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Nanotechnology in waste water treatment: A review

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***Abstract:** In today's context of diminishing water resources, effective wastewater treatment has become essential for economic growth. The development and implementation of advanced technologies that offer high efficiency and low capital costs are crucial. Recent advancements in nano-material sciences have garnered significant attention from researchers as a promising solution. However, the body of knowledge in this area remains limited. This manuscript reviews the emerging potential of nanotechnology in the realm of wastewater treatment, discussing the application of various categories of nano-materials in these processes. The review identifies four primary classes of nano-materials used in wastewater treatment. The first category includes nano-adsorbents such as activated carbon, carbon nanotubes, graphene, manganese oxide, zinc oxide, titanium oxide, magnesium oxide, and ferric oxides, which are primarily utilized to extract heavy metals from wastewater. The second class comprises nano-catalysts, including photocatalysts, electrocatalysts, Fenton-based catalysts, and chemical oxidants, all of which demonstrate the ability to eliminate both organic and inorganic pollutants. The third category involves nano-membranes designed for the efficient removal of dyes, heavy metals, and other foulants, utilizing carbon nanotube membranes, electrospun nanofibers, and hybrid nano-membranes. Lastly, the manuscript covers the integration of nanotechnology with biological processes such as algal membrane bioreactors, anaerobic digestion, and microbial fuel cells, highlighting their potential in enhancing wastewater purification.*

***Keywords:** Nano-adsorbents, Nano-catalysts, Nano-membranes.*

I. INTRODUCTION

Water constitutes one of Earth's most abundant natural resources, yet only about 1% is accessible for human use. Over 1.1 billion individuals lack sufficient drinking water, primarily due to the increasing cost, population growth, and various climatic and environmental challenges. One of the major obstacles to the water supply is the ongoing contamination of freshwater sources by diverse organic and inorganic pollutants. While treating wastewater and drinking water can mitigate these issues, traditional treatment methods often fall short of effectively removing emerging contaminants and adhering to stringent water quality standards. Furthermore, existing wastewater treatment technologies face numerous limitations, including high energy demands, insufficient pollutant removal, and the production of toxic sludge. Biological methods of wastewater treatment are commonly employed, but they tend to be slow, are hindered by non-biodegradable contaminants, and can sometimes introduce toxicity to microorganisms from harmful pollutants. Physical processes like filtration can eliminate contaminants but often result in the creation of highly concentrated and toxic sludge that is difficult to manage. Given these challenges, there is a pressing need for more effective and robust technologies for treating municipal and industrial wastewater. This can be achieved either by innovating entirely new methods or by enhancing existing techniques through strategic interventions. Among the emerging technologies, advancements in nanotechnology have shown remarkable promise for addressing wastewater remediation and various environmental issues. Nanotechnology delves into the manipulation of materials at the nanoscale, focusing on structures that are a few nanometers in size. Nano-materials are the smallest engineered structures developed to date, with nanoparticles defined as having at least one dimension less than 100 nm. These materials come in various forms, including nanowires, nanotubes, films, particles, quantum dots, and colloids. In wastewater treatment, a diverse range of efficient, eco-friendly, and cost-effective nano-materials have been designed, offering unique functionalities for the decontamination of industrial effluents, surface water, groundwater, and drinking water. In recent years, research has increasingly focused on the potential of nano-particle materials as adsorbents. Their reduced size enhances the surface area, which in turn increases their chemical reactivity and adsorption capacity for metals.

II. Nano-Adsorbents

The adsorption process is influenced by factors such as the adsorption coefficient and the partitioning of pollutants under equilibrium conditions. For persistent inorganic pollutants, redox reactions can facilitate ionic structure transformations, although changes in redox conditions may also impact the toxicity of these pollutants. Nano-adsorbents can be categorized into several groups based on their roles in the adsorption process, including metallic nanoparticles, nanostructured mixed oxides, magnetic nanoparticles, and metallic oxide nanoparticles. Recent developments also include carbonaceous nano-materials like carbon nanotubes, carbon nanoparticles, and carbon nanosheets, as well as various silicon-based nano-materials. Other materials such as nanoclays, polymer-based nano-materials, nanofibers, and aerogels are also employed for the adsorption of heavy metals from wastewater.

2.1 Classification of nano-adsorbents

The properties of nano-adsorbents are governed by several factors including size, surface chemistry, agglomeration state, shape, chemical composition, and solubility. The high chemical activity and fine grain size of nano-particles distinguish them from traditional substances like standard titanium dioxide and alumina. Modifications to the nano-particles can be performed using various reagents to enhance their properties for pre-concentrating metal ions. Oxide-based nanoparticles, which are inorganic and typically synthesized from metals and non-metals, are widely utilized for removing hazardous pollutants from wastewater. These include titanium oxides, zinc oxides, magnesium oxides, manganese oxides, and ferric oxides, known for their high surface area, minimal environmental impact, and lack of secondary pollutants. Ferric oxide, due to its natural abundance and simple synthesis, is a cost-effective solution for adsorbing toxic metals.

III. Nano-Catalysts

The nano-catalysts, especially those of inorganic materials such as semiconductors and metal oxides, are gaining considerable attention of the researchers in application of wastewater treatment. Various kinds of nano-catalysts are employed for wastewater treatment such as photocatalysts (Dutta et al., 2014), electrocatalysts (Dutta et al., 2014), and Fenton based catalysts (Kurian and Nair, 2015) for improving chemical oxidation of organic pollutants (Ma et al., 2015) and antimicrobial actions (Chaturvedi et al., 2012).

3.1 Nano-materials as photocatalysts

Nanoparticle photocatalytic reactions are based on interaction of light energy with metallic nano-particles and are of great interest due to their broad and high photocatalytic activities for various pollutants (Akhavan, 2009). Usually these photocatalysts are comprised of semiconductor metals that can degrade variety of persistent organic pollutants in wastewater such as dyes, detergents, pesticides and volatile organic compound (Lin et al., 2014). Furthermore, semiconductor nano-catalysts are also highly effective for degradation of halogenated and non-halogenated organic compounds, PCPPs and also heavy metals in specific situation (Adeleye et al., 2016). Semiconductor nano-materials are required a mild operation conditions and very effective even at a small concentration. The simple mechanism of the working of photocatalysis is based on the photoexcitation of electron in the catalyst. The irradiation with light (UV in case of TiO_2) generates holes (h^+) and exited electrons (e^-) in the conduction band. In an aqueous media, the holes (h^+) are trapped by water molecules (H_2O) and generate hydroxyl radicals ($^{\bullet}OH$) (Anjum et al., 2016a). The radicals are indiscriminate and powerful oxidization agent. These hydroxyl radicals on reaction oxidize the organic pollutants into water and gaseous degradation products (Akhavan, 2009).

3.1.1 Doping/Modification of Photocatalysts

The application of visible light in the photocatalytic treatment of wastewater has become a significant area of research. To facilitate this, modifications to the nano-materials or semiconductors are necessary to lower the band gap energy from the UV to the visible spectrum (Anjum et al., 2016b). Numerous studies have assessed the photocatalytic performance of modified nano-catalysts under visible light conditions. Typical modification techniques for catalysts include dye sensitization, metal doping, the creation of hybrid nanoparticles or composites using narrow band-gap semiconductors, and the addition of anions (Ni et al., 2007). The introduction of new metals and anions into the composite establishes impurity energy levels that, when exposed to visible light, can inject electrons into the semiconductor, thereby initiating the catalytic reaction (Qu et al., 2013).

A detailed overview of the photocatalytic efficiency of various modified nano-catalysts for the removal of organic pollutants from wastewater is presented in Table 2. 3.2 Photocatalysts as Antimicrobial Agents Photocatalysis has emerged as a viable method for the purification and treatment of diverse wastewater types (Yu et al., 2001).

It effectively inactivates pathogenic organisms, such as bacteria, present in the wastewater (Yu et al., 2003). As mentioned earlier, TiO2 is a widely utilized photocatalyst recognized for its strong antimicrobial properties. However, using TiO2 powder poses challenges, such as the difficulty of separating the mobilized nanoparticles post-treatment. To enhance antimicrobial effectiveness, it is essential to immobilize these nanoparticles and increase their surface area (Liu et al., 2008).

Various studies have explored modifications with other materials to boost catalyst efficiency. For instance, Akhavan (2009) demonstrated that incorporating Ag nanoparticles onto TiO2 films resulted in a 6.9-fold increase in antimicrobial efficacy against E. coli compared to TiO2 alone under visible light. Similarly, a mesoporous composite of Ag and TiO2 (Ag/TiO2) exhibited superior antibacterial activities compared to commercial P-25 TiO2 films. The composite's formation with other materials enhances the surface area, creating more active sites for degrading microorganisms (Liu et al., 2008).

However, during antimicrobial processes, extracellular polymeric substances (EPS) can diminish the catalyst's efficacy. EPS significantly impacts antibacterial kinetics by competing with bacteria for reactive oxygen species. Therefore, it is crucial to eliminate EPS for effective photocatalysis in wastewater disinfection (Chaturvedi et al., 2012).

3.2 Photocatalysts as antimicrobial agent

Photocatalysis has been proven as a promising technique for purification and treatment of various kinds of wastewater (Yu et al., 2001). In addition, it has an efficient ability to inactive the pathogenic organism such as bacteria, in the wastewater (Yu et al., 2003). As discussed in the above section, TiO_2 is extensively used photo catalyst and reported for its high antimicrobial power. The use of TiO_2 powder has some drawback for instance; the post separation is these mobilized nano-particles is difficult. Thus, for efficient antimicrobial activity the nano-particles need to be immobilized and increase in surface area (Liu et al., 2008). For this concern, various studies have been conducted to increase the effectiveness of catalyst by modification with other materials.

Akhavan (2009) showed that the storage of Ag nano-particles on TiO_2 films achieved 6.9 times high antimicrobial activity against *E. coli* bacteria compared to that of TiO_2 under visible light. Similarly, in another study the mesoporous composite of Ag with TiO_2 films (Ag/TiO_2) showed high antibacterial actions as compared to the commercial P-25 TiO_2 spinning film. This is because the composite formation with other materials increased the surface area providing more active sites at mesoporous catalyst to degrade microorganisms (Liu et al., 2008). During antimicrobial action, the presence of extracellular polymeric substance (EPS) may decrease the antimicrobial efficiency of the catalyst. EPS is found to play a significant role in determining antibacterial kinetics as it increases the competition for reactive oxygen species between EPS and bacteria. Thus, it is important to remove EPS to achieve high efficiency of photocatalysis for wastewater disinfection (Chaturvedi et al., 2012).

3.3 Nano-materials as electro-catalysts

The process of electrocatalysis in microbial fuel cell is an emerging topic of discussion for wastewater treatment and direct electricity generation. In microbial fuel cell, electro-catalyst plays a detrimental role in working of a fuel cell (Chen et al., 2015). The use of nano-material as electro catalyst can improve the performance of fuel cell by achieve larger surface area and uniform distribution of catalyst in the reaction media (Liu et al., 2005). Tremendous research has been conducted on development of carbon supported nano-electrocatalysts for application in fuel cells (Tang et al., 2005; Chaturvedi et al., 2012).

3.3 Nano-materials as Electrocatalysts Electrocatalys is within microbial fuel cells is a developing area of interest for wastewater treatment and direct electricity generation. In this context, the electro-catalyst is crucial to the fuel cell's operation (Chen et al., 2015). Utilizing nano-materials as electrocatalysts can enhance fuel cell performance through increased surface area and uniform catalyst distribution within the reaction medium (Liu et al., 2005). Significant research has been dedicated to developing carbon-supported nano-electrocatalysts for fuel cell applications (Tang et al., 2005; Chaturvedi et al., 2012).

3.4 Nano-material Based Fenton Catalyst

The Fenton reaction is widely employed for oxidizing organic pollutants in wastewater treatment (Neyens and Baeyens, 2003). However, this process has notable drawbacks, including the continuous loss of catalyst material in the effluent and the need for acidic conditions (pH = 3) for optimal performance (Kurian and Nair, 2015; Ferroudj et al., 2013). To address these challenges, nano-material based Fenton reagents have been introduced.

3.5 The Role of Nano-catalysts in Pollutant Oxidation

In wastewater treatment, nano-material catalysts can facilitate the chemical oxidation of organic pollutants. Nano-particles derived from noble metals, such as Au, Pt, and Pd, demonstrate effective catalytic capabilities for degrading a range of organic and inorganic contaminants (Liu et al., 2013; Wang et al., 2013a,b). Compared to traditional treatment methods, employing nano-catalysts in chemical oxidation offers several advantages, including targeted removal of recalcitrant compounds, reduced treatment duration, and conversion of waste into valuable by-products (Wigginton et al., 2012; Hering et al., 2013). Hildebrand et al. (2009) noted that Pd could selectively eliminate pollutants, such as chloro hydrocarbons, from wastewater with commercial viability.

The synthesized Pd-based nano-catalyst (Pd/Fe3O4) exhibited high hydro dechlorination rates and facilitated easy recovery through magnetic separation. Despite the benefits of using nano-catalysts, challenges such as the high cost of metal nanoparticles (like Pt) and recovery difficulties persist. Thus, a pressing issue is how to minimize the high capital costs and maintain catalyst replenishment for ongoing treatment processes.

Recent studies have suggested that enhancing the reactivity of noble metal nanoparticles by creating bimetallic alloys through blending with other metals is an effective strategy for making catalytic processes more cost-effective (Ma et al., 2015).

IV. NANO-MEMBRANES

Among the advanced wastewater treatment techniques available today, membrane filtration technology utilizing nano-materials stands out as exceptionally effective (Ho et al., 2012; Zhang et al., 2013a,b). Concepts from nanotechnology extend the capabilities of water treatment membranes, providing functionalities such as catalytic reactivity, enhanced permeability, and resistance to fouling (Pendergast and Hoek, 2011). The advantages of this technology include superior quality of treated water, effective disinfection, and minimal space requirements for treatment plants (Jang et al., 2015). Additionally, it is more economical, efficient, and simpler in design compared to other methods (Zhou et al., 2014; Zhang et al., 2015; Guo et al., 2016). In wastewater treatment, nano-membrane separation technology is effectively utilized to remove dyes, heavy metals, and other contaminants (Jie et al., 2015).

4.1 Fouling and Membrane Modification

Although commercially available membranes can serve various applications, the need to produce new water resources from wastewater requires membranes with enhanced productivity and fouling resistance at lower costs (Pendergast and Hoek, 2011). Membrane fouling occurs when organic compounds in water interact with hydrophobic membranes, leading to the accumulation of particles on the membrane surface or within its pores (Baker, 2004; Judd, 2006; Yang et al., 2015). This results in lower quality treated water, decreased reliability of filtration equipment, and limitations in further developments (Gu et al., 2013). At low pressure, the flux of nano-filtration membranes can be considerably reduced (Guo et al., 2016). To mitigate the effects of fouling, it may be necessary to clean membranes chemically or mechanically, or sometimes even replace them entirely (Yang et al., 2015).

4.2 Carbon Nanotube Membranes

Carbon nanotubes are gaining prominence as nano-materials for creating high-performance polymer composite membranes. These composites feature numerous advantages, including low mass density, remarkable strength, high flexibility, and large aspect ratios that enhance their performance (Liu et al., 2016). Depending on their structure, carbon nanotubes can be classified as single-walled carbon nanotubes (SWCNTs) or multi-walled carbon nanotubes (MWCNTs) (Popov, 2004; Rajabi et al., 2013). Several studies have focused on synthesizing modified nanotube membranes. For example, Jie et al. (2015) reported creating a composite of Carboxyl multi-walled carbon nanotubes/calcium alginate (CMWCNT/CA) using polyethylene glycol 400 as a pore-forming agent in a hydrogel nano-filtration membrane, achieving a strength of approximately 1.83 MPa. Moreover, this membrane exhibited excellent anti-fouling properties, achieving a flux of 96.87% compared to pure water flux (PWF) for bovine serum albumin (BSA) solution. In another study, Guo (2016) developed nanofibrous filtration membranes composed of polyhydroxybutyrate-calcium alginate/carboxyl multi-walled carbon nanotube composites.

4.3 Electrospun Nano-fiber Membranes

Electrospun nanofiber membranes (ENMs) represent a novel approach in wastewater treatment (Matsuura et al., 2010; Botes and Eugene Cloete, 2010; Qu et al., 2013). This innovative technique is characterized by lower energy consumption, reduced costs, and lighter processing compared to traditional methods. Notably, the higher porosity and surface-to-volume ratio are significant advantages of this approach (Balamurugan et al., 2011; Tabe, 2014). Electrospinning offers advantages over standard nanofiber production techniques by enabling the creation of fibers that are significantly thinner, which increases the surface area-to-volume ratio and influences membrane porosity. The fiber diameter can be adjusted by varying process parameters such as solution concentration, applied voltage, surface tension, and spinning distance (Theron et al., 2004; Tabe, 2014).

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4.4 Hybrid Nano-Membranes

Hybrid membranes have been created to add new functionalities, such as adsorption, photocatalysis, and antimicrobial properties. This enhancement can be realized by adjusting factors like the hydrophilicity, porosity, pore size, mechanical stability, and charge density of the membranes. Yurekli (2016) combined filtration and adsorption by utilizing a polysulfone (PSf) membrane infused with zeolite nanoparticles to effectively remove lead and nickel from wastewater. They discovered that modifying the membrane fabrication conditions, such as the loading of NaX and the evaporation duration of the casting film, significantly improved both the sorption capacity and hydraulic permeability of the membrane.

Table1 Efficiency of various types of nano-membranes for treatment of wastewater.

Table 3 Efficiency of various types of nano-membranes for treatment of wastewater.

Technology	**Contaminant**	**Efficiency**	**Comments**	**Reference**
Nano-filtration with forward osmosis	COD, Paracetamol and Nebivolol compounds from industrial wastewater	COD (97%), Paracetamol and Nebivolol compounds (100%)	The level of treated water is of reusable criteria Problem of drop in flux and membrane fouling can be overcome	Thakura et al. (2015)
Nano-filtration membranes	Reactive dye Black 5 removal from textile effluent	99%	The negatively charged hollow fiber composite NF membrane could effectively remove the dye from textile effluent through submerged filtration Less amount of electrolytes in the effluents Excellent antifouling property and high water cleaning efficiency	Zhu et al. (2013)
Nano-membrane prepared from coating γ-alumina and titania nanocrystallites	Microorganisms and ions rejection from wastewater	Microbes (100%), ions (25%)	Successful removal of microorganisms Ion rejection can be enhanced by proper pH adjustment	Shayesteh et al. (2016)
Nanoporous membrane filtration	TSS, TDS, oil, grease, COD, BOD from oil wastewater	TSS (100%), TDS (44%), oil (99%), Grease (80%), BOD (76%)	The optimum conditions for efficient water purification were; feed temperature of 45 °C, cross flow velocity of 1.3 m/s, trans-membrane pressure of 4 bar, salt concentration of 11.2 g/L and pH of 10. Treated water can be used for agricultural purpose	Salahi et al. (2015)
Nano-structured polymer based membrane	Oil removal	99.75%	Achieved a new methodology for combining nano-filtration and floatation for oil in water demulsification The increased sorbent surface area and concentration (weight) enhanced system efficiency	Ahmed et al. (2015)

			High adsorption capacity of the sorbent was due to its porous structure	
Sodium titanate nanobelt membrane (Na-TNB)	Removal of oil and radioactive Cs+ ions and Sr2+	Sr2+ (97.5%) , Cs+ (57.7)	The developed membrane posses high adsorption capacity and rapid ions exchange kinetics	Wen et al. (2016)
			Membrane can be used for large area deposition of different materials	
			Significant ions exchange behavior of TNB at room temperature	
Integrated carbon nanotube (CNT) polymer composite membrane with polyvinyl alcohol layer	Treatment of oil contaminated water	Over 95%	Integration of CNT with polymer composite increases suitability of membrane for practical application due to ultimate tensile strength, toughness and young's modulus	Maphutha et al. (2013)
			Increasing CNT concentration increases membrane flux	
Hydrophilic electrospun nanofiber membrane	Suspended particles		Efficient turbidity and total dissolved solids removal	Asmatulu et al. (2013)
			Overcoming on membrane fouling and blocking problems	
			Efficient particle removals by membrane due to coagulation process	
Carbon nanofiber membrane	Metal and metal oxide nano-particles	Up to 95%	Mechanically strong and bendable membrane	Faccini et al. (2015)
			Withstand filtration under high pressure or vacuum	
			Capability to produce easy and cost efficient nanofiber by electrospinning	
ZrO2 microfiltration membrane	Pretreatment of dimethylformamide (DMF) wastewater	Turbidity removal (99.6%), suspended solids (99.9%)	Effective removal of suspended fine particles from DMF wastewater	Zhang et al. (2014)
			Effective flux recovery by combined ultrasonic, chemical cleaning and flushing	

V. Combination of Biological-Nano Technology Process

The intersection of biological processes and nanotechnology has shown promise in addressing various water quality issues through the use of nano-catalysts, nano-adsorbents, nanotubes, nanostructured catalytic membranes, nanopowders, and micromolecules (Gupta et al., 2006).

These nanoparticles and colloids have a substantial effect on the water treatment process (Diallo and Savage, 2005). Research indicates that combining biological methods of wastewater treatment with advanced nanotechnology can lead to highly effective water purification systems (Yin et al., 2013). Below is a summary of the integration of nanotechnology with biological processes for wastewater treatment.

5.1 Algal membrane bioreactors (A-MBR)

that incorporate nanoparticles represent a promising approach to energy production and water purification. Many algae species thrive in wastewater due to the presence of essential micronutrients (such as trace metals and vitamins) and macronutrients (like nitrates and phosphates) that support their growth (Abou-Shanab et al., 2013; Chong et al., 2000). The combination of these nutrients and water, along with light and carbon dioxide, fosters algal growth while simultaneously removing nutrients from wastewater and generating biomass for energy (Grima et al., 2003).

5.2 In terms of pretreatment for aerobic digestion using nanoparticles,

traditional biological processes like activated sludge have been effective for municipal wastewater; however, industrial wastewater poses more significant challenges due to toxic and less biodegradable pollutants (Rittmann and McCarty, 2001). The need for high-quality treated water that is low in toxicity and balanced in nutrients has led to the exploration of emerging technologies. One such technology is zero valent iron (ZVI) nanoparticles, which have potential for degrading organic contaminants and have been used to remediate chlorinated organic compounds in groundwater (Metcalf and Eddy, 2003).

5.3 Improvement of microbial fuel cells efficiency through nanotechnology

Nanotechnology is also enhancing the efficiency of microbial fuel cells (MFCs), which present the dual advantage of water treatment and energy generation from organic and inorganic compounds in wastewater using microbes as biocatalysts (Ghasemi et al., 2013a; Logan and Regan, 2006). The energy produced by MFCs could significantly reduce electricity consumption associated with conventional treatment methods (Ghangrekar and Shinde, 2007), as bacteria decompose complex organic molecules into water and carbon dioxide (Logan et al., 2008).

5.4 Electrospinning technology has emerged as a cost-effective method for producing nanofibers or nanowebs,

Which possess unique properties such as a high surface area and nanoscale porosity, making them suitable for membrane and filter applications (Wendorff et al., 2012). Integrating electrospun nanofibers with microbes can enhance purification and filtration capabilities. Research has demonstrated that combining these nanofibers with algae or bacteria can yield significant environmental benefits (San et al., 2014).

VI. THIS REVIEW HIGHLIGHTS THREE PRIMARY CATEGORIES OF NANOPARTICLES UTILIZED IN WASTEWATER TREATMENT

Nano-adsorbents, nano-catalysts, and nano-membranes. Each category presents distinct advantages and challenges regarding efficiency, applicability, and environmental and health risks.

6.1Nano-adsorbents

are highly effective in removing heavy metals from wastewater, with carbon nanotubes (CNTs) and metal oxides being the most frequently employed nanoparticles (Ray and Shipley, 2015). These nanoparticles offer key benefits, including a large surface area, microporous structure, high dispersion ability, and eco-friendliness (Gupta et al., 2015; Li et al., 2003a, 2003b). However, their small size can complicate separation from aqueous solutions, leading to potential secondary pollution (Ray and Shipley, 2015).

6.2 Nano-catalysts

Nano-catalysts hold significant potential for advancing catalytic purification techniques like photocatalysis, electrocatalysis, and Fenton catalysis. However, the commonly used ZnO and TiO2 photocatalysts face limitations due to their requirement for ultraviolet light activation, which is necessary due to their broad band gap energy.

6.3 The adoption of membrane

Filtration technology is driven by its advantages in providing quality water treatment, effective disinfection, and a compact footprint (Jang et al., 2015). It is also simpler and more cost-effective compared to other treatment methods (Zhou et al., 2014; Zhang et al., 2015; Guo et al., 2016). Nano-membrane technology is particularly effective for removing dyes and heavy metals (Jie et al., 2015). However, the manufacturing process of nano-membranes raises environmental concerns, as indicated by Khanna et al. (2008), who reported that the lifecycle impact of carbon nanofibers is significantly greater in terms of toxicity and environmental degradation compared to traditional materials. Another challenge is membrane fouling, which occurs when organic compounds in water interact with hydrophobic membranes.

These nanoparticles offer key benefits, including a large surface area, microporous structure, high dispersion ability, and eco-friendliness (Gupta et al., 2015; Li et al., 2003a, 2003b). However, their small size can complicate separation from aqueous solutions, leading to potential secondary pollution (Ray and Shipley, 2015).

6.4 Integrated nano-particles and biological process

The integration of biological processes with advanced nanotechnology has proven effective in wastewater treatment, yielding improved purification results (Ma and Zhang, 2008). Various nanoparticles, including CNTs (Ghasemi et al., 2011), TiO2 (Yin et al., 2013), nanofibers, and ZVI (Metcalf and Eddy, 2003), have been successfully employed to enhance wastewater polishing. Studies have shown that integrating nanoparticles can significantly boost the efficiency of biological processes such as A-MBR (Abou-Shanab et al., 2013), MFC (Ghasemi et al., 2013a), and the activated sludge process (Bell et al., 2003), with reported pollutant removal efficiencies reaching up to 98.5% for nutrients, 95% for dye decolorization, and reductions of 96% and 86% for BOD and COD, respectively (Sarioglu et al., 2013).

VII. Conclusion

There is a pressing need for innovative water treatment technologies to ensure high-quality water, eliminate chemical and biological contaminants, and enhance industrial wastewater processing. In this context, nanotechnology presents a viable solution for advanced wastewater treatment. Various nano-materials, including nano-adsorbents, photocatalysts, electrocatalysts, and nano-membranes, have been effectively developed and investigated for this purpose. These materials can be integrated with biological processes to further enhance water purification efficiency. Each technology offers distinct advantages and pollutant removal capabilities. Nano-adsorbents are particularly effective for eliminating heavy metals, while photocatalysts can target both toxic substances and heavy metals, especially when modified to utilize visible light. In electrocatalytic processes, the use of nanoparticles can enhance surface area and catalyst distribution. While the efficacy of nanomaterials in wastewater treatment is well established, it is crucial to address potential environmental risks associated with their use, as nanoparticles may inadvertently enter the environment during production and treatment, leading to long-term accumulation and health hazards. Future research should focus on developing nanoparticles that minimize environmental toxicity to mitigate these risks.

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