Nanomaterials and Purification Techniques for Water Purification and Wastewater Treatment

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Abstract Access to safe and clean water has become a more challenging task worldwide as water resources are limited, and the population that relies on these limited supplies is expected to grow. The presence of pollutants in water affects human health and hygiene and decreases food safety. The supply of clean water is required for all the phases of food production, including processing, transportation, and consumption. Environmentally viable nanomaterials are being used to purify wastewater because of their distinctive characteristics, like high effectiveness and selectivity, larger surface area, cost-effective, recyclable, and high thermal and mechanical stability. This chapter provides an overall review of nanomaterials and their types and techniques used to eliminate organic and inorganic contaminants from wastewater.

Keywords Nanomaterials · Carbon nanomaterials · Photocatalyst · Absorbent · Water purification

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J. K. Katiyar et al. (eds.), *Nanomaterials for Advanced Technologies*,
https://doi.org/10.1007/978-981-19-1384-6_6

1 Introduction

Water is the most critical component for every living creature present in the world. Clean and drinkable water is a primary need for all living things and mankind on this earth. Fresh and clean water supply is a major challenge faced by human society and is expected to increase in the coming years. Availability of drinking water is far from the demand due to the gradual increase in population and various contaminates (Kunduru et al. 2017). A constant supply of safe and reliable water is required for proper sanitation for optimal health. The individual water requirements range from 7.5 L per day for drinking purposes and approximately 20–50 L per day for other daily needs (Khan and Malik 2019).

On the other hand, both developed and developing countries have reported water-borne diseases and believe that 50% of people in underdeveloped countries do not have access to clean and safe drinking water. Therefore, in developing countries, the uncontrolled discharge of contaminants that inadequacy of water purification system is the main problem (Figoli et al. 2017a; Borji et al. 2020). The causes of water pollution include improper sewage disposal, mining, industrial waste, oil spills, chemical fertilizers, pesticides, radioactive water discharge, etc. (Fig. 1a) (Kaur et al. 2020). The contaminants of wastewater affect our human health and cause several health problems like diarrhea, jaundice, impaired nerve function, skin infections, brain damage, dysfunction of the liver, etc. (Fig. 1b) (Cínti et al. 2019).

The prospect of the increasing freshwater source is limited because of the competing demands of the world's growing population. Industrial development improved the lifestyle of humans and damaged our natural resources and aquatic systems. Industries such as leather, food, pharmaceuticals, and packaging generate an enormous daily amount of wastewater which contains heavy metals, organic dyes, and other harmful chemicals. These gallons of wastewater are dumped into our

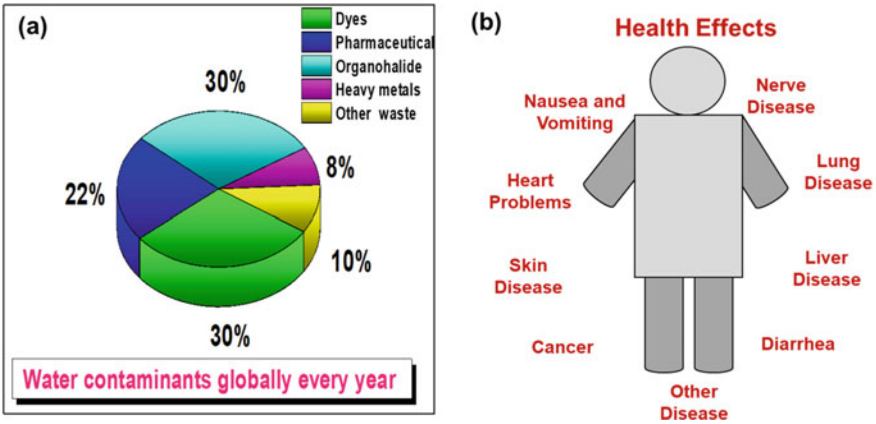

Fig. 1 **a** Global release of various pollutants into the water every year [Redrawn from Kaur et al. (2020)], **b** Possible effects of water contaminants on human health (Cínti et al. 2019)

aquatic ecosystem without any meaningful treatment. Thus, the effective removal of such contaminants is needed. Nanotechnology has shown the potential to solve water quality problems effectively due to its environment-friendly and non-toxicity properties for water purification. In particular, the vast range of nanostructures (NSs) such as metal oxide (ZnO, TiO_2, ZnS, Fe_3O_4, etc.) NSs [NPs (NPs), nanorods (NRs), etc.] and their nanocomposites (NCs), Carbon nanotubes (CNTs) or Carbon nanotube (CNT), graphene oxide (GO), reduced graphene oxide (rGO) graphene nanosheets (GNs) helps to develop a more effective treatment in advanced water purification systems (Amin et al. 2014). Unique advantages of nanomaterials like high surface-to-volume ratio, small size, well-organized structure, and ability of filtration make them a potential alternative for water treatment. Although, there are still some major challenges like high production cost, specific selectivity and availability, sustainability, and recyclability. Worldwide, various scientific groups are trying to develop highly effective and environmentally viable nanomaterials at a cost-effective for ecological purification of wastewater which contains hazardous heavy metals ions, dyes, detergents, and chemical waste from industries (Nasrollahzadeh et al. 2021).

In this chapter, we have discussed nanotechnology-enabled technologies that utilize different nanomaterials like silver NPs, metal-based NPs, carbon-based nanomaterials, etc. Their properties and reviewed other technologies for water purification adsorption disinfection, photocatalytic action, membranes, etc. Properties of various nano materials are reviewed in this chapter and varius technologies like water purification adsorption disinfection, photocatalytic action, membranes, etc. are discussed.

1.1 Nanomaterials for Water Purification

1.1.1 Zero-valent Metal NPs

Silver (Ag) is a transition metal (soft and shiny) whose atomic number is 47 (Fig. 2a) and exhibits greater electrical conductivity (~6.3×10^7 m/Ω) and thermal conductivity (~429 W/m K). Ag NPs are the most extensively utilized material because of their low toxicity and can be easily extracted from their salts, such as silver nitrate and silver chloride. Ag NPs have been used for various applications such as antibacterial, thin films, and water purification (Chamoli et al. 2017; Maninder and Baojun 2019). Ag NPs have strong microbial inactivation in water and show excellent antibacterial effects against various micro-organisms such as viruses, bacteria, and fungi. Therefore, it is commonly used for water disinfection due to its antibacterial properties (Lu et al. 2016). In particular, Ag NPs have been synthesized and utilized for the photodegradation of various organic dyes. For example, Pandey et al. synthesized Ag NPs from κ-Carrageenan gum and investigated their photocatalytic activity in the presence of UV with RhB and MB as the target pollutants. They were able to remove up to 100% in a short period of time (Pandey et al. 2020). Similarly, Rajkumar et al. have synthesized Ag NPs by utilizing cell-free extract of Chlorella Vulgaris. The

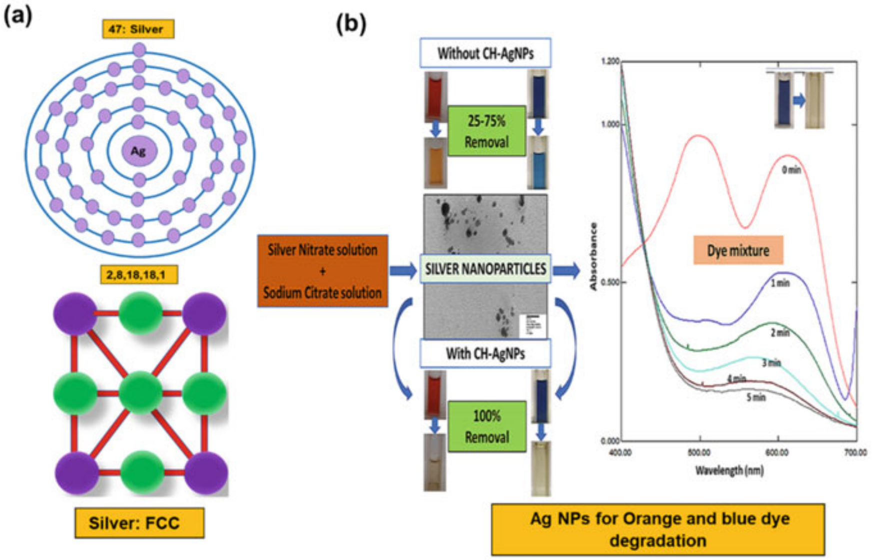

Fig. 2 **a** Crystal structures of Ag and **b** Ag NPs for orange and blue dye degradation. Reproduced with permission from Gola et al. (2021)

synthesized Ag NPs showed 96.51% of photocatalytic decolorization activity using methylene blue dye (100 ppm) within 3 h incubation time (Rajkumar et al. 2021). However, Gola et al. have synthesized Ag NPs and achieved degradation up to 100% from blue dye and orange dye ~97.4% degradation, respectively. Further, dye mixture studies (orange + blue dye) have been examined and found 100% degradation in just 5 min (Fig. 2b) (Gola et al. 2021). Jain et al. have prepared aqueous Ag NPs (Pa–Ag NPs) using leaf extract of C. papaya and studied dye degradation ability for blue CP and yellow 3RS with degradation ability 90 and 83%, respectively (Jain et al. 2020).

1.1.2 Metal Oxide NSs and NCs

TiO_2 NSs

Titanium dioxide (TiO_2) is a wide bandgap semiconductor with three different crystallographic forms (polymorphs, Fig. 3a), viz., anatase (with a bandgap of 3.1 eV), rutile (3.02 eV), and brookite (2.96 eV) (Haggerty et al. 2017). TiO_2-anatase is an extensively used photocatalyst due to its high photocatalytic activity, low price, and good biological and chemical stability. Under the presence of light (UV and visible), TiO_2 NSs act as an excellent photocatalyst and successfully degrade various organic contaminants. Primarily, TiO_2 produces many reactive oxygen species that can entirely deteriorate pollutants in a short reaction time under ultraviolet irradiation (Ali et al. 2018a).

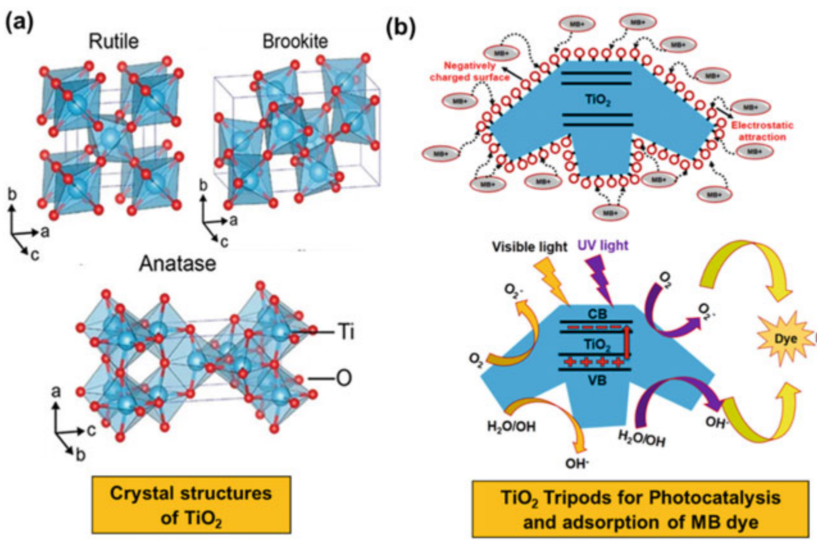

Fig. 3 **a** Crystal structures of TiO_2: rutile; brookite, and anatase; Reproduced with permission from Haggerty et al. (2017) and **b** TiO_2 tripods for photocatalysis and adsorption; Reproduced with permission from Chamoli et al. (2021a)

For example, Gautam et al. have prepared TiO_2 (both anatase and rutile) NPs and successfully degraded MB dye in the presence of UV (8 W) light irradiation, and the degradation efficiency (DE, ~88%) is obtained by using anatase NPs in 150 min (Gautama et al. 2016). Tayeb et al. have synthesized TiO2 NPs and effectively degraded MB dye under UV (15 W) light irradiation with degradation efficiency (DE) of ~ 98% in 90 min (Tayeb and Hussein 2015). Sathiyan et al. have prepared TiO_2 NPs and effectively degraded MB dye up to 88% in 180 min in the presence of UV–visible light (Sathiyana et al. 2020). Chamoli et al. used Mangifera indica leaf extract to make TiO_2 tripods (TiTPs) via a rapid microwave (180 s, 100 W) green method. TiTPs have shown excellent photocatalytic ability against MB, achieving dye degradation of ~75% (under visible light in 75 min) and 96% (under UV light in 9 min). Moreover, TiTPs have exhibited good adsorbent capabilities, with a maximum adsorption capacity ~17.54 mg/g based on the Langmuir model owing to their porous nature (Fig. 3b) (Chamoli et al. 2021a).

ZnO NPs

ZnO is a compound semiconductor material of group-II-VI. The majority of the materials in this group-II-VI are cubic zinc-blende or hexagonal wurtzite structures (four cations surround each anion at the corners of a tetrahedron). ZnO is a 3.37 eV broad bandgap semiconductor with the structure of wurtzite (B4), zinc-blende (B3), and rock salt (B1) (Fig. 4a), and its ionicity is intermediate between covalent and

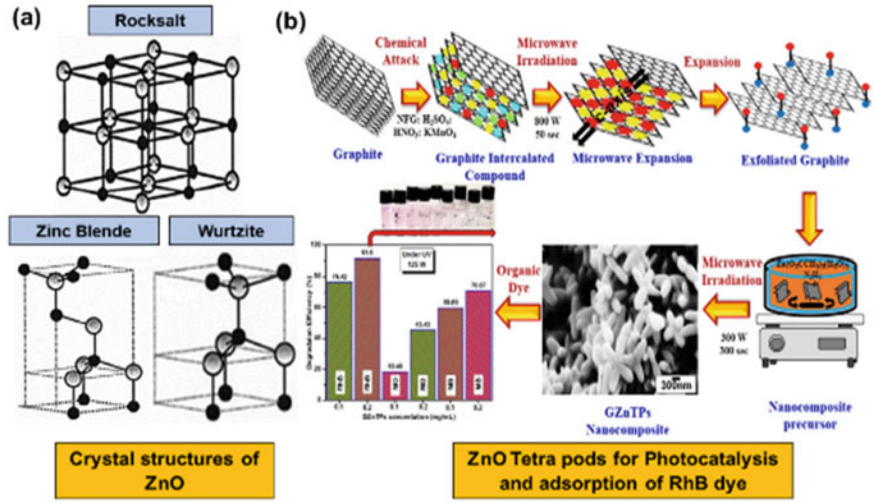

Fig. 4 **a** Stick and ball representation of ZnO crystal structures: cubic rock salt (B1), cubic zinc-blende (B3), and hexagonal wurtzite (B4). The shaded gray and black spheres denote Zn and O atoms, respectively. Reproduced with permission from Özgür et al. (2005). **b** GZnTPs for photocatalysis and adsorption of RhB dye, Reproduced with permission from Chamoli et al. (2021b)

ionic semiconductors (Özgür et al. 2005). ZnO is extensively employed in materials because of its ease of production and low toxicity. It is useful in wastewater remediation due to its distinctive features, such as direct and wide bandgap in the near-ultraviolet spectral region, high oxidation ability, and enhanced photocatalytic performance.

For example, Fan et al. have synthesized zinc oxide-reduced graphene oxide (ZnO/rGO) NCs for photocatalytic degradation of MB, MO, and RhB in the presence of ultraviolet (UV) light irradiation (150 W) and showed degradation efficiency (DE) of ~99% in 30 min (Fan et al. 2015). Ravi et al. have produced ZnO/rGO NCs for photocatalytic degradation of Congo red (CR) and eosin yellow (EY) in the presence of UV light and found 98% removal of the dyes in 90 min (Ravi et al. 2018). Jabeen et al. have attained 68% removal of methylene blue (MB) dye in 120 min in the presence of UV light (500 W) by employing ZnO/rGO NCs (Jabeen et al. 2017). Furthermore, for the removal of RhB, ternary ZnO/CuO/rGO NCs have also been produced, with 99% degradation efficiency (DE) obtained in 20 min in the presence of visible light (150 W) (Kumaresan et al. 2020). Chamoli et al. have synthesized grapheme—ZnO tetrapods (GZnTPs) and investigated their potential to photodegrade RhB, MO, and MB dyes in the presence of UV and visible (both 125 W) light irradiation. Upon UV light irradiation, GZnTPs behave as an outstanding photocatalyst for RhB, with such a higher degradation efficiency of 91.6% (Chamoli et al. 2021b). Compared to numerous semiconductor metallic oxides, ZnO NPs can adsorb a much broader solar spectral range and more light quanta. Like TiO_2 NPs, the light absorption of ZnO NPs is limited to the UV range due to its large band energy. In addition, the utility of ZnO particles is hindered by photo-corrosion, leading to the fact that the photo-generated charges recombine rapidly, resulting in lower photocatalytic efficiency.

Zinc Sulfide (ZnS) NSs

ZnS (II-VI group semiconductor) is an important photocatalyst studied at the nanoscale because of its outstanding physical properties and peculiar photocatalytic properties. Cubic (sphalerite) and hexagonal (wurtzite) are two main crystalline forms of ZnS with coordination geometry at Zn and S are of tetrahedral having 3.72 and 3.77 eV bandgaps for cubic and hexagonal ZnS, respectively, (Lee and Wu 2017). This large bandgap of ZnS enables candidacy as an important photocatalyst for various dye degradation and wastewater remediation. For example, Maji et al. have prepared ZnS NCs (rod and sphere) using ethylenediamine and hexadecylamine, which show effective photocatalytic activity against rose bengal dye (RB) under light irradiation. The DE has been achieved ~93% at 225 min (Maji et al. 2011). Zhang et al. have successfully prepared ZnS microcrystals (polyhedron, fan-shaped sheet, hexagonal rectangle, and missing angle rectangle) using a simple hydrothermal method against MB. The degradation efficiency (DE) has been achieved ~91% at 60 min (Zhang 2014). However, metal (Pb, Cu, Ni)-doped ZnS photocatalyst obtained by various methods, and also conjugated ZnS complexes obtained through polyreaction have been shown to have the potential to defluorinate hexafluorobenzene by visible light (Lee and Wu 2017). Thio-glycerol and uncapped ZnS NPs have been produced to use a substantial component of solar energy for dye degradation. Although ultraviolet irradiation is excellent at degrading dyes, naturally occurring solar radiation is also beneficial in dye degradation. As a result, it could be an effective approach for the safe disposal of textile waste into waterways (Sharma et al. 2012), while Lee et al. have been summarized ZnS-assisted photocatalytic degradation of pollutants and water splitting under various conditions (Lee and Wu 2017).

Fe_3O_4 NSs

In recent years, people have been more interested in using iron oxide NPs due to their simplicity and easy accessibility to degrade organic dyes and remove heavy metals from wastewater. Iron oxide NPs have different forms (Fig. 5) and are commonly used as nanoadsorbents such as magnetic magnetite (Fe_3O_4), magnetic maghemite (γ Fe_2O_4), and non-magnetic hematite (α Fe_2O_4). Separating and recovering them from wastewater during photocatalytic degradation is a challenging task. Thus, Fe_3O_4 and Fe_2O_4 can be easily be separated and recovered by using an external magnetic field from the wastewater system (Xu et al. 2012). Therefore, iron oxides are widely used in the purification of water.

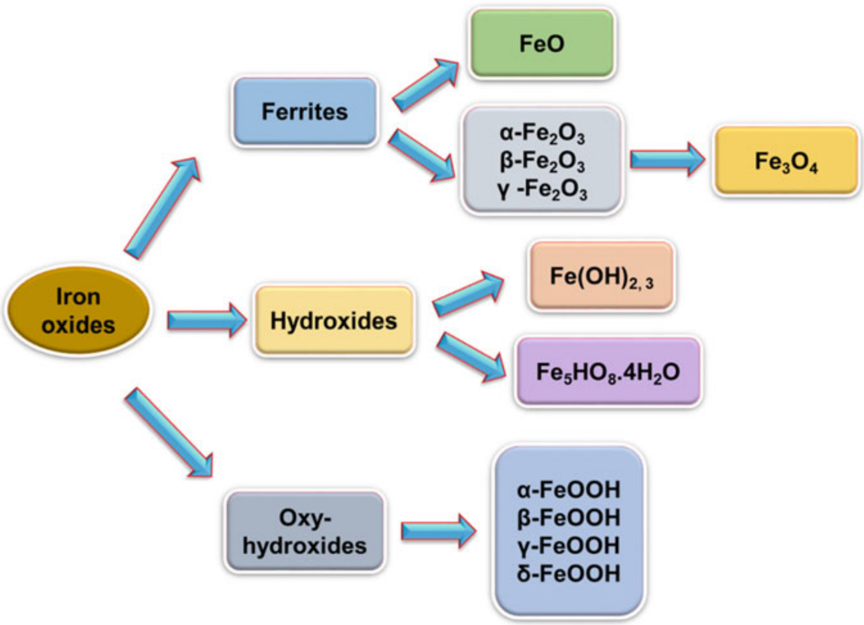

Fig. 5 Different forms of iron-based NPs: oxides, hydroxides, and oxyhydroxides (Aragaw et al. 2021)

For example, Bhuiyan et al. have synthesized α-Fe_2O_3 NPs from hexahydrate ferric chloride ($FeCl_3.6H_2O$) using papaya (Carica papaya) leaf extract and obtained ~76.6% RR dye degradation after 6 h (Bhuiyan et al. 2020). Balu et al. have prepared iron oxide Fe_2O_3 NPs by Raphanus sativus leave extract to degrade MB and MR. Both the dyes have undergone complete degradation (100%) in 1 h (Balu et al. 2020). However, functionalization of iron oxide NPs with various ligands such as mercaptobutyric acid or polymers boosts absorption efficiency and removes interference from other metal ions (Aragaw et al. 2021). The majority of iron oxide NCs are amorphous NPs with an average size of about 5 nm, which is a suitable size. These distinctive characteristics of amorphous NPs of iron oxide provide a large surface area for (FeO_x-GO-80) with an iron oxide content of 80 wt% with a prominent mesoporous structure, resulting in increased adsorption sites and, as a result, increased adsorption capacity for the removal of heavy metal pollutants from wastewater (Su et al. 2017; Rashida et al. 2021). A comparative study has been done for dye degradation using various metal oxides NPs and NSs and tabulated in Table 1.

1.1.3 Carbon-based Nanomaterials

Carbon nanomaterials are attractive materials for various applications because of their strength and capability to make bonds with other elements. Various allotropes of

Table 1 Comparison of degradation of dyes by various metal oxide NPs, NSs, and NCs

Nanomaterials	Dye	DC (mg/L)	PC (mg/mL)	Light source	Time (min)	DE (%)	Source
TiO_2 NPs	MO	25	1.5	Sunlight	30–60	90	Ljubas et al. (2015)
TiO_2 NPs	RhB	30	1.5	Microwave irradiation	20	96	Zhong et al. (2009)
N-doped TiO_2	Azo dyes	0.03	0.01	Visible light	240	97	Liu et al. (2005)
C-TiO_2 NPs	RB-19	–	1.6	Visible light	120	100	Helmy et al. (2018)
ZnO NPs	MB	20–100	0.25	UV	180	92.5	Balcha et al. (2016)
ZnO NPs	Rh B	–	–	UV	70	95	Rahman et al. (2013)
Ag-ZnO NPs	MB	0.20		Visible light	180	98.66	Singh et al. (2017)
(Er, Yb)-ZnO NPs	MO	0.004	6	Visible light	90	100	Ahmad (2019)
Cr-ZnS NPs	MO	0.025	5	UV	300	65.22	Eyasu et al. (2013)
ZnS NPs	MR	–	–	Visible	120	95.10	Ye et al. (2018)
Fe_2O_3 NPs	RB-4	20	0.15	UV	56	95.08	Su et al. (2017)
FeO NPs	MG	100	0.4	Sunlight	300	97	Bibi et al. (2019)
ZrO_2/GO	RhB	8	0.5	UV	40	100	Rani et al. (2016)
Au NPs	MB	10	0.15	UV	15	87	Leon et al. (2016)
Nanocupper	MO	20	0.2	Visible	88	35	Liu et al. (2016)
TiO_2/2/β-FeOOH	MO	80	0.2	Visible	120	7.50	Xu et al. (2013)
Ag/Fe_3O_4	MB	40	1	UV	30	99	Liu et al. (2018)

(continued)

Table 1 (continued)

Nanomaterials	Dye	DC (mg/L)	PC (mg/mL)	Light source	Time (min)	DE (%)	Source
CeO_2NCs	MG	30	0.5	UV	21	90	Madhukar Sreekanth et al. (2019)
Ag/COW	RY	100	1	UV	110	96.05	Yola et al. (2014)
Pd/Fe_3O_4-Al	MO	20	0.05	UV	2	90	Cui et al. (2017)
Fe_3O_4/PDA/Ag	MB	40	1	UV	4	100	Cui et al. (2018)
Fe–Ni-PVP NPs	RhB	125	0.75	UV	120	97.44	Kale and Kane (2018)
Pt/N/TiO_2	RB	10	0.3	Visible	90	83.4	Huang et al. (2007)
Ag NPs	MO	10	0.1	Visible	120	51	Jyoti and Singh (2016)
Ag NPs	CR	35.5	0.0002	UV	15	85	Kolya et al. (2015)

carbon like fullerene, graphene, etc., are CNTs (Fig. 6) and are utilized for wastewater treatment (Selvaraj et al. 2020).

Fullerenes

In 1985, Fullerene was discovered and gained considerable attraction because of its remarkable photochemical and photophysical features (Selvaraj et al. 2020). Fullerenes formed a cage-like structure (Fig. 6) with twelve 5-member rings and an unspecified number of 6-member rings. Fullerenes are most commonly found in the form of hexagonal rings with carbon atoms organized inside, but sometimes they also contain pentagonal rings. It is prominent that structures with lesser hexagons show sp^3 bonding, high strain energy. Several research studies have shown that fullerene behaves as an adsorbent to adsorb organic waste and heavy metal ions from wastewater. For example, in wastewater, hydrophobic organic compounds such as naphthalene could be adsorbed by adsorbent C_{60} fullerene, which was coated as a thin film and disseminated in water by magnetic mixing. As a result of its hydrophobic surface, C_{60} fullerene is projected to be an ideal adsorbent for a wide range of organic compounds present in contaminated water (Selvaraj et al. 2020; Geim and Novoselov 2007).

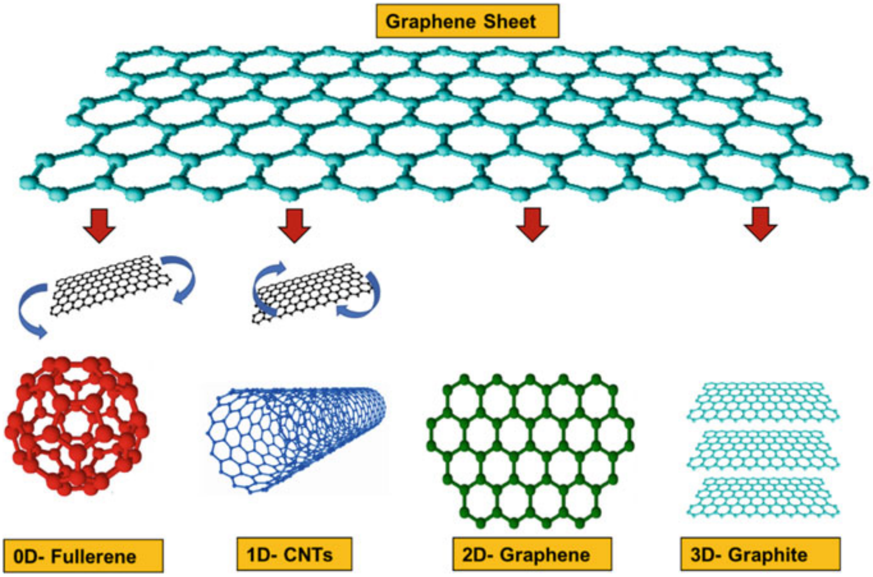

Fig. 6 Graphene as a building block of other forms. An illustration of different allotropes of carbon emerging from a graphene sheet. Redrawn from Geim and Novoselov (2007)

Carbon Nanotubes (CNTs)

CNTs are made up of graphene sheets wrapped into cylinders with diameters ranging from 1 to 100 nm. Their unusual structure and electrical properties make nanotubes attractive for basic research and various applications like the adsorption process (Selvaraj et al. 2020). Its advantages in treating wastewater are due to (i) the ability to adsorb various types of pollutants, (ii) fast adsorption kinetics, (iii) greater specific surface area, and (iv) selectivity to aromatics. CNTs are very effective in eliminating bacterial pathogens. It has been extensively used to remove biological impurities and has received special attention because of its excellent capability to eliminate biological contaminants from wastewater. It has antibacterial properties against various micro-organisms, including bacteria like *Escherichia coli* and Salmonella. Compared with carbon-based adsorbents, the adsorption of cyanobacterial toxins on carbon nanotubes is also greater, mainly because of the larger specific surface area, larger outer diameter, and large mesoporous volume of CNTs. Carbon nanotubes have extraordinary structures and unique characteristics, making them a good candidate for adsorption phenomena, such as metal removal. Single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT) are two types of carbon nanotubes. Both single-walled and multi-walled carbon nanotubes have unique features, such as greater surface area available for adsorption, accessibility of adsorption sites, light mass density. Compared with activated carbon, they also have high adsorption efficiency, which is currently used as the main adsorbent in the purification of water (Rashida et al. 2021).

Graphene

Graphene is a sp^2-bonded carbon sheet that can be single or multi-layered. It is a hexagonal lattice of carbon atoms that is only one atom thick. It is another type of carbon nanomaterial. It has many excellent properties in physics and chemistry (Selvaraj et al. 2020; Geim and Novoselov 2007; Duklan et al. 2020). Due to its distinctive 2D structure and exceptional mechanical, thermal, and electrical capabilities, graphene, which is made up of a few atomic layered graphites, has also been used to analyze the adsorption of pollutants of wastewater. Graphene oxide nanosheets manufactured from graphite using an improved Hummers method are reported to be used as adsorbents to remove CO^{2+}, Cd^{2+} from many aqueous solutions. The adsorption of metal ions on graphene oxide nanosheets was highly reliant on pH and weakly reliant on ionic strength, as seen by manipulating variables such as pH, ionic strength, and humic acid on CO^{2+}, Cd^{2+}. When the pH is less than 100 °C, the presence of humic acid decreases the adsorption of CO^{2+}, Cd^{2+}, on graphene oxide nanosheets. At pH 6.0, the maximum adsorption capacity of CO^{2+}, Cd^{2+} on graphene nanosheets is approximately 106.3 and 68.0 mg/gm, and the temperature is approximately 303 K (Thines et al. 2017). According to this research, graphene is considered the main material for the purification of water if they were manufactured at a larger scale at an affordable cost. Several studies have shown that graphene can be used not only to adsorb heavy metals but also to adsorb fiber dyes for the purification of water (Das et al. 2020). It has been reported that graphite is used for adsorption of dye from an aqueous solution after oxidizing the graphite by using the Hummers-Offeman method (Geim and Novoselov 2007).

2 Removal Techniques

Hazardous pollutants like heavy metals, organic pollutants, and anions are introduced into the system of freshwater supply through industrial and agricultural waste. The types of new organic pollutants cannot be deteriorated by the chemical, biological, and photolytic processes in the environment, including pesticides, drugs, hormones, types of various aromatic compounds, etc. (Thines et al. 2017). The traditional methods for purification of wastewater cannot remove all the contaminants, and even the very low concentration of pollutants will cause to form dangerous disinfection by-products (DBP). The presence of contaminants affects health and hygiene and reduces food safety. The availability of clean water is necessary for food production, including preparation, distribution, and consumption. Due to the increase in the number of water-borne diseases caused by the number of inorganics, organic hazardous waste, the new and innovation of effective treatment processes are vital. Nanotechnology has shown excellent results in the removal of the aforementioned type of pollutants. Many studies have been conducted on wastewater treatment processes supported by nanotechnology, many of which have shown superior performance over traditional technologies (Figoli et al. 2017b). According to the types of nanomaterials, wastewater treatment is divided into three categories: (i) nanoadsorption, (ii) nanocatalyst, and (iii) nanomembrane.

2.1 Nanoadsorption

Adsorption is a surface phenomenon in which contaminants are adsorbed onto a solid surface. Adsorption occurs in all physical forces, but it can also be linked to weak chemical bonding in specific cases. Nanoadsorption is generally used in wastewater treatment to remove organic and inorganic pollutants. The distinctive characteristics of the nanoadsorbent, such as small size, high catalytic potential, high reaction activity, high surface area, ease of separation, and a high number of active sites for interaction with various pollutants, are helpful for wastewater treatment (Table 2).

Table 2 Comparison of maximum adsorption capacity of different NCs against organic dyes

Adsorbent	Pollutant	Dye volume (mg/L)	Adsorbent volume (g/L)	MAC mg/g	Ref.
Ag NPs	IC	3.55	0.4	73.05	Gemeay et al. (2018)
RGO-CNT-PPD	MO	30	0.1	294	Sarkar et al. (2014)
Polypyrrole	MO	50	0.8	143.89	Alghandi et al. (2019)
Banana peel	Rh. B	100	0.5	28.8	Akter et al. (2021)
NZVI	MB	10	0.5	208.33	Arabi and Reza Sohrabi (2014)
GO	MG	50	0.2	416.7	Sykam et al. (2018)
Au-RGO	MB	15	0.25	338.65	Dutta et al. (2013)
Ag NPs	MB	50	1	213.7	Karthiga Devi et al. (2016)
MPA/PMNPs	CV	25	0.5	88.65	Ali et al. (2018b)
rGO/PVA	MB	20	4	231.12	Cheng et al. (2015)
Au NPs/AC	MO	20	0.005	161.29	Ghaedi et al. (2015)

2.2 Carbon-based Nanoadsorbents

Carbon-based nanoadsorbents are, such as graphene, graphene oxide, and carbon nanotubes. Carbon nanotubes can be divided into single-walled nanotubes (SWNT) and multi-walled nanotubes (MWNT) as advanced water purifiers. These materials are rarely used in their pure form. Still, the most common composition, either dispersed in a polymer or decorated with metal NPs, such as silver (Ag) and iron oxide (Fe_3O_4) NPs (Smith and Rodrigues 2015). Due to their hydrophobic surface, the carbon nanotubes dissolve the bundle in an aqueous medium, which reduces the active surface area. These aggregates are high-energy locations for adsorbing organic pollutants in the water. The reason for the adsorption is as follows: (i) the availability of larger pores in carbon nanotubes bundles and (ii) greater accessible adsorption sites.

2.3 Metal-based Nanoadsorbents

In the water purification process, metal-based nanoadsorbents, like zinc oxide, titanium oxide, iron oxide, are employed to remove heavy metals. These adsorbents are both efficient and cost-effective. The oxygen in metallic oxides forms a compound with the heavy metals found in wastewater. That is how they work. Magnetic nanoadsorbents, for example, maghemite (γ Fe_2O_3), hematite (α-Fe_2O_3), and spinel ferrite ($M^{2+}Fe_2O_4$, Where M^{2+}: Co^{2+}, Fe^{2+}, etc.) are very excellent adsorption materials used to collect and eliminate toxic and carcinogenic pollutants from wastewater (Ahmad et al. 2021). The environmental advantage is reflected in its magnetism. They can be easily detached from the reaction medium by applying an external magnetic field. Various studies proved that metal-based nanoadsorbents remove various elements from wastewater, for example, ionic forms of lead, nickel, arsenic, chromium, cobalt, etc. ZnO nanoadsorbents are employed for the removal of Zn^{2+}, Cd^{2+}, and Hg^{2+} ions from aqueous solutions in work published in the literature. Metals ions are adsorbed onto ZnO NPs at discrete amounts. Because Hg^{2+} has the smallest hydrated ionic radius among metal ions, it has the highest adsorption capacity (Ahmad et al. 2021). Alumina nanoadsorbents can also be manufactured because of their large surface area, good thermal stability, and relatively inexpensive. They are used to remove metal ions, like cadmium, chromium, copper, lead, and mercury. Metal-based nanoadsorbents are employed for the elimination of heavy metals in water and high-efficiency nanoadsorbents in wastewater because of their merits, like large adsorption capacity, faster kinetics, etc. (Ahmad et al. 2021).

2.4 Polymer-based Nanoadsorbents

Polymer-based nanoadsorbents have recently acquired attraction toward wastewater treatment. They are used as a structure that can insert nanoscale inorganic materials or a bed or template for preparing NPs. Polymer-based magnetic nanoparticles efficiently removed heavy metal ions like Zn^{2+}, Cd^{2+}, Pb^{2+} from aqueous solutions and have a high maximum capacity of adsorption of pH 5.5 (Ahmad et al. 2021; Kumar et al. 2011). This nanoadsorbent can be reused for at least four cycles. In recent studies, bi-metal micro- and nano-multifunctional polymeric adsorbents were developed for the elimination of fluoride and arsenic (V). Suspension polymerization is used to make the polymer. To make bi-metal-doped nanoadsorbents, aluminum and iron salts are added during the polymerization process. When compared to fluoride, iron-doped nanoadsorbents had excellent adsorption for arsenic, while aluminum-doped nanoadsorbents had excellent adsorption for fluoride (Kumar et al. 2011). Hence, polymer-based nanoadsorbents are magnificent materials due to their structures, pore sizes, and tunable functional groups; making them selective for a specific contaminant is challenging to remove heavy metal ions from wastewater. The adsorptive capacity is quite low, and regeneration is required when CO is high.

2.5 Nanocatalysis

Nanocatalysis is a rapidly emerging technology in which nanomaterials are used as catalysts in various applications such as reduced global warming, wastewater treatment. Different types of NPs are used as the catalyst for eliminating organic contaminants such as pesticides, dyes, fertilizers, oil grease and inorganic pollutants such as calcium, potassium, chloride, sulfate, nitrate. Nowadays, NPs of titanium oxide (TiO_2) have emerged as an attractive photocatalyst for water treatment (Adesina 2004). TiO_2 is highly adaptable; they can be used in various applications and can act as an oxidizing and reducing catalyst for the removal of organic and inorganic contaminants from wastewater. The addition of NPs of TiO_2 substantially improved the deterioration of organic pollutants in wastewater in the presence of ultraviolet radiation (Fig. 7) (Nawaz et al. 2020). It is reported that NPs of TiO_2 effectively (i) deteriorate organic pollutants like chlorinated alkanes and benzene, dioxins, furans, etc. and (ii) remove toxic metal ions like Cr^{6+}, Pt^{2+} in aqueous solutions under ultraviolet light. When ultraviolet light in the range of 200–390 nm is irradiated on $TiO_{2,}$ electron–hole pairs are photoexcited. They move to the conduction and valence bands, leading to the separation of charge for an efficient photocatalytic function that depends on the substrate's redox potential. As a result, in a pretreatment phase, the biodegradability of decomposable elements can be improved. Primarily, steady mixtures, like anti-microbial or other micro-contaminants, might be removed by photocatalysis polishing (Ahmad et al. 2021).

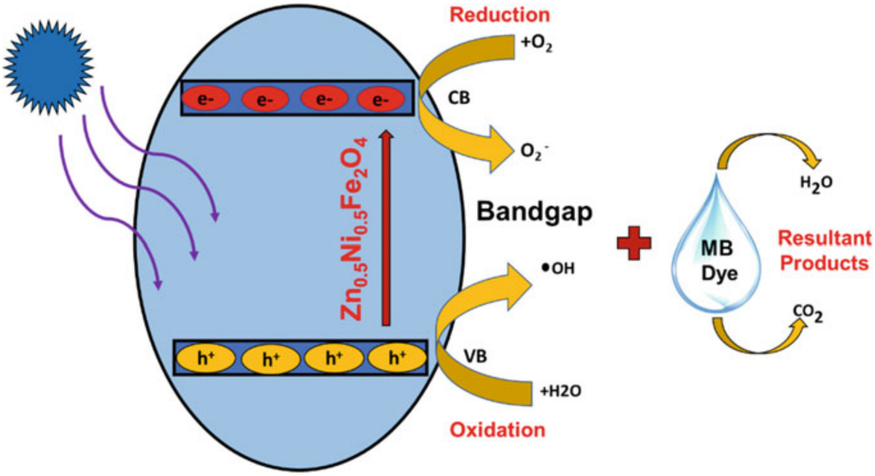

Fig. 7 Schematic of degradation of MB organic dyes. Redrawn and reprinted with permission from Nawaz et al. (2020)

TiO_2 is activated by ultraviolet light, but daylight or apparent light lamps are additionally allowed. KRONO clean 7000, a photocatalyst bandgap moved toward smaller energy: This contributes toward using a broader spectrum in sunlight (Gehrke et al. 2015). Modified technology has been explored to enhance the photocatalytic performance of titanium dioxide, including activity-enhancing or redshift for saving of energy, such as the combination of nano-silica (good thermal and chemical stability) and nano-titanium dioxide (nano-semiconductor) creates new surface-active sites. The catalytic performance of the silica/titanium dioxide nanocomposite is highly dependent on the content and distribution of TiO_2. Photocatalysis has a promising future as a long-term, eco-friendly, and cost-effective water purification technique. However, there are several technical hurdles to overcome before it can be used on a wider scale, for example, (i) catalyst tuning to enhance quantum yield or to use visible light, (ii) designing an effective photocatalytic reactor, and (iii) upgrade reaction selectivity.

2.6 Membranes for Water Purification

A nanomembrane is a permeable thin-layered membrane having pores sizes of 1–10 nm that enables water molecules to pass through it while preventing bacteria, viruses, heavy metals, pesticides, etc., from passing through them. The membrane's operation is dependent whether on pressure-driven or electrical technology. Pressure-driven membrane technique is an excellent approach for wastewater treatment (Kumar et al. 2014). Membrane filtration procedures have become more sophisticated techniques of industrial wastewater treatment. Membranes segregate materials based on the size of the pore and the molecule. It is a sustainable and systematic method for the purification of wastewater. The membrane material determines the membrane system's efficacy. Membrane permeability, theoretical resistance, thermal and mechanical stabilities are enhanced by incorporating functional nanomaterials into membranes. Surface-functionalized membranes and nanocomposite membranes, which can be produced from mixed materials, are practical filtration units. Nanofillers are used in mixed matrix membranes, and the majority of them are inorganic. They have a large surface area and are incorporated into polymeric or inorganic oxide matrix (Sarkar et al. 2014). Hydrophobic membranes (Fig. 8) are used in various industries for industrial wastewater treatment. For these various hydrophilic metal oxides, nanomaterials are used, such as Al_2O_3, TiO_2, and zeolites. Ag NPs, CNTs, bimetallic NPs are also used for membrane filtration (Karthiga Devi et al. 2016).

NCs membranes are made up of nanofillers, which are thin-film polymeric grids made up of a sequential arrangement of mesoporous carbons. They are semi-permeable, and reverse osmosis uses the top surface. Hydrophobic mesoporous carbons are transformed to hydrophilic carbons by atmospheric pressure plasma. A small amount of hydrophilic carbon increases hydrophilicity; this leads to an increase in the permeability of pure water. Thin-film nanocomposites were composed of polyamide and nano-NaX zeolite of 40–150 nm and are covered by interfacial polymerization using trimethyl chloride and m-phenylenediamine monomers over polyethersulfone. This membrane has a high permeability to purify freshwater,

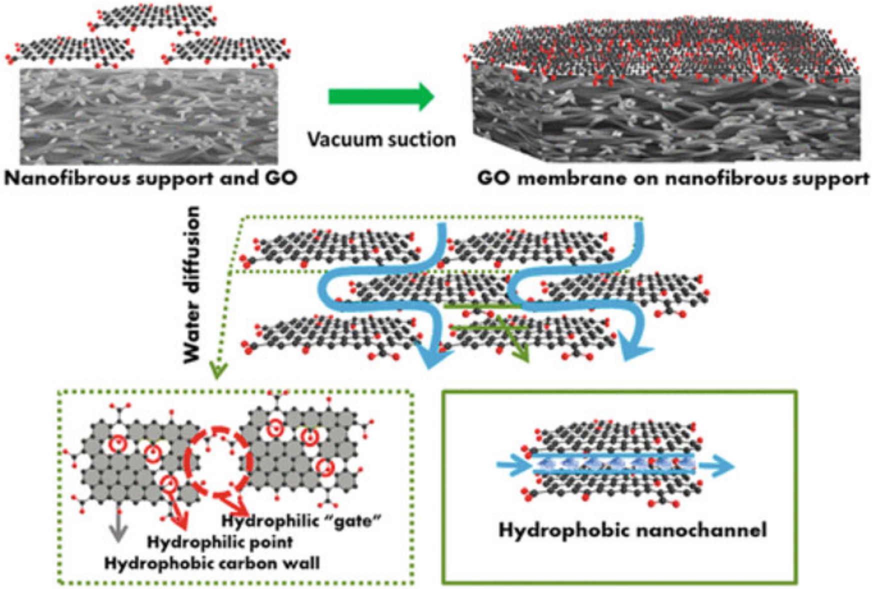

Fig. 8 GO-based porous nanofibrous membrane for water treatment. Reproduced with permission from Wang et al. (2016)

leaving pollutants behind the membrane (Fathizadeh et al. 2011). Electrospinning is a useful strategy for modifying the surface characteristics of nanomaterials, and various nanofibers have been successfully employed for wastewater treatment. These nanofibers have a large surface area and porosity, resulting in a nanofiber mat with a complex pore structure. Nanofibers are highly active against water pathogens, have low toxicity, and minimize health hazards. It is extremely simple to dope functional nanomaterials to form a filtration membrane, which has greater reactivity and selectivity to various pollutants.

3 Conclusion

In the present era, wastewater treatment techniques that would provide high-quality freshwater, eliminate organic and inorganic pollutants, and enhance industrial activities are very important. The opportunity is provided by nanotechnology; the distinctive characteristics of nanoparticles, such as greater surface area, size, shape, and dimensions, make them an excellent choice for water purification. Nanoparticles can be used to remove metal ions, anions, organic chemicals, and micro-organisms. Because the nanoparticle doses required for water purification are minimal, their use is reasonably cost-effective. This chapter highlights various nanotechnologies such as nanoadsorption, nanocatalysis, and nanomembranes, among others. Under UV and solar irradiation, photocatalytic processes successfully remove various types of water impurities, including organic and inorganic pollutants. As reactive oxygen species have a limited lifetime, surface modifications may boost the photocatalytic activity of selected compounds and enhance the affinity of modified nanomaterials toward several rising water pollutants. Bimetallic nanomaterials have also been proven to be useful in the treatment of wastewater contaminants. The prospects of NPs in water treatment are promising, but it will take a combined effort from scientific and corporate resources to develop a rapid, environmentally friendly, and practical system for the purification of wastewater. It will be achievable if everyone works with each other to overcome the problem of worldwide water contamination.

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