMENT TECHNIQUES

4.1 ADSORPTION

Adsorption is a fundamental mechanism employed in nanoparticle-based wastewater treatment. Nanoparticles, with their high surface area, provide ample sites for the attachment of contaminants. Activated carbon nanoparticles, for instance, are widely used for their exceptional adsorption capacity for organic dyes and heavy metals (Rani and Shanker, 2018).

4.2 PHOTOCATALYSIS

Photocatalysis involves the use of nanoparticles, typically metal oxides like TiO_2 and ZnO, to harness light energy and generate reactive oxygen species. These reactive species initiate chemical reactions that lead to the degradation of organic pollutants. Photocatalytic processes are highly effective in treating recalcitrant compounds (Govindaraj *et al.* 2021).

4.3 COAGULATION AND FLOCCULATION

Nanoparticles, especially metal-based ones, can act as coagulants or flocculants in wastewater treatment. The addition of nanoparticles destabilizes particles in the water, promoting their aggregation. This aggregation leads to the formation of larger flocs that can be easily separated from the water through sedimentation or filtration (Chahal *et al.* 2022).

4.4 MEMBRANE FILTRATION

Nanoparticles are incorporated into membrane technologies to enhance filtration efficiency. Functionalized nanoparticles can modify the surface properties of membranes, improving their selectivity and anti-fouling characteristics; this makes membrane filtration processes more effective in removing contaminants from wastewater (Hethnawi *et al*. 2017).

4.5 NANOZYMES

Nanozymes are nanomaterials that exhibit enzyme-like catalytic activities. Cerium oxide nanoparticles, for example, possess peroxidase-like activity. This property enables them to catalyze the breakdown of organic pollutants in wastewater, providing an effective means of treatment.

4.6 NANOMATERIALS FOR HEAVY METAL REMOVAL

Nanoparticles, especially those composed of iron oxides, are highly effective in sequestering heavy metals from wastewater. Their magnetic properties facilitate easy recovery, making them suitable for the removal of toxic metals (Zhong *et al.* 2020).

4.7 PHOTOCATALYTIC DEGRADATION OF WASTEWATER BY SYNTHESIZED NANOPARTICLES

Water pollution, primarily driven by industrial activities, poses a significant threat to the environment and human health. Traditional wastewater treatment methods often struggle to efficiently remove persistent organic pollutants and dyes. In recent years, photocatalytic degradation using synthesized nanoparticles has emerged as a promising and sustainable solution. This review provides a comprehensive examination of the principles, applications, challenges and prospects of photocatalytic degradation in wastewater treatment, focusing on the nanoparticles synthesized for this purpose.

4.8 PHOTOCATALYTIC REACTION MECHANISM

Photocatalysis involves the use of a semiconductor material, typically titanium dioxide (TiO_2), which, when exposed to light, generates electron-hole pairs. These reactive species participate in redox reactions with water and oxygen, producing highly reactive radicals, such as hydroxyl radicals (•OH). These radicals are potent oxidizing agents that can break down organic pollutants into simpler and less harmful compounds (Forgacs *et al.* 2004).

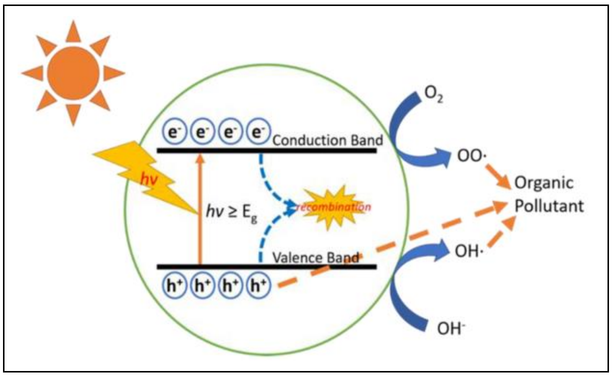

Fig. 1: Organic pollutants from the earth (Zhongwei *et al.* 2021)

4.9 SEMICONDUCTOR MATERIALS IN PHOTOCATALYSIS

a. Titanium dioxide (TiO_2)

TiO_2 is the most widely used semiconductor in photocatalysis due to its excellent stability, non-toxicity and high photocatalytic activity under ultraviolet (UV) light. However, its wide bandgap limits its activity to UV light, prompting the development of modified TiO_2 and other semiconductor materials to extend the photocatalytic response to visible light (Bandi *et al.* 2013).

b. Zinc oxide (ZnO)

ZnO is another semiconductor with favorable properties for photocatalysis. It exhibits a lower bandgap than TiO_2, thus allowing better utilization of visible light. ZnO nanoparticles have demonstrated effectiveness in degrading various organic pollutants in wastewater (Thevarajah *et al.* 2005).

c. Other Semiconductor Nanoparticles

Advancements in nanotechnology have led to the synthesis of various semiconductor nanoparticles, such as tungsten oxide (WO_3), bismuth vanadate ($BiVO_4$) and g-C_3N_4, each offering unique properties for photocatalytic applications.

5. APPLICATIONS OF PHOTOCATALYTIC NANOPARTICLES IN WASTEWATER TREATMENT

5.1 DEGRADATION OF ORGANIC POLLUTANTS

Photocatalytic nanoparticles have demonstrated remarkable efficacy in the degradation of a wide range of organic pollutants, including dyes, phenols, pesticides and pharmaceuticals. The generation of highly reactive radicals during photocatalysis enables the breakdown of complex organic compounds into simpler, less toxic by-products (Kumar *et al.* 2022).

5.2 REMOVAL OF HEAVY METALS

Semiconductor nanoparticles, especially TiO_2 and ZnO, have shown potential in the removal of heavy metals from wastewater through photocatalytic reduction and precipitation. This application contributes to the remediation of industrial effluents containing toxic metal ions (Mohammadi *et al.* 2011).

5.3 ANTIBACTERIAL ACTIVITY

The photocatalytic properties of nanoparticles, particularly silver nanoparticles, contribute to their antibacterial activity. Photo-generated reactive species inhibit bacterial growth and enhance the disinfection of water, addressing microbial contamination in wastewater (Esplugas *et al.* 2007).

5.4 FUTURE PROSPECTS AND EMERGING TRENDS

5.4.1 Advanced Nanocomposites

The development of nanocomposites involving multiple nanoparticles or hybrid materials is an emerging trend. These advanced nanocomposites aim to synergize the unique properties of different materials, enhancing photocatalytic efficiency (Phor *et al.* 2022).

5.4.2 2D Materials in Photocatalysis

The integration of two-dimensional (2D) materials, such as graphene and graphene oxide, with photocatalytic nanoparticles is gaining attention. These materials can serve as excellent supports, enhancing electron transport and promoting catalytic activity.

5.4.3 Tailored Nanoparticles for Specific Pollutants

Customizing the synthesis of nanoparticles for specific pollutants is an evolving approach. Tailored nanoparticles can exhibit enhanced selectivity and efficiency in degrading particular classes of contaminants (Zhang *et al.* 2022).

6. CONCLUSION

The catalytical degradation of industrial dyes using biosynthesized nanoparticles represents a transformative approach in the realm of wastewater treatment. This comprehensive review has delved into the multi-faceted aspects of this innovative technology, exploring its principles, synthesis methods, applications, challenges and prospects. In conclusion, the catalytical degradation of industrial dyes using biosynthesized nanoparticles emerges as a transformative and sustainable strategy for addressing the environmental challenges posed by dye-contaminated wastewater. This review has systematically explored the principles, synthesis methodologies, applications, challenges and prospects of this innovative technology.

The utilization of biological entities in nanoparticle synthesis, such as microorganisms and plant extracts, highlights the paradigm shift towards green and eco-friendly approaches. The inherent reducing and stabilizing properties of these biological agents streamline the synthesis process, emphasizing the importance of environmentally conscious methods in nanotechnology.

The applications of biosynthesized nanoparticles in the catalytical degradation of industrial dyes span a spectrum of industries, offering a versatile and effective solution to the complex problem of dye pollution. Their demonstrated efficacy across various dye classes underscores their potential as a universal treatment method for diverse industrial effluents.

Despite the promises, challenges such as scalability, reproducibility and stability persist. Overcoming these hurdles requires continued interdisciplinary research, collaborative efforts and the development of standardized protocols. Addressing these challenges is crucial for the practical implementation of biosynthesized nanoparticles in large-scale wastewater treatment facilities.

Looking forward, the future of catalytical degradation using biosynthesized nanoparticles holds exciting prospects. The integration of advanced analytical techniques, exploration of nanocomposites and the potential incorporation of artificial intelligence in process optimization signal a dynamic and evolving field. Through ongoing research and a commitment to sustainable practices, biosynthesized nanoparticles are poised to play a pivotal role in shaping the future of industrial dye wastewater treatment. As we conclude this review, it is evident that biosynthesized nanoparticles hold tremendous potential in addressing the environmental impact of industrial dye discharges.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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