Review of Use of Nanomaterials for Wastewater Treatment

[1]Dr. Shiva Sharma, [2]Dr. Maya Datt Joshi, [3]Anvesha Sinha, [4]Dr. Niladry Sekhar Ghosh
[1,2,3]Shobhit Institute of Engineering and Technology (Deemed to be University), Meerut
[4]Shobhit University, Gangoh
Email Id- [1]shiva@shobhituniversity.ac.in, [2]mayadatt.joshi@shobhituniversity.ac.in, [3]msanvesha@gmail.com, [4]niladry.ghosh@shobhituniversity.ac.in

ABSTRACT: Drinking water has become a competitive resource in many areas of the globe due to fast growing population, diminishing water supplies, and climate change resulting in protracted droughts and floods. The water business requires the development of cost-effective and reliable materials and techniques for delivering sufficient quantities of fresh water. Due to rising water demand, strict health standards, and new pollutants, traditional water/wastewater treatment methods remain inadequate in delivering sufficient clean water. Water/wastewater treatment is becoming more cheap because to nanotechnology-based multipurpose and highly efficient procedures that do not depend on huge infrastructures or centralized systems. The purpose of this research is to look at how nanoparticles/fibers may be used to remove contaminants from water and waste water. The paper will give a brief overview of the various nanomaterials (particles or fibers) that are available and used to remove viruses, inorganic solutes, heavy metals, metal ions, complex organic compounds, natural organic matter, nitrate, and other pollutants from surface water, ground water, and/or industrial water. Finally, based on existing nanotechnology uses in the water sector, suggestions are given for a stand-alone water filtration device capable of eliminating all kinds of pollutants from wastewater.

KEYWORDS: Wastewater, Metal ions, Nanoparticles.

1. INTRODUCTION

Water affects many areas of human existence, including health, food, energy, and the economy, to name a few. Aside from the negative environmental, economic, and social consequences of inadequate water supply and sanitation, fresh water is critical for the protection of children and the poor. Waterborne illness kills 10–20 million people per year, while nonfatal infection kills more than 200 million people. Every day, about 5,000–6,000 children die as a result of diarrhea caused by contaminated water. There are now about 0.78 billion people in the world who do not have access to clean drinking water, resulting in serious health issues. More than one billion people in the globe are projected to lack access to clean drinking water, and the existing water supply will be reduced by one-third within a few decades. The freshwater resource on which people rely is the fraction of total run-off that forms steady run-off flow. This steady fresh water flow has been projected to be between 12,500 and 15,000 km3 per year, with 4000 km3 per year considered total freshwater for agriculture, industrial, and household uses, and is expected to rise to between 4300 and 5000 km3 per year by 2025 [1], [2].

Alternatively, just 0.5 percent of the world's 1.4 billion km^3 of water is accessible fresh water, which is also inadequately dispersed across the globe. Due to conflicting needs of growing populations across the globe, there is little chance of an increase in fresh water supply; furthermore, water-related issues are projected to worsen due to climate change and population expansion over the next two decades. According to UN estimates, the global population would grow by 2.9 billion people between now and 2050. In many areas of the globe, the exploitation of water resources for residential, industrial, and agricultural uses has resulted in a shortage of fresh water supplies. The strain on freshwater resources is rising as the world's need for food, energy, and other commodities rises, owing to population increase and the danger of climate change. Another reason of decreased fresh water supply is pollution of surface and ground water sources. Multiple issues such as seawater intrusion, soil erosion, insufficient sanitation, pollution of ground/surface waters by algae blooms, detergents, fertilizers, pesticides, chemicals, heavy metals, and so on are depleting and polluting aquifers throughout the globe.

Existing traditional water/wastewater treatment facilities have been inefficient in meeting environmental requirements due to the emergence of new/emerging micro-contaminants (e.g., endocrine disrupting chemicals (EDCs)) in contaminated water/wastewater. All living creatures have been impacted by the release of these chemicals into the aquatic environment. Traditional materials and treatment technologies such as activated carbon, oxidation, activated sludge, nano-filtration (NF), and reverse osmosis (RO) membranes are ineffective in treating complex and complicated polluted waters containing pharmaceuticals, personal care products, surfactants, various industrial additives, and a variety of chemicals. The removal of a broad range of harmful compounds and pathogenic microorganisms in raw water is not effectively addressed by traditional water treatment methods [3].

2. NANOTECHNOLOGY FOR WATER/WASTEWATER PURIFICATION

Freshwater sources/resources are decreasing owing to extended droughts, increasing population, climate change concerns, and stringent water quality requirements, resulting in increased demand for clean water across the globe. Due to limited and decreasing fresh water resources, people in developing nations are turning to unconventional water sources (e.g., storm water, polluted fresh water, brackish water). Existing water treatment and distribution systems, as well as throwaway habits and large-scale centralized plans, are no longer viable. The present studies do not go far enough in addressing the procedures that ensure the availability of water for all users while adhering to strict water quality requirements. On a daily basis, a variety of commercial and noncommercial technical advancements are used, but nanotechnology has shown to be one of the most sophisticated methods for water/waste water treatment. Nanoscale research has enabled the development of cost-effective and ecologically stable treatment systems for efficiently treating water and wastewater while satisfying ever-increasing water quality requirements.

Nanotechnology advancements have offered possibilities to satisfy future generations' fresh water needs. It is claimed that utilizing various kinds of nanoparticles and/or nanofibers, nanotechnology may effectively solve many of the water quality problems. When compared to other fields such as chemistry, engineering, and materials science, nanotechnology utilizes materials with sizes less than 100 nm in at least one dimension, meaning at the level of atoms and molecules. Because of their structure and greater surface area-to-volume ratio, materials at this size have new and substantially altered physical, chemical, and biological characteristics, allowing for treatment and remediation, sensing and detection, and pollution prevention. Nanomaterials' distinctive characteristics, such as high reactivity and strong sorption, are being investigated for use in water/wastewater treatment based on their roles in unit processes. Nanoparticles may penetrate deeper and therefore treat water/wastewater in ways that traditional technologies cannot. Nanomaterials have a greater surface area to volume ratio, which increases their reactivity with environmental pollutants. Nanotechnology, in the context of treatment and remediation, has the potential to offer both water quality and quantity in the long term via the use of membranes that enable water reuse and desalination, for example. Furthermore, the development of continuous monitoring equipment results in low-cost and real-time readings.

Nanoparticles with strong absorption, contact, and reaction capabilities may function as a colloid when combined with aqueous solutions and exhibit quantum size effects. Because of their tiny sizes, energy conservation and cost savings are feasible; nevertheless, the technology's total use cost should be compared to other methods on the market. Membrane technology is one of the most sophisticated water/wastewater treatment methods, and nanomaterials have successfully contributed to the creation of more efficient and cost-effective water filtering procedures. Nanoparticles have been widely utilized in membrane fabrication, allowing for permeability control and fouling resistance in a variety of shapes and functions. The assembly of nanoparticles into porous membranes or the blending process are used to make both polymeric and inorganic membranes. Metal oxide nanoparticles, such as $TiO2$, are an example of nanomaterials utilized in this creation. CNTs have produced desirable outcomes such as enhanced permeability, microbial inactivation, and so on. Finally, because of their high permeability and tiny pore size, nanofibrous media have been utilized to enhance filtering systems. They're made using a novel and fast manufacturing method called electrospinning, and they may have a variety of characteristics based on the polymers used. In short, the development of nanomaterials such as nanosorbents, nanocatalysts, zeolites, dendrimers, and nanostructured catalytic membranes has enabled the disinfection of disease-causing microbes, the removal of toxic metals, and the removal of organic and inorganic solutes from water and wastewater. In the next section, based on the existing literature, an effort is made to emphasize the variables that may affect the effectiveness of the removal procedures [4]–[6].

3. POLLUTANTS REMOVAL USING DIFFERENT NANOMATERIALS

3.1. Disinfection:

Microorganisms, natural organic matter (NOM), and biological toxins are the three types of biological pollutants. Human diseases and free-living microorganisms are examples of microbial pollutants. In traditional water treatment methods, cyanobacterial toxins are difficult to remove. Many adsorbents, including activated carbon, have reasonable removal efficiencies, and the removal process is influenced by a variety of variables. Both ground and surface water may be contaminated by bacteria, protozoans, and viruses. The toxicity of conventional chlorine chemical disinfection, as well as the production of carcinogenic and very hazardous by-products, has previously been noted. Chlorine dioxide is costly, because the manufacturing process produces dangerous chemicals such as chlorite and chlorate. Ozone, on the other hand, leaves no trace but generates unidentified organic reaction products. Longer exposure times are needed for UV disinfection to be successful, and there is no residual impact. Despite improvements in disinfection technologies, waterborne illness outbreaks continue to occur. So, in addition to their potential for large-scale deployment, new disinfection methods must at least eradicate emerging diseases. Waterborne disease-causing microorganisms may be disinfected using a variety of nanomaterials, including Ag, titanium, and zinc. They have antibacterial characteristics due to their charge capacity. Photo catalysts made of TiO_2, as well as metallic and metal-oxide nanoparticles, are among the most promising antimicrobial nanomaterials [7]. Many studies have emphasized the effectiveness of metal ions in water disinfection. This section of the article discusses how antimicrobial nanomaterials may be used to disinfect water.

3.1.1. Silver Nanoparticles:

Due to its low toxicity and microbial inactivation in water, silver is the most frequently utilized substance, with a well-documented antibacterial action. Silver nanoparticles are made from silver salts such as silver nitrate and silver chloride, and their efficacy as biocides has been demonstrated. Although the antibacterial impact is size dependent, smaller Ag nanoparticles (8 nm) were shown to be the most effective, whereas bigger particle sizes (11–23 nm) had reduced bactericidal activity. Furthermore, truncated triangular silver Nano plates had greater antibacterial effects than spherical and rod-shaped nanoparticles, suggesting that form affects antibacterial activity. The production of free radicals that damage bacterial membranes, interactions with DNA, adherence to the cell surface that alters membrane properties, and enzyme damage are all processes implicated in the bactericidal effects of Ag nanoparticles [8].

3.1.2. TiO2 Nanoparticles:

TiO2 nanoparticles are one of the most promising photo catalysts for water filtration currently available. The generation of highly reactive oxidants, such as OH radicals, for disinfection of microbes, bacteria, fungus, algae, viruses, and other microorganisms is the fundamental mechanism of semiconductor-based photo catalysts such low-cost TiO2 with excellent photo activity and nontoxicity. TiO_2 has been shown to decrease the survival of many waterborne pathogens, including protozoa, fungus, E. coli, and Pseudomonas aeruginosa, after 8 hours of simulated sun exposure. A research demonstrating the photocatalytic disinfection effectiveness of TiO2 showed 100% eradication of fecal coliforms under sunshine. The photocatalytic capacity of TiO2, which was previously confined to UV light, has been greatly enhanced by expanding its optical absorbance to visible light.

3.1.3. Carbon nanotubes and other nanomaterials:

CNTs have been shown to be very efficient in the removal of bacterial infections. CNTs (a kind of nanosorbent) that have been used to remove biological pollutants have gotten a lot of interest because of their superior ability to remove biological contaminants from water. CNTs have antibacterial properties against a variety of pathogens, including bacteria and viruses such as E. coli and Salmonella. Because of the huge specific surface area, exterior diameter of CNTs, large content of mesoporous volume, and other factors, cyanobacterial toxins adsorb better on CNTs than on carbon-based adsorbents [9], [10].

3.2. Desalination:

Desalination is regarded as a viable option for getting fresh water. Despite their high cost, membrane-based desalination technologies represent the majority of desalination capacity, with RO accounting for just 41%. Increasing the flow of water across the membrane to reduce fouling is one of the parameters that influence the desalination cost. RO plants have become more energy efficient as a consequence of recent advances in membrane technology. CNT filters, for example, utilize nanomaterials to create more efficient and less expensive nanostructured and reactive membranes for water/wastewater treatment and desalination. CNTs, zeolites, and graphene are examples of nanomaterials that may help reduce the cost of desalination while also increasing its energy efficiency.

3.3. Heavy metals and ions removal:

For the removal of heavy metals from water/wastewater, several nanomaterials have been developed, including nanosorbents such as carbon nanotubes (CNTs), zeolites, and dendrimers, which have excellent adsorption characteristics. Many studies have looked at CNTs' capacity to adsorb heavy metals including Cd2+, Cr3+, Pb2+, and Zn2+, as well as metalloids like arsenic (As) compounds. In a few experiments, composites of CNTs containing Fe and cerium oxide (CeO2) have been shown to remove heavy metal ions. Arsenic is efficiently adsorbed by cerium oxide nanoparticles supported on carbon nanotubes. The readily accessible adsorption sites and low intra particle diffusion distance are the primary reasons for CNTs' fast adsorption kinetics.

3.4. Organic Contaminants Removal

NOM is made up of a variety of hydrophobic (humic and fulvic acids) and hydrophilic organic molecules that contribute substantially to water pollution. NOM has been removed from raw water using a variety of carbon-based adsorbents, and many variables influence NOM sorption. Nanosorbents such as carbon nanotubes (CNTs), polymeric materials (e.g., dendrimers), and zeolites have excellent adsorption characteristics and are used to remove organics from water/wastewater. Because of their excellent water treatment characteristics, carbon nanotubes (CNTs) have gotten a lot of interest, and the adsorption of organics on CNTs has been intensively researched. CNTs have a greater NOM removal rate than carbon-based adsorbents, owing to their huge surface areas and other considerations. CNTs may also be used to eliminate atrazine and polycyclic aromatic chemical pollutants. The organic sorption equilibrium constants for benzene, toluene, xylene, and ethylbenzene were significantly higher in nanoporous activated carbon fibers produced by electrospinning CNTs than in granular activated carbon.

In addition to CeO2, metal oxide nanoparticles such as TiO2 have been employed as catalysts in ozonation procedures for rapid and relatively complete degradation of organic contaminants. Water polluted with organic pollutants such as polychlorinated biphenyls (PCBs), benzenes, and chlorinated alkanes may be successfully treated using photocatalysts such as TiO2 nanoparticles. In one research, the inclusion of TiO2 nanoparticles improved the removal of total organic carbon from wastewater. TiO2 nanoparticles were also utilized to degrade microcystins in water in a "falling film" reactor. Multiwalled carbon nanotubes (CNTs) functionalized with Fe nanoparticles have been shown to be excellent sorbents for aromatic chemicals such as benzene and toluene.

4. DISCUSSION

Because the water sector is obliged to provide high-quality drinking water, there is a clear need to create cost-effective and reliable materials and techniques to meet the difficulties of supplying sufficient fresh water. There are novel therapeutic approaches being developed; nevertheless, they must be stable, cost-efficient, and more successful than current procedures. Traditional treatment technologies must be modernized, that is, updated, changed, or replaced with more efficient, cost-effective, and dependable materials and techniques. This is especially essential in order to save a significant amount of potable water by reusing wastewater, as well as to address the steadily deteriorating drinking water quality. Nanotechnology has been shown to be useful in addressing water quality and quantity issues. Nanomaterials (for example, carbon nanotubes (CNTs) and dendrimers) are helping modern water systems create more effective treatment procedures. There are numerous elements of nanotechnology that can be used to solve the many issues surrounding water quality in order to maintain environmental stability. By concentrating on future research problems, this study offers a new viewpoint on fundamental nanotechnology research for water/wastewater treatment and reuse. Following the introduction, which briefly covers historic and contemporary methods in water/wastewater treatment, the article is divided into three parts. The characteristics and kinds of nanomaterials, as well as their significance in water/wastewater treatment, are covered in Section 2. Section 3 delves into the many kinds of nanomaterials, with an emphasis on membranes for the treatment of various contaminants in water and wastewater. The use of nanoparticles is examined in terms of their roles in unit operating processes.

Due to rising population, protracted droughts, climate change, and other factors, safe water has become a scarce resource in many areas of the globe. Nanomaterials offer unique properties, such as high surface areas, size, form, and dimensions that make them ideal for water/wastewater treatment applications including disinfection, adsorption, and membrane separations. Water/wastewater treatment utilizing nanoparticles is a potential area for present and future study, according to a review of the literature. When used for this purpose, surface modifications of various nanomaterials such as nanoscale TiO2, nZVI by coupling with a second catalytic metal may result in improved water/wastewater quality by improving the selectivity and reactivity of the chosen materials. Due to the short lifespan of reactive oxygen species, surface modification may improve photocatalytic activity of chosen chemicals and increase the affinity of modified nanomaterials for numerous developing water pollutants. Bimetallic nanoparticles have also been shown to be efficient in the removal of pollutants from water. However, further research is needed to fully comprehend the process of degradation on bimetallic nanoparticles that is accountable for the increased efficiency. However, for effective applications of novel nanocomposites for water/wastewater treatment in the real world, a better knowledge of the process mechanism is critical.

5. CONCLUSION

Different nanofibrous filters have been effectively utilized as antifouling water filtration membranes thanks to electrospinning's ability to alter the surface characteristics of nanomaterials. They have a high surface-to-volume ratio and porosity, are very active against waterborne pathogens, are less toxic with less health concerns, and provide options for ensuring clean water. It's simple to dope functional nanomaterials to create multifunctional media/membrane filters with improved reactivity and selectivity for various pollutants. Although these electrospun nanofibers may be made in a simple and cost-effective manner, industrial scale production remains a problem, and it is critical to examine the topic from an engineering standpoint. The usage of nanofibrous composite membranes for water/wastewater treatment is restricted, therefore a standalone method for eliminating all kinds of pollutants, including bacteria/viruses, heavy metals and ions, and complex organic compounds, is suggested.

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