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APPROACHES TO CONTROL BIOFOULING IN POTABLE WATER DISTRIBUTION NETWORKS

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ABSTRACT

Water is a critical resource that sustains life, and its availability should be secured.The freshwater is contaminated due to human activities and consequently is enriched in foreign and potentially dangerous species. These pollutants can be classified into biological components that include microbes (bacteria, viruses and fungi), inorganic compounds (radioactive materials and heavy metals), and organic compounds (drugs, soaps, pesticides, fertilizers, and oils) are not only harmful to human health and the environment but also induce changes in natural aqueous habitats and organisms thus affecting the water quality and ecological balance.

Fulfilling the demand for clean drinking water to the general public has been a challenging task in developing countries. Among various water treatment technologies, the utilization of nanomaterials and nanostructures has received significant consideration due to their sustainability and stability. The dimensions of nanomaterials impart exceptional chemical and physical properties, such as multivalent interactions with bio-molecular and cellular systems. This paves the way to treat biofouling of water with nanomaterial due to their antimicrobial properties and reduces the possibility of harmful disinfection by-products (DBPs) formation. Different types of nanomaterials that can act as nanosorbents, nanocatalysts, bioactive nanoparticles, nanostructured catalytic membranes, nanomembranes and nanoparticles (nanocelluloses) provide an efficient methodology for solving water bio fouling problems. These highly efficient nanomaterials owing to the high aspect ratio, surface charge, surface area and mechanical strength can serve as remediation for biofouling of water. However, the major issue with nanomaterials synthesized conventionally is their toxicity although the synthesis of nanomaterials using green routes can serve as an answer to this problem.

Keywords: Biofouling, Water

1. INTRODUCTION

Water is a vital resource to sustain life and thus is the most basic and irreplaceable need of our ecosystem. Its adequate, safe and accessible supply must be available to all. Improved access to safe drinking water might aid in improved health worldwide. So, every effort should account for safe drinking water that is free of any toxins (chemical, physical or biological) Prest et al.(2016) As per WHO guidelines, safe drinking water does not represent any significant risk to health over lifetime consumption and it includes the different sensitivities that may occur between life stages. Safe drinking water is required for all domestic purposes that include drinking, food preparation and personal hygiene.

The advanced anthropogenic activities have led to an exponential rise in water pollution thus mortifying the quality of drinking water. This polluted water contains heavy metals, pesticides, fertilizers and a high organic load. This puffed-up organic load adds to higher microbial growth within water bodies which accounts for waterborne diseases all over the world and the greatest threat to public health is the consumption of unsafe water-carrying microbes from human and animal excreta. The number of waterborne disease outbreaks have been associated with poor treatment of water supplies and substandard management of drinking water distribution systems Schurer et al. (2019).

As per WHO, in 2020 there were 5.8 billion people (74% of the global population) safely managed drinking-water services while the remaining two billion were without safely managed services. Those who are generally atrisk of waterborne diseases areinfants and children, the elderly or one with sensitive immune responses. The majority of this population belongs to the continents of Asia and Africa.

The differential access to safely managed water services between developed and developing world is due to sharp geographic, socio-cultural and economic inequalities in rural and sub-urban areas. Access to low-quality water-borne services accounts for 8,29,000deaths per year, out of which half are children. The sources of drinking water such as water bodies or groundwater may contain several microbial pathogens which may pose a serious threat to human health. The drinking water might be contaminated with faeces from animals, birds and humans. Faecally derived pathogens are the foremost concern in setting health-based goals for microbial safety WHO (2022). The water might be contaminated during the withdrawal, collection, storage and transportation of water. Importantly, water contamination at the source is minimal as compared to storage spaces. The contamination of these biological infectious entities shoots up with their multiplication and the presence of biofilms in water storage and distribution systems Vavourakis et al. (2020).

Among microbial pathogens, bacterial infection stands out.Bacterial pathogens such as Burkholderiapseudomallei, Escherichia coli, Pseudomonas aeruginosa, Salmonella typhi, Vibrio cholerae, Yersinia enterocolitica, Plesiomonas, Campylobacter spp., Shigella spp., etc.may prove lethal to human systems. These bacterial pathogens may lead to infections such as typhoid, cholera, intestinal infections and many more Abdulrahman (2022).

Since the early twentieth century, conventional methods have been used for water treatment such as coagulation, decontamination, disinfection, desalination, filtration and sedimentation. These processes require large systems, infrastructure and engineering expertise which makes them highly labour-intensive and burdensome. Disinfection is undeniably important in a safe drinking water supply and should be used for both surface and underground water subject to faecal contamination. The destruction of pathogenic microbes ensures their safety to consumers. Furthermore, the chemicals such as chlorine, ammonia, hydrochloric acid, alum, ozone and coagulants can contaminate the fresh water to great extent. Disinfection efficacy may also be unsatisfactory against microbes forming flocs, films or particles which increase their resistance to the disinfectants. Hence, the situation demands low-cost, effective and robust techniques. Here nanotechnology can offer a promising solution as the nanoparticles are known to kill the resistant bacterial species and break down the robust bacterial films which cannot be breached by chemicals Makabenta et al. (2021), Sahli et al. (2022).

2. CLINICALLY IMPORTANT BACTERIA IN WATER

Waterborne diseases are caused by pathogenic bacteria, parasites and viruses and are responsible for widespread health risks associated with drinking water. The public health burden of disease is calculated by the severity and incidence of the illness caused by the pathogen, its infectivity and microbial load Rani (2021).

Waterborne pathogens have the following properties that differentiate them from other contaminants:

1) These can cause both acute and chronic health effects.
2) These microscopic entities are aggregated or adhered to the suspended solids in the water.
3) The microbes can grow in the water and are discrete.
4) The invasiveness and virulence of the pathogen determine its infectivity.
5) The disease progression in the host depends upon exposure to microbial load and the immune status of the host. Once the disease is established, the microbes multiply in the host.

The presence of different types of these pathogens determines the water microbiology. The microbial growth of these microbes is supported by water. The principal bacterial agents that cause various waterborne infectionssuch as Salmonella typhicausing typhoid fever; Salmonella paratyphi-A responsible for paratyphoid fever; Salmonella (and other serotypes) causative agents of salmonellosis and enteric fever; Vibrio cholerae causing cholera and Pseudomonas aeruginosa leads to various infections. These bacterial agents causing a different type of infectionsthat are summed up in Table 1 Although the mere presence of these bacterial agents is not sufficient to cause the infection. The minimum viable cells (for example a dose of 106-108 Salmonellae per person in strain) are required to elicit the infection though virulence may vary from strain to strain. The infecting dose also varies with the age and immune resistance of the infected population. The most susceptible are infants, the elderly and immuno-compromised patients (Mackenzie et al. (1968), Kumar et al. (2022).

Virulence is a genetic trait Meynell (1961), Brown et al. (2006). The phenotypic expression of virulence may vary even in a clone of the strain. In a given population of cells, a small number of microbes can be unusually virulent Meynell (1961), Brown et al. (2006). Thus, some enteric microbes can infect even if a few numbers of cells are present. Some pathogens are shown to transfer virulence from infectious strains to non-infectious ones thus transferring them to virulent ones. Thus, these virulent factors can be transferred to residential non-infectious intestinal microbial flora.

Table 1

Table 1 Water-Borne Microbial Infections

Pathogen	Infection	References
Vibrio cholerae	Cholera	Kumar et al. (2014)
V. alginolyticus	Soft Skin Infections	
V.fluvialis V. hollisae V. mimicus	Diarrhea & Gastrointestinal Infections	Abraham (2011)
V. parahaemolyticus	Gastro-enteritis	Ottaviani et al. (2012)

V. vulnificus	Speticemia& Wound Infection	Gulig et al. (2005)
Salmonella enterica	Salmonellosis	Kumar et al. (2014)
Shigella dysenteria	Shigellosis	
S. sonnei		
S. fiexneri,		
Escherichia coli	Gastroentritis, diarrhea, traveller's diarrhea	Kumar et al. (2014)
Enterohemorrhagic E. coli (EHEC strains) e.g., E. coli O157: A	Bloody diarrhea, hemolytic uremic syndrome	Goldwater et al. (2012)
Mycobacterium Avium Complex (Mac)	Highly resistant cholera	Uchiya et al. (2015)
Helicobacter pyroli	Gastritis (Peptic & duodenal ulcer disease and gastric carcinoma)	Graham. (2014)
Aeromonas hydrophyla	Gastroenteritis, Septicemia, meningitis and wound infection	Rao et al. (2022)
Clostridium perfringens	Gastroenteritis	Yonogi et al. (2014)
Leptospira sp.	Leptospirosis	Kumar et al. (2014)
Francisellatularensis	Tularemia	Maurin (2020)
Yersinia enterocolitica	Gastroenteritis	Kumar et al. (2014)

3. WATER DISINFECTION PROCESSES

The water borne pathogens pose serious global challenges with millions of people losing their life every year worldwide. Biological contamination of water can be curbed with water disinfection techniques. Among various methods, chlorination is preferred method in various developing countries and developed countries because of its simple application and cost effectiveness.Biological pollutants are detoxicated by various physical processes such as adsorption, heating, distillation and filtration; chemical processes like flocculation, light irradiation and photo catalysis and biological processes such as activated sludge. These methods not only battle the microbial pollution but also oxidize iron and manganese in water bodies, enhancing coagulation and filtration activity and eliminating taste and color. The incompetence of these processes has directednecessity of more efficient systems for microbial inactivation as the byproducts of these processes are chlorites, chloral hydrates, dibutyl phthalates, haloacetic acids and haloacetonitriles that are highly mutagenic and carcinogenic. There are around 600 biproducts among whichchlorate tops the chart followed by bromochloro-, bromodichloro-, dibromochloro-, and tribromoacetic acid, trichloronitromethane, and chloral hydrate Muellner et al. (2007). As per Muellner, the limitations of current disinfectants can be enlisted as follows:

1) Short range of anti-microbial activity.
2) Harmful by-products during and after the processes of disinfection.
3) Highly corrosive for surfaces and equipment's.
4) Rapid degradation needs instant formulations which are tedious methods.
5) Disposal of these products needs biosafety considerations.
6) Storage of such disinfectants is also labor intensive.

7) These techniques are slow, and their repeated use can create resistant microbial flora which needs to be tackled.

The resistant microflora is another major challenge. This free-living microflora can attach to the surface and aggregate to form multicellular communities known as biofilms. These biofilms are made up of extracellular polymeric substancesthat are recalcitrant to antibiotics therapies. These are one of another major cause of recurrent and persistent infections of clinically important microbes such as Pseudomonas aeruginosa, Escherichia coli, and Staphylococcus aureus.

Thus, these conventional techniques of water disinfection with range of issues needs to be replaced by eco-friendly, highly robust and advance technique with high efficiency and efficacy Kooij (2000), Arshad et al. (2019).

4. NANOTECHNOLOGY

The declining freshwater quality has increased the application of wide range of disinfection processes for producing drinking water. The expensive methods are applied for disinfection of drinking water. Most of modern disinfection processes rely upon physical and chemical treatment technologies. The traditional methods for managing the pathogenic microbes involve the water heating Cabral (2010), Tahir (2019), UV irradiation Tsenter et al. (2022), chlorine and ozone treatment Tony et al.(2016), Zhang et al.(2016), Morrison et al. (2022). These methods are highly effective but may generate excessive secondary pollutants with greater toxicity than parent molecule. Highly toxic elements like trihalomethanes (such as DBP) are formed after chlorine treatment which might cause significant health hazard above 160ppb Bellar et al. (1974), Costet et al. (2011), Singh et al. (2020), Kumari and Gupta (2022). Other conventional systems for water disinfection are filtration through membrane systems. These includes the membrane-based processes like reverse osmosis (RO), nanofiltration and ultrafiltration where the membrane choking is most common problem which decreases the membrane efficiency Mishra et al. (2021), Yu et al. (2022).

The chemical treatments are based on oxidation of organic components in the living cells. However, this particular disinfection is not equally effective especially for the viruses that are less susceptible. The answer to current problem can be solved by nanotechnology. Nanotechnology ismanipulation of materials at the nanometer scale in order to improve and obtain new properties of materials Hornyak et al.(2008), Srinivas (2014), Kumar et al.(2021). Nanomaterials are the materials with dimensions smaller than 100nm (at least one dimension) and can be synthesized by self-assembling of atoms. These nanostructures can be:

1) **Zero Dimensional Nanomaterials (0D-NMs):** Nanoparticles are zero dimensional structures Grzelczak et al.(2008), Hornyak et al. (2008), Ray et al.(2020), Shen et al.(2023). These have all their dimensions at nano scales such as nanoparticles.
2) **One Dimensional Nanomaterial (1D-NMs):** Thes nano-materials have two dimesions at nanoscales. Nanorods, belts, fibres, tubes and nanowires are one dimensional structure Sugunan et al. (2006), Khan and Hossain (2022).
3) **Two Dimensional Nanomaterials (2D-NMs):** These nanomaterials have material thickness at nanoscales. Sheets, plates, thin films, flakes and coatings are two dimensional structures Aoki et al. (2005), Ray et al. (2020), Khan and Hossain (2022). Graphene sheets were first synthesized as 2D-NMs.

4) **Three Dimensional Nanomaterials (3D-NMs):** 3D-NMs are synthesized using basic units of 0D-NMs, 1D-NMs or 2D-NMs. Arrays, hierarchical structures are three dimensional structures Von et al. (2010), Singh et al. (2020), Khan and Hossain (2022)

This availability of vast range of nanostructures with controlled properties and in nanometer sizes that to similar with most of biomolecules have sparked widespread interest in their application. At nanoscale, these materials possess novel properties that can be used for water disinfection. Some of these applications are based on the high specific surface ratio that adds to fast dissolution, high reactivity and strong sorption while others take advantage of properties such as superparamagnetism, localized surface plasmon resonance, and quantum confinement effect Von et al. (2010), Hajipour et al. (2012), Guo et al. (2013), Philip and Kumar (2022).

5. SYNTHESIS OF NANOSTRUCTURES

Synthesis of nanostructures especially nanoparticles include two main approaches i.e. (1) Top-down synthesis and (2). Bottom-up synthesis. In top-down synthesis, destructive approach is employed. The larger molecule is decomposed to smaller ones which are then converted to suitable nanostructures. Various decomposition techniques used are grinding/milling, CVD (Chemical VapourDeposition), Physical VapourDeposition, Sonication etc. Abid et al. (2022), Gutiérrez et al. (2022). This approach was used to synthesize magnetite nanoparticles from natural iron oxide ($Fe2O3$). The size of nanoparticles formed in presence of oleic acid was reported to be 20nm to 50nm Pal (2020), de et al. (2022).

Another method is Bottom-up synthesis.Here,nanomaterials are formed from simpler substances thus known as bottom-up approach. Various techniques employed in bottom up approach are sedimentation and reduction techniques including sol gel, green synthesis, spinning and biochemical synthesis Nkele and Ezema (2020), Guan et al.(2022), Samuel et al.(2022). Nanoparticles based $TiO2$ anatase were synthesized. These $TiO2$ based nanoparticles had graphene domainsand were synthesized using alizarin and titanium isopropoxide precursors. Well uniform spherical nanoparticles were synthesized. More recently, green and biogenic bottom-up synthesis is being followed by many researchers as this process is more feasible and less toxic in nature. The synthesis of nanomaterials is achieved via biological systems such as plant extracts, bacteria, yeast, fungi and human cells making them more cost effective and nature friendly Shah et al. (2021), Noah and Ndangili (2022).

5.1. APPLICATIONS

The recent advances in nano sciences offer surmount opportunities for treatment of water and water systems. Nanotechnology enabled water treatment systems to overcome the major challenges faced by existing treatment technologies Qu et al. (2013).

The antibacterial properties of various nanostructure vary from one nanoparticle to another.

1) **Carbon Based Nano-Adsorbents**

Carbon is one of most abundant and versatile elements on the planet. It has wide range of applications.Carbon nanomaterials are known for their sorption qualities due to their unique structures and electronic properties. These can adsorb wide range of contaminants with faster kinetic rates and also have large surface area. There are array of carbon nanomaterials ranging from carbon nanotubes (CNTs) to carbon beads. Among these fullerenes and CNTsare most widely scrutinized due to their stability Arshad et al. (2019).

2) Fullerenes

Fullerenes are the allotropes of carbon where the carbon atoms are sp2hybridized to form globular hollow cage like nanostructurewith various shapes (hollow sphere, ellipsoid etc.)as shown in Figure 1. The spherical fullerene is known as buckminsterfullerene (C60; bucky balls or bucky onions). C60 is primary structure of all fullerenes. The cage like fused ring shape is made up by twenty hexagons and twelve pentagons. The 'buckyballs' is the favorably regarded as it has ability to form the derivatives of fullerenes and nanocomposites. The derivatives of fullerenes range from diphosphonate, phosphonates to organophosphorus compounds. However, the fullerenes lag at solubility and nearly insoluble in organic solvents such as toluene and carbon disulphide. Theirmoderate solubility at room temperature has been put to use. These can be synthesized via various methods such as arc discharge, CVD, laser ablation, laser irradiation of polyaromatic hydrocarbons (PAHs) and resistive arc heating of graphite.Fullerenes and their derivatives have outstandingfunctions as antioxidants, biopharmaceutical compounds, catalysts, organic photovoltaics and water purification/ bio-hazard protection catalysts Shah et al.(2021).

These nanostructures testified to have high electron affinity, high electrical conductivity, high strength, stable structure and are highly versatile Astefanei et al. (2015), Kurosawa et al. (2021). Pentacatonic fullerenes designed by Thota and co-workers had high water solubility and were found to be effective against both gram-positive and gram-negative bacteria Thota et al. (2012).

Fullerenes can also be substituted with polyhydroxyl groups to generate fullerenols. These fullerenols have shown high antioxidant activity due to increase in number of oxygen atoms. These nanoparticles have high specific area and chemically incorporated antibacterial action making them attraction to researchers in last few years Shah et al. (2021).

Figure 1

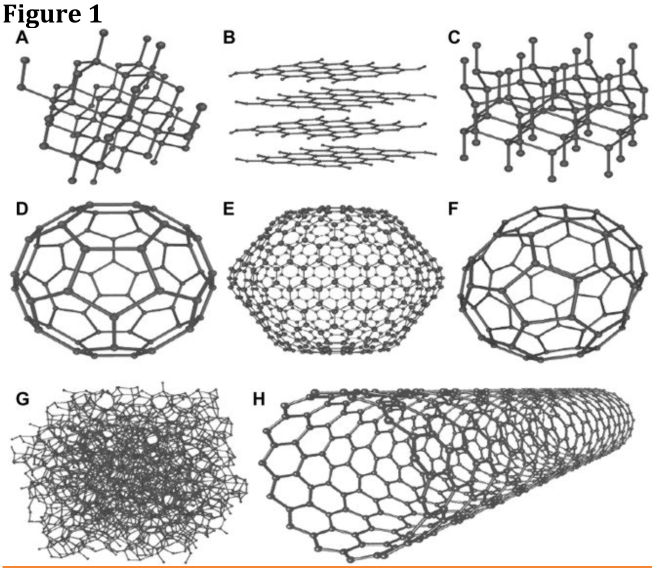

Figure 1 The Different Allotropes of carbon: (A) Diamond (B) Graphite, (C) Lonsdaleite, (D) C60 (Buckminsterfullerene or Bukyball), (E) C540 Fullerene, (F) C70 Fullerene, (G) Amorphous carbon, (H) Single-walled carbon nanotube Aqel et al. (2012)

3) Fullerene Composites

The fullerene/polystyrene film composites were found to be effective against various bacteria like Staphylococcus aureus, E. coli and Candida albicans. The polystyrene film alone was however unable to exhibit such bacteriostatic properties while clear zone lacking microbial growth was observed in composites Alekseeva et al. (n.d.)These characteristics are imparted to composites by the fullerenes. In another research, fullerene composites with cellulose, chitosan and γ cyclodextrin were reported to have antimicrobial activity against vancomycin-resistant enterococci Duri et al.(2017) A photostable and photodynamic nanocomposite of fullerene (C60) was created in which fullerene C60 is covalently linked to ethylenedioxythiophene (EDOT) and this was found to be effective against Staphylococcus aureus with 99.9 % reduction in bacterial populations after visible light irradiations Reynoso et al. (2021). Ballatore and coworkers evaluated the microbial inactivation by porphyrin-fullerene C60 polymeric rings. These nanocomposites displayed excellent phototoxic features against S. aureus and E. coli. The scientist also substituted the porphyrin-fullerene C60 by carbazoyl groups. These modified nanocomposites were capable of inactivating S. aureus after 30 minutes of irradiation Ballatore et al. (2022). Thus, fullerene nanocomposites feature a fascinating, flexible, photodynamic and active surface that can produce ROS and hence can annihilate microbes.

4) Carbon Nanotubes (CNTs)

CNTs are graphene cylinders with diameter of unit nanometer Ibrahim et al. (2019). CNTs have been predicted as metallic or semiconducting in nature Aqel et al. (2012), Peng et al.(2019), Obeid and Sun(2022) .CNTs are graphite sheets rolled in itself Figure 1 and Figure 2. These rolled sheets can be single walled or double walled, hence classified as below on basis of their structure:

1) The single layer graphene sheets rolled up into cylinders (SWCNTs)
2) The two-layergraphene concentric cylinders (DWCNTs)
3) The multiple layered concentric cylinders known as multiwalled carbon nanotubes (MWCNTs).

Figure 2

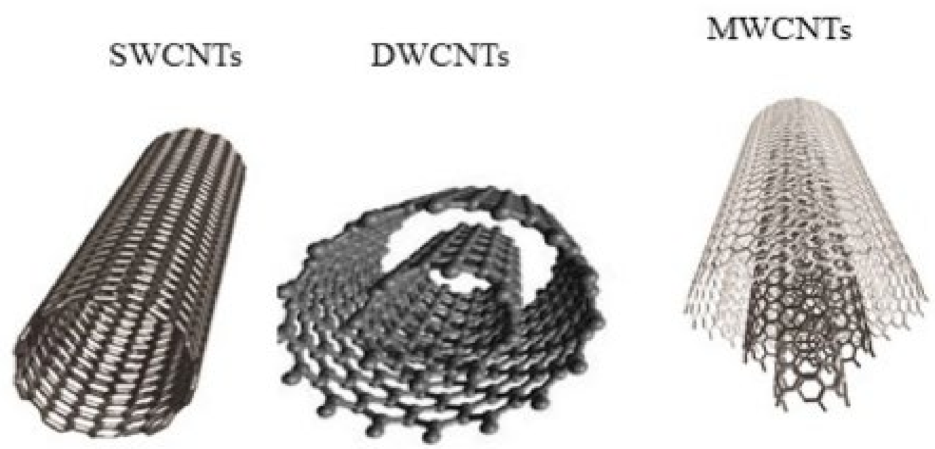

Figure 2 Variable Structures of Carbon Nanomaterials (CNTs). SWCNTs: Single-Wall Carbon Nanotubes; DWCNTs: Double-Walled Carbon Nanotubes; MWCNTs: Multi-Wall Carbon Nanotubes. Azizi-Lalabadi et al. (2020).

CNTs are known to accelerate the transfer of electrons between electro-active species and electrodes Zhou et al. (2019) and proven to have elevated adsorptive ability Mubarak et al. (2016), conductivity Saifuddin et al.(2013) and high surface to volume ratio Yadav et al. (2020). The applications of CNTs in nanotechnology range from drug delivery, gene manipulation, tissue engineering to antimicrobial agents. The major fall back is insolubility of CNTs in various solvents thus limiting its usage which can although be altered with various modifications. The preferred methods for synthesis of CNTs are arc discharge process, laser ablation, chemical vapor deposition (CVD) and ball milling, Azizi-Lalabadi et al. (2020). Due to unique physical and chemical properties such as super adsorption, CNTs has been used as an antibacterial agent. The size of these nanomaterials plays an outstanding role in microbial deactivation. The further decrease in size increases their surface to volume ratio consequently their strong bond with cell envelopes leading to disruption of cellular membrane, metabolic processes and morphological structure Khan et al. (2016). These antibacterial properties are observed due to direct contact of CNTs to cell membrane which results in cell death via changes in membrane fluidity, oxidative stress, enzyme inhibition, and reduced transcription of several key genes. The antimicrobial activity of CNTs is strongly related to their aggregation degree, concentration, degree of purification diameter, length, surface functionalization and time and intensity of contact. The addition of metals and other supports to CNTs improves the adsorption, mechanical, optical and electrical properties of nanotubes. Apart from cellular destruction with decrease in size of CNTs the increase in cellular efflux was observed Maksimova (2019). The other properties like surface area and dispersibility can be enhanced by increasing the number of oxygen, nitrogen and other specific groups attached to the surface Karim et al. (2017), Perazzoli et al.(2017), Mbiri et al. (2018).

The first CNTs were single walled carbon nanotubes (SWNTs) and multi-walled carbon nanotubes were latter synthesized by Kang and co-workers in 2007. These CNTs effectively removed various microbial cells such as Escherichia coli, Micrococcus lysodeikticus, Streptococcus mutans, E. coli, Salmonella spp. cells Kang et al. (2007), Liu et al. (2018), Maksimova (2019). The cytotoxicity of CNTs is affected by the various physiochemical properties of these nanomaterials and their transport behaviour in the solution. The antibacterial efficiency may vary with the size and diameter of CNTs, their dispersing ability in the culture medium, dosage, reaction time and mode of action between the bacteria and CNTs. The workers further observed that the size of these particles affect their activity in 2008. Both SWCNTs and MWCNTs were tried against microorganisms and SWCNTs were found to be much more effective by reason of active surface area. The toxicity of CNTs is based on their contact with cell surface. Therefore, diameter of CNTs is an imperative factor in the microbial cell deactivation. The SWCNTs were found to be more toxic owing to higher surface area, better penetration into the cell because of smaller diameter, unique chemical and electronic characteristics and their role in changing the expression of stress related genes. Indeed, SWCNTs offers substantial number of antibacterial properties against both Gram-negative and Gram-positive bacteria. However, MWCNTs lag in such bacteriostatic properties. SWCNTs connect to cell wall thereby aggregating and thus inducing cell wall damage. The surface charge on CNTs is also related to antibacterial activity as the bacterial growth is deterred by generation of reactive oxygen species Bing et al. (2016). The aggregation and agglomeration between the cells is supported by van der Waals forces. The higher concentration of SWCNTs proved to be highly antimicrobial versus Salmonella enterica and E. coli .The length of CNTs also impact the antimicrobial properties Yang et al. (2020). The increase in length of SWCNTs increases the aggregation and antimicrobial properties. CNTs can prevent formation of biofilms by preventing the adherence of cells to surface. CNTs are found to be more beneficial against biofilms if introduced at earlier stages of biofilm production.

Another excellent property of CNTs is adsorption. Carbon nanotubes are highly efficient adsorbents for organic chemicals than active carbon Pan and Xing (2008), Zhang et al. (2019). This is mainly due to high surface area (external surface area) of CNTs and their interactions with the biological contaminants Yang and Xing (2010). The CNTs have high adsorption capacity for bulky organic molecules because of their larger pores in the bundles and have more accessible adsorption sites than activated carbon which on the other hand contains micropores are inaccessible to bulky organic molecules such as many antibiotics and pharmaceuticals compounds Pan and Xing (2008). CNTs are also known to adsorb low molecular weight polar organic compounds. These nanoparticles penetrate the cell envelopes and thus alter the cellular mechanisms both at the molecular and biochemical levels. These CNT-contaminant interactions can be hydrophobic, pep interaction, hydrogen bonding, covalent bonding or electrostatic interactions Yang and Xing (2010), Dubey et al. (2021). These are excellent adsorbents with high adsorption specificity for various contaminants such as dichlorobenzene Wang et al.(2016), Zn2+ Tang and Wang (2018), Pb2+, Cu2+, and Cd2+ He et al.(2019), ethyl benzene Yin et al.(2020), and dyes Quirós et al. (2015).

The major limitation in its application is the development of CNTs which is a costly affair. To decrease the cost of synthesis composite nanotubes were synthesized. These were prepared by combining the adsorption properties of CNTs with magnetic properties of iron oxide, thus aiding their easy recovery and reusability.Apart from synthesis, their limited water dispersal decreases the interaction of CNTs with microbes hence might lower efficacy of CNTs Yang and Xing (2010), Dubey et al. (2021).

The derivatization and attachment of functional groups to the nanoparticles and CNTs might change their biological effects including toxicity. The nanoparticle related long-term injuries can be associated with their accumulation in organs like lungs, liver and spleen. These are also known to cross the blood-air barriers, blood-alveolus barrier, blood-brain barriers and blood-placenta barrier, hence causing major injuries. The toxicological effects include apoptosis, autophagy, inflammatory response and necrosis Tang and Wang (2018), Wu et al. (2021)

5) CNT Composites

The carbon nanomaterials composites with biopolymers and NPs like Ag, CuO, TiO2, ZnO have assured antimicrobial effects Ahmad et al. (2019), Azizi-Lalabadi et al. (2020) Carbon nanomaterials can be functionalized with various chemical groups that adds to dispersion capability of these materials. The powerful synergistic effect has been observed in CNTs composite. Dong and co-workers proved that use of Ag and CNT composite enhances bactericidal properties than CNT alone. This effect is enhanced due to their mechanisms that disrupt the cell membranes which ease the penetration of other nano-molecules into the cells. In another research, AgNPs (Silver Nanoparticles) were deposited on MWCNTs along with polyamidoamine. These nanocomposites induced bacteriostatic effects against S. aureus, E. coli and Pseudomonas aeruginosa Yuan et al. (2018). A good example of synergistic effect is study of CNT/poly(L-lysine) or poly (L-glutamic acid) composite film where population of E. coli and Staphylococcus epidermis was reduced by 90% Aslan et al. (2012). The composites of chitosan with CNTs were reported to be efficient against the removal of E.coli and Candida tropicalis. With increase in the concentration of CNTs the bacteriostatic properties of composites are also enhanced. These composites displayed a well-defined porous structure with high water uptake and efficiency Xia et al. (2018). In 2019, Beningo along with co-workers conducted research involving low-polyethylene (LDPE)-based nanocomposites containing MWCNTs that exhibited remarkable antimicrobial activity against DH5α E. coli. The effect of these nanocomposites was also studied on biofilms.

6) Graphene and Graphene Oxide

Graphite is two dimensional naturally occurring crystalline carbon material or layers of graphene molecules lying upon one another. The carbon atoms are sp2 hybridized in a hexagonal network forming graphite molecules. Each of graphite plate is connected to another by Van der Waals forces. Geim along with coworkers introduced the two-dimensional graphene in 2004 that exhibits exceptionally high crystal and electronic quality. The graphene and graphene oxide were reported to have ample of applications in range of fields. The graphene oxide is an intermediate product of the graphene chemical synthesis. It consists of graphene molecule functionalized with groups such as hydroxyls, carboxyls, carbonyls and epioxides Geim and Novoselov (2007), Jin et al. (2020). In fact, graphene oxide (GO) and reduced graphene oxide (rGO) are the two products which are formed. Among which rGO has been reported to have strong barrier properties against He, H2, water vapor, NaCl and hydrofluoric acid in films. Graphene has ample applications in electronics, medicine and technology. The most successful application of graphene and its molecules has been reported in sensor technology, however antimicrobial applications have also been scrutinized. This antimicrobial nature of graphene and graphene oxide is due to superlative features such as extensive surface areas aswell as unique thermal, electrical and physio mechanical nature Azizi-Lalabadi et al. (2020).The physiochemical properties such as aggregation, arrangement mode, dispersibility, edges, layer numbers, shape, sheet size and surface functionalization affect the antibacterial nature of graphene and graphene oxide nanomaterials Omran and Baek (2022)

The production of graphene and graphene oxide is simple, fast and cheap and it have minimal toxicity on mammalian cells Bolotin et al. (2008). The graphene and graphene oxide interact the cell membrane and cell wall through reactive oxygen species through physical demolition and chemical oxidation Akhavan and Ghaderi (2010), Dolati et al. (2023). The graphene-based nanomaterials have been reported to effectively inhibit the growth of E. coli bacteria while minimum toxicity was reported Hu et al. (2010). In another study, the graphene and graphene oxide sheets could entrap the bacterial cells and thus preventing their replication Akhavan et al. (2011). Khan and coworkers synthesized graphene oxide/carbon nanotube/poly (O-toluidine) (GO-CNT-POT) nanocomposite that was found to effective against Gram positive bacteria Bacillussubtilis and Gram-negative bacteria Escherichia coli. Graphene oxide was reported to have high antimicrobial activity than reduced graphene oxide particles Khan et al. (2016), Godoy-Gallardo et al. (2021). Thus, above mentioned allotropes of carbon can be considered as potent antimicrobial agents and can be used for water disinfection processes owing to high efficacy and low toxicity.

6. METAL-NANOPARTICLES

Microbial resistance to most of antibiotics and anti-microbial agents decreases the efficacy of eradication methods. So, development of new methods seems to be of supreme importance. Metal nanoparticles and their oxides such as silver nanoparticles (AgNPs), Titanium nanoparticles (Ti/ TiO2 NPs), Iron nanoparticles (Fe/Fe oxide NPs) and Zinc nanoparticles (Zn/ZnO NPs) have been applied as an antimicrobial agent Palza (2015), Brandelli et al. (2017), Hoseinzadeh et al. (2017), Sánchez-López et al. (2020), Ribeiro et al. (2022). Metal precursors forms the basis of these metal nanoparticles. The antimicrobial efficiency and efficacy of these nanoparticles is governed by type of materials used for NPs preparation, facet, particle size and shape Seil and Webster (2012), Roy et al. (2013), Agnihotri et al. (2014), Saied et al. (2022). With decrease in the particle size, the surface/volume ratio is increased that noticeably increases the dissolution rate, catalytic activity, heat treatment and mass transfer thus increasing the bactericidal effects of nanoparticles Shaterabadi et al. (2022). The possible mechanisms were proposed for antimicrobial effects of metal nanoparticles:

(a) the free metal ions dissolute from surface of NPs leading to toxicity

(b), via formation of reactive oxygen species (ROS) that causes oxidative stress Zhang et al. (2013a), Sarfraz et al. (2020), Kessler et al. (2022)

These NPs also possess unique optical properties that aids to surface plasmon resonance. NPs of metals like Cu, Ag, Pt and Au have broad absorption bands in the visible range of the electromagnetic spectrum. These advanced optical properties of metal nanoparticles make them preferred choice for much research-based applications Khan et al. (2019). The metal nanoparticles can be functionalized with antibodies, peptides, RNA and DNA to target different biological systems such as microorganisms, protozoa and viruses. These metal nanoparticles can be classified on the basis of valency such as:

6.1. ZERO-VALENT METAL NANOPARTICLES

Metal based nanoparticles such as zinc, silver, iron etc. are effective methods for water disinfection. These metal oxides are also known to adsorb heavy metals and radionuclides Koeppenkastrop and De Carlo (1993), Kumar et al. (2020)

6.1.1. SILVER NANOPARTICLES

Silver nanoparticles are most common inorganic nanoparticles used as an antimicrobial agent against wide range of bacteria. The highly toxic Silver Nanoparticles (AgNPs) have been widely used for disinfection of water due to its good antimicrobial properties against broad range of microbes, including viruses' bacteria, and fungi Homem and Santos (2011), Wols and Hofman-Caris (2012), Luo et al. (2014), Bag et al. (2021), Yu et al. (2022). The mechanism of antimicrobial action is still debatable; however, range of theories were put forth. AgNPs are reported to act in following ways:

1) AgNPs triggers the release of free radicals and oxygen reactive species when AgNPscome in contact with the bacterial surface. These free radicals damage the cell membrane leading to cell death Siddiqi and Rao (2018).
2) AgNPs are reported to adhere to the bacterial cell wall and subsequently penetrate it. This adherence results in structural changes within the membrane of cell hence magnifying its permeability to various other antimicrobial substances Ng et al. (2019).
3) AgNPs are reported to release Ag+ ions on dissolution which interacts with the thiol groups of many vital enzymes. These interactions inactivate the enzymes by disrupting the thiol bonding, subsequently altering normal metabolic balance of the cell Wanda et al. (2017).

4) Another explanation of cell death by AgNPs is by their interaction with sulphur and phosphorus elements in DNA. This interplay results DNA destruction Sousa et al. (2018).

In recent years, AgNPs have been successfully applied to the treatment of drinking water. The silver nanoparticles successfully eliminated S. aureus and E. coli. The efficiency of removal was enhanced with decrease in size of nanostructures and were less toxic than synthetic fungicides. The shape of AgNPs also play vital role in determining the antibacterial efficiency. Among various shapes such as spherical, rod shaped and truncated triangular, latter was found to be most effective against S. epidermis, Pseudomonas aeruginosa and B. megaterium due to high atom density surface Pal (2020). However, the direct application of these nanomaterials is limited because of AgNPs tend to aggregate in aqueous media Benstoem et al. (2017). These aggregations reduce the long-term efficiency of nanomaterials. This process has been proved to be more efficient and cost-effective when nanoparticles are attached to the filter material Gerbersdorf et al. (2015). This can be achieved bydepositing silver from silver nitrate by its reduction on to cellulose membranes. These AgNPs sheets were capable of inactivating Escherichia coli and Enterococcus faecalis in water samples with low silver loss from sheets. Therefore, AgNPs sheets can prove to be effectiveemergency water treatment solution Gavrilescu et al. (2015).

In another study, chitosan cryogels decorated with silver nanoparticles were reported to have efficient bactericidal capacity against Escherichia coli and Bacillus subtlis Fan et al. (2018) . Silver nanoparticles immobilized in glass capillary tubes were used for water disinfection in fix bed reactor. The AgNPs can also be incorporated to polyethersulfone (PES) microfiltration membranes via chemical reduction. These membranes exhibited strong antimicrobial properties nearby the membranes, thus can have great potential for water treatment application. The microfiltration membranes modified with silver nanoparticles inhibits the growth of microbial films thus potentially increasing the biofouling resistance Yu et al. (2021).

AgNPs also have been successfully applied to ceramic filters made up of clay and sawdust. It was also reported that colloidal AgNPs enhanced the filter performance for E. coli removal with rates as high as 97.8% and 100% Hennebel et al. (2012). The ceramic membranes exhibited remarkable household water disinfection properties. The membranes were capable of efficiently removing Escherichia coli bacteria Barbosa et al. (2016), Ali et al. (2019).

Although the use of AgNPs appears to be attractive due to antibacterial properties, however the presence of these in potable water may have substantial health effects asthese small size nanoparticles are highly reactive species.

6.1.2. IRON NANOPARTICLES

Iron nanoparticles are extensively scrutinized among zero-valent metal nanoparticles as these possess excellent adsorption properties, are of low cost and could be easily recovered under the influence of magnetic field. The reduction potential of iron is low because of low standard reduction potential. Fe0 under aerobic conditions is oxidized by H2O or H+ to generate Fe2+ and H2, both of which are potentially reducing agents for contaminants. Fe2+ is further oxidized to Fe3+, that forms Fe (OH)3 with increase inthepH.Fe(OH)3 is a flocculent thus removes the contaminants. These redox reactions also generate the free radicals that have strong oxidizing potential for range of organic compounds Hopkins et al. (2016).

Hong and co-workers reported the efficient removal of E.coli with 100% sterilization by use of magnetic iron oxide nanoparticles immobilized with sugar containing poly (ionic liquid). Zaki and co-workers synthesized green iron nanoparticles in 2019 under aerobic and anaerobic conditions via nitrate reductase. These green nanoparticles were effective against algal and biofilm formations in real water (fresh, sea and salt) and wastewater (municipal, agricultural and industrial). Inanother study, PEG coated nanoparticles functionalized with antimicrobial peptide was found to be effective against E. coli K-12 DSM 498 and Bacillus subtilis with minimum inhibitory concentration of 500µm for both of the strains Zaki et al. (2019).

6.1.3. ZINC NANOPARTICLES

Zn has more negative reduction potential than iron thus is a stronger reductant compared to Fe. Hence it can be used to treat water for removal of contaminants from it.Fe doped ZnO nanoparticles were investigated for disinfection capability against multi drug resistant E.coli from river, pond and municipal tap Duri et al. (2017). In another study, alginate beads encapsulated with ZnO were examined for inactivationof Staphylococcus aureus in both synthetic and surface water and were reported to remove 200 cfu/ml of bacteria within70 minutes of exposure Motshekga et al. (2018).

Munnawar along with co-workers in 2017 scrutinized antifouling polyethersulfonate membranes for water disinfection with fabricated Chitosan Zinc oxide hybrid nanoparticles. The membranes were obtained to have significant antibacterial aswell as antifungal properties due to synergistic effect of chitosan and ZnO against range of bacteria and fungi such as S. aureus, B. cereus, E. coli, S. typhi and A fumigatus.

6.2. METAL OXIDES NANOPARTICLES

6.2.1. TIO2 NANOPARTICLES

Figure 3

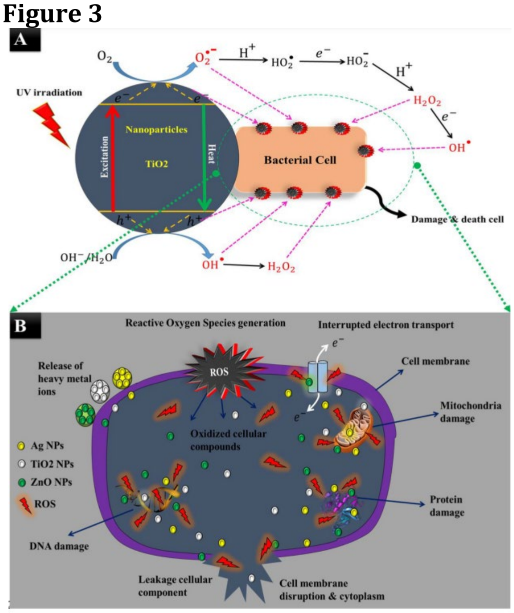

Figure 3 Mechanisms of Antimicrobial Activity of Nanoparticles (B). Nanoparticles Generate free Radicals that Causes Oxidative Stress (i.e., ROS) (A). The ROS Destroy the Morphological Structure of Cell by Efflux of Cell Materials Sharmin et al. (2021)

The crystal structure, size and shape impart the antimicrobial activity to TiO2 nanoparticles. The NPs create oxidative stress by generating reactive oxygen species (ROS) such as hydroxyl radicals and hydrogen peroxide that causes the site-specific DNA damage Zhang et al. (2013b), Maksimchuk et al. (2020). The spores, particularly bacterial endospores, fungal spores and protozoan cysts, in resting stages and are more resistant due to increased cell wall thickness. The cell death by TiO2 nanoparticles involves the degradation of cell wall and cytoplasmic membranes by ROS which initially leads to efflux of cellular contents which may be followed by complete mineralization of the cell. The mechanism involves photoexcitation of TiO2 surface to generate electron-hole pairs that migrate to TiO2 surface Mohammed Sadiq et al. (2010). The photogenerated holes in TiO2 can react with adsorbed water or hydroxylions at the catalyst/water surface to produce the highly reactive hydroxyl ions and electrons that react with oxygen to form superoxide ions. The mechanism of action is depicted in Figure 3.

The wide range of micro-organisms such as Gram-positive and Gram-negative bacteria, fungi, algae, protozoa and viruses can be removed by photocatalytic degradation. The presence of catalyst along with light trigger the oxidation eventually transforming these into CO2 and H2O. TiO2 has high photo-catalytic activity and photostability hence most widely preferred photocatalyst among various semi-conductors. It is also reported to has good chemical and biological stability Chauhan et al. (2019), Ibrahim et al. (2019), Zhang et al. (2019). The TiO2 absorbs in ultraviolet region. This absorption generates reactive oxygen species (ROS) which act upon the microbes. However, this absorption in UV-region is the limiting factor for nanoparticles. Thus, research has been conducted to improve the photocatalysis in the visible range was reported to be enhanced by metal doping which inactivated the bacteriaand viruses Adeleye et al. (2018), Peng et al. (2019). For example, among metal doping, Ag has been widely studied and it improves the visible light absorbance of TiO2 NPs Anirudhan and Deepa (2017), Zhao et al. (2018). Another report of C-TiO2 nanoparticles synthesized by sol gel methods photochemically inactivated Listeria monocytogenes Shim et al. (2016), Piatkowska et al. (2021). Some nonmetals elements such as N, F, S and C have also been reported to narrow the band gap significantly, enhancingthe adsorption in visible region Fahiminia et al. (2019), Wang et al. (2021). Also, H2O2titanium dioxide suspensions have been used against Staphylococcus epidermis biofilms disinfections.

Besides, the production process for TiTO2 based Nanoparticles is rather difficult, hence these should be recovered from wastewater. These particles can be coupled to membranes such as poly(vinylidene fluoride) Park et al. (2018), Huang et al. (2019), Yang et al. (2020), polyethersulfone Fang et al. (2017), Park et al. (2018), polymethyl methacrylate, and poly(amide-imide) Zhang et al. (2018), Pandiyan et al. (2019). This coupling of NPs to membranes aids in its separation by simple filtration processes. Another solution to this problem is by doping magnetic nanoparticles which can be trapped by magnetic traps Coker et al. (2012), Akhil et al. (2016), Stueber et al. (2021).

6.2.2. ZNO NANOPARTICLES

ZnO NPs have strong oxidation ability and photocatalytic property Fakhriet al. (2018), Trawiński and Skibiński(2019) making them one of the preferred choices for water treatment. These are eco-friendly as they are compatible with organisms Islam et al. (2018). Both TiO2 and ZnO NPs have similar band gap energies but latter ones have low cost over the other. Being similar to TiO2 NPs the light absorption is limited to ultraviolet region. Besides, they have low photocatalytic efficiency as these might be impeded by photocorrosion (Nogueira et al., 2018). This can be greatly enhanced by metal doping with various types of anionic dopants, cationic dopants, rare-earth dopants, and codopants Nogueira et al. (2015), Lee et al.(2016). Also, coupling with other semiconductors, such as CdO, CeO2, SnO2, TiO2, graphene oxide (GO), and reduced graphene oxide (RGO), has also been reported to enhance the photocatalytic efficiency of ZnO NPs Lee et al. (2017) , Xiang et al. (2017), Jiao et al. (2018), Li et al. (2018), Neamtu et al. (2018), Zhao et al. (2018), Zheng et al. (2022).

The Zinc Oxide (ZnO) is safe for human skin which make it proper additive in water disinfection Schilling et al. (2010); Ayyaru et al. (2020), Deka et al. (2022). Li and workers in 2018, reported antibacterial effects of ZnO on gram-positive and gram-negative bacteria as well as on high temperature and pressure resistant spores.The antibacterial efficiency is enhanced by concentration increase and size reduction The vi Rasheed et al.(2020)ability of microbes is believed to be decreased by one of the following mechanisms. One proposed is generation of H2O2 particles while another study reported the accumulation of nanoparticles on the bacterial cell surface due to electrostatic effects Hussein et al. (2019). The other reasons being the ROS generation from the surface of the particles, zinc ion release, membrane dysfunction and nanoparticle internalization. ZnO NPs have bacteriostatic effects against wide range of bacteria such as P. aeruginosa, L plantarum, L. monocytogenes E. coli, S. choleraesuis, S. aureus, Saccharomyces cerevisiae, A. niger, C jejuni Xie et al. (2020), da et al. (2019), Gudkov et al. (2021)

6.2.3. IRON OXIDES NANOPARTICLES

The ease of recovery duetomagnetic properties of iron it is also preferred for water treatment processes. The iron oxides such as magnetic magnetite (Fe3O4) and magnetic maghemite (γ-Fe2O4) and nonmagnetic hematite (α-Fe2O3) can be used as nanoadsorbents for heavy metals. The recovery of small sized nanosorbent NPs can be easily assisted with external magnetic field Chen and Li (2016), Sharma and Feng (2019), Rasheed et al. (2020)

Ferrate based nanoparticleswith physiochemical properties like oxidatioin, co-agulation and disinfection were studied for elimination of diverse range of chemical and biological species from, water/waste water samples Rai et al. (2018) . In another study, iron oxide nanoparticles have been functionalized with range of ligands such as ethylenediamine tetraacetic acid (EDTA), L-glutathione (GSH), mercaptobutyric acid (MBA), α-thio-ω-(propionic acid) hepta(ethylene glycol) (PEG-SH), and meso-2,3-dimercaptosuccinic acid (DMSA) Rojas and Horcajada (2020) or polymers (e.g., copolymers of acrylic acid and crotonic acid) Ma et al. (2019) that are reported to enhance their adsorption efficiency. The ligand polymers form a flexible shell that facilitates the incorporation of various functional groups. This shell prevents the aggregation of particles and improves the dispersion stability of nanostructures Zeng et al. (2015). The polymer molecules not only ensure the intactness of properties of Fe3O4 nanoparticles but also binds with the metal ions thus acting as carriers of metals Ma et al. (2019).

Among various iron oxide nanoparticles, hematite is stable and cheap thus can be used in catalysis and sensors Zeng et al. (2015). Nanohematite particles have been reported to be an effective adsorbent from heavy metal spiked tap water.The enhanced surface area with multiple spaces and pores was reported in flower-like α-Fe2O3 structures. This aided in better removal of As (V) and Cr (VI) from water than previous studies Wang et al. (2018).

7. CERAMIC BASED NANOMATERIALS

Ceramic based nanoparticles are synthesized from nonmetallic solids via heat and successive cooling Sigmund et al. (2006), Punia et al. (2021). These are amorphous, polycrystalline, dense, porous or hollow structure have been successfully applied to catalysis, photocatalysis, photodegradation Thomas et al. (2015), Vinayagasundaram et al.(2023). These ceramic based nanoparticles can be used for water disinfection processes.

8. NANOMATERIALS WITH SEMICONDUCTING PROPERTIES

Semiconducting materials possess properties of both metals and non-metals. Semiconductors possess wide bandgaps and therefore were reported to show significant alteration in their properties with bandgap tuning. These can be thus proveto be landmark for futuristic water disinfection processes.

9. POLYMERIC NANOPARTICLES

These polymeric nanoparticles are organic based NPs that are mostly nanospheres or nanocapsular in shape Zielińska et al. (2020). The nanospheres have solid matrix particles with other molecules adsorbed at the outer spherical surface while in nanocapsule the solid mass is encapsulated within the particle Rao and Geckeler (2011), Sharma et al. (2020).These PNPs can be functionalized and thus have multiple application. In one such study, macroporus methacrylic acid copolymer beads were prepared with silver nanoparticles adsorbed to its surface. These polymeric molecules were tested to be effective against both gram-positive and gram-negative bacteria Zaharia et al. (2022).

10. NANOCOMPOSITES

The various drawbacks of nanomaterials can be overcome by synthesizing the composites of nanoparticles where mixing of two or more nanomaterials are combined for different properties. For example, the chemical deposition of nZVIon CNTs imparted good adsorbent properties and magnetic properties adding to both efficiency of contaminant (nitrate) removal and recovery of nanocomposites Awasthi et al. (2019).

Utilization of spinel ferrite nanocomposites (SFNCs) for water purification either as photocatalyst or as an adsorbent is considered as one of the best cost-effective, ecofriendly and simple technology Kefeni et al. (2017). The application of chitosan nanocomposites has also been extensively studied, for their efficiency in treating wastewater as they are good chelating agents, absorbents and support other nano size particles. Chitosan nanocomposites possess remarkable antimicrobial, biodegradable and non-toxic properties Babaei et al. (2021).

Copper ferrite nanocomposites (CuFe2O4) have also attracted the attention of many researchers due to their potential application in water treatment. CuFe2O4 is an important spinel ferrite, because of its capability to change its physical characteristics, which range from magnetic, electrical, electrical switching and semiconducting properties when they are exhibited under different experimental conditions. CuFe2O4 nanocomposites possess good magnetic properties and are stable under various environmental states. The overall cost of the water treatment process is lowered by the use of CuFe2O4 nanocomposites, as they require visible light as an energy source and can also be reused many times Hosseini et al.(2022).

In last few years, extensive research has been conducted to develop efficient and selective polymeric membranes and adsorbents. Polymeric nanocomposites consist of nanoparticles dispersed in polymeric matrices such as cellulose, resins, dendrimer, etc., to improve their physicochemical, thermophysical, and mechanical properties. Polymer nanocomposites can be developed by using various methods, and the most prevalent techniques are in-situ polymerization, melt-mixing, mixing, selective laser sintering and electrospinning. Polymer nanocomposites are applied as adsorbents and filtering membranes to remove chemical impurities from aqueous media Adeol and Nomngongo (2022). The synthesis of clay polymer nano-composites (CPNs), is becoming famous because it combines the beneficial attributes of both clay minerals and polymers in a single adsorbent. CPNs possesses numerous applications in various industries, including water decontamination Awasthi et al. (2019).

Nanostructured sorbents also possess great potential for the removal of contaminants from the wastewater. The research is now focused on the development of polymer nanocomposites (PNCs), which have increased their efficiency in pollution remediation. Many chemical contaminants, such as heavy metals, hydrocarbons and dyes, have been removed from polluted water using polymer nanocomposites. Both natural as well as synthetic polymers can be utilized for the development of PNCs. Natural polymers include wool, cellulose, proteins and silk. Synthetic polymers consist of polyester, polyethylene, epoxy and teflon.

Nanotechnology have shown great promise in the laboratory studies however its commercialization is the real task. Full scale commercialization of nanoparticles requires significant amount of research

11. CONCLUSION

Nanotechnology for water and wastewater treatment is gaining momentum globally. The unique properties of nanomaterials and their convergence with current treatment technologies present great opportunities to revolutionize water and wastewater treatment. Although many nanotechnologies highlighted in this review are still in the laboratory research stage, some have made their way to pilot testing or even commercialization. Thus commercialization of these technologies is real task and full scaling requires significant amount of research.

Despite of superior performance, the adoption of nanoparticles for water disinfection must overcome the technical hurdles cost effectiveness and potential environment and human risk. The cost effectiveness can be improved by retaining and reusing the nanoparticles or using low purity nanomaterials with equivalent efficiency Qu et al. (2013). The existing infrastructure must be compatible with the new technologies such as nanotechnology.

Among them, three categories show most promise in full scale application in the near future based on their stages in research and development, commercial availability and cost of nanomaterials involved, and compatibility with the existing infrastructure: nano-adsorbents, nano-technology enabled membranes, and nano-photocatalysts Anjum et al. (2019). The use of nanomaterials for disinfection of water processes or waste-water treatment is restricted by the limited performance of various nanotechnologies in testing the real natural or waste waters. Future research needs more realistic conditions that can assess the application of nanomaterials at commercial scale. Another aspect of nanotechnology-based applications for water disinfection is limited due to limited research on long term effects of these nanoparticles on the flora and fauna present in water Vukoje et al. (2014).

The challenges faced by water/wastewater treatment nanotechnologies are important, but many of these challenges are perhaps only temporary, including technical hurdles, high cost, and potential environmental and human risk Kumari et al. (2019). To overcome these barriers, collaboration between research institutions, industry, government, and other stakeholders is essential. It is our belief that advancing nanotechnology by carefully steering its direction while avoiding unintended consequences can continuously provide robust solutions tour water/wastewater treatment challenges, both incremental and revolutionary Hossain and Hossain (2021).

CONFLICT OF INTERESTS

None.

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