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Review Article

Application of Nanostructured Materials for the Remediation of Microbes Contaminated Water and Sustainable Water Treatment

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Abstract
Regardless of whether pollution originates from inorganic sources such as heavy metals, or organic waste such as industrial discharges; it poses a grave threat toward human health and environmental equilibrium. Air and water quality, soil health, ecosystem integrity—all can suffer negative impacts due to these pollutants with far-reaching effects on both public health and our surroundings. To alleviate this pervasive problem effectively: comprehensive strategies must be implemented that encompass strict regulatory measures; advocate for sustainable industrial practices – promoting environmentally conscious behaviors is also key, and recent decades have seen a marked rise in pollutants in water sources. Human existence depends on having access to clean water, yet numerous sources are now seriously contaminated. Fortunately, using several cutting-edge methods, nanotechnology provides intriguing and useful options for wastewater cleaning. Numerous pollutants, including germs, sediments, and dangerous chemicals like Mercury and Arsenic, may be removed using nanotechnology. The development of wastewater treatment alternatives is being aided by cutting-edge nanotechnology, which has the potential to improve the reuse of water, recycling, and restoration. This not only improves the quality and durability of the water over the long term, but also assures future generations will have access to it. Diverse procedures and strategies are now used in the field of water purification, many of which use nanomaterials. Nanofiltration is a particularly effective and straightforward technique. Low pressure water is used in this method to flow through nanofiltration filters; these filters may be quickly cleaned by simply back-flushing. Utilizing carbon nanotubes, which are recognized for their efficiency in eliminating a wide range of water contaminants because of their incredibly smooth interiors, is another benefit of nanofiltration. When compared to traditional microstructure materials, nanostructured materials, such as Ag (silver), Au (gold), metal oxides, and CNTs (carbon nanotubes), provide several advantages in the purification of water. They are excellent alternatives for tackling the urgent problems caused by water contamination because of their increased surface area and exceptional qualities. In conclusion, the use of nanomaterials in water filtration, such as Ag, Au, metal oxides, and CNTs, marks a huge step towards protecting our planet's most valuable resource. We can create a sustainable future where everyone has access to clean, secure drinking water by using the potential of nanotechnology.
Keywords: Nanomaterials, carbon nanotubes (CNTs), microbial removal, water treatment, desalinization

1. Introduction

The need for drinkable, clean, and safe water has reached a crucial crossroads in the globe coping with an alarming deterioration in the purity of freshwater supplies. Water quality deterioration has far-reaching repercussions, impacting not only human health but also the ecosystem and the worldwide economy [1]. Throughout history, mankind has explored ways to provide access to safe water, resulting in the creation of diverse measures to ensure a healthier future [2].

The fundamental necessity of clean water to drink cannot be emphasized since it is necessary for living a healthy life. Water purification technologies such as chlorination, filtration, and disinfection have long been recognized as potential sources of economic growth in developed nations. These techniques have demonstrated significant returns for investments [3, 4]. However, the difficulties that underdeveloped nations confront, such as inadequate maintenance, unpredictable water supply, pollution, and a lack of chlorination, frequently result in a gloomy tableau of illnesses and sad mortality [5, 6].

In the ashes of the global crisis, nanotechnology shines as a light of hope. Nanotechnology capitalizes on the amazing physicochemical features of nanoscale particles cause of large surface area smaller in size, strong, cost effective highly porous that can enhance the capability of nanoparticles. Nanotechnology's efficacy in purifying water is closely tied to the stage at which it becomes incorporated into the purification process. Surprisingly, nanotechnology could remove a wide range of pollutants, including bacteria, sediments, and hazardous compounds such as Arsenic and Mercury. Importantly, the use of nanomaterials in water filtration has no negative health or environmental consequences when used below certain limitations [7].

MXenes, boron nitride-based nanomaterials, and carbon-derived sustainable nanomaterials are all actively used in water purification procedures [8-10]. Nanotechnology has a substantial benefit over chlorine-based technologies, which emit cancer-causing byproducts including chlorine and chloramine [11]. Notably, when exposed to UV light, nanomaterials such as Titania have the extraordinary capacity to remove bacteria and destroy organic contaminants, making photocatalytic Titania-coated nanomembranes an exciting option for water purification [12].

The use of atomic layer deposition techniques to cover nanomembranes with antibacterial and photocatalytic compounds predicts enhanced water purification systems, particularly in impoverished nations [13]. Furthermore, modified nanomembranes with nanoparticles included show extraordinary performance in eliminating hazardous metals from water, addressing a major health problem [14]. Nanoscale ions with negative valences emerge as effective adsorbents for separating and removing contaminants from water bodies, stimulating the photochemical reactions oxidation process to improve the removal of pollutants [15].

Innovative materials with high adsorption capabilities, such as carbon nanotubes and dendrimers, are commonly used in sophisticated systems for water purification[16]. The worldwide water issue, compounded by a growing population and the harmful effects of industrial pollution, needs novel solutions. Conventional approaches, on the other hand, sometimes manage to solve specific water quality concerns and can produce undesired byproducts, worsening land contamination [17].

The present nanotechnology research and development environment, together with the incorporation of hybrid membranes into water purification processes, portends an exciting time for water recycling, reuse, and the treatment of wastewater. This discussion dives at numerous strategies, such as nanotechnology membranes and nanoparticles of metal, that have been precisely constructed to remove contaminants including metals, pathogens, and harmful compounds from the water [18].

2. Antimicrobial Water Remediation

Only a small fraction of Earth's water resources approximately 1.2% is suitable for human consumption [19]. The intensification of agricultural and industrial operations has resulted in the generation of diverse inorganic pollutants in aquatic ecosystems. Even at minimal concentrations, these pollutants pose considerable environmental hazards and can severely impact human health [20]. Contamination of drinking water is commonly categorized into four main types: Physical, Chemical, Microbial, and Radiological [20]. Physical contamination involves the presence of suspended sediments and organic matter in water, while chemical contaminants encompass various compounds that may pose risks to living organisms, including nitrogen, salts, pesticides, metals, and toxins microbiological contaminants include a range of organisms such as viruses, bacteria, protozoans, and parasites, which can lead to waterborne diseases like diarrhea, typhoid, and cholera radiological contaminants consist of chemical elements with unstable atoms capable of emitting ionizing radiation [20].

To address microbial contamination, conventional water treatment methods such as chlorine, chloramines, and ozone are commonly employed to control microbial pathogens. However, these disinfectants may react with other water constituents, leading to the formation of harmful disinfection by-products (DBPs) [21].

Substances with antibacterial properties are which can selectively eliminate bacteria or inhibit their growth without causing harm to surrounding tissues. Nanotechnology-derived products show promise in reducing harmful compounds to levels below parts per billion, thereby aiding in achieving water quality standards established by health advisories.

Two most used tests to characterize the antimicrobial activity of materials are Agar diffusion and Broth dilution.

2.1. Agar diffusion method

Procedure: In this method, a bacterial suspension of known concentration is spread uniformly over the surface of a Mueller-Hinton agar plate, creating a bacterial lawn. Paper discs containing different antimicrobial drugs of known concentrations are then placed onto the agar surface. The plate is then incubated for 18 to 24 hours at an appropriate temperature.

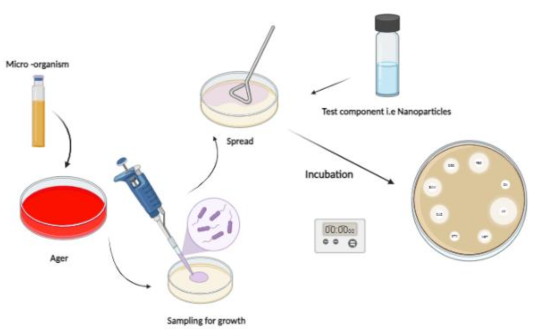

Figure 1. Scematic overview of agar duffusion system for bacterial incubation.

Interpretation: Following incubation, the plates are inspected for zones of inhibition surrounding each disc, which manifest as regions where bacterial growth is suppressed. The diameter of each zone of inhibition is measured and compared to a standardized chart to ascertain the sensitivity of the bacteria to the tested medications. Greater vulnerability is shown by larger zones, whereas resistance is indicated by smaller or nonexistent zones.

Application: The agar diffusion method is a frequently employed technique in clinical microbiology laboratories for conducting regular antibiotic susceptibility testing. It offers a qualitative evaluation of the susceptibility of bacteria to particular antibiotics.[20, 22].

2.2. Broth microdilution method:

Procedure: In this method, a standardized bacterial suspension is inoculated into each well of a microdilution plate containing various concentrations of antimicrobial drugs. The antimicrobial drugs are usually tested at several concentrations, often in twofold dilutions. The plates are then incubated for 18 to 24 hours under appropriate conditions.

Interpretation: Following the incubation period, the wells are inspected for any observable signs of growth. The minimum inhibitory concentration (MIC) is the lowest concentration of the medication at which no growth is detected for a certain isolate. The minimum inhibitory concentration (MIC) is the smallest amount of the medicine required to prevent the development of bacteria.

Application: Broth microdilution method is a quantitative assay used to determine the MIC values of antimicrobial drugs against specific bacterial isolates. It provides precise MIC values, which are crucial for guiding antibiotic therapy and detecting emerging resistance patterns. [23]

3. Water purification techniques

Different treatment strategies are used to treat water. In this way, nanotechnology is indeed a breakthrough in water treatment. Different technologies used for wastewater treatment are shown in Figure 3. But the most common techniques used in the market on large scale is conventional techniques which is sub divided in physical, chemical and biological, but these techniques have their own drawbacks such as high cost, high out flux, time consuming and byproduct is hazardous toward the environment which may cause other type of pollution such

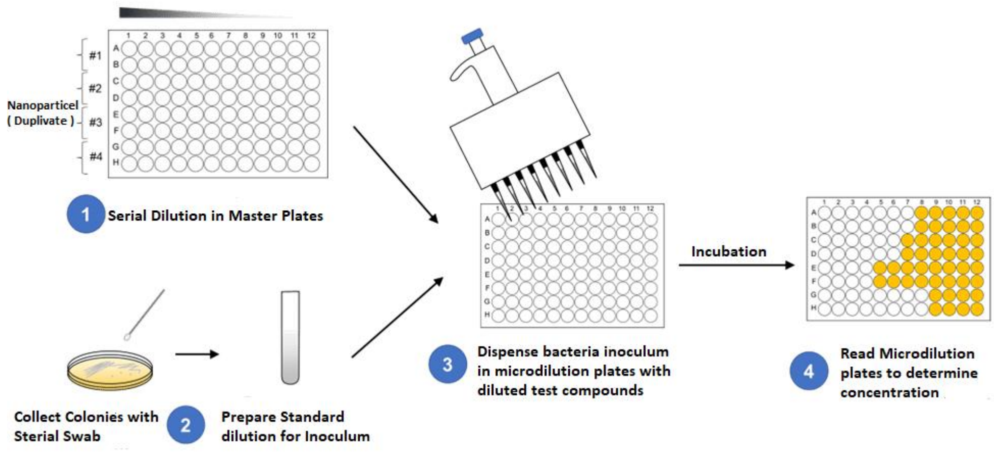

Figure 2. Broth microdilution is used for bacterial isolation and detection.

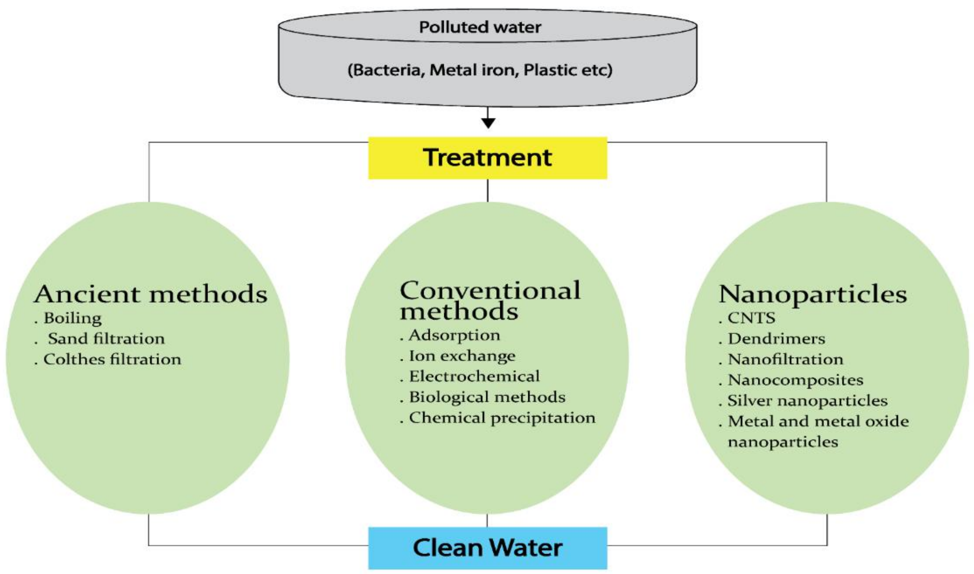

Figure 3. Wastewater treatment strategies.

as land which is discussed in Table 1 [24] that is why new techniques are used which is work on basis of adsorption is a process frequently used in water treatment [25]. Adsorption can refer to several processes used in water treatment and purification [26]. As adsorbents, a wide range of nanomaterials, including catalytic membranes, biomimetic membranes, thin film nanocomposite membranes, and others, can be used in the water purification process [17, 27-33].

3.1. Nanomembranes

At this time, nanomembranes modified with nanofibers are being utilized to remove microparticles, heavy metals, and microbes [66]. Figure 4B (show the Electro spun nanofiber decorated with TiO_2 can filter out various contaminants found

Table 1. Different types of physical, chemical, and biological methods for wastewater treatmen

Physical	Ingredients/elements	Removal efficiency	Advantageous	Disadvantages	Ref .
Settling and filtration	Sand, clay, and large particles can be seen by the naked eye with gravity	<68%	low chemical use, cost-effective and maintained easily	Just use for larg particals i.e sand clay Not purify dye micronse etc	[27, 28]
Sand filtration	floating and sinkable particles also suspended particles by physical encapsulation	98% of those elements	low maintenance, cost-effective, remove particles till 20-30 microns	Sometime need a chemical to increase the performance	[34]
Crossflow filtration membrane	fat, gum, salt, minerals etc.	low solid 0-15 and for high solid 10-70% by volume	effective, no backflow of materials, can increase the life span of the membrane.	With time flux out is decreased and increase in pressure searing of membrain occurs	[35, 36]
Sedimentation	accumulated solid and sludge but coagulant materials are used for it	96%-98% based on chemicals	simple process, low cost,	high maintenance	[37]
Screening	plastic, metals, and paper	good/very effective against large materials	low cost, easy installation,	not effective toward small partials	[38, 39]
Aeration	CO_2 from water and other gases	effective at 20 °C and very good	water becomes cool and stope materials growth or slows down it	more O_2 water becomes corrosive	[40]
Degasification	CO_2 from water and other gases	Control water pH, a very good cause that protects materials from corrosion	cost-effective and	maintenance is very hard, causing some time corrosion to occur	[23, 41]

Chemical					
Disinfection	chlorine, chloramine, and chlorine dioxide and effective for microbes	Good long contact time, time, and chemical-dependent	speed up reaction time, remove solid, form large sludge, cost-effective.	hard to handle, need more manpower	[42, 43]
Deformers	cause by biological activity, mechanical action	Good but used in industries	Fast reaction, non-selective process	Expensive	[44, 45]
Coagulation	suspender solid, clay, iron, algae	water naturalization 95-99%	good quality, low cost,	high maintenance, time-consumin	[46]
Corrosion inhibitors	Anodic, cathodic, film-forming	Not good	Effective toward metal removal	form corrosive gases, need more time, high chemical use, some chemicals form flammable gas I. Hydrazine	[47-49]
Biological					
Aerobic	break organic contaminations and nitrogen and phosphorus with the help of O_2	according to WWTP 98% efficient	Effective toward high organic contamination	new aeration machine will attach, high cost, higher maintenance requirements, water test good	[50]
Detoxification	highly toxic materials, cadmium etc.	Excellent	Nil	Dissolved solid cannot be removed	[51]
Oxidation ponds	biological aeration by photosynthesis and from slug by the help of chemical settle down	excuse process is natural	natural process,	cost-effective in terms of its construction, maintenance, and energy requirements	[52]
Nitrification	ammonia to nitrite and nitrite to nitrate	decreases from 90–94% at 15 °C to about 55% at 2 °C	Effective toward removal of ammonia	Occurred in warm temp only, High cost on mentanance and monitering	[53]

Table 2. Removal of toxic elements from water using different techniques.

Treatment approaches	Ingredients/ elements	Pollution	Removal efficiency	Advantages	Disadvantages	Ref.
Lime softening and Aeration	Calcium Strontium and Magnesium ions	High concentration in hard water	70-90% depends on water hardness and use of chemical	Reduced hardness nvironment friendly Control Ph	Rise in pH and precipitate calcium Slow process	[61, 62]
Wood-based biochar	Copper, Calcium, Cadmium and Arsenic	High concentration of metals, phosphorous, nitrogen and organic contaminants in polluted water	50-70% if specific modification occurs	asy removal of fine particles High operational temperature, low availability of biochar	Low term stability Emission of carbon in process	[56, 63]
Removal of ammonia	zeolite and powdered activated carbon, ozone microbubbles	Used for ammonia	90-95% decreased temperature efficiency decreased	High adsorption capacity Compatible for bacterial removal	ligh cation-exchange ability Costly	[64]
Sorption method, activated carbon	Oil and grease	Organics, mixed oil, and grease	Effective	Compatible and Dependable and does not produce toxic byproducts.	Low surface area but depend of process	[65]

in water, such as textiles waste re, particulate removal, dust, sand, effluent treatments, heavy metals, pathogens, microbes, and bacteria, as well as desalination of salty seawater [67]. The ultra filtration UF membrane successfully eliminated 99.7% of the bacterial cells from the UF feed. The capacity of UF membranes to selectively filter bacterial cells is well known. As a result, the findings described in [68] were perfectly predictable. Bacterial cell counts remained continuously low following the UF treatment throughout all downstream water treatment steps. In fact, the permeates from the final NF membrane had a 99.99% reduction in microbe counts when compared to the raw water source.

Although some bacterial cells were still detected in the nanofiltration NF permeate, research has shown that some microbial cells can pass through theoretically impermeable reverse osmosis RO membranes [69]. The water distribution systems can be affected if these bacterial cells are left untreated; they can grow in the presence of nutrients and form problematic biofilms. The downstream water distribution system should have certain measures to avoid biofouling [70]. These membranes are required for the reverse osmosis pretreatment method. It has been demonstrated that inorganic nanomembranes doped with titanium oxide can degrade chemicals, particularly chlorinated compounds [31, 71]. To prevent biofilm formation, polymeric membranes doped with Nano-Ag are applied to the membrane's surface. Viruses are rendered helpless, reducing the amount of biofouling. With nano catalysts' unique properties, they are extremely useful for removing contaminants from water quickly and effectively. Catalysts like these can degrade environmental pollutants like halogenated pesticides, herbicides, and nitrogenous aromatic compounds [72, 73]. Wastewater treatment with biological nanoparticles has a lot of untapped potential. In Figure 2B have a Tio_2 which will work as a antibacterial activity against gram-positive and gram-negative bacteria and cellulose acetate fibers implanted with Ag nanoparticles, making them candidates for treatment in waterborne pathogens [74, 75].

3.2. Nanofiltration

The nanofiltration method can remove contaminants from both groundwater and surface water, which is important in producing drinking water. Nanofiltration (NF) membranes are frequently used in pharmaceutical and textile industries to remove organic and trace contaminants and produce high-quality water. NF performance and integrity can be compromised by biofouling of the NF membrane, which can permeate water quality [76]. The pressure drop along the membrane module grows as biomass builds up on the membrane surface [76, 77], increasing energy consumption. The mechanism of biofouling in the NF process and its effects have been thoroughly investigated [78, 79]. However, a deeper understanding of how biocides work to eliminate organic pollutants, particularly AOC, is required. Further exploration is needed to acquire a complete knowledge of the physical and chemical properties of organic carbon that can cross the NF membrane. [75, 80]. The most common application of nanofiltration is softening of water, also used to remove micropollutants and microorganisms. The fact that these NF membranes have been installed successfully in various industrial settings demonstrates their dependability. The drinking water industry has invested heavily in nanofiltration systems. The primary reason for their widespread use in the water industry is their ability to function as membranes that soften water [81]. The primary goal of nanofiltration is to reduce hardness in water. Because nanofiltration can easily remove naturally occurring organic matter, it is also used in surface water treatment units. The mechanism is illustrated in Figure 5 [82].

4. Nanomaterials for the purification of water

While nanotechnology has made significant strides in water purification, further advancements are necessary to establish a sustainable water treatment process. Numerous developments have been made in this area, with nanotechnology-based products holding promise in reducing the concentrations of toxic substances to extremely low levels and meeting health advisory-prescribed water quality standards [83].

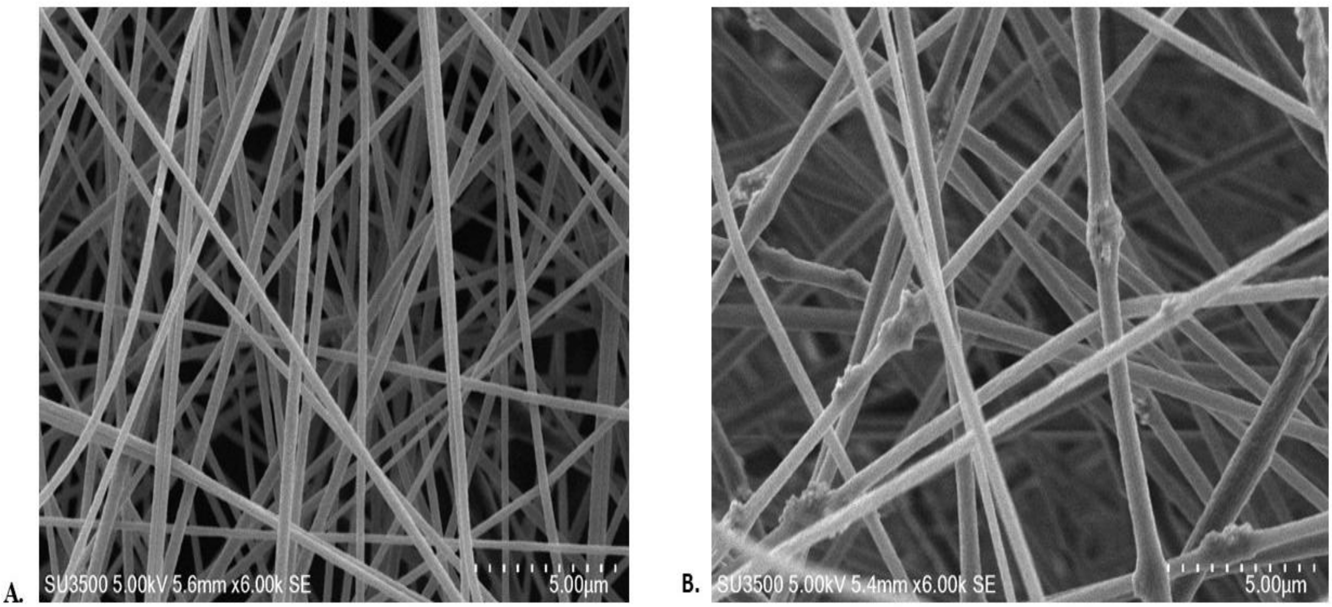

Figure 4. (A) Electrospun PAN nanofiber (B) Electrospun nanofiber with TiO2 Nanopaticlas.

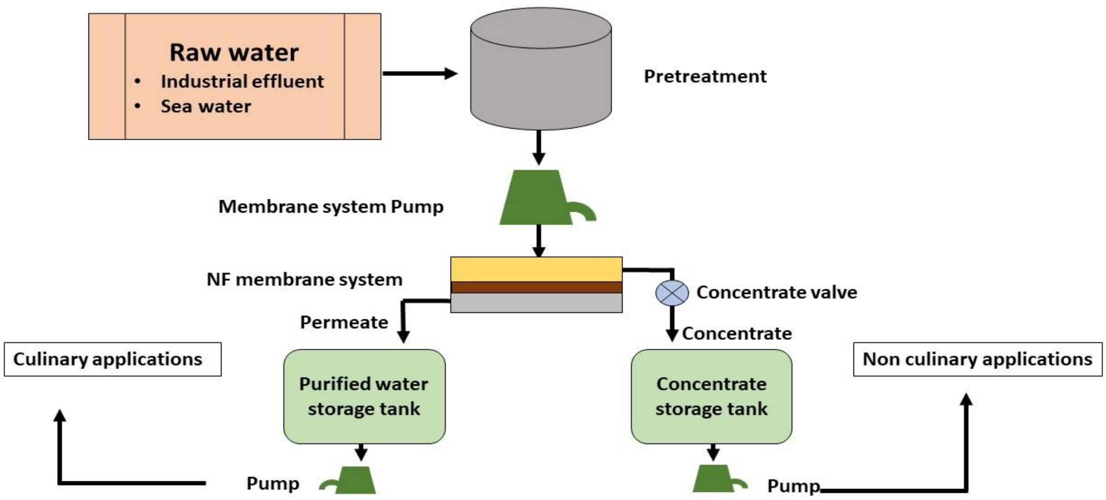

Figure 5. Schematic representation of nanofiltration. Feed water or raw water to the membrane system is continuously supplied by high-pressure pumps. Feed water is separated into purified permeates and concentrated in the membrane system. A concentrate valve can control the amount of feed water and permeate that is diverted to the concentrate stream. This valve also controls the amount of concentrate produced from the feed.

Antibacterial efficacy is linked to compounds that selectively target bacteria without causing harm to surrounding tissues. Through nanotechnology, nanoparticles made from metals, transition metal oxides, carbon-based materials, and dendrimers have been developed to inhibit bacterial growth, and some can eradicate bacteria upon contact [84].

Addressing water treatment challenges necessitates the development of efficient, cost-effective, and environmentally friendly solutions for various applications. While nanotechnology has made significant strides in water purification, further advancements are essential to establish a sustainable water treatment process. Ongoing developments in this field continue to push towards achieving this goal [85].

Nanomaterials, which exhibit distinct properties compared to their bulk counterparts and typically measure less than 100 nm, find extensive use in advanced applications across electronics, biomedicine, energy storage, and environmental remediation. These materials can be classified based on their shape, ranging from zero-dimensional (0D) to three-dimensional (3D), each demonstrating unique properties owing to their size. Variances include pore size distribution, reactivity, surface functionality, tensile strength, conductivity, mechanical and electrical properties, as well as optical functions[86].

Nanostructures such as nanorods offer versatile applications due to their reflective properties, which can be adjusted by altering their orientation using an applied electrical field. Nanowires find utility as additives in advanced composites, metallic interconnects at the nanoscale, and in quantum devices, serving roles in various electronic, optoelectronic, and nanoelectromechanical systems [87].

Metal oxide nanoparticles like titanium oxides, zinc oxides, magnesium oxides, manganese oxides, and ferric oxides hold promise as adsorbents for environmental remediation efforts. These nanoparticles possess a notably high surface area to volume ratio, along with heightened selectivity, sensitivity, and reactivity, making them valuable in wastewater purification applications [54].

4.1. Metal Nanoparticles

4.1.1. Silver Nanoparticles

Silver nanoparticles are highly effective antibacterial agents on top of being extremely toxic to a wide variety of microorganisms, including bacteria, viruses, and fungi [87-89].

Due to their antimicrobial properties, silver nanoparticles can be used as an effective water disinfectant Silver nanoparticles are currently being used in water purification because they are an effective disinfectant see Table 3 [90]. Metal and metal oxide nanoparticles have broad-range antimicrobial activity that can penetrate bacterial cells and severely alter the structure of DNA, lysosomes, ribosomes, and enzymes. This can result in oxidative stress, electrolyte imbalances, inactivation of enzymes, gene expression, and proteins, and a range of other adverse effects. Metallic nanoparticles inhibit the growth of E. coli and other Enterobacter species, promoting bacteriostatic and bactericidal effects and decreasing waterborne diseases.

Since the precise and conclusive mechanism by which silver nanoparticles kill bacteria is still under investigation, at the moment it has not been fully understood how the silver ions can modify ribosomes which would significantly alter the structure of the cell and that the DNA's sulfur and phosphorus atoms stop the DNA's replication cycle [90]. Some of the antibacterial characteristics of silver nanoparticles (AgNPs) are mentioned herein. 1) Disruption of the cell wall and the cytoplasmic membrane is caused by silver ions (Ag^{+}) produced by silver nanoparticles that bind to or pass through the membrane. 2) Denaturation of ribosomes by silver ions, which prevents protein production as demonstrated in Figure 6. Despite the versatile use of Ag nanoparticles, they also possess some limitations toward humans and the environment which are discussed in Table 4. (NCBI).

Porous polyurethane foam (PUF), a polymer composed of organic units linked by carbamate bonds, is commonly used in various applications such as insulation, cushioning, and packaging. coated porous polyurethane foam with stable silver nanoparticles for point-of-use treatment of drinking water contaminated with E. coli [91]. Similarly, developed a highly efficient conducting nano-sponge of polyurethane coated with carbon nanotubes and silver nanowires for water treatment. This setup achieved significant bacterial and viral removal with minimal energy consumption [92]. Porous copper foam, known for its electrical conductivity and ductility, was utilized for drinking water disinfection by introducing silver-plated porous copper foam with copper nanospikes. The synergistic effect of high voltage and reactive oxygen species (ROS) generation resulted in effective bacterial deactivation [93]. Developed emergency filters containing silver nanoparticles embedded in blotting paper, demonstrating significant reduction in bacterial contamination when tested with E. coli and E. faecalis-containing water [92]. Devised a filtration system comprising silver nanowire-carbon nanotube matrix fabricated chitosan-coated silver nanoparticles within cotton fiber, which facilitated rapid gravity filtration and eradication of E. coli [94, 95]. Polymeric microspheres containing silver nanoparticles, stabilized with carboxylic functional groups, exhibited antibacterial properties against various pathogens and achieved significant removal within a short contact time [96].

4.1.2 Iron-based Nanoparticle.

Iron nanoparticles (Fe NPs) come in various forms; some of which are called zero-valent iron nanoparticles, various polymorphs of iron oxides, oxyhydroxides, and iron hydroxides. Because of their lower cost and the fact that iron is the second most abundant metal on the planet, iron nanoparticles have received increased attention for their applications in treating contaminants in wastewater [74, 78]. Zero-valent Fe nanoparticles have also shown antibacterial properties when tested with bacteria. Antibacterial activity tests were performed for gram-positive bacteria *S. aureus* and *B. subtilis* and gram-negative bacteria *Ps. aeruginosa* and *E. coli* [97][97][97]. The zero-valent nanoparticles produced ROS species. The zero-valent iron nanoparticles effectively inhibited bacterial growth because of the corrosive properties of Fe^{2+} and Fe^{3+} ions, which interfered with the bacterial cell membrane. The potential use of zero-valent iron NPs in systematic wastewater treatment is increased by this growth inhibition [23, 98].

Nanoparticles composed of iron can be fabricated in a variety of different forms, including magnetite, maghemite, hematite, iron oxyhydroxide, and metallic zerovalent iron shown in Figure 7 [5, 43, 50]. Iron is a material that can be used in industrial wastewater treatment that is both feasible and environmentally friendly due to its superparamagnetic properties, low production costs, high natural abundance, and relative simplicity of synthesis. When used as a nano-adsorbent in wastewater treatment, they can remove a wide range of contaminants in Table 3. Producing iron oxide nanoparticles can be accomplished through a few different approaches, each of which comes with its own individual set of benefits and drawbacks such as toxicity toward human and environment which are shown in the Table 4. Moreover, the water purification capability of Fe NPs can be enhanced by surface modification as shown in Figure 8. [28, 54, 99].

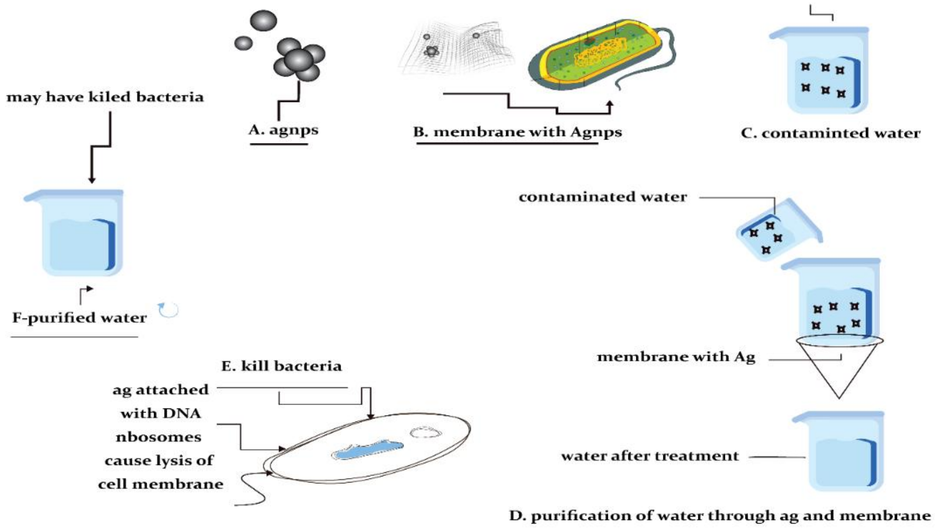

Figure 6. Schematic illustration of water purification through Ag nanoparticle-based membrane.

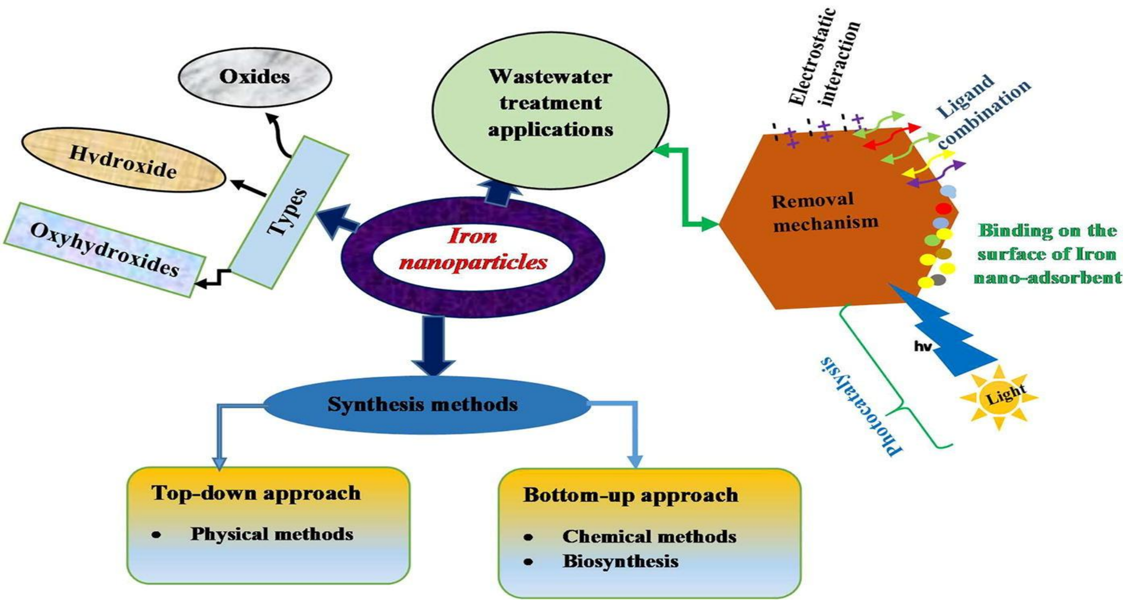

Figure 7. Iron nanoparticles and their synthesis methods [28].

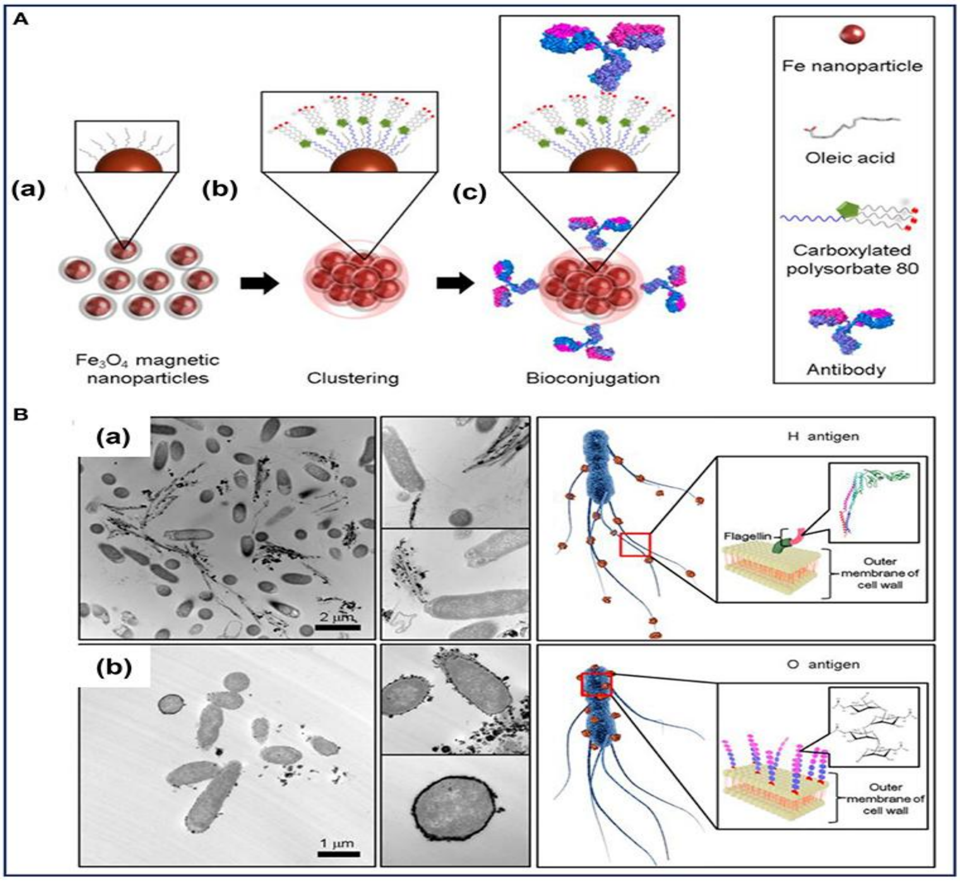

Figure 8. Representation of the process to generate bioconjugated magnetic clusters of Fe nanoparticles using antibodies in (A) and of the many antigens that Salmonella typhimurium primarily targets in (B Reproduced with permission).[99]

4.1.2. . Copper (CU)

Copper (Cu) has long been recognized for its efficacy in combating bacteria. Copper and its compounds have shown effectiveness against a broad spectrum of yeast and fungi, including Aspergillus species, Candida albicans, Cryptococcus neoformans, and various others [1]. However, the use of copper compounds may raise environmental concerns and necessitate high dosages. Therefore, efforts have focused on developing chelated forms of copper to mitigate toxicity and reactivity with other water constituents, such as copper-8-quinolinolate and its derivatives [100].

The antibacterial action of copper stems from its ability to disrupt microbial proteins and nucleic acids, leading to structural alterations and inhibition of biological functions. The redox cycling between Cu2+ and Cu1+ results in the generation of highly reactive hydroxyl radicals, enhancing copper's antimicrobial effectiveness [101]. Increased copper concentration within cells, disruption of membrane integrity, and interference with protein bonding contribute to its antibacterial properties [102].

Metallic elements like silver (Ag) and copper (Cu) are well-known for their antibacterial prowess, particularly when utilized at the nanoscale. Their properties are accentuated at this scale, underscoring their potential in antimicrobial applications [103].

Quasi-crystals possess unique physical properties due to their complex crystal structure Figure 9, which includes perfect long-range order without translational periodicity and forbidden symmetries. These properties include low thermal and electrical conductivity, high hardness, a low coefficient of thermal expansion, a low coefficient of friction, and good corrosion resistance [104-106].

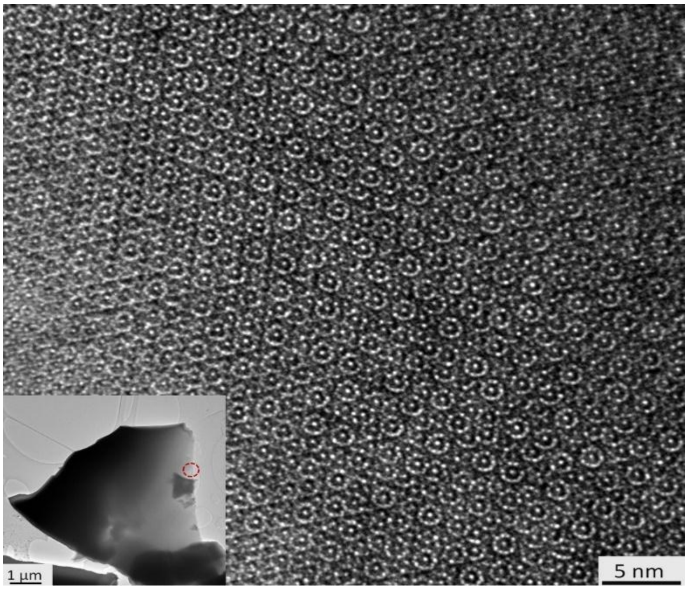

Figure 9. The high-resolution transmission electron microscopy (HRTEM) image reveals a real-space structure characterized by a uniform, quasiperiodic, and ten-fold symmetric pattern. Reproduced with permission [107]. Copyright (2015), Nature Publishing Group.

In a study comparing the antimicrobial properties of quasicrystals Al–Cu–Fe, Al–Cu–Fe–B, and Al–Cu–Fe–Co under leached and unleached conditions, leaching with 10M NaOH resulted in an increase in copper and iron concentration on the surface. Al–Cu–Fe–Co exhibited greater resistance to gram-positive (B. cereus, K. rosea) and gram-negative (E. aerogenes, K. pneumoniae) bacteria. Leached Al-Fe-Cu-Co displayed an inhibition zone close to copper, indicating its efficacy in bacterial inhibition [108, 109].

4.1.3. Metal oxide nanoparticles

Nanoparticles of metal oxide are composed entirely of metal precursors. Nanoparticles are essential to studying physics, chemistry, and material sciences in various subfields. When thermal elements are present, various oxide compounds can be formed. Depending on the configuration, these can have an almost infinite number of structural geometries and their electronic structures can have the properties of an insulator, a semiconductor, or a metal [5, 28, 43, 50, 59, 110]. Due to the one-of-a-kind characteristics of metal oxide nanoparticles such as their high surface areas and low concentration, these particles have a significant amount of unrealized potential for treatment for contaminated water. Nanoparticles of different metal oxides, such as MgO, TiO_2, ZnO_2, MnO_2, Fe_3O_4/Fe_2O_3, MnO_2, AlO_3, and CeO_2, and the in Table 3 applications of these nanoparticles in water treatment [111].

Zinc oxide is a potential agent for various applications as it has shown antimicrobial properties at the nanoscale [32]. Researchers have successfully incorporated ZnO as an antimicrobial agent into textiles, surface coatings, cosmetics, and cellulose fibers to inhibit microbial growth. Because of this, ZnO is commonly regarded as a useful antibacterial agent and is thought to be a safe material for both humans and animals because of its stability and selectivity Table 4 [28, 36, 112].

ZnO nanoparticles antibacterial mechanism is still unclear, but they show different activities in the presence of light than in the dark as shown in Figure 8. Reactive oxygen species (ROS) are produced in the presence of light, which may involve photocatalytic activity in developing the antibacterial action. ROS, in addition to photocatalytic action, also causes oxidative stress, damaging the bacteria membrane. The release of ROS from the nanoparticles' surfaces, photocatalytic activity, the release of Zn^{2+}, direct interaction with the cell membrane, and the morphology or size of the nanoparticles can all be used to explain the antibacterial activity of ZnO nanoparticles [28, 36, 46, 52, 110, 112]. ZnO nanoparticles are activated by UV and visible light, so ROS release depends on their photocatalytic activity. ROS is generated after the electrochemical reaction. The internalization of Zn^{2+} is facilitated by the action of ROS at the cell wall and membrane level, which causes strong oxidative stress that leads to cell growth inhibition and, eventually, cell death Figure 10.

4.1.3.1. Titanium dioxide (TiO_2)

TiO2 NPs have demonstrated promising activity against fungal pathogens as well as both Gram-positive and Gram-negative bacteria [113]. Photocatalytic inactivation of microorganisms was initially demonstrated [114].

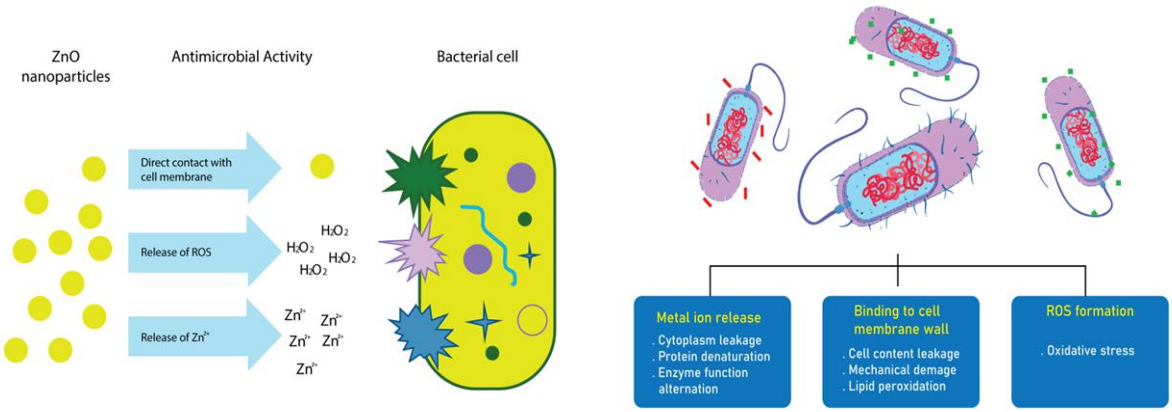

Figure 10. Metal oxide nanoparticles and their Mode of action against bacterial cells.

The antibacterial mechanism of nanomaterials primarily involves the production of reactive oxygen species (ROS), release of metal ions, and membrane damage for wastewater purification.

In many cases, TiO2 is utilized in conjunction with other substances to enhance material properties. Nano-adsorbents have emerged as potential materials for adsorption due to their increased surface area, which enhances chemical activity and adsorption capacity [115, 116].

Nano-catalysis exploits the unique properties of nanomaterials, such as high surface area to volume ratio and surface chemistry, to accelerate chemical reactions. Various nano-catalysts, including photocatalysts, electrocatalysts, and Fenton-based catalysts, are employed for wastewater treatment, facilitating chemical oxidation of organic pollutants and antimicrobial actions [117, 118].

Nano-membranes represent an advanced wastewater treatment approach, leveraging nanomaterials to enhance permeability, selectivity, and fouling resistance. Integration of nanotechnology, such as TiO_2-graphene oxide (GO) grafting onto membrane surfaces, enhances organic contaminant degradation under UV and sunlight, increases membrane flux through photocatalysis-induced hydrophilicity, and improves contaminant removal via photodegradation [119].

4.1.3.2. Zinc Oxide (ZnO)

Zinc oxide (ZnO) nanomaterials, predominantly in the form of the stable Wurtzite phase, exhibit remarkable photocatalytic properties under light exposure, generating reactive oxygen species (ROS) which aid in the degradation of harmful substances and pathogens. ZnO, like TiO2, possesses a high band gap, necessitating modifications to extend its utility. However, both ZnO and TiO_2 suffer from photo-corrosion due to rapid electron-hole recombination in aqueous environments, which limits their effectiveness. Nonetheless, through modifications and doping to decrease the band gap, they can absorb visible light, mitigating this issue.

One mechanism of ZnO's antibacterial action involves the release of Zn2+ ions, which can disrupt cell membranes and intracellular contents, leading to toxicity against various microorganisms. Additionally, ZnO's photoactivity involves the generation of electron-hole pairs upon exposure to light, initiating a cascade of reactions resulting in the production of ROS, particularly hydrogen peroxide, which can penetrate bacterial cell membranes and induce cell death.

4.1.3.3. Mechanism for release of ROS

The mechanism proposed for photoactivity involves the activation of zinc oxide (ZnO) by UV and visible light, leading to the formation of electron-hole pairs:

$$ZnO + \text{light energy } (h\nu) \rightarrow e^- + h^+$$

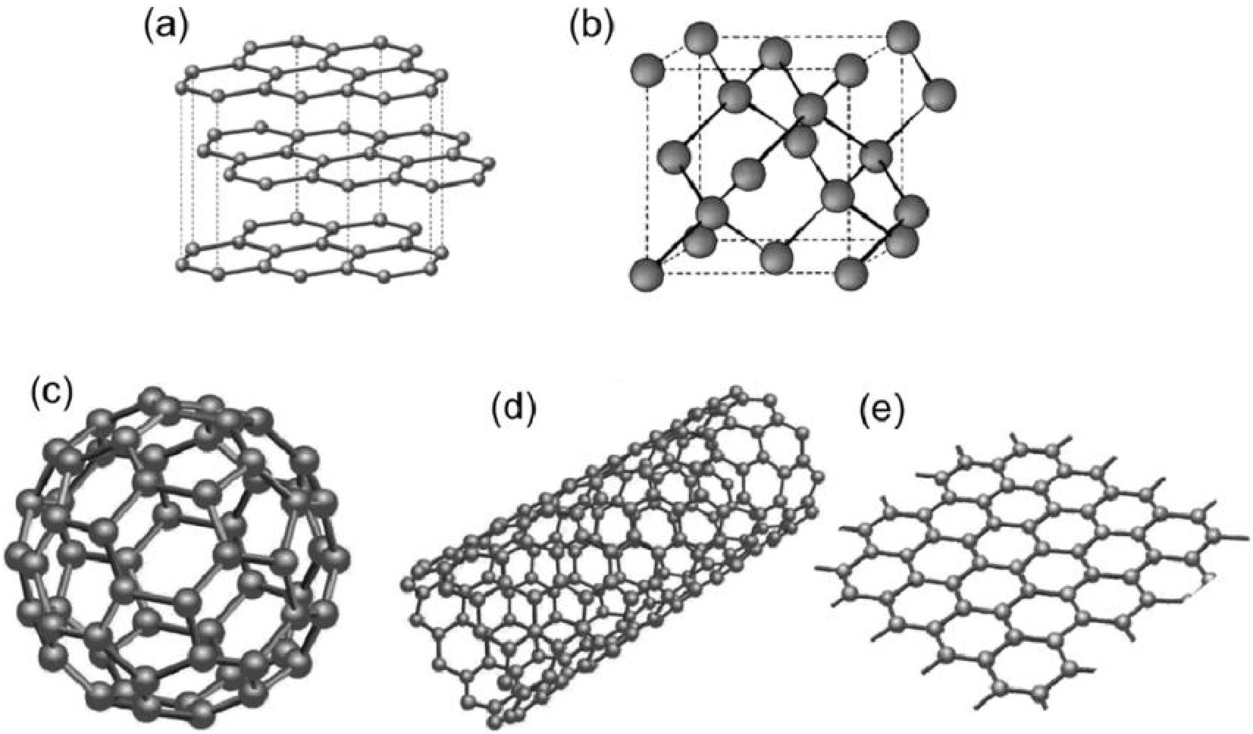

Figure 11. show shapes (a) graphene (b) Diamond (c) buckminsterfullerene (d) 1D nanotubes (e) 2D graphene [125]

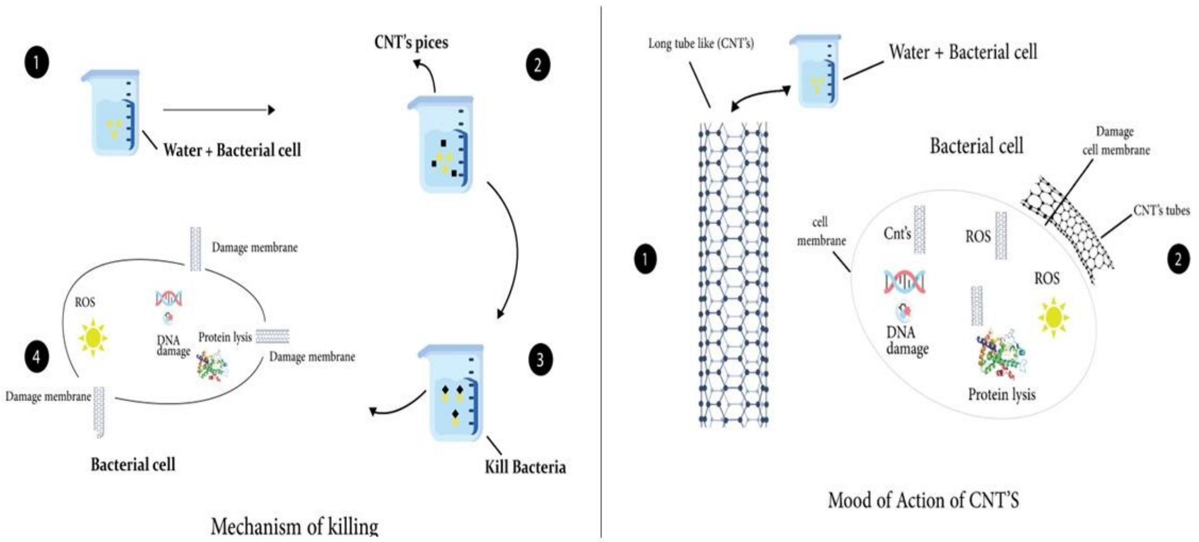

Figure 12. Mechanism of antibacterial activity of CNTs.

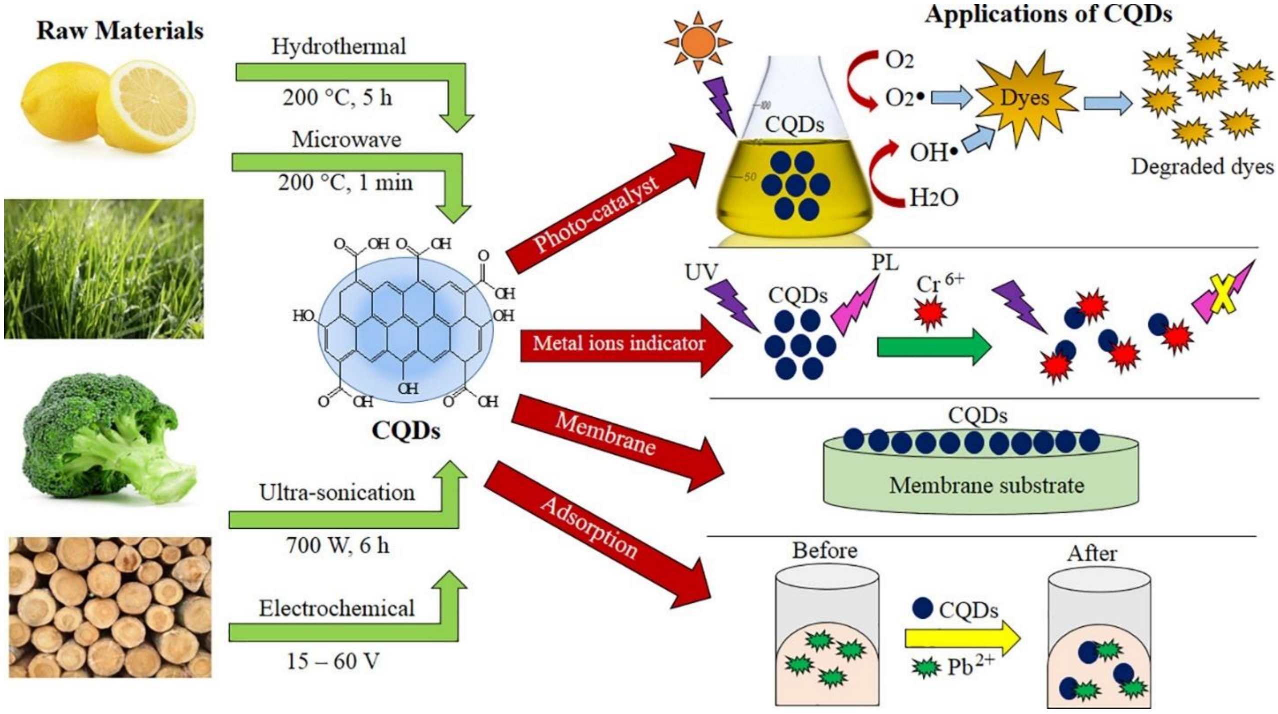

Figure 13. Carbon quantum dots (CQDs) and its application in wastewater treatment [136].

These electron-hole pairs then interact with water molecules in the ZnO suspension, splitting them into hydroxyl radicals (OH^-) and hydrogen ions (H^+):

$h^+ + H_2O \rightarrow OH^- + H^+$

Oxygen molecules (O_2) are converted into superoxide anions (O^{2-}) through the donation of an electron:

$e^- + O2 \rightarrow O2^-$

The superoxide anions then react with hydrogen ions to produce hydroperoxyl radicals (HO^{2-}):

$O^{2-} + H^+ \rightarrow HO^{2-}$

Hydroperoxyl radicals further interact with electrons, generating hydrogen peroxide ions (H_2O^{2-}), which, in turn, react with hydrogen ions to form hydrogen peroxide molecules (H2O2):

$HO^{2-} + H^+ + e^- \rightarrow H_2O^{2-}$ $\qquad$ $H_2O^{2-} + H^+ \rightarrow H_2O^2$

Hydrogen peroxide molecules are capable of penetrating the cell membrane of bacteria, ultimately leading to their demise [74, 120].

5. Carbon Nanotubes (CNT)

Carbon nanotubes (CNTs) are cylindrical macromolecules made of carbon atoms arranged in a hexagonal lattice **and** capped with half of a fullerene-like structure at their ends. They are classified into two main types based on the hybridization of carbon atoms within their layers: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). SWCNTs typically range from 1-3 nm in diameter, while MWCNTs can be up to 100 nm in diameter [121].

Table 3. Implantation of nanoparticles for wastewater treatment

Nanoparticle type	Removal of pollutants	Size	Pros and Cons	Ref.
Nano metal (Ag, au, Fe, Al, Zn, Ni, Cu, Sn, Co, Mg, Ce, Bi, etc.) and Nano metal oxides (MgO, CuO etc.)	Heavy metals (Arsenic) radionuclides Microbes like bacteria etc.	1nm to 100 nm	No expensive equipment applicable in different systems Limitations in scale-up, Reproducibility	[137]
Nano catalysts (silver Nano catalysts etc.)	Pesticides	49 to 180 nm based on the shape	Chemical inertness Cross selectivity	[138]
Bioactive nanoparticles (Sliver nanoparticles)	Bacteria and Fungi	Same as silver	Offering potential ways of treatment Costly	[139]
Carbon and its nanocomposites (graphene and CNTs)	Organic contaminants including dichlorobenzene, ethylbenzene, Zn^{2+}, Pb^{2+}, Cu^{2+}, and Cd^{2+} dyes	CNTs 10 to 100 nm difference is on the type of CNTs	Lighter than conventional composites, improved properties Economic disruption	[57, 58]

These one-dimensional nanomaterials, formed by folding two-dimensional graphene sheets into hollow cylinders, exhibit exceptional properties due to their unique structure. SWCNTs have shown stronger antibacterial activity compared to MWCNTs, possibly due to their smaller diameter and larger specific surface area, which facilitate stronger surface interaction with bacterial cells [122].

The cytotoxicity of CNTs may be influenced by their purity, with impurities generated during preparation potentially affecting microbial control [123]. Mechanistically, attachment of CNTs to bacterial cells can lead to cell membrane damage, altering membrane structure, permeability, and proton motive force [124].

Carbon nanomaterials (CNMs) are intriguing candidates for use as adsorption agents. The CNMs are advantageous in wastewater treatment because of their large surface areas and aromatic compound selectivity. Because of their structure, Figure 11.

carbon nanotubes are being used more effectively than other carbon nanomaterials [56, 60, 76]. These factors contribute to the diverse application of these CNTs in water purification as shown in Table 3 [58].

Antibacterial properties of CNTs were examined, it was discovered that decreased CNTs could hinder bacterial growth and that the sharp edges of the graphene sheets can kill bacteria by generating stress at their cell edges [4, 10]. Moreover, due to the electronic structure of CNTs, the antibacterial mechanism can change in response to physical, chemical, and bacterial oxidation impacts[71]. CNTs can specifically adsorb cations, dyes, ethylbenzene, and other substances. The functionalization of CNTs increases the adsorption capacity of the particles by increasing both their surface area and dispensability [60, 78]. It is possible to extract Chromium from water using a nanocomposite adsorbent composed of CNTs, which possess adsorption properties, and iron oxide, which possesses magnetic properties. When these two different substances were brought together, a nanocomposite adsorbent was produced, but the antibacterial mechanism of CNTs is still unknown [126] but it is highly toxic toward humans at activated form and not harmful toward environment see in Table 4[127].

Several mechanisms have been proposed in the literature, as shown in Figure 10. It is expected that CNTs get attached to the surface of microbial cells, disrupting transmembrane electron transfer, and damaging the membrane and cell wall Figure 12. The CNTs penetrate bacterial cells, damaging DNA and causing protein malfunction. Secondary products, such as harmful reactive oxygen species (ROS), are formed.

6. Carbon quantum dots (CQDs)

Emerging nanomaterials exhibit unique properties for antibacterial applications. Their nano-sized dimensions and core-shell structure, typically composed of sp^2-hybridized carbon atoms, make them promising candidates for combating bacterial infections. CQDs are effective against Gram-positive Staphylococcus strains. CQDs' antibacterial activity can be enhanced through various synthetic routes, such as doping with nitrogen atoms, which introduces amine and amino groups on the surface, facilitating electrostatic interactions with bacterial membranes [128]. Furthermore, doping with different atoms like nitrogen and sulfur can significantly alter the structural, photo-luminescent, and antibacterial properties of CQDs [129]. The small size of CQDs leads to quantum confinement effects, enhancing their antibacterial efficacy through the generation of reactive oxygen species (ROS) under light irradiation. Furthermore, their low dark cytotoxicity makes them ideal candidates for biomedical applications, particularly in photodynamic therapy.

CQDs are characterized by their core-shell structure, typically composed of sp^2-hybridized carbon atoms arranged in a graphene-like structure [130]. Various synthetic routes, such as nitrogen and sulfur doping, have been explored to enhance their antibacterial activity. These synthetic modifications significantly alter the structural and photo-luminescent properties of CQDs, thereby influencing their efficacy as antibacterial agents [131].

Antibacterial Mechanisms of CQDs Under blue light irradiation, CQDs exhibit photoactivity, generating ROS like singlet oxygen, which demonstrate strong antibacterial effects [4]. The antibacterial activity of CQDs can be further enhanced through functionalization with compounds like ethylenediamine (EDA) combined with hydrogen peroxide (H2O2), leading to synergistic effects [132]. Moreover, when incorporated into nanocomposites like CQDs@TiO2, CQDs enhance ROS generation, offering potential applications in combating bacterial infections [133].

Evaluation of NCQDs against Staphylococcus Recent studies have evaluated nitrogen doped CQDs (NCQDs) for their antibacterial activity against Gram-positive Staphylococcus strains [134]. Results indicate that NCQDs exhibit specific antibacterial effects against Staphylococcus, disrupting the cellular structure of the bacteria Figure 13 [135].

7. Nanocomposites

There are many different nanomaterials. Because of their magnetic properties, nanocomposites have quickly become one of the most investigated materials. Additionally, because of these properties Isolating the nanocomposites from the solvent is a relatively easy process. [34]. The production of a nanofiltration membrane requires multiple steps, two of which are incorporating titanium oxide (TiO_2, salts etc.) nanoparticles into the membrane and fabricating a co-polyamide network on top of a polyimide backing Figure 14.

Both steps must be completed before the membrane can be used. Today's most popular water treatment membrane methods involve ultrafiltration, microfiltration, forward osmosis, or reverse osmosis processes (using hollow or spiral-shaped membranes), which often operate under high pressure and ultraviolet radiation [79].

Standard commercial systems employing polymer-based membranes provide the continuous operation of the membrane during water permeability operations. However, the graphene-based nanocomposite membrane functions as a selectively permeable barrier. Graphene nanocomposite membranes can enhance the efficiency of water desalination, filtration, purification, dye or metal degradation, ultrafiltration, pollutant detection, and water separation applications.

[49].

Graphene membranes have enhanced hydrophilicity, antifouling properties, pore structures, and surface roughness in comparison to pure polymer membranes. In addition, the antibacterial activity, hydrophilicity, water flow, and fouling qualities of graphene membranes can be improved by incorporating components such as CNTs, polymers, or metal oxides into a modified composite membrane structure. [58].Optimizing the stability and antifouling properties of the membrane, as well as altering its surface functionalization, can enhance the membrane's performance and make it more effective in separation processes. [6].Utilizing sound waves in membrane-based water treatment systems offers an eco-friendly solution for enhancing water flow, safeguarding the membrane from contamination, preventing impurity buildup on the membrane surface, and prolonging its lifespan. This approach does not require the use of any additional chemicals, apart from modification and functionalization.[27].

Water flow and the ability of filtering membranes to filter substances can be supported by sound waves with acoustic frequencies of 20–20 kHz and ultrasonic frequencies of more than 20 kHz [61]. A key role is played by nanocomposites in all their varying guises, including polymer nanocomposites, carbon nanocomposites, and metal oxide nanocomposites. They also have a unique binding capacity obtained through chelation and ion exchange.

Table 4. Various nanomaterials and their toxicity toward human environment and microbes.

Nanostructured Material	Toxicity Toward Microorganisms	Toxicity Toward Humans	Toxicity Toward Environment	Ref.
Silver (Ag)	Effective antimicrobial agent	Lower toxicity: safe for humans but can cause discoloration of skin	Accumulation in aquatic ecosystems may harm aquatic life	[7]
Gold (Au)	Biocompatible; low toxicity to humans	Biocompatible; low toxicity to humans	Low environmental impact	[140]
Iron (Fe)	Potential toxicity when producing reactive oxygen species	Potential toxicity; depends on nanoparticle characteristics	Environmental impact depends on nanoparticle release	[141]
Zinc Oxide (ZnO)	Effective antimicrobial agent; potential environmental impact	Low toxicity to humans; environmental impact in aquatic ecosystems	Accumulation in water bodies may harm aquatic life	[142]
Carbon Nanotubes (CNTs)	Potential toxicity in biological systems	Potential toxicity: depends on CNT characteristics normally cause lung inflammation	Limited environmental impact	[127]

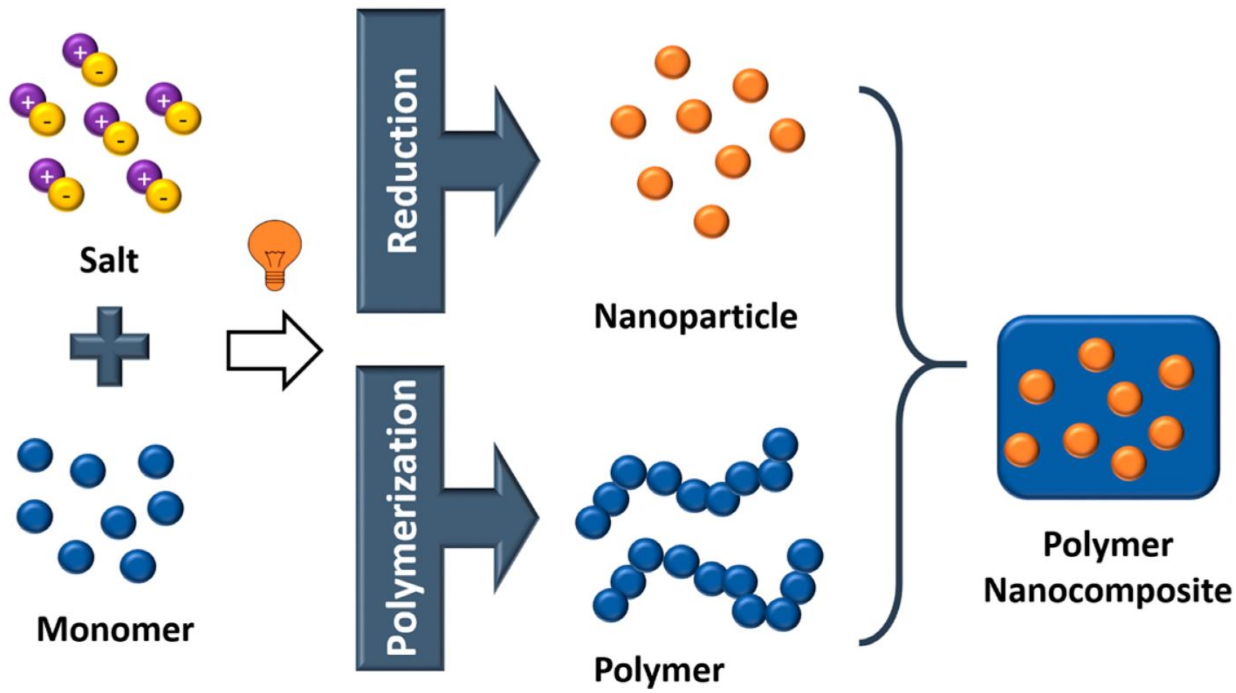

Figure 14. schematic diagram of nanocomposite [143]

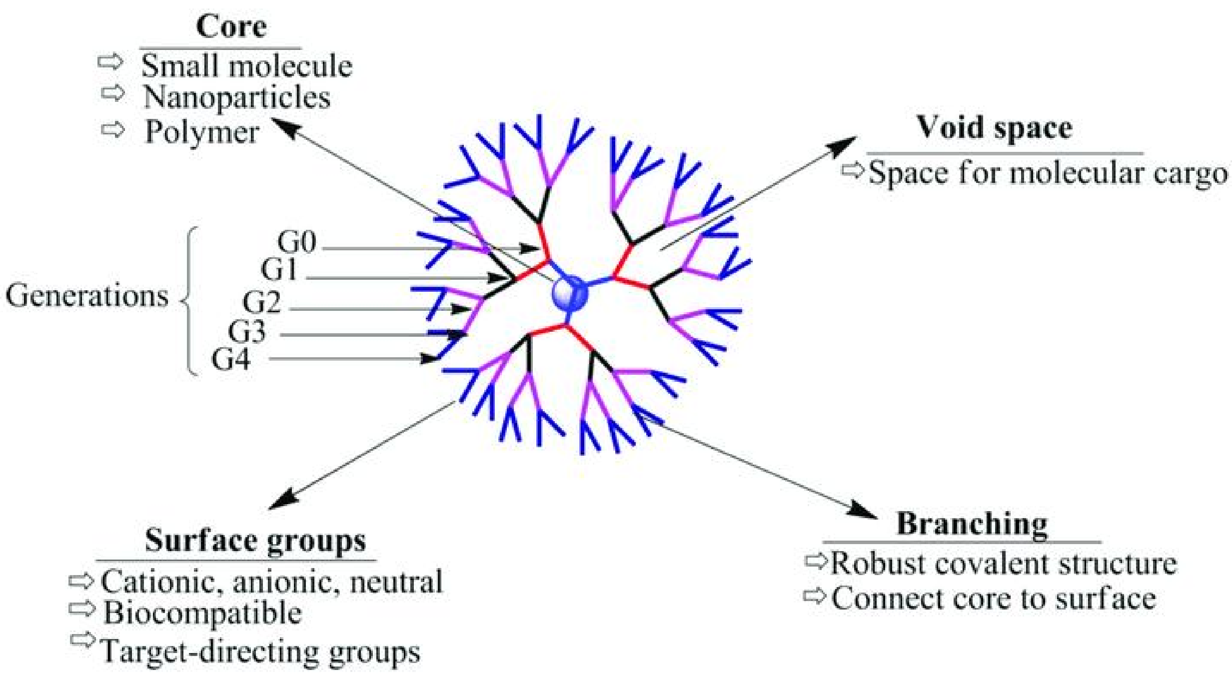

Figure 15. 3D structure of dendrimers [144]

Chitosan nanocomposites have shown promise as potential materials for wastewater decontamination [75]. Polymer nanocomposite development has contributed to the search for solutions to today's environmental challenges. It has garnered attention due to its high potential for reducing gas emissions and removing pollutants, heavy metals, and dyes from the environment. This is the main reason which has made the polymer nanocomposites favorable for water purification. [27].

8. Dendrimers

Dendrimers are distinct, nanosized, three-dimensional macromolecules with a core, inner, and outer shell. They are novel synthetic polymer nanostructures with a balanced structure and a unique three-dimensional arrangement Figure 15. Its functional groups can interact with different functional moieties at the intermolecular level. They are superior because of their exceptional properties, which are absent in linear polymers. The most popular application for poly(amidoamine) dendrimers is as an adsorbent for water purification [88]. These are polymers with random hyperbranched. They mostly consist of spherical macromolecules combined using terminal clusters and cross-linking shell morphology to form a clearly defined structure [81].

Dendrimers range in size from 2 to 20 nm and can take on a variety of shapes, including cones, discs, spheres, and more. These structures are made possible by the interaction of many dendrons with multifunctional properties. They are symmetrical, monodispersed, and of nanoscale size. The use of dendrimers facilitates the synthesis of materials with more intricate nanostructures. These particles are used in materials engineering applications as nanoscale building blocks, such as dendrimer-encapsulated NPs [82]. Dendrimers can also be functionalized with other materials to speed up extracting various metal ions from water. This can increase the overall efficiency of the process. Dendrimers have additional applications, such as chemical detection and heavy metal removal in water treatment. Dendrimers are ligands that are soluble in water, and as such, they are useful for removing toxic heavy metal ions during water purification [89].

9. Conclusion

In conclusion, the application of nanostructured materials for the remediation of microbes contaminated water is a highly promising area of research. The use of nanofabrication techniques such as nano filtration and nanoparticles have shown enormous potential for the removal of microbes from water, conventional methods are effective for large particles, i.e., sand, plastic, etc. Still, for the removal of microbes, dyes, pharmaceutical waste, and heavy metals, modern technology has introduced effective and efficient water purification. Hence, nanomembrane and nanofiltration are among the best methods along with the nano particles (Ag, Au, TiO_2, CNTs, and CNF), which are more effective for removing microbes, dye, and heave metals. Nanofiber/nanomembrane and CNTs or CNF are more effective than other nanoparticles for removing dyes and microbes from contaminated water. This technology could have a significant impact on the provision of clean drinking water to communities worldwide thus both processes have their own limitation and drawbacks such as nanofiltration is not capable of removing large particles otherwise filter blockage will occur. On the other hand, conventional methods need more inputs, and it is not effective toward nanoparticles removal.

10. Recommendation

According to the study and literature, Firstly, there is a need for the optimization of nanofabrication techniques to ensure the scalability and cost-effectiveness of these technologies. This will enable wider adoption of nanostructured materials for water treatment and allow for their application in large-scale water treatment facilities.

Secondly, there is a need for the development of standardized protocols for the evaluation of the efficacy of nanostructured materials in water treatment such as for shape size and form i.e. single cell or conjugated molecule on the other hand if we talk about the shape so cylindrical and flower shape nanoparticles is mor effective toward the elimination of bacteria from water cause of more surface area and pointed ends cause eruption of cell membrane easily. This will enable comparisons between varied materials and technologies and will ensure that the results are reliable and reproducible.

Thirdly, there is a need for further research into the potential environmental impacts of the use of nanostructured materials in water treatment. This will enable the development of sustainable and environmentally friendly technologies that minimize any negative impact on the ecosystem.

Finally, there is a need for increased collaboration between researchers, engineers, and policymakers to ensure that the benefits of nanostructured materials for water treatment are realized. This will enable the development of policies that encourage the adoption of these technologies and will ensure that they are integrated into existing water treatment infrastructure.

CNTS and CNF will have high impacts over other nanoparticles because they can be used as a membrane, and for the other nanoparticles, they will need some substrate for the attachment, such as nanofiber or a nanomembrane, on the water purification and elimination of microbes from the water because of the high surface area, more active sites, and the fact that they are easily available and not expensive. The activation process is also quite easy and not expensive.

In conclusion, the future of nanostructured materials for water treatment is highly promising, and there are several areas that could benefit from further research and development. By addressing these areas, we can ensure that these technologies are optimized, standardized, sustainable, and integrated into existing water treatment infrastructure, thereby providing communities worldwide with access to clean drinking water.

Authors Contribution:

All authors contributed to the study's conception and design. Literature search, data collection, and figure design performed by Yasir Anwar and Alkaif Rafi Dina Gamgali. Data analyses were performed by Awais Ahmad, and Muhammad Sufyan Javed review the article. Mohtashim Asif and Haseeb-Ur-Rahman performed additional literature search and review. The first draft of the manuscript was written by Yasir Anwar and Shehryar Khan. All authors commented on the previous version of the manuscript. Yasir Anwar supervision and Alkaif Rafi Dina Gamgali did the overall supervision, and corrected and edited the final manuscript. Asad Ali provided the funding.

Conflicts of Interest

There are no conflicts of interest reported by the writers.

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Data Availability statement

The data presented in this study are available on request from the corresponding author.

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