Overview of Nano-Biotechnology Potential in Wastewater and Effluent Treatment

Sunday A. Afolalu, Osise Okwilagwe, Biodun B. Matthew and Moses E. Emetere
Department of Mechanical Engineering, Department of Physics
Covenant University
Ota, Nigeria
sunday.afolalu@covenantuniversity.edu.ng
osiseokwilagwe@gmail.com

Omolola O. Yusuf
Department of Microbiology
Obafemi Awolowo University
Ile-Ife, Nigeria

Olusegun D. Samuel
Department of Mechanical Engineering
Federal University of Petroleum Resources
Effurun, Delta –State. Nigeria

Abstract

The release of toxic effluents into water bodies over the past few decades have upsurged, making access to drinkable water difficult. Water is the most sought-after resource for sustaining not only humans but wildlife and aquatic life and is imperial for economic growth and development. Rapid industrialisation, agricultural expansion as well as inconsiderate human activities are some of the factors liable for the present increase in water pollution and water insecurity plaguing the 21st century. In a bid to address this challenge, conventional water treatment methods like membrane filtration, chemical coagulation, activated carbon adsorption, etc., have been implemented. Consequently, the limitations resulting from these conventional methods in terms of their limited active sites, low sorption capacity, lack of selectivity, and short adsorption to regeneration cycle, has led to the unfolding of innovative, cost-effective, ecologically sustainable and efficient wastewater treatment technologies. Among these technologies, nanotechnology and biotechnology have separately played significant roles. This review is centred on nano-based absorbents materials used in wastewater and effluent treatment.

Keywords

Nano-biotechnology; Nanomaterials; Wastewater; Treatment; Nano-based; absorbents

1. Introduction

Water is a valuable and finite earth resource which occupies roughly 71% of the Earth's surface (An & Springer, 2020). It is one of the most important resources for preserving and sustaining human, animal and aquatic life. The global need for fresh and affordable water is on the increase because of the increase in population growth, urbanisation, climate change, water quality deterioration and rapid advancements in the industrial and agricultural sectors (Ali & Aboul-Enein, 2004). The provision of potable water to match human needs is a huge challenge of the 21st century. Reports show that roughly ten to twenty million people die yearly due to waterborne diseases (Malik et al., 2012). The World Health Organisation (WHO) and UNICEF in 2017 recorded that over 785 million people still lack basic access to reliable water services (World Health Organization & UNICEF, 2017). Access to safe, clean water is extremely vital for economic growth and development, as water is a lifeline for all forms of life on earth and is gotten from two predominant sources namely groundwater like water from wells and borehole water and natural surface water such as rivers, streams, oceans, freshwater lakes, etc., (Bej et al., 2020). Generally, wastewater is a by-product generated from activities performed domestically, commercially, industrially or agriculturally, and from sewer infiltration or storm water/surface runoff (Tilley et al., 2008). The characteristics of wastewater are dependent on its source. As a result, wastewater can be grouped as domestic, industrial and municipal wastewater, which are respectively generated from households, industries and communities (Maity et al., 2020). Wastewater can also be categorised as black water, greywater and yellow water

(Ghosh et al., 2020). More so, the contaminants present in wastewater can be biological, chemical or physical. Biological contaminants include paper, tissue, vegetable matter, yeast surplus (from breweries), hair (from tanneries) and human wastes whereas, effluents generated from industrial and agricultural expansion, majorly contain chemical substances (both organic and inorganic) such as chromium, lead, mercury, pesticides, fertilizer, etc., which are non-biodegradable (Nafees et al., 2020). While physical contaminants are majorly suspended solids. Inconsiderate human behaviour in disposing of effluents into water bodies like river, streams, lakes, estuaries or coastlines contribute to water pollution as well as lack of improved sanitation facilities, which poses threats to humans, the environment and aquatic life (Karri et al., 2019).

Wastewater is said to contain approximately 99.90 percent water and 0.10 percent dissolved or suspended solids which are primarily bioorganic (Ghosh et al., 2020). Wastewater also contains several pathogenic organisms like viruses, bacteria, heavy metals, helminths and protozoan, which are directly linked to diseases such as leptospirosis, hepatitis A and campylobacteriosis (Singh et al., 2019). Several attempts have been made to address and exploit water quantity through the establishment of several hydraulic structures such as reservoirs, dams and channels. Water stressed countries have explored technological options such as recycling, water conservation, desalination of water as well as the implementation of conventional treatments technologies such as activated carbon adsorption, advanced oxidation processes, coagulation-flocculation, membrane filtration, electrochemical treatment, ion exchange, reverse osmosis to eliminate contaminants from effluent waters. These technological techniques have limitations in terms of high capital investment and energy requirements (Werkneh & Rene, 2019). The drawbacks associated with these conventional water purification methods calls for novel technological innovation and framework for water treatment management and optimization of treatment processes to achieve water security (Bora & Dutta, 2014). Research efforts show that nano-biotechnology holds great potential in addressing this challenge without having to rely on costly infrastructures. Nano-biotechnology is an approach/discipline that immensely takes advantage of the attributes of biomolecules in living organisms and nanotechnology (Sahu et al., 2019). In this field, various microorganisms for the treatment and removal of hazardous substance present in water have been explored. The characteristics and principles guiding nanotechnology can be applied in biological processes to develop novel products. These biological processes are demonstrated in techniques like nano-proteomics, nano-fluids, nano-bio sensors and fillers/membranes. Also, nano-biotechnology can be used alongside other water treatment methods such as membrane technology, photocatalysis, adsorption and coagulation (Jegatheesan et al., 2016). This paper emphasizes a summary of recent trends in nano-biotechnology as a potential to wastewater and effluent treatment.

2. Current Nano-Based Technologies in Wastewater and Effluent Treatment

Novel innovations and technologies are rapidly replacing orthodox water treatment methods (Kanchi, 2014). Nanomaterials are a good match for water purification and could be defined as materials whose particle size are of one billionth of a meter (10^{-9}). At this scale, nanomaterials are characterized in terms of their chemical, biological and physical properties which differ from their bulk counterparts. Many of these properties have been investigated for implementation in wastewater and effluent treatment (Werkneh & Rene, 2019). Some of these applications take advantage of the superparamagnetic nature of these nanomaterials, while other applications make use of the easily adjustable size-dependent properties of nanomaterials which relate to the high specific surface area, such as elevated sorption efficiency, high reactivity, rapid dissolution and adjustable surface chemistry. This review focuses on some of the nano-based absorbents utilized in water treatment (Jegatheesan et al., 2016).

2.1. Carbon-Based Nano Adsorbents

Adsorption can be defined as the spontaneous physical attachment or bonding of molecules, ions or atoms from a gas, dissolved solids or liquid onto a surface (Nafees et al., 2020). Wastewater containing organic, inorganic and biological pollutants are removed primarily through adsorption (Karri et al., 2019). Due to the limitations linked with conventional absorbents such as limited active sites, lack of selectivity, low sorption capacity and short life span like short adsorption to regeneration cycle which limits their economic rationality, carbon-based absorbents are progressing through the evolution of carbonaceous materials (CNMs) (Werkneh & Rene, 2019). These carbonaceous materials include carbon nanoparticles, carbon nanotubes (CNTs) and carbon Nano sheets (Karri et al., 2019). Carbon nanotubes are the most important Nano sorbent for wastewater treatment. In wastewater purification systems CNTs have scaffold functions and are utilized as hybrid catalysts for enzyme immobilization in Nano carriers (Singh et al., 2019). Carbon nanotubes are categorised as single-walled nanotubes (SWNT), double-walled nanotubes (DWNTs) and multivalued nanotubes (MWNTs), which are distinguishable by their layering systems (Singh et al., 2019).

CNTs are preferred to activated carbon (powdered or granular forms) for the removal of organic effluent contaminants because of their elevated adsorption efficiency owing to their surface multi-functionality or varied contaminant-CNT interactions (i.e. their ability to chemically bind and react easily with several neighbouring atoms and molecules) and high specific surface area (Liu et al., 2013). Other properties include their mechanical strength, chemical reactivity, layered structure and hollowness (Kunduru et al., 2017). In aqueous mediums, carbon nanotube forms loose bundles or aggregates along the length of their tube axis as a result of the hydrophobicity of their graphitic surfaces which lowers their active surface area (Ali & Aboul-Enein, 2004). These bundles consist of interstitial space and peripheral grooves which form high absorption energy sites for trapping organic molecules. The peripheral groove, interstitial space, external surface and inner sites are the four likely sites for absorptions on CNTs. CNTs can absorb organic bulky molecules due to their large pore and increased absorption sites. This is due to their surface functional groups which enables them to absorb metals such as nickel ions through chemical bonding and electrostatic interactions by increasing their colloidal activity, chemical reactivity and thus facilitates contaminant adsorption (Singh et al., 2019). CNTs are also capable of attracting organic compounds in wastewater due to their distinct contaminant-CNT interactions forces such as electrostatic interactions (for positively charged organic pollutants like antibiotics), pi-pi electron coupling (for polycyclic aromatic hydrocarbons, polar aromatic compounds), covalent bonding, hydrogen bonding (for compounds having -NH_2, -OH, -COOH functional groups), hydrophobic effect, and ion exchange (Karri et al., 2019).

Oxidized CNTs have greater absorption capacity for metal ions and faster kinetics. For instances, CNTs oxidized with hydrogen peroxide (H_2O_2), nitric acid (HNO_3) and potassium permanganate ($KMnO_4$) and are used in the removal of Cd^{2+} from aqueous solutions. Oxidized CNTs may not be a perfect substitute for activated carbon as an all-round adsorbent, but they can be utilized in targeting specific contaminants by manipulating their surface chemistry. They may possess potential implementations in polishing steps to get rid of unruly compounds or in pre-concentration of trace organic pollutants for analytical purposes (Werkneh & Rene, 2019). There have been reports om the tremendous absorption by CNTs in the removal of lead, cadmium and organic 1,2-dichlorobenzene (DCB) (Nafees et al., 2020). Furthermore, a major advantage of CNT nano sorbents is that they can be continuously regenerated and reduced for the efficient removal of Zn^{2+} while a major drawback is associated with their implementation on pilot studies or mass applications because of high production costs (De Volder et al., 2013). Another drawback is that CNTs exhibit a clotting phenomenon with certain algae and organic pollutants and lose their nano-identity or structure (Ali, 2012).

2.2. Metal-Based Nano Absorbents

Metal oxides which are formed by the reaction between electropositive metals and electronegative oxygen are one of the most stable naturally occurring compounds (Rudakiya.& Gupte, 2019). They are currently the most extensively used nanomaterials owing to their good electrical and thermal conductivity, high chemical stability, availability and tuneable bandgap. Metal-based nano absorbents like metal oxides nanoparticles (MNPs) have extraordinary potential as an ecologically benign, economical, convenient, ease of functionalisation and sustainable water treatment technology (Bora & Dutta, 2014). Their elevated specific surface area and short intra-particle diffusion length can be compressed without a noticeable reduction in surface area, ease of reuse and increased absorption sites are some of the properties these nanoparticles exhibit (Singh et al., 2019). Metal oxides that are super-paramagnetic offer a superior edge for the elimination of heavy metals due to their exceptional absorption performance and catalytic properties in the presence of a heat source or light in comparison to the conventional activated carbon (Werkneh & Rene, 2019). This superior absorption performance is significant because of the fusion of oxygen molecules present in the metal oxide groups and dissolved metals. This is often regarded as a two-step process such that on the exterior surface of MNPs quick adsorption of the metal ions occurs which is closely accompanied by an intra-particle diffusion along the micro-pore walls (Karri et al., 2019). Elevated specific surface area, shorter intra-particle diffusion length and increased quantity of surface reaction sites (corners, edges and vacancies), results in these nanoparticles having faster kinetics and high absorption capacity. Examples of these MNPs include iron oxide, zinc oxide (ZnO), titanium oxide (TiO_2) and aluminium oxide (Al_2O_3) (Adegoke & Stenström, 2019).

2.1.1. Iron Oxide Nanoparticles

The mounting curiosity in the utilization of iron oxide nanoparticles in the elimination of different contaminants, in particular, toxic metal ions is due to their availability and simplicity (Lu et al., 2016). The novel properties and functions of iron oxide nanoparticles including their synthesis and usage have been profoundly studied due to their nano-metric size, super-paramagnetic and high surface volume. The ability of iron oxide nanoparticles to remove heavy metals such as nickel, mercury, lead, copper, etc., has been demonstrated in laboratories and onsite field tests and have shown an exceptional potential to be more successful than activated carbon (Qu et al., 2013). Iron oxides like magnetic magnetite (Fe_2O_3), magnetic magnetite (Fe_3O_4), nonmagnetic hematite (α-Fe_2O_3) and spinel ferrites (($M^{2+}Fe_2O_4$) along with its variants are often used as nano adsorbents. The small size of conventional nano absorbent materials creates a limitation in water treatment in terms of their separation and recovery from polluted water. However, because of the magnetic nature of iron oxide, iron oxide nanoparticles can magnetically be separated from the system with the aid of an external magnetic field (Bora & Dutta, 2014) (Adegoke & Stenström, 2019). Hence, they exhibit excellent absorption capacity for heavy metals ions in water systems, in their study illustrated that the conjugation of adsorption properties of CNTs along with the magnetic properties of iron oxide nanoparticles was used to prepare a composite absorbent which was successful in removing chromium from water. Also, ample reports from literature show the use of these nano-sized magnetic iron oxides in the removal of various elements like arsenic, copper, lead, nickel, cobalt and chromium in their ionic forms and displayed superior absorption performance compared to activated carbon (Gupta et al., 2011).

2.1.2. Zinc Oxide Nanoparticles

(ZnO) nanoparticles are an ideal choice for the purification of wastewater owing to their remarkable photocatalytic properties, strong oxidation capacity and wide bandgap in the UV spectrum (Rana et al., 2018). Zinc oxides are stronger reducing agents than iron oxides. Significant applications of zinc oxide can be found in paints and coatings to constrain biofilm and hinder bacteria growth (Sahu et al., 2019). Zinc ion (Zn^{2+}) are excellent antimicrobial agents against a diversified range of pathogenic bacteria. ZnO nanoparticles have been successfully employed for the separation of unfriendly metal ions (Kanchi, 2016). An important characteristic of Zinc oxides is the presence of inherent defects. A common approach used in enhancing the effectiveness of zinc oxide nanoparticles by changing their surface properties through utilization metal dopants like codopants, anionic dopants, cationic dopants and rare-earth dopants (Badreddine et al., 2018; Mun et al., 2016). Although limited literature exists on the application of zinc oxides to remove heavy metals in solution, they are however used in the treatment of H_2S contamination (Zito & Shipley, 2015).

2.1.3. Titanium Oxide Nanoparticles

As an upcoming technology, photo-catalysis has attracted attention since its discovery in 1972 when Fujishima and Honda demonstrated the spitting of water on a titanium oxide semiconductor electrode, making TiO_2 one of the most intensely researched materials (Fuente & Hortelano, 2019). Titanium oxide nanoparticles are the most sought-after nanoparticles used in photocatalytic degradation technology particularly for water treatment because of their nontoxicity, low cost, highly reactive oxidants like OH radicals, cost-effectiveness, and high photocatalytic activity, chemical and biological stability (Iwamoto et al., 2000). Also, in the presence of a catalyst and light, pollutants are slowing oxidized into intermediate products of lesser molecular weight and are ultimately transformed into water, carbon dioxide and anions like Cl^- NO_3^- and PO_4^{3-}. Since TiO_2 displays little selectivity, they are used to degrade a large number of pollutants like chlorinated organic compounds, heavy metals, polycyclic aromatic hydrocarbons, pesticides, cyanide, dyes and phenols (Murakami et al., 2009). The least concentration of titanium oxide used in killing bacterial pathogens in wastewater ranges between 0.1 to 1 gram per litre and is completely dependent on the particulate size and wavelength (light). The doping of noble metals such as silicon (Si) into TiO_2 enhances its efficiency in decomposing organic compounds because of the increase in crystallinity and surface area caused by the production of enhanced hydroxyl radical (Amin et al., 2014; Han et al., 2012; Afolalu et al., 2019). For instance, it is proven that nitrogen-doped TiO_2 nanoparticles catalysts are effective for the degradation of microbial pollutants in water (Pan et al., 2009). The latest discovery of TiO_2 which has drawn significant interest among many researchers is their ability to eliminate a variety of viruses like hepatitis B, herpes simplex and polio (Khajeh, 2013).

1.1. Polymeric Nano-Adsorbents

Polymeric nano adsorbents have only recently gained attention as an alternative to activated carbon due to their perfect mechanical rigidity, pore size arrangement, tunable surface chemistry, large surface area and feasible regeneration under mild conditions (Taylor & Kurniawan, 2012). They are either utilized as a system for the insertion of inorganic nanosized materials or as a template for the preparation of nanoparticles (Y. Han et al., 2019). Generally, polymeric adsorbents and its derivate are used in the removal of contaminants like organic acids, phenolic compounds, aromatic or polyaromatic hydrocarbons, alkanes and their derivatives. Polymer-inorganic nano adsorbents have excellent thermal stability over a variety of pH, good adsorption capacity and the resistance of polymeric groups and their linkages to acidic and alkaline hydrolysis. Polymeric nano absorbents are tailored absorbents, capable of removing organic and heavy metals contaminants through specific cavities (Liu et al., 2012). A polymeric nano absorbent nanoparticle consists of three distinct structural parts, covalently bonded together namely an interior branch cell, an ethylene diamine central core and a terminal branch cell (external surface) of amine (NH_2) functional groups (Chin et al., 2006). Such that the interior shells of theses absorbents are used in the sorption of organic compounds while heavy metals are adsorbed at their exterior surface because of the presence of amine or hydroxyl functional group (Afolalu et al., 2018). For instance, the polymer can be applied to improve ultrafiltration for the removal of Cu^{2+}. The sorption process can be based on hydrogen bonding, hydrophobic effect, electrostatic interactions and complexation (Tewari et al., 2010).

3. Retention and Reuse of Nanomaterials

A vital role in nanotechnology-enabled device design is the preservation and reuse of nanomaterials, as these parameters dictate the efficiency of the process, cost of operation and influence on public health (Silva et al., 2011). This is achieved by immobilizing the nanomaterials or implementing a separation device in the treatment approach. Membrane filtration which offers minimal chemical use and allows continues commercial operation was observed to be a viable choice. Polymeric and ceramic (inorganic) membranes are widely used in water treatment but ceramic (inorganic) are known to be more advantageous in terms of better chemical and physical stability and are more resistant to UV in ozonation applications (Silva et al., 2011; Zhang et al., 2016). The major limitation of this process is that the film or reactor membrane holds the suspended solid particles present in the wastewater which are harmful to it, thus significantly reducing its effectiveness. As a result, the pre-treatment of raw water is necessary to lower the turbidity (Bishoge et al., 2018). The immobility of nanomaterials on a variety of platforms like membranes and resins to prevent further separation is achievable. Nevertheless, current immobilization practices typically bring about huge efficiency loss. Hence, additional research into developing effective and efficient techniques to immobilize nanomaterials without significant influence on its efficiency is required (MacHado et al., 2019).

There's little literature available on the release of nanomaterials from nanotechnology-based devise. Although, the expected release is predicated to tremendously depend on the immobilization methods and processes used for separation. Nanomaterials with surface treatment coats can be extracted quickly and completely if there's no downstream separation process being applied (Mauter et al., 2018). While the removal of nanomaterials implanted in a solid matrix is quite difficult with insignificant discharge until they are disposed (Afolalu et al., 2019).. For nanomaterials that give off metal ions, their disintegration needs to be cautiously influenced by rationalizing their size, morphology and coating thickness. For toxicity assessment, recognition of nanomaterials released is a hard-headed hurdle and remains problematic. The few methods capable of distinguishing nanomaterials in complex aqueous wastes are highly sophisticated and expensive and with many constraints (Zito & Shipley, 2015).

4. Justification

Water scarcity is among the world's top environmental challenges (Sahu et al., 2019). The need for potable water is on the increase due to growing industrialization, urbanization, population growth, poor water quality and uncontrolled water pollution such as unimproved hygiene, salt interference, soil erosion and pollution of surface and ground waters by detergents, chemicals, pesticides and heavy metals (Kunduru et al., 2017). This necessitates the need for pioneering technology to provide safe, clean and affordable water, as conventional water treatment methods are no longer efficient in achieving water quality standards (Ajayi et al., 2019). In the last few decades, nanotechnology has gained considerable attention as a prospective substitute to address the inadequacies associated with conventional treatment methods (Karri et al., 2019). The recent developments in the manipulation of nanomaterials have facilitated the application of nanotechnology in water and wastewater treatments as discussed in this review (Mahmoodi, et al., 2013; Zare et al., 2018)

5. Conclusion

The release of effluents into water bodies remains a global menace. Nanotechnology is a promising field that has received enormous recognition and momentum, especially in the field of water treatment. Through the development of effective, efficient and environmentally benign nanomaterials, nanotechnology has made remarkable improvements in handling wastewater contamination.

Acknowledgements

We acknowledge the financial support offered by Covenant University in the actualization of this research work for publication.

Reference

Adegoke, A. A., & Stenström, T. A. (2019). Metal oxide nanoparticles in removing residual pharmaceutical products and pathogens from water and wastewater. *Nanoparticles in Pharmacotherapy*, 561–589. https://doi.org/10.1016/b978-0-12-816504-1.00016-8

Afolalu, S. A., Asonaminasom, E. H., Ongbali, S. O., Abioye, A. A., Udo, M. O., & Salawu, E. Y. (2018). Dataset on experimental investigation of optimum carburizing temperature and holding time of Bi-Nano additives treatment of *AISI 5130 steel. Data in Brief,* 19 (1) 2279-2283

Afolalu, S. A., Oladipupo, S., Ongbali, S. O., Abioye, A. A., Ajayi, O. O., Abdulkareem, A., & Olamilekan, R.

O. (2019, December). Quenching A Significant Index Control In Heat Treatment–An Overview. In *Journal of Physics: Conference Series* (Vol. 1378, No. 3, p. 032034). IOP Publishing

Afolalu, S. A., Ongbali, S. O, Ohwofa O, Ajayi O.O.,., Abioye, A. A. (2019, November). Nanocomposite and Its Morphological Characterization -Review. In *IOP Conference Series: Materials Science and Engineering* (Vol. 640, No. 1, p. 012067). IOP Publishing

Ajayi, O. O., Aba-Onukaogu, C. C., Salawu, E. Y., Owoeye, F. T., Akinlabu, D. K., Afolalu, S. A., & Abioye, A. A. (2019). Effect of Biomaterial (Citrullus Lanatus Peels) Nanolubricant on the Thermal Performance and Energy Consumption of R600a in Refrigeration System. In *Energy Technology 2019* (pp. 91-102). Springer, Cham.

Ali, I. (2012). New generation adsorbents for water treatment. *Chemical Reviews*, *112*(10), 5073–5091. https://doi.org/10.1021/cr300133d

Ali, I., & Aboul-Enein, H. Y. (2004). Chiral Pollutants: Distribution, Toxicity and Analysis by Chromatography and Capillary Electrophoresis. *Chiral Pollutants: Distribution, Toxicity and Analysis by Chromatography and Capillary Electrophoresis*. https://doi.org/10.1002/0470867825

Amin, M. T., Alazba, A. A., & Manzoor, U. (2014). *A Review of Removal of Pollutants from Water / Wastewater Using Different Types of Nanomaterials*. *2014*.

An, T., & Springer, O. (2020). *Nanotechnology as Potential and Innovative Platform Toward Wastewater Chapter 12 Nanotechnology as Potential and Innovative Platform Toward Wastewater Treatment : An Overview*. *February*, 2–3. https://doi.org/10.1007/978-3-030-34544-0

Badreddine, K., Kazah, I., Rekaby, M., & Awad, R. (2018). *Structural , Morphological , Optical , and Room Temperature Magnetic Characterization on Pure and Sm-Doped ZnO Nanoparticles*. *2018*.

Bej, S., Mondal, A., & Banerjee, P. (2020). *Effluent Water Treatment: A Potential Way Out Towards Conservation of Fresh Water in India* (pp. 33–46). https://doi.org/10.1007/978-981-15-0706-9_4

Bishoge, O. K., Zhang, L., Suntu, S. L., Jin, H., Abraham, A., & Qi, Z. (2018). *Toxic / Hazardous Substances and Environmental Engineering Remediation of water and wastewater by using engineered nanomaterials : A review*. *4529*. https://doi.org/10.1080/10934529.2018.1424991

Bora, T., & Dutta, J. (2014). Applications of nanotechnology in wastewater treatment-A review. *Journal of Nanoscience and Nanotechnology*, *14*(1), 613–626. https://doi.org/10.1166/jnn.2014.8898

Chin, S. S., Chiang, K., & Fane, A. G. (2006). The stability of polymeric membranes in a TiO2 photocatalysis process. *Journal of Membrane Science*, *275*(1–2), 202–211. https://doi.org/10.1016/j.memsci.2005.09.033

De Volder, M. F. L., Tawfick, S. H., Baughman, R. H., & Hart, A. J. (2013). Carbon nanotubes: Present and future commercial applications. *Science*, *339*(6119), 535–539. https://doi.org/10.1126/science.1222453

Fuente, L. De, & Hortelano, C. (2019). *New Developments in Composite to Metallo-Polyurethanes*. 363–388. https://doi.org/10.1016/B978-0-12-813908-0.00009-5

Ghosh, S. K., Saha, P. Das, & Di, M. F. (2020). Recent Trends in Waste Water Treatment and Water Resource Management. In *Recent Trends in Waste Water Treatment and Water Resource Management*. https://doi.org/10.1007/978-981-15-0706-9

Gupta, V. K., Agarwal, S., & Saleh, T. A. (2011). Chromium removal by combining the magnetic properties of iron oxide with adsorption properties of carbon nanotubes. *Water Research*, *45*(6), 2207–2212. https://doi.org/10.1016/j.watres.2011.01.012

Han, K. N., Yu, B. Y., & Kwak, S. Y. (2012). Hyperbranched poly(amidoamine)/polysulfone composite membranes for Cd(II) removal from water. *Journal of Membrane Science*, *396*, 83–91. https://doi.org/10.1016/j.memsci.2011.12.048

Han, Y., Kim, S., Kim, T., Kim, K., & Park, J. (2019). The role of terminal groups in dendrimer systems for the treatment of organic contaminants in aqueous environments. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2019.119494

Iwamoto, S., Tanakulrungsank, W., Inoue, M., Kagawa, K., & Praserthdam, P. (2000). *Synthesis of large-surface area silica-modified titania ultrafine particles by the glycothermal method*. *101*, 1439–1443.

Jegatheesan, V., Pramanik, B. K., Chen, J., Navaratna, D., Chang, C. Y., & Shu, L. (2016). Treatment of textile wastewater with membrane bioreactor: A critical review. *Bioresource Technology*, *204*, 202–212. https://doi.org/10.1016/j.biortech.2016.01.006

Kanchi, S. (2014). Nanotechnology for Water Treatment. *Journal of Environmental Analytical Chemistry*, *01*(02), 10–13. https://doi.org/10.4172/jreac.1000e102

Kanchi, S. (2016). *Nanotechnology for Water Treatment Environmental Analytical Chemistry Nanotechnology for Water Treatment*. *January 2014*. https://doi.org/10.4172/JREAC.1000e102

Karri, R. R., Shams, S., & Sahu, J. N. (2019). 4. Overview of Potential Applications of Nano-Biotechnology in Wastewater and Effluent Treatment. In *Nanotechnology in Water and Wastewater Treatment*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813902-8.00004-6

Khajeh, M., Laurent, S., & Dastafkan, K. (2013). *Nanoadsorbents : Classification, Preparation, and Applications (with Emphasis on Aqueous Media)*. 199:60

Kunduru, K. R., Nazarkovsky, M., Farah, S., & Pawar, R. (2017). *Nanotechnology for water purification: Applications of nanotechnology methods in wastewater treatment* (Issue February 2018). https://doi.org/10.1016/B978-0-12-804300-4.00002-2

Liu, X., Wang, M., Zhang, S., & Pan, B. (2013). Application potential of carbon nanotubes in water treatment: A review. *Journal of Environmental Sciences (China)*, *25*(7), 1263–1280. https://doi.org/10.1016/S1001-0742(12)60161-2

Liu, X., Zhang, S., & Pan, B. (2012). Potential of carbon nanotubes in water treatment. *Recent Progress in Carbon Nanotube Research*, 1–30. https://doi.org/10.5772/51332

Lu, H., Wang, J., Stoller, M., Wang, T., Bao, Y., & Hao, H. (2016). *An Overview of Nanomaterials for Water and Wastewater Treatment*. *2016*.

MacHado, A. B., Rodrigues, G. Z. P., Feksa, L. R., Berlese, D. B., & Tundisi, J. G. (2019). Applications of nanotechnology in water treatment. *Revista Conhecimento Online*, *1*, 3–15. https://doi.org/10.25112/rco.v1i0.1706

Mahmoodi, N. M., Najafi, F., & Neshat, A. (2013). Poly (amidoamine-co-acrylic acid) copolymer: Synthesis, characterization and dye removal ability. *Industrial crops and products*, *42*, 119-125.

Maity, S., Sinha, D., & Sarkar, A. (2020). *Wastewater and Industrial Effluent Treatment by Using Nanotechnology* (pp. 299–313). https://doi.org/10.1007/978-3-030-34544-0_16

Malik, A., Yasar, A., Tabinda, A. B., & Abubakar, M. (2012). *Water-Borne Diseases , Cost of Illness and Willingness to Pay for Dis- eases Interventions in Rural Communities of Developing Countries*. *41*(6), 39–49.

Mauter, M. S., Zucker, I., Perreault, F., Werber, J. R., Kim, J. H., & Elimelech, M. (2018). The role of nanotechnology in tackling global water challenges. *Nature Sustainability*, *1*(4), 166–175. https://doi.org/10.1038/s41893-018-0046-8

Mun, K., Wei, C., Sing, K., & Ching, J. (2016). Recent developments of zinc oxide based photocatalyst in water treatment technology : A review. *Water Research*, *88*, 428–448. https://doi.org/10.1016/j.watres.2015.09.045

Murakami, N., Kurihara, Y., Tsubota, T., & Ohno, T. (2009). *Shape-Controlled Anatase Titanium (IV) Oxide Particles Prepared by Hydrothermal Treatment of Peroxo Titanic Acid in the Presence of Polyvinyl Alcohol*. *Iv*, 3062–3069.

Nafees, M., Ali, S., Rizwan, M., Aziz, A., Adrees, M., Hussain, S. M., Ali, Q., & Junaid, M. (2020). *Effect of Nanoparticles on Plant Growth and Physiology and on Soil Microbes*. https://doi.org/10.1007/978-3-030-34544-0_5

Pan, B., Pan, B., Zhang, W., Lv, L., Zhang, Q., & Zheng, S. (2009). *Development of polymeric and polymer-based hybrid adsorbents for pollutants removal from waters*. *151*, 19–29. https://doi.org/10.1016/j.cej.2009.02.036

Qu, X., Alvarez, P. J. J., & Li, Q. (2013). Applications of nanotechnology in water and wastewater treatment. *Water Research*, *47*(12), 3931–3946. https://doi.org/10.1016/j.watres.2012.09.058

Rana, N., Ghosh, K. S., Chand, S., & Gathania, A. K. (2018). *Investigation of ZnO nanoparticles for their applications in wastewater treatment and antimicrobial activity*. *56*(January), 19–25.

Rudakiya, P. D. M., & Gupte, A. (2019). *L ACCASES IN N ANO - BIOTECHNOLOGY : RECENT TRENDS AND ADVANCED APPLICATIONS Complimentary Contributor Copy*. 33(56)

Sahu, J. N., Zabed, H., Karri, R. R., Shams, S., & Qi, X. (2019). Chapter 11 - Applications of nano-biotechnology for sustainable water purification. In *Industrial Applications of Nanomaterials*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-815749-7.00011-6

Silva, B. F. da, Pérez, S., Gardinalli, P., Singhal, R. K., Mozeto, A. A., & Barceló, D. (2011). Analytical chemistry of metallic nanoparticles in natural environments. *TrAC - Trends in Analytical Chemistry*, *30*(3), 528–540. https://doi.org/10.1016/j.trac.2011.01.008

Singh, S., Kumar, V., Romero, R., & Sharma, K. (2019). *Applications of Nanoparticles in Wastewater Treatment*. 395–418. https://doi.org/10.1007/978-3-030-17061-5

Taylor, P., & Kurniawan, T. A. (2012). *Critical Reviews in Environmental Science and Technology Nanoadsorbents for Remediation of Aquatic Environment : Local and Practical Solutions for Global Water Pollution Problems Nanoadsorbents for Remediation of Aquatic Environment : Local and Practical . June 2013*, 37–41. https://doi.org/10.1080/10643389.2011.556553

Tewari, P. K., Singh, R. K., Batra, V. S., & Balakrishnan, M. (2010). Membrane bioreactor (MBR) for wastewater treatment: Filtration performance evaluation of low cost polymeric and ceramic membranes. *Separation and Purification Technology*, *71*(2), 200–204. https://doi.org/10.1016/j.seppur.2009.11.022

Tilley, E., Lüthi, C., Morel, A., Zurbrügg, C., & Schertenleib, R. (2008). Compendium of Sanitation Systems and Technologies. *Development*, 158. http://www.eawag.ch/organisation/abteilungen/sandec/publikationen/publications_sesp/downloads_sesp/compendium_high.pdf

Werkneh, A. A., & Rene, E. R. (2019). *Applications of Nanotechnology and Biotechnology for Sustainable Water and Applications of Nanotechnology and Biotechnology for Sustainable Water and Wastewater Treatment*. *January*. https://doi.org/10.1007/978-981-13-3259-3

World Health Organization, & UNICEF. (2017). Progreso en agua potable, saneamiento e higiene. In *Who* (Issue February). https://doi.org/10.1371/journal.pone.0164800

Zare, E. N., Motahari, A., & Sillanpää, M. (2018). Nanoadsorbents based on conducting polymer nanocomposites with main focus on polyaniline and its derivatives for removal of heavy metal ions/dyes: a review. *Environmental research*, *162*, 173-195.

Zhang, Y., Wu, B., Xu, H., Liu, H., Wang, M., He, Y., & Pan, B. (2016). Nanomaterials-enabled water and wastewater treatment. *NanoImpact*, *3–4*, 22–39. https://doi.org/10.1016/j.impact.2016.09.004

Zito, P., & Shipley, H. J. (2015). RSC Advances Inorganic nano-adsorbents for the removal of heavy metals and arsenic : a review. *RSC Advances*, *5*, 29885–29907. https://doi.org/10.1039/C5RA02714D