

Review

Sustainable Management of Water Resources for Drinking Water Supply by Exploring Nanotechnology

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Abstract: Freshwater is a limited resource that is needed by all living things. However, the available amount of it cannot counterbalance the explosion of the human population in recent years. This condition is worsened because of the contamination of many bodies of water by industrialization and urbanization. Nanomaterials offer an alternative sustainable solution due to their unique size-dependent properties, i.e., high specific surface area and discontinuous properties. These advantages can be utilized to reuse wastewater to become a sustainable water source for drinking water. Many recent studies have proven that nanotechnologies in the forms of nano-adsorbents, nanomembranes, and nano-catalysts have high performances in water contaminants removal. This review provides a comprehensive discussion around these nanotechnologies from the mechanism, applications, efficacy, advantages, disadvantages, and challenges in applications for producing drinking water including by wastewater reusing. Each nanotechnology reviewed here has been proven to perform effectively for water contaminants removal in laboratory scale. An initial study is also performed in this review to analyze the sustainability of nanotechnology for producing drinking water. In spite of the great efficacy, nanotechnologies utilization in commercial scales is still limited which requires further studies.

Keywords: nanotechnology; sustainable water management; nano-adsorbents; nanomembranes; nano-photocatalysts



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1. Introduction

Water is the source of living things that covers 70% of the earth's surface, but water scarcity has become a real danger affecting more than 2.4 billion people of the world's population today [1]. The explosion of the population in recent years has taken the world to the global water crisis. The available amount of freshwater on earth cannot counterbalance the growth of the human population [2]. Thus, the global water crisis has threatened the life of more than 800 million people in the world [1]. In 2022, around 2.2 billion people did not have access to a safely managed drinking water service, which is defined as the water available when needed and free from contamination [1]. Global water withdrawal increased from around 1700 km³/year in 1960 to almost 4000 km³/year in 2010 and by

the end of the century, it was projected to reach 6000 km³/year [3]. Following this trend, more than half of the world's population will face water-stressed conditions caused by an insufficient amount of water by 2025.

As only 3% of water is freshwater, including lakes, ponds, rivers, streams, springs, wetlands, and frozen glaciers, there are not plenty of usable sources [4]. Moreover, the increasing economic activities in the past years have resulted in cumulative contaminated water. Pollution occurs when external objects and the amounts of chemicals, both natural and unnatural, in an aquatic ecosystem accumulate or increase. There is enough freshwater on the planet for now, but it is distributed unevenly and too much of it mundanely wasted, contaminated, and unsustainably handled; hence, the present condition will insinuate the phenomenon if it is not being alleviated immediately [5].

Clean freshwater is needed for human and industrial activities, especially for food and drink production. It was reported that 80% of the world's untreated wastewater is recklessly discharged to the body of water, back to the rivers, lakes, and oceans [6]. As a result, waterborne diseases are threatening the lives of citizens, such as diarrhea, dysentery [7], arsenicosis [8], polio [9], trachoma [10], typhoid fever [11], schistosomiasis [12], cholera [13], lead poisoning [14], etc. For example, extremely contaminated water in Woburn, Massachusetts between 1969 and 1979 was responsible for leukemia and birth defects of 12 children in the suburban city. The water in wells G and H which were used as the Woburn municipal water supply was contaminated by the spill from chemical barrels because they were connected to the Aberjona River in a historically industrial area. Ten years after the residents complained, the Massachusetts Department of Public Health announced that the wells were contaminated with tetrachloroethylene/perchloroethylene (PERC), trichloroethylene (TCE), chloroform, 1,2-dichloroethene, and inorganic arsenic by 20.8 µg/L, 267.4 µg/L, 11.8 µg/L, 53 µg/L, 10 µg/L, respectively [15].

One of the major causes of waterborne diseases is low drinking water quality. The limited access to clean drinking water has affected around 2.3 billion people across the world with water-related diseases [16]. In 2020, it is estimated that nearly 2 billion people globally still drank fecal-contaminated water [17]. Therefore, the Sustainable Development Goal (SDG) target 6.1 from the United Nations aims for universal and equitable access to safe and affordable drinking water by 2030. In order to achieve this target, some actions need to be taken to guarantee the availability of freshwater including sustainable water management by wastewater treatment as also emphasized by SDG target 6.3 [18].

As a universal solvent, water easily dissolves various contaminants and contains more substances than any other liquid element on earth. The classification of water pollution falls into six categories, i.e., groundwater, surface water, ocean water, point source, nonpoint source, and transboundary [19]. Groundwater comes from the rain that is absorbed deeply into the earth, filling the cracks and porous spaces. It gets polluted when the contaminant leaks from landfills [20] and septic systems [21]. Surface water pollution sources are rivers, lakes, and oceans that get contaminated. A point source is when contamination comes from a single source; for example, wastewater, sewage, oil spills, and illegal dumping. For example, water contamination in Nansi Lake, China, was caused by several industries along the shore of the lake, such as the mining and washing of coal, manufacture of raw chemical materials and chemical products, papermaking industry, and food processing industry [22]. The nonpoint source refers to contamination from diffusion; for example, debris blown from uncontained landfills. Trans-boundary is pollution as a result of a significant disaster in a country into waters in other places; for example, oil spills as happened in Montara and sparked debates between Australia and Indonesia [23].

In recent years, nanomaterials have attracted many people and industries to treat wastewater in order to gain clean freshwater ready for reuse. Nanomaterials have unique size-dependent properties related to their high specific surface area (fast dissolution, high reactivity, strong sorption) and discontinuous properties (such as super-paramagnetism, localized surface plasmon resonance, and quantum confinement effect) [24] which overcome several difficulties and drawbacks in applying conventional water treatment technologies.

Treatment effectiveness of contaminants can be increased with the application of nanomaterials, thanks to the increased selectivity and reactivity, as well as the ability to undergo reactions that are not possible with conventional materials. The treatment process can thus be made simpler, with a reduction in energy, time, and cost [25]. Thus, nanotechnology is perceived as a sustainable way to manage water resources for providing freshwater for the population [26].

This review paper will focus on various nanotechnology applications for drinking water production from different water resources, including reusing contaminated wastewater. Based on the data available, an initial sustainability evaluation of nanotechnology available for water treatment will be performed in this review paper. The possibility of nanotechnologies for potable water production at a large scale will also be assessed based on the advantages, drawbacks, and challenges in the current development stage.

2. Limited Drinking Water Sources and Efforts to Reuse Wastewater

Conventionally, drinking water is produced from groundwater or surface freshwater (rivers or lakes) that undergoes several treatments to satisfy the quality for drinking [27]. The World Health Organization and United Nations Children's Fund (WHO/UNICEF) Joint Monitoring Program for Water Supply, Sanitation and Hygiene has defined five levels of drinking water services, i.e., [28]:

- Safely managed: drinking water comes from an improved source that is available when needed and free from fecal and priority chemical contamination;
- Basic: drinking water is sourced from an improved source with a collection time no more than 30 min for a round trip;
- Limited: drinking water is sourced from an improved source with a collection time more than 30 min for a round trip;
- Unimproved: drinking water comes from an unprotected dug well or unprotected spring;
- Surface water: drinking water is sourced directly from a river, dam, lake, pond, stream, canal or irrigation canal.

In 2022, 73% of world population gained safely managed drinking water sources, while around 18% had access to basic drinking water sources. Only 4% had limited drinking water sources, another 4% had unimproved source, and 1% sourced their drinking water directly from surface water [28]. Although it seems that most of the world population has gained sustainable sources of drinking water, this condition can be worsened in the future as shown by water stress level. The condition of the water stress in the world in 2023 is depicted in Figure 1. The water-stressed condition starts when the available water in a country drops below $1700 \text{ m}^3/\text{year/person}$ or $4600 \text{ L/day/person}$. Water scarcity is reached at below $1000 \text{ m}^3/\text{year/person}$ or $2700 \text{ L/day/person}$ [29]. There were 25 countries which were categorized as extremely high water-stressed from annually withdrawn water reported, as the higher percentage indicates the higher difficulty of obtaining water.

The most common way to ensure a stable freshwater source is desalination of seawater and runoff waters [30]. Recently, an unconventional yet interesting alternative, namely treated wastewater, has gained attention. Methods for the treatment and reuse of water from grey and industrial wastewater systems have been developed [31,32]. A San Francisco Bay-based company, Silicon Valley Clean Water, has designed an effective wastewater treatment system that is claimed to be capable of removing 97% of organic materials, solid wastes, and pathogens, and is also beneficial for around 200,000 people in the surrounding area [33]. The benefit of this approach is enjoyed the most in the agriculture area, especially since the treated water has a high nutrient content [34].

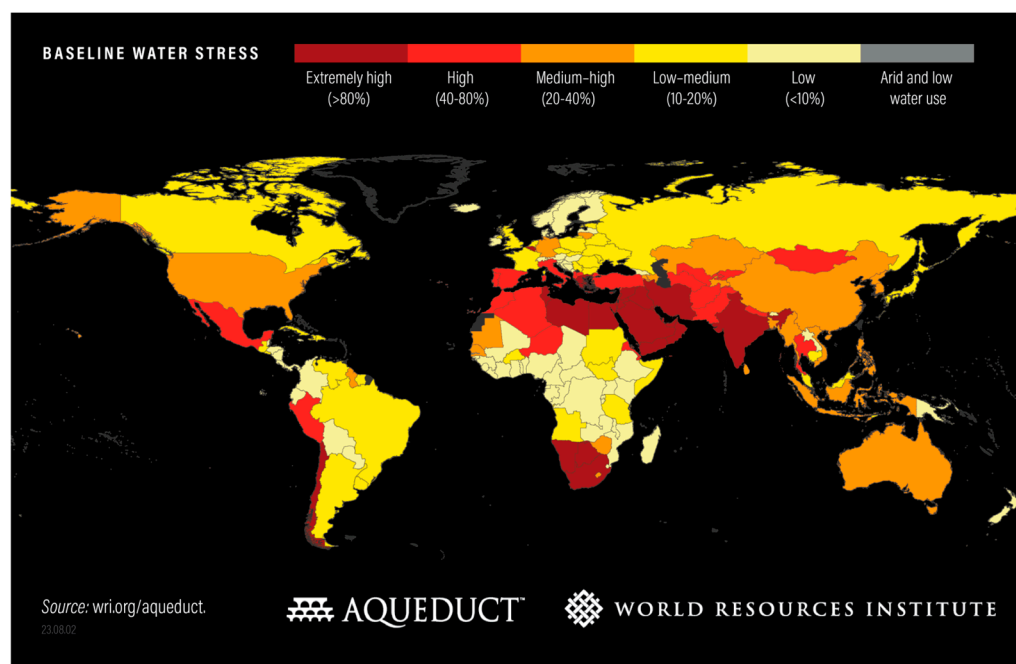


Figure 1. Water-stressed level area all over the world [35].

Another successful story of reusing wastewater to obtain potable water for a large population is the NEWater project in Singapore. This plant utilized mainly domestic sewage to produce clean industrial and drinking water by a series of treatments, i.e., sedimentation, microfiltration, ultrafiltration, reverse osmosis, and ultraviolet disinfection [36]. This plant can recover around 73.5% of the wastewater feed, with a very high performance of water purification, including 93.4% turbidity removal, higher than 99% desalination rate, and 99.4% total organic carbon separation rate [37]. The produced potable water satisfies Singapore's and the World Health Organization's drinking water standards [37], which fulfills around 30% of Singapore's water demand, and is expected to increase to 55% by 2060 with a capacity of producing 440 million gallons of clean water per day [36]. From a sustainability perspective, assessed by a life cycle assessment (LCA), NEWater potable water has much lower water depletion potential compared to the usual tap water, although produces around twice as much carbon dioxide per m³ water produced as carbon dioxide from conventional tap water production [38].

3. Drinking Water Sources Contamination

In the industrialization era, it is quite common that drinking water sources (groundwater and surface water) become contaminated by human activities. No contamination is usually observed in groundwater from deep and confined aquifers, but groundwater from shallow aquifers are prone to industrial wastes, agricultural chemicals seepages, and sanitation discharges [39] which cause chemical contamination and high bacteriological content in groundwater [40]. Surface water quality is affected by upstream anthropogenic activities, such as animal farming, agriculture, household activities, and industrial discharges, which may create a transboundary issue if a river flows through several countries [40].

In order to preserve the bodies of water, every government has set a regulation of wastewater requirement before being discharged. Although enforcement of the law has been maximized, still some non-compliant industries with wastewater composition exceeding the thresholds can be observed [41]. Rivers in heavily industrialized, irrigated, or populated areas around the world tend to have lower quality which sometimes occur more than half the year or even year-around [42]. In Europe, it has been observed that small receiving water bodies are sometimes not sufficient to dilute the amount of wastewater

discharged, thus more than half of the rivers and streams are still in a low ecological status in spite of intense regulatory efforts [43].

Chemical contaminants in wastewater can be divided into two categories, i.e., organic and inorganic pollutants. Organic contaminants can come from various industries, such as agricultural (fertilizers and pesticides), oil and gas (hydrocarbons and phenols), pharmaceuticals [44], and even food industries such as sugarcane mills [45] and dairy [46]. Nowadays, a group of organic pollutants called emerging organic contaminants (EOCs) from pharmaceuticals, personal care products, and pesticides has received the public's attention because of its harmful effects even in small quantities and its difficulties to be degraded [47]. Some of the common inorganic contaminants in wastewater are heavy metals (e.g., arsenic, chromium, mercury, lead, cadmium, chromium, and cobalt), halides, oxyanions, and radioactive materials. The main contributors for inorganic contaminants are iron and steel industries, thermal and nuclear power plants, mine and quarries, chemical industries, and pulp and paper industries [48]. Freshwater for drinking water also has to be free from biological contaminants, which include parasites, pathogenic bacteria (for example, *Escherichia coli*, *Salmonella typhi*, *Staphylococcus aureus*, *Klebsiella* sp., *Shigella*, and *Vibrio cholera*) [49], and viruses such as hepatitis viruses, rotavirus, astrovirus, and adenovirus [50].

Many countries have developed their own standards for safe drinking water quality. The World Health Organization also established general guidelines for drinking water quality with chemical and biological thresholds [39]. In order to fulfill these standards of drinking water quality, several treatment steps are needed to remove the contaminants from the water sources, especially if wastewater is used as the drinking water source.

4. Nanotechnology Applications for Drinking Water Treatment

Nanotechnology can be implemented in the drinking water treatment and reuse of wastewater as a drinking water source. The utilization of nanomaterials in water and wastewater treatment has attracted much attention, because of their unusual properties [51] and the importance of water as a limited resource [52–54]. This strategy is thus suitable for countries with increasing concerns over the rapid deterioration of water quality and access, as well as for countries with increasing demand for cleaner water.

The quality and cleanliness of drinking water, in particular, have become concerns, with arsenic and mercury as two principal toxic (metal) pollutants that cause many serious health problems. Some conventional techniques that are mainly applied for eliminating these heavy metals are adsorption, chemical oxidation, electrochemical and photocatalytic oxidations, chemical coagulation, filtration, ion exchange, reverse osmosis, and bioremediation [51,55]. Nanotechnology serves as an alternative way for those conventional technologies to treat contaminated water for drinking water supply due to several properties as listed in Table 1.

Table 1. Prospects for engineered nanomaterials in wastewater treatment and reuse [34].

Required Engineered Nanomaterials Properties	Engineered Nanomaterial-Aided Technologies	Citation
Specific and greater surface area	Higher sorbents with great irreversible adsorption ability (useful in the removal of arsenic and other toxic heavy metals by using magnetite nanoparticles) and reactants and reactants	[56]
Improved catalytic properties	Titanium dioxide- and fullerene-based photocatalysts were used as hyper-catalysts, and a hybrid of palladium/gold was also used in the reduction process of wastewater treatment for pesticide residues	[57,58]
Antimicrobial properties	Titanium dioxide and fullerenes derivatives were used as disinfectants without toxic byproducts	[59,60]

Table 1. Cont.

Required Engineered Nanomaterials Properties	Engineered Nanomaterial-Aided Technologies	Citation
Unique characteristic properties (antibiotic, catalytic, etc.)	Self-cleaning ability, nanofiltration membranes that have unique features in deactivating virus and terminating organic pollutants	[61]
Self-assembly on surfaces	This feature will reduce bacterial contact with electrode surface, the formation of biofilms, and corrosion in water storage systems	[62]
High conductivity	New electrodes for electrosorption (fast deionization) and a cost-effective, energy-efficient desalination process	[63]
Fluorescence	Rapid detection of pathogens and other pollutants using sensor technology	[64]

Several techniques are used to manufacture nanomaterials to obtain those properties. In general, the manufacturing approaches can be divided into two categories, namely top-down approach and bottom-up approach [65].

- Top-down approach

This approach is used to convert bulk materials into smaller particles within nanometer sizes to produce nanomaterials. The simplest method of the top-down technique is ball milling, whose principle is applying high energy to mechanically grind powder materials (such as metals and polymers) by frictions of balls inside a rotating drum [66]. Ball milling is suitable for high-capacity production, although it also has some drawbacks such as excessive energy requirements and the possibility of destroying crystal structures during processing [65]. Another method to produce nanomaterials through a top-down approach is by thermal evaporation. In this method, bulk materials are heated to a specific temperature to break chemical bonds [67]. The materials are then evaporated and deposited into a substrate to form a thin layer [65] by various methods, such as electrochemical and sputtering which involves high energy plasma or gas [68]. Laser ablation is a method to generate nanostructures using a pulsed laser to remove molecules from a substrate surface [69]. For producing carbon-based nanomaterials, the arc discharge method can be used. This technique generates high temperature plasma by electricity to allow sublimation of carbon in the cathode. The carbon vapors are subsequently aggregated and deposited onto the anode to form carbon nanostructures [70].

- Bottom-up approach

This approach is the opposite of the top-down approach, where nanomaterials are grown from atoms and molecules to nano-sized particles. The most common technique for the bottom-up method is the sol-gel procedure, where nanomaterial precursors are hydrolyzed to form a colloidal structure with suspended solid particles called sol [67]. The suspended solids are then condensed through an ageing process to form a gel structure, which afterwards can be separated from the liquid by various drying methods, such as thermal, supercritical, or freeze-drying [65]. Another common method to produce nanomaterials by the bottom-up approach is by chemical vapor deposition/CVD. This method utilizes a high temperature to perform heterogeneous chemical reactions of reactant gases on a heated surface. The reactions then form a continuous thin film [71]. The requirement of special apparatus and formation of highly toxic gases as by-products are disadvantages of the CVD method [67]. Frequently used chemical reactions in CVD with an example for each reaction are [72]:

Thermal decomposition: $\text{SiH}_{4(g)} \rightarrow \text{Si}_{(s)} + 2 \text{H}_{2(g)}$

Reduction reaction: $2 \text{BCl}_{3(g)} + 3 \text{H}_{2(g)} \rightarrow 2 \text{B}_{(s)} + 6 \text{HCl}_{(g)}$

Exchange reaction: $\text{SnCl}_{4(g)} + \text{O}_{2(g)} \rightarrow \text{SnO}_{2(s)} + 2 \text{Cl}_{2(g)}$

Coupled reaction: $2 \text{AlCl}_{3(g)} + 3 \text{CO}_{2(g)} + 3 \text{H}_{2(g)} \rightarrow \text{Al}_2\text{O}_{3(s)} + 3 \text{CO}_{(g)} + 6 \text{HCl}_{(g)}$

The co-precipitation method is another bottom-up technique to manufacture nanoma-

terials. In this method, a precipitation chemical reaction is performed in a solution with the addition of precipitation agents drop-by-drop, thus producing nano-sized particles. Precipitates can then be aged to obtain bigger particles, and separated from the solution with the centrifugation or filtration process [67]. Nanomaterials can also be synthesized with the hydrothermal or pyrolysis method. The solution precursor is fed into a reactor with a high temperature and high pressure to produce nanomaterials through several chemical reactions [65,67].

5. Available Nanotechnologies for Drinking Water Treatment

Among studies conducted by researchers, nanotechnologies that show the most advanced results in water treatments are (a) nano-adsorbents; (b) nanomembranes; and (c) nano-photocatalysts. The application of nanomaterials as sensors for monitoring water quality is also discussed in this chapter.

5.1. Nano-Adsorbents

The nano-adsorbents method takes advantage of contaminant molecules' ability to adhere to the surface of nanomaterials. The solids whose surfaces are attracted into are called adsorbents, while the adsorbed material is called adsorbate. Several examples of nano-adsorbents that have been used and studied for water treatment are explained below.

5.1.1. Carbon Nano Tubes

Carbon Nano Tubes or CNTs (as shown in Figure 2) have been deeply studied in the last ten years because of their particular properties in optical, electronic, vibrational, mechanical, and thermal properties [73]. Because of some other exceptional properties, for example a large surface area, uncomplicated chemical or physical modification, and capability of removing organic and also inorganic pollutants, carbon-based nanomaterials have some potencies as alternatives for water treatment [74]. Chemical modification was reportedly performed by adding functional groups of $-\text{COOH}$, $-\text{NH}_2$, or $-\text{OH}$ on the surface of carbon nanotubes to improve adsorption capacity.

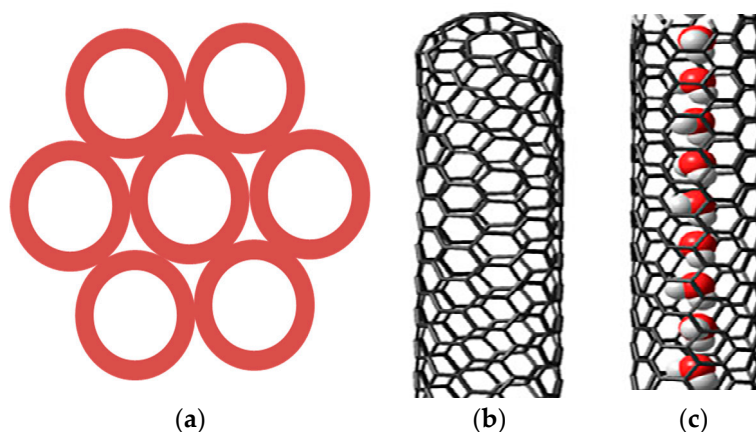


Figure 2. (a) A bundle of open-ended single-walled carbon nanotubes (SWNTs); (b) a sealed and empty single-walled carbon nanotube; and (c) a nanotube filled with water molecules [75].

CNTs exhibit antimicrobial properties due to oxidative stress in bacteria, causing the cell membranes to disrupt. There are no toxic side products produced although chemical oxidation may happen, thus making it advantageous for the disinfection of water [76]. Adsorption-based technology has a potential for point-of-use water treatment such as desalination. Nevertheless, the capacity for salt adsorption is limited. For this challenge, plasma-treated ultralong CNTs with an ultrahigh specific adsorption capacity has been developed successfully [77].

CNTs have proved their specialty and effectiveness in removing contaminants in water and reusability in some applications at large municipal water and desalination plants. Plata et al. [78] from Duke University stated that using high-purity carbon nanotubes will lead to a 15-fold yield improvement, a 50 percent reduction in energy costs, and an order of magnitude reduction in the volume of hazardous byproduct formation. Table 2 shows some applications of CNT materials to adsorb various contaminants in water.

Table 2. Adsorption performances of CNT-based nanomaterials for various pollutants.

No.	Adsorbent	Adsorbate	Adsorption Capacity (mg/g)	Initial Concentration (mg/L)	Removal Rate (%)	Reference
1	Deep eutectic solvents functionalized CNTs	Hg(II)	186.97	5.0	93.97	[79]
2	Amino-functionalized Fe ₃ O ₄ /multi-walled CNTs (MWCNTs)	Cu(II)	30.49	n.d.	n.d.	[80]
3	CNT-coated poly-amidoamine dendrimer	As(III) Co(II) Zn(II)	432 494 470	n.d.	n.d.	[81]
4	MWCNTs	Ni(II)	12.3–37	n.d.	n.d.	[82]
5	CNT sheets	Pb(II) Cd(II) Co(II) Zn(II) Cu(II)	101.05 75.84 69.63 58.00 50.37	n.d.	n.d.	[83]
6	Acidified MWCNTs	Pb(II) Cd(II)	15.6 3.6	n.d.	n.d.	[84]
7	Activated carbon supported CNTs	Cr(VI)	9.0	0.5	100	[85]
8	CNTs prepared by molten salt electrolysis	U(VI)	150	n.d.	n.d.	[86]
9	MWCNTs functionalized with L-tyrosine	Methylene blue	440	50	100	[87]
10	Single-walled CNTs	Acid blue 92 dye	86.91	50	99.1	[88]

Note: n.d. = not defined.

5.1.2. Graphene Oxide

Graphene oxide (GO) is a carbon-based nanomaterial that has an effective ability in removing heavy metals from the wastewater. It is produced from the oxidation of graphene and contains various oxygen groups such as hydroxyl, carboxyl, epoxide, and carbonyl functional groups. It was reported that fluoride ions can be captured with a capacity of 35.6 mg/g at pH 7.0 and 25 °C [89]. Another application of GO is to adsorb the presence of humic acid in an aqueous solution with a capacity of 190 mg/g by following the Langmuir isotherm. Gao et al. [90] also reported the use of GO for the adsorption of some types of antibiotics, i.e., tetracycline, oxytetracycline, and doxycycline, with estimated maximum adsorption capacities of 313, 212, and 398 mg/g for the three substances, respectively. Table 3 presents some GO materials that have been investigated.

Table 3. Graphene Oxide Materials and Adsorption Performances.

No.	Adsorbent	Adsorbate	Adsorption Capacity (mg/g)	Initial Concentration (mg/L)	Removal Rate (%)	Reference
1	Ethylenediamine triacetic acid on GO	Pb(II)	479 ± 46	100	95.86	[91]
2	GO	Au(III)	108.342	50	n.d.	[92]
		Pd(II)	80.775	30		
		Pt(IV)	71.378	30		
3	GO	Zn(II)	246	40	n.d.	[93]
4	Polyacrylamide on reduced GO	Pb(II) Methylene blue	1000 1530	n.d.	n.d.	[94]
5	Polyethyleneimine GO composite	Cr(VI)	539.53	10.96	96.35	[95]
6	Polyvinylpyrrolidone-reduced GO	Cu(II)	1689	3.5	95	[96]
7	GO-MnFe ₂ O ₄	Pb(II)	673	20	100	[97]
		As(III)	146	20	99.5	
		As(V)	207	20	96	
8	Graphene-based magnetic nanocomposite	Fuch sine	89.4	20	99	[98]
9	Cylindrical graphene–carbon nanotube	Methylene blue	81.97	10	97	[99]
10	RGO hydrogels	Methylene blue	7.85	8.54	100	[100]
		Rhodamine blue	29.44	9.82	97	
11	GO-Fe ₃ O ₄	Methylene blue	167.2	n.d.	n.d.	[101]
		Neutral red	171.3			
12	Chitosan/GO	Pb(II)	461.3	n.d.	n.d.	[102]
		Cu(II)	423.8			
		Cr(VI)	310.4			
13	Poly amino siloxane oligomer-modified graphene oxide composite	U(VI)	310.63	n.d.	n.d.	[103]
		Eu(III)	243.90			
14	Functionalized GO-embedded calcium alginate beads	Pb(II)	602	100	~100	[104]
		Hg(II)	374	100	~100	
		Cd(II)	181	100	~100	
15	Few-layered GO nanosheets	Cd(II)	106.3	n.d.	n.d.	[105]
		Co(II)	68.2			
16	GO/magnetic chitosan	Reactive Black 5	391	20	81	[106]

Note: n.d. = not defined.

5.1.3. Polymeric Nano-Adsorbents

Polymeric nano-adsorbents are repetitively branched molecules with the capabilities of removing organics and heavy metal. It consists of the interior part of hydrophobic shells to absorb organic compounds and the outer part which can be modified to adsorb specific heavy metals. Another type of polymeric nano-adsorbent is Molecular Imprinted Polymers (MIPs) with a rebinding mechanism to effectively absorb dye. Polymeric matrix β -cyclodextrin and chitosan were imprinted and tested to have negative Gibbs energy. The process is endothermic with a high preference for dye molecules [107]. Biodegradable, biocompatible, and nontoxic bio-adsorbents such as chitosan are preferred in the future. A chitosan and hydroxyapatite nano-composite has been studied to adsorb norfloxacin, a type of antibiotic, from municipal wastewater and showed a good performance with a

maximum adsorption capacity of 625 mg/g [108]. A study with nano-adsorbent created from polypyrrole-polyethyleneimine for Pb^{2+} ion elimination from wastewater also showed good results with a maximum adsorption capacity of 75.60 mg/g [109].

5.1.4. Nano-Silicate

Silica-based nanomaterials, as shown in Figure 3, have nontoxic and superior surface properties. They are commonly found in sand. The size of nano-silicate materials is 10–20 nm and it has a specific surface area of 60–600 m²/g. It is effective in removing heavy metals. Nano-silicate could be modified by adding functional groups such as -NH₂, -SH, or serve as the support for other nanocomposite materials. The addition of silica to polymeric membranes could increase the hydrophilicity of the membrane surface and reduce fouling. Nano-silicate can also be added to titania in photocatalytic agents to enhance activity or red-shift for energy saving [110]. An experimental study was performed to investigate the efficiency of using nano-silicate coupled with herbal additives such as turmeric, cinnamon, and saffron to treat the water in the swimming pool and resulted in a better quality of water [111]. Other studies regarding the application of nano-silicate for dyes and heavy metals removal from water are displayed in Table 4.

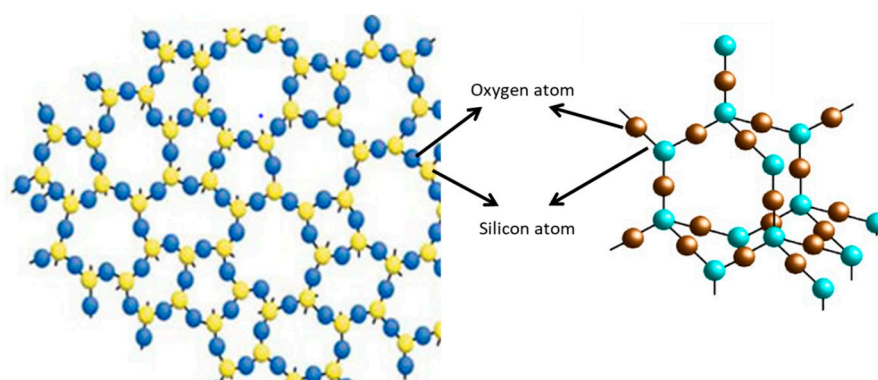


Figure 3. Nano-silicate atoms and molecules of SiO₂.

Table 4. Application of nano-silicate for dyes and contaminants removal.

No.	Adsorbent	Adsorbate	Adsorption Capacity (mg/g)	Initial Concentration (mg/L)	Removal Rate (%)	Reference
1	Hexagonal mesoporous silica/HMS	Remazol Red 3BS	~15	n.d.	n.d.	[112]
2	HMS-NH ₂	Remazol Red 3BS	~125	n.d.	n.d.	[112]
3	HMS-β-cyclodextrin	Remazol Red 3BS	~250	n.d.	n.d.	[112]
4	Bifunctional silica nanospheres	Cu(II) Methylene blue	139.8 99.0	n.d.	n.d.	[113]
5	Amino functionalized silica nano hollow sphere	Pb(II) Cd(II) Ni(II)	96.79 40.73 31.29	n.d.	n.d.	[114]
6	Nano-silica sorbent with nano-polyaniline	Cu(II) Cd(II) Hg(II) Pb(II)	108 90 120 186	n.d. n.d. n.d. n.d.	99.3 84.1 71.0 89.9	[115]

Table 4. Cont.

No.	Adsorbent	Adsorbate	Adsorption Capacity (mg/g)	Initial Concentration (mg/L)	Removal Rate (%)	Reference
7	Nano-silica sorbent with crosslinked nano-polyaniline	Cu(II)	105	n.d.	96.2	[115]
		Cd(II)	118	n.d.	81.9	
		Hg(II)	271	n.d.	72.0	
		Pb(II)	300	n.d.	86.9	
8	Nano-silica particles decorated with amine groups	Methyl orange	5.4	10	100	[116]
9	Nano-silica–biochar composite	Methylene blue	99.30	200	99.51	[117]
		Tetracycline	19.87	100	96.03	

Note: n.d. = not defined.

5.1.5. Other Nano-Adsorbents

Nano-silver and nano-titanium oxides have adsorbent properties to remove heavy metal and radionuclides contaminants. They have high specific surface areas, feature a short intraparticle diffusion distance, and are compressible without a significant reduction of surface area [24]. They have bactericidal and nontoxic properties although they have low durability, leading to high maintenance costs. They also act as anti-biofouling agents on the surfaces [24]. TiO₂ needs to be activated by ultraviolet lamps while nano-silver does not need external energy to be activated.

Silver nanoparticles exhibited reactivity in reducing mercury with the removal capacity reaching 800 mg/g [118]. Gold nanoparticles could be used for removing mercury in the wastewater up to 4.065 g/g, with easy recovery when supported on aluminum [119,120]. Other frequent materials used as adsorbents are oxide of iron (Fe), manganese (Mn), silicon (Si), and tungsten (W). Metal oxides are low-cost materials and easily accommodated various needs. Iron-based metal oxides also have superparamagnetic properties that promote easy separation. Fe-La composite oxide with a size of 20–200 nm effectiveness to remove As(III) was investigated by Zhang et al. [121]. It showed a rapid kinetic process by achieving 80% of the adsorption capacity equilibrium in 240 min with a maximum adsorption capacity of 58.2 mg/g in neutral acidity. Tungsten oxide also shows efficient adsorption of organic dyes in water [122].

The presence of lead, copper, and arsenic in the water is hazardous and could lead to various diseases. Anatase nano-adsorbent has the capability to remove all of these contaminants. It was produced by a sol-gel technique followed by calcination at 400 °C. The amount of contaminant adsorbed was constant along with the dynamic change in pH. The sorption kinetic trend corresponded to the pseudo-second-order model. The optimum capacities were reached at 31.25 mg/g, 23.74 mg/g, and 16.98 mg/g for Pb(II), Cu(II), and As(III), respectively [123].

Nano zero-valent iron (nZVI) in suspension also displayed a beneficial capacity in water remediation. Zero-valent metal nanoparticles are highly reactive reducing agents used in groundwater treatment contaminated by hydrocarbons or heavy metal [73,124–126]. In recent years, various zero-valent nanoparticles have been extensively investigated; for example, nano-sized zero-valent zinc was observed to have effectively removed dioxin contaminants [127]. Zero-valent iron has received significant attention for its performance in the removal of heavy metals such as Hg(II), Cr(VI), Cu(II), Ni(II), Cd(II), etc. [128–130]. The nanoparticles consisting of zero-valent iron coated by ferric oxide have been proven to be able to remove polychlorinated biphenyls, chlorinated solvents, and heavy metals [131]. All of these nano-adsorbent applications for heavy metal and dye contaminants are listed in Table 5.

Table 5. Adsorption Capacity and Performance of Various Nanomaterial Adsorbents.

Adsorbent	Pollutant	Adsorption Capacity (mg/g)	Initial Concentration (mg/L)	Removal Rate (%)	Reference
Nanosilver					
Nanocellulose-Ag nanoparticles	Pb(II)	9.42	25	99.48	[132]
	Cr(III)	8.93	25	98.30	
Ag@mercaptosuccinic acid	Hg(II)	800	2	~95	[118]
Biosynthesized nano-silver	Methylene blue	121.04	10	95.6	[133]
Alginate–Silver nanoparticle/Mica bio-nanocomposite	Methylene blue	352	20	99.07	[134]
	Brilliant green	249	20	91.53	
Metal oxides					
Nano-sized TiO ₂	Cr(VI)	12.6	n.d.	n.d.	[135]
TiO ₂ nanoparticles	Cd(II)	120.1	100	37.5	[136]
	Cu(II)	50.2	100	14.9	
	Ni(II)	39.3	100	47.8	
	Pb(II)	21.7	100	14.9	
Mesoporous TiO ₂	Cr(VI)	25.8	n.d.	n.d.	[137]
Kaolinite clay coated with TiO ₂ -magnetic Fe ₃ O ₄ nanoparticles	As(III)	462.0	25	92	[138]
Anatase nano-adsorbent	Pb(II)	31.25	10	97.41	[139]
	Cu(II)	23.74	10	62.57	
	As(III)	16.98	10	49.29	
Mesoporous ZrO ₂	Cr(VI)	73.0	n.d.	n.d.	[137]
ZrO ₂ /B ₂ O ₃ nanocomposite	Co(II)	32.2	n.d.	n.d.	[140]
	Cu(II)	46.5			
	Cd(II)	109.9			
Nano-sized hydrated ZrO ₂ inside cation exchange resin D-001	Pb(II)	319.4	0.5 mmol/L	~100	[141]
	Cd(II)	214.7	0.5 mmol/L	~100	
Manganese dioxide/gelatin	Pb(II)	318.7	10	100	[142]
			100	92.8	
	Cd(II)	105.1	10	87.9	
			100	34.7	
Nanoscale manganese dioxide	Tl(I)	672	10 mM	~87	[143]
Mesoporous Nb ₂ O ₅	Cr(VI)	74.7	n.d.	n.d.	[137]
ZnO/chitosan core-shell nanocomposite	Pb(II)	476.1	10	88	[144]
	Cd(II)	135.1	10	74	
	Cu(II)	117.6	10	53	
ZnO nanoparticles	Zn(II)	357	100	78	[145]
	Cd(II)	387	100	54	
	Hg(II)	714	100	42	
Casein-capped ZnO nanoparticles	Cd(II)	156.74	n.d.	n.d.	[146]
	Pd(II)	194.93			
	Co (II)	67.93			
ZnO nanoparticles	Pb(II)	163.6	100	~90	[147]
CuO nanoparticles	Pb(II)	153.8	100	~100	[147]
CuO nanoparticles	Safranin-O dye	189.54	50	95.80	[148]
Magnesium ferrite (Mg _{0.27} Fe _{2.50} O ₄) nano-crystallites	As(III)	127.4	0.044	~98	[149]
	As(V)	83.2	0.071	~98	

Table 5. Cont.

Adsorbent	Pollutant	Adsorption Capacity (mg/g)	Initial Concentration (mg/L)	Removal Rate (%)	Reference
MgO nanoparticles	Cd(II)	135	100	>94	[136]
	Cu(II)	149.1	100	>94	
	Ni(II)	149.9	100	>94	
	Pb(II)	148.6	100	>94	
MgO nanoparticles	Cd(II)	2294	n.d.	n.d.	[150]
	Pb(II)	2614			
Hexagonal mesoporous MgO nanosheets	Ni(II)	1684.25	300	99.4	[151]
Hydrotalcite-based calcined Mg/Al	Remazol Red 3BS	134.4	n.d.	n.d.	[152]
CeO ₂ nanoparticles	Cr(VI)	121.95	0.6	96.5	[153]
			37.5	67.8	
			80	50.6	
CeO ₂ nanoparticles	As(III)	71.9	50	92	[154]
	As(V)	36.8	50	79	
Samaria-doped CeO ₂ nano-powder	Pb(II)	23	25	94.5	[155]
γ -Al ₂ O ₃ nanoparticles	Pb(II)	47.08	50	97	[156]
	Cd(II)	17.22	50	87	
Al ₂ O ₃ nanoparticles	Cd(II)	118.9	100	31	[136]
	Cu(II)	47.9	100	8.5	
	Ni(II)	35.9	100	11.7	
	Pb(II)	41.2	100	18.7	
Fe ₃ O ₄ @organodisulfide polymer	Pb(II)	533.13	n.d.	n.d.	[157]
	Hg(II)	603.16			
	Cd(II)	216.59			
Fe–La composite oxide nano-adsorbent	As(III)	58.2	n.d.	n.d.	[121]
Fe/Mn oxy-hydroxide (δ -Fe _{0.76} Mn _{0.24} OOH)	As(III)	6.7 μ g/g	n.d.	n.d.	[158]
	As(V)	11.7 μ g/g			
Fe–Ti bimetallic magnetic oxide	F	57.22	n.d.	n.d.	[159]
Amino functionalized Fe ₃ O ₄ nanoparticles	Cr(VI)	232.51	5	98.02	[160]
	Ni(II)	222.12	5	93.03	
Carboxymethyl- β -cyclodextrin Fe ₃ O ₄ nanoparticles	Cu(II)	47.2	n.d.	n.d.	[161]
Fe ₃ O ₄ @SiO ₂ /Zr-Metal-Organic Frameworks	Pb(II)	102	10	~100	[162]
	Methylene blue	128	20	98	
	Methyl orange	130	20	99	
Fe@MgO	Pb(II)	1476.4	50	98.7	[163]
	Methyl orange	6947.9	200	90.8	
Water goethite (α -FeOOH)	Cu(II)	149.25	n.d.	n.d.	[164]
Goethite nanocrystalline powders	Cd(II)	167	n.d.	n.d.	[165]
Magnetite nanoparticles	Pb(II)	37.3	150	~96	[166]
	Cu(II)	10.8	150	~93	
	Zn(II)	10.5	150	~86	
	Mn(II)	7.69	150	~85	
Nano-hematite	Cr(VI)	6.33–200	n.d.	n.d.	[167]
Maghemite nanoparticle	Pb(II)	68.9	10	59.2	[168]
	Cu(II)	34.0	10	25.9	

Table 5. Cont.

Adsorbent	Pollutant	Adsorption Capacity (mg/g)	Initial Concentration (mg/L)	Removal Rate (%)	Reference
Hydrous ferric oxide (HFO) nanoparticles on poly(trans-Aconitic acid/2-hydroxyethyl acrylate) hydrogel	Pb(II)	303.8	n.d.	n.d.	[169]
	Cu(II)	107.5			
	Cd(II)	149.8			
	Ni(II)	85.87			
HFO nanoparticles	As	92	300	99.9	[170]
HFO-carboxymethyl cellulose	As(V)	355	38.2	90.5	[171]
Mercapto-functionalized nano-Fe ₃ O ₄ magnetic polymers	Hg(II)	140	20	100	[123]
Ferrite-coated apatite magnetic nanomaterial	Sr(II)	20.10	20	86.1	[172]
	Cd(II)	73.75	200	87.1	
	Eu(III)	157.14	200	76.4	
Polypyrrole-polyaniline/Fe ₃ O ₄	Pb(II)	243.9	20	100	[173]
Nano zero-valent iron					
Au-doped nZVI	Cd(II)	188	50	98	[174]
Bentonite composite nZVI (B-nZVI)	Pb(II)	50.25	25	99.7	[175]
	Cu(II)	70.20	25	98.9	
	Cd(II)	14.25	25	44.6	
	Co(II)	12.90	25	43.2	
	Ni(II)	16.50	25	53.9	
	Zn(II)	34.95	25	93.6	
nZVI modified by sodium dodecyl sulfate	Cr(VI)	253.68	50	98.92	[176]
nZVI-rice straw-based activated carbon	Pb(II)	140.8	50	99.6	[177]
nZVI-supported lemon-derived biochar	Methylene blue	1959.94	50	96.17	[178]
Others					
Chitosan microspheres	Basic blue 3G	109.91	100	~70	[179]
Chitosan microspheres–acrylamide	Basic blue 3G	177.79	100	~80	[179]
Chitosan microspheres–acrylic acid	Basic blue 3G	259.33	100	~90	[179]
Chitosan/alginate nanocomposite	Cr(VI)	108.8	100	79.91	[180]
Synthetic mesoporous carbons	Remazol Red 3BS	500–580	204	~100	[181]
Mercaptoethylamino monomer	Ag(I)	260.55	20	~65	[182]
	Hg(II)	237.60	20	~95	
	Pb(II)	118.51	20	~85	
	Cd(II)	91.55	20	~55	
Hydroxyapatite/zeolite	Pb(II)	55.55	100	95	[183]
	Cd(II)	40.16	100	100	

Note: n.d. = not defined.

5.2. Nanomembranes

Nanomembranes are very thin selective permeable membranes, with less than 100 nanometers in thickness, that utilize the filtration principle to remove contaminants present in the water [184]. It is a pressure-driven process to separate particles less than 0.5–1 nm in size [24]. The desired properties of nanomembranes are molecular sieve, hydrophilicity, antimicrobial, nontoxic materials, self-cleaning, high mechanical, and chemical stability [185]. The critical point of nanomembranes is the membrane material, whose types are nanocomposite, nanofiber, self-assembling, and aquaporin-based membranes.

5.2.1. Nanocomposite Membranes

Nanocomposite membranes are nanomembranes prepared by adding nanoparticle materials as filler into macroscopic membrane matrix materials [186]. Metal oxide materials are widely used as the filling materials for nanocomposite membranes; for example Al_2O_3 , TiO_2 , and zeolite. The usage of metal oxide is purposely to supply hydrophilicity and reduce fouling. To add antimicrobial properties, nano-silver and CNTs are commonly used. Alumina [187], silica [188], zeolite [189], and TiO_2 [190] addition to polymeric ultrafiltration membranes enhance the material hydrophilicity, water permeability, or fouling resistance.

Nano-zeolite is the most commonly used dopant in thin film nanocomposite (TFN) membranes. It was found to increase the membrane permeability, negative charge, and thickness of the polyamide active layer [191]. A novel-type TFN was developed by incorporating nanomaterials into the active layer via doping in casting solutions or surface modification. The addition of ordered mesoporous carbons as nanofillers into TFN membranes created semipermeable membranes with a selective layer on the upper surface that is usually applied for reverse osmosis [192].

CNT-embedded membranes were fabricated by depositing CNTs onto the ceramic membrane through a chemical vapor. The integrated ceramic and CNTs displayed complete rejection of oil with a flux rate of 36 L/(h.m².bar) and also showed resistance of organic fouling [193]. Nano-silver grafted to polymeric membranes was proven to prevent biofouling due to the antimicrobial nature in nano-silver [194,195]. The combination of TiO_2 nanoparticles into a thin-film composite layer led to the increasing resistance of salts while maintaining permeability. The addition of aminosilanized TiO_2 nanoparticles into the polyamide skin layer was able to reduce surface energy, thus improving NaCl resistance to 54% [196].

A novel thin-film S-layer protein applied on a metallic micro-sieve using the layer-to-layer process was being developed by Gehrke in 2014 [197] with high selectivity of heavy metals removal. There are vast opportunities to advance the membrane using bio nanocomposite materials such as polylactic acid, cellulose, acetate, etc. The use of natural polymer will allow the materials to degrade without endangering the environment.

5.2.2. Nanofiber Membranes

Nanofiber membranes are manufactured from fibrous materials within 1 to 100 nm diameter [198]. Ultrafine fibers for nanofiber membranes are synthesized by electrospinning polymers, ceramics, or metals [199]. It is adequate to remove micro-sized particles without noticeable fouling [200]. Distinct nanomaterials can be doped effortlessly into the spinning solutions to impregnate the nanofiber [201]. An example of a nanofiber membrane commercial product is Nanoceram[®], a small diameter fiber with a high surface area (300–600 m²/g). A study investigated the addition of 10, 20, and 40% of tetramethyl orthosilicate to polyvinylidene fluoride membrane via electrospinning and thermal treatment. The membranes showed enhanced mechanical properties and hydrophobicity, and effectively separated organic solvents with high flux efficiency [202]. Further work is needed to develop composite nanofiber membranes and bio-nanofiber membranes with higher porosity, higher permeate efficiency, and the ability to disinfect.

5.2.3. Self-Assembling Membranes

The self-assembling membrane, also known as the block co-polymer-based membrane, is a membrane produced by a technique that utilizes different properties of the functional parts (blocks) of the monomer. The main block of the co-polymer serves as the matrix, while the other blocks will form the membrane's pores with a homogenous size [203]. This method produces high pore density which induces high water permeability at around 1000–3000 L/(m².h.bar) with molecular weight cut-off at around 70 kDa [204]. High-density cylindrical nanopores are formed to fit the micro/nanofluidic devices [197].

A study to produce a selective membrane for Pd(II) recovery from electroplating wastewater was performed by Ma et al. [205]. By assembling a triblock co-polymer namely

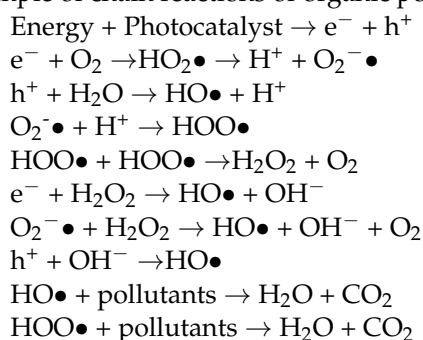
poly(4-vinylpyridine)-b-polysulfone-b-poly (4-vinylpyridine), the researchers successfully created a membrane with excellent Pd(II) rejection from the wastewater, reaching up to 96.8%. The 4-vinylpyridine block of the co-polymers enhances hydrophilicity of the membrane with high water flux. It also provides high adsorption capacity for the Pd(II) ions at around 103 mg/g. The aforementioned membrane showed high selectivity towards Pd(II) compared to other cations in the wastewater, e.g., Cu(II) and Ni(II).

5.2.4. Aquaporin-Based Membranes

Aquaporin membranes are membranes with a protein channel that allows water flux across the cell membranes. They are also known as biologically inspired membranes. The high selectivity and water permeability properties have made it an interesting approach to improve polymeric membranes. It is used in low-pressure desalination although the drawback would lie in the durability of the membranes. Aquaporin-Z made from *Escherichia coli* impregnated into amphiphilic tri-block polymer vesicles showed the full rejection of glucose, glycerol, salt, and urea [206]. The lipid bilayer has also been used in commercial nanofiltration membranes with certain capabilities. The first commercial membrane incorporated with aquaporins is Aquaporin Inside from Denmark which could withstand pressure up to 10 bar and a water flux rate up to 100 L/(h·m²). Further study to improve the stabilization process of surface imprinting and polymer embedding is necessary in order to be applied in larger industries.

5.3. Nano-Photocatalysts

Photocatalytic oxidation is a process to remove trace contaminants and microbial pathogens from water by oxidation with the aid of light energy and catalysts. It can be used as a pretreatment method in promoting biodegradability for hazardous and non-biodegradable contaminants and a polishing step for recalcitrant organic compounds [207,208]. Due to its high availability, low toxicity, cost efficiency, and well-known material properties, nano-sized TiO₂ is frequently utilized as a photocatalyst. TiO₂ is irradiated by ultraviolet light with a wavelength in the range of 200–400 nm, which will cause electrons to be excited and move into the conduction band as result. Due to photonic excitation, electron-hole (e[−] and h⁺) pairs are created, leading to an oxidative-reductive reaction chain [24]. The example of chain reactions of organic pollutants using photocatalysts are [209]:



With this oxidation-reduction reaction chain, nano-photocatalysts can degrade various contaminants in water, including heavy metals, organic pollutants, bacteria, and viruses [210]. This property is proven by an experiment using a nano-photocatalyst produced from composites of K₄Nb₆O₁₇ nanosheets with g-C₃N₄, iron nitride (Fe₃N), and Fe₂O₃ which was used to degrade a pesticide compound (acetamiprid) and U87-MG cancer cells. This nano-photocatalyst efficiently degrades acetamiprid with 76% removal even after being used for five repeated cycles. It also had sufficient efficacy to eradicate the cancer cells under visible light [211]. Table 6 summarizes some other research utilizing nanomaterials as photocatalysts to degrade pollutants from wastewater.

Table 6. Photocatalyst nanomaterial performances on pollutant degradation from wastewater.

Photocatalyst	Catalyst Addition (g/L)	Contaminant	Initial Concentration (mg/L)	Treatment Duration (hour)	Removal Rate (%)	Reference
1% Co-TiO ₂	0.5	Methyl Orange	33	6	34.7	[212]
5% Al/ZnO	1	Methyl Orange	50	0.67	99	[213]
Co ₃ O ₄ modified by citric acid	0.5	Malachite green	3.65	1.67	91.2	[214]
Co ₃ O ₄ modified by oleic acid	0.5	Malachite green	3.65	1.67	66.6	[214]
Chitosan-TiO ₂ -ZnO	0.5	Tetracycline	20	3	97.2	[215]
S-TiO ₂	0.4	Diclofenac	10	4	93	[216]
ZnO with pullulan as capping agent	0.5	Amoxicilin Paracetamol	30	2	85.7 96.8	[217]
ZnO-TiO ₂	0.6	Phenol	60	2.67	100	[218]

5.4. Nanomaterials for Water Quality Sensors

The monitoring of water quality is challenging due to the low concentration of pollutants, as well as the variability and complexity of the matrix. Nanotechnology-enabled sensors are promising tools for widespread and inexpensive monitoring of drinking water pollutants [219]. A nano-sensor consists of (1) a nanomaterial, (2) a recognition element, and (3) a mechanism for signal transduction. Sensors respond to physical stimuli induced by chemical and biological substances and convert them into electronic signals that are conveyed to the reading devices [51]. The specificity is achieved either by detecting an intrinsic signal from the analyte or by employing highly specific recognition elements that ideally bind only to a given target. The use of nanomaterials in sensors increases the surface zones, detection limit, speed, and overall sensitivity, thanks to the big surface-to-volume ratio.

Since the promising reports of the use of a nanowire [220] and quantum dot [221], nanotechnology-enabled sensing has gained increasing attention from the scientific community. However, as suffered by many nanotechnology products, only a few sensor devices can be found in the market [219]. Some examples of utilizations of nanotechnology-enabled water quality sensors are presented in Table 7.

Table 7. Documented utilizations of nanomaterial for water quality sensor [219].

Sensing Strategy	Nanomaterial Types	Analytes
Optical		
Colorimetric	Gold nanoparticles, silver nanoparticles	NO ₂ [−] , NO ₃ [−] , cocaine, Pb(II), Cu(II), Hg(II)
Fluorescence	Quantum dots	Heavy metals [Cd(III), Pb(II), Hg(II), Cu(II)]
Surface-enhanced Raman spectroscopy (SERS)	Gold nanoparticles	Pesticides, bacteria, viruses, protozoa
Electrical		
Chemiresistors	Gold nanowires	Halides
	Metal oxide semiconductor nanowires	Fe(III), Volatile Organic Compounds (VOCs), ammonia
	Polymer nanowires	VOCs, NO ₂

Table 7. Cont.

Sensing Strategy	Nanomaterial Types	Analytes
Field-effect transistors	Silicon nanowires	Nucleic acids, influenza
	Two-dimensional transition metal dichalcogenides	Glucose, H ₂ O ₂ , proteins, Hg(II), pH
	Gold nanoparticles functionalized polymeric FETs	Hg(II)
	Phosphorene	igG protein
Electrochemical	Graphene	Bacteria
	Carbon nanotubes	Ammonium, Co(II), organo-phosphate pesticides
	Copper nanowire electrodes	Nitrate
	Polymeric nanocomposite membranes	Ag(I), Hg(II), Cu(II)
	Reduced graphene oxide/gold nanoparticle nanocomposite	Organo-phosphate pesticides
Magnetic		
Magnetoresistance	Magnetite (Fe ₃ O ₄)Maghemite (γ -Fe ₂ O ₃)	Mycobacteriumbovis, Influenza A
Hydrodynamic property changes	Magnetite (Fe ₃ O ₄)	Spore detection
T ₂ relaxation magnetic resonance	Magnetic beads	<i>Salmonella enterica</i> and Newcastle disease virus; <i>Escherichia coli</i> 0157:H7

6. Advantages and Disadvantages of Nanotechnologies for Drinking Water Treatment

The previous chapter has summarized the benefits of several nanotechnologies for contaminants removal to produce drinking water. Despite the high performance of those technologies, there are still some disadvantages that prevent nanotechnologies to be used commercially. The advantages and disadvantages of the nanotechnologies in comparison with conventional water treatment technologies are listed in Table 8.

Table 8. Advantages and disadvantages of each nanotechnology reviewed in this publication [208,222–225].

Nanomaterials	Advantages	Disadvantages
Carbon-based nano-adsorbents	Better mechanical and thermal stability, ability to tune the surface functional groups	High regeneration cost, lower performance after regeneration
Metal-based nano-adsorbents	Highly reactive with faster kinetics, easier separation with magnetic property, mostly water insoluble	Cost-effective, greater tendency to aggregate, toxicity of some metals, occasionally generate sludge
Polymer-based nano-adsorbents	Better mechanical stability, higher chemical functionality, better adsorption rate	Higher maintenance cost
Nanocomposite membranes	High fouling resistance, better water permeability, higher thermal and mechanical stability	Release of nanoparticles to water, membrane pore blockage
Nanofiber membranes	Small diameter with high porosity, high specific surface area, good pore channel connectivity	Poor recyclability and reusability, shrinkage tendency

Table 8. Cont.

Nanomaterials	Advantages	Disadvantages
Self-assembling membranes	Possibility to control the pore functionality by molecular design, thus enhancing the selectivity for specific molecules or micropollutants	Scaling-up process
Nano-photocatalysts	High surface area to volume ratio, antimicrobial activity, do not form toxic by-products	Possibility of inert substrates fixation which reduce performance, mostly require UV irradiation to boost degradation efficiency, low reaction selectivity

7. Initial Sustainability Analysis on Nanotechnology

Nanotechnology is still in the research and development phase and still far from maturity. Nonetheless, nanotechnology started to gain the trust of the public as a potential technology to support the sustainability of human systems. In order to provide civilization with the nanotechnology for sustainable drinking water, a sustainability analysis must be performed with the adequacy of data. A life cycle assessment (LCA) of nanotechnology has been conducted by many authors and researchers to evaluate its sustainability. In spite of many various analyses, there are still some challenges in general for comparing the result with equal criteria. Following the model of sustainability, the evaluation of sustainability is down to three domains: economy, environment, and society (Figure 4).

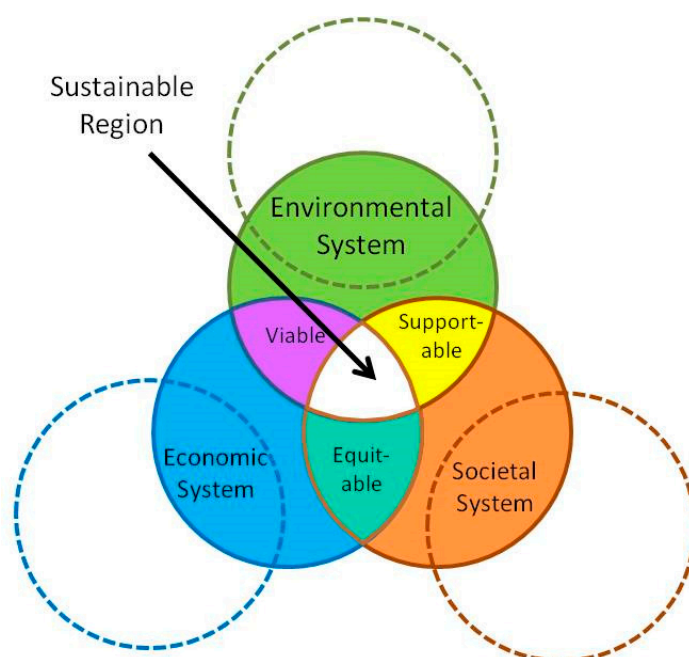


Figure 4. Generally accepted sustainability model (modified with permission from [226]).

Mata et al. [227] has formulated some indicators to analyze the sustainability and some future challenges of the nanotechnology application in daily life. The application of those indicators in evaluating CNTs as a model for nanotechnology application in water treatment is shown in Table 9.

Table 9. Initial sustainability analysis of nanotechnology application in water treatment [227].

Indicator	Impact			Analysis
	Environmental	Societal	Economic	
Energy intensity (MJ/kg product)	Yes	Yes	Yes	Higher energy in manufacturing, lower energy in utilization [76]
Material intensity (kg/kg product)	Yes	Yes	Yes	Different types of CNTs exhibit different behavior [200]
Potential chemical risk (dimensionless)	Yes	Yes	Yes	High risk due to the uncertain mechanism [200]
Potential environmental impact (dimensionless)	Yes	Yes	Yes	High risk due to lack of knowledge [200]
Water use (m ³ /kg product)	Yes	No	Yes	Uncertain
Global warming (kg CO ₂ -eq/kg product)	Yes	No	Yes	Uncertain
Ultrafine particle emissions (kg/kg product)	Yes	No	No	Uncertain
Wastewater generated (m ³ /kg product)	Yes	No	No	Uncertain
Net cash flow generated (EUR/kg product)	No	No	Yes	Not developed
Direct employment (persons/ton product)	No	Yes	No	Not developed

By looking through the indicators, the lack of information needed to evaluate the system will become clear. There are a lot of examples that when a technology is made to please society, there is less effort in addressing its hazard meticulously including its sustainability. Therefore, by learning from mistakes, the approach for making efficient progress and appropriate nanomaterials for human wealth has to be conducted in a holistic way supported by adequate data and universal guidelines.

8. The Challenges

The main challenge in nanotechnology applications is the fact that very few nanomaterials have been produced commercially, despite many reports showing how promising they are [34]. The industrialization of nanotechnology applications in water treatment so far is limited by the high production cost [25]. It is common that new technologies face the reluctance of investors in funding the research and production of new products. Moreover, there is also a lack of government guidance and support (for example, regulations) for the implementation.

An example of challenges faced by nanotechnologies is reviewed by Lens [228] for the commercial viability of nanomembranes in Figure 5. It shows that nowadays, there are no types of nanomembrane with high potential performance enhancement which possess potential commercial viability due to high material costs and difficult manufacturing scalability. However, there might be changes in the future when biologically inspired membranes reach maturity, thus providing nanomembranes in the optimal (upper right) quadrant.

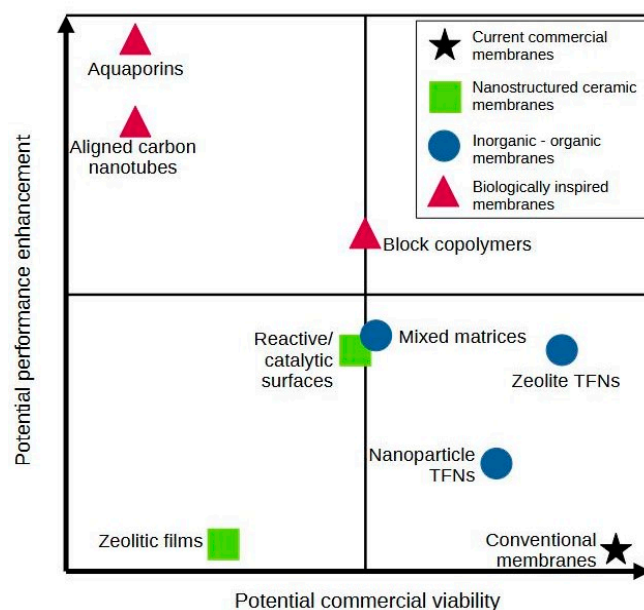


Figure 5. Comparison of potential performance and commercial viability of various nanomembranes and conventional membranes technology [228].

8.1. Safety and Environmental Risks

Some questions remain regarding the safety and potential toxicity of nanomaterial utilization, as well as their life cycle in the environment, not only in the environmental remediation industry but additionally in daily life applications [25]. The knowledge gaps that must be addressed and clarified before wide application in the industry are still wide.

The main issue for the environmental risks is the useful properties of the nanomaterials themselves, i.e., small size, shape, reactivity, conductivity, and mobility. These properties make it easier for nanomaterials to be inhaled, ingested, or up-taken. A small size can be a tricky property when it comes to detection [51]. Small sizes make the deposit rate of nanomaterials in the air very low, while high mobility favors rapid mixture and results in higher spreading. They can enter the body via various routes [229]. Nanoparticles in the air may present the risk of photochemical conversion when exposed to the ultraviolet wavelength of daylight [230].

According to the European Chemicals Agency's (ECHA) guidance on the registration, substances like nanomaterials can be differentiated into those that exist only in nano-forms and those that also exist in bulk (non-nano) forms. The various forms create further problems in detection and toxicity evaluations. Safety data generated for one form might not be adequate for the other forms. Moreover, differentiation between the forms or types of nanoparticles itself can be a difficult task. Studies using pure nanoparticles cannot be reliable for assessing the used particles [231]. Most toxicological studies were carried out by using laboratory culture media composed of proteins and other biological compounds. The results cannot be directly interpreted as representing real environmental conditions.

Studies on nanomaterials concentration in drinking water are still very few. Most studies discussed air-borne nanoparticles and their inhalation by living beings. The exposure of aquatic and terrestrial life to nanoparticles in water and soil is still not explored enough [231]. However, several early studies have indicated that some nanomaterials caused cellular and membrane damage to different aquatic organisms [232]. Engineered nanoparticles (ENPs) are far less commonly found than natural nanoparticles (NNPs) in drinking water. Nanoparticles could also come from corrosion of distribution pipes or in-home premise plumbing. They are incidentally released into the drinking water; thus, they are also referred to in the study as incidental nanoparticles (INPs). The three categories have similar elemental compositions or geometries [233,234]. Shape or composition is therefore not useful for the classification [235,236].

While the toxic effects have been widely studied for aquatic organisms and mammalian cells, they are still poorly understood when it comes to humans and other animals [25]. Environmental suitability of the materials with regards to the diversity of ecosystems should be the focus of research [237].

In general, the major preoccupation problems are as follows [238]:

- Limited public knowledge about the ecotoxicity and increasing exposure to nanomaterials.
- Absence of information regarding the risks of consumption of each nanomaterial.
- Insufficient regulatory controls that guarantee protection improvement and exploitation of nanomaterials.
- The hesitation and lack of commitment of the producers in communicating information about the risks to the customers.

To obtain a detailed risk assessment, characterization, and management, there are two important actions: hazard assessment and exposure assessment [239,240]. Some known environmental hazards of nanomaterials are listed in Table 10. In the laboratory, safe practices of handling nanomaterials can be ensured by using three different control approaches [229]:

- Engineering control: ventilation, use of less toxic materials, specially designated storage cabinet.
- Administrative control: warning notices, chemical hazard labels.
- Personal protective equipment.

Table 10. Some known environmental effects of nanomaterials [51].

Nanomaterial	Environmental Effects
Nano-TiO ₂	Perturbing aquatic ecosystem's carbon and nitrogen cycles
Carbon nanotubes	Impacts upon contact with the surface of the environmental organisms; environmental harm
Various types of nanostructures	Toxicity determined by various physicochemical as well as environmental factors
Silicon nanoparticles	Important dangerous factor for environmental exposure; negative effect on ecosystem
Nanostructured flame retardants	Endurance and tendency to regroup in the environment; toxic to wildlife and plants
Nano-silver	Origin of multiple transformations when it is released into the environment and creates adverse influences
Fullerenes	Impact on soil organisms and enzymes; aquatic ecosystems; the coupling of chemicals to fullerenes (nanoparticles) can have an influence on the toxicity of some environmental pollutants
Polymer nanocomposites	The important dangerous factor for environmental exposure

8.2. Regulations

The regulations about the use of nanomaterials are surprisingly still limited, although their industrialization has been running for years. The production and use of nanomaterials in the European Union (EU), for example, is regulated under Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) [241], which is the most comprehensive legislative provision for chemicals in the region [242]. Some EU countries, such as Denmark, France, Sweden, and Belgium, also have their regulations and schemes for nanotechnology-related products [242]. In the USA, the manufacturing of nanomaterials falls within the regulation of the Toxic Substances Control Act of the Environmental Protection Agency (EPA). Organization for Economic Cooperation and Development (OECD) via its Working Party on Manufactured Nanomaterials (WPMN) pays special attention

to human health and environmental safety aspects of nanomaterials. It aims to ensure the safe use of nanotechnology through appropriate methods and strategies [243]. In the future, regulations regarding nanomaterials are needed with hazard studies as the basis for constructing the laws.

8.3. Synthesizing Cost

Manufacturing the cost of nanomaterials still pose a huge challenge for the wide application of nanotechnologies. GadelHak et al. [244] has compared several nano-adsorbents prices with conventional adsorbents prices, and found that generally nano-adsorbents cost higher than conventional ones. For example, the price of TiO_2 nanoparticles vary from 10,000 to 16,000 USD/ton; the price of ZnO nanoparticles is around 20,000–285,000 USD/ton, the price of CNTs can range from 50,000 to 120 million USD/ton; the nZVI price is around 4.2 million USD/ton; and nano-silver prices can reach 37.5 million USD/ton. In comparison, commercial activated carbon that is commonly used for conventional water contaminants adsorption process costs around 500–395,000 USD/ton.

From an operating cost perspective, nanotechnologies sometimes can offer a cheaper option to conventional methods. Nano- TiO_2 particles activated by UV light for treating textile wastewater was estimated to cost lower than the oxidation process with H_2O_2 or FeSO_4 , where nano-photocatalysis using nano- TiO_2 cost around 0.77 USD/ m^3 of wastewater, while oxidation using H_2O_2 and FeSO_4 cost 1.62 and 2.00 USD/ m^3 , respectively [245]. Another study of textile wastewater treatment using nano-bimetallic iron/copper estimated a cost of 6.37 USD/ m^3 , which is higher than treating using electrocoagulation and the ozonation process (5.8 USD/ m^3). However, a cost reduction is still possible if the iron/copper nano-adsorbents can be reused [246].

A suggested way to reduce the manufacturing cost of nanomaterials is by applying green nanoscience. This method uses environmentally friendly materials to produce nanomaterials so it is expected to reduce the overall cost of the treatment process and give a lower environmental footprint [34]. The lower overall production costs are certainly attractive for developing countries. However, green nanoscience often suffers from a lack of guiding scientific principles in the initial exploration stage. Moreover, there are only very few reported data that support the promising claims of green chemistry, especially the lower energy and material consumptions [231]. It also faces stricter regulatory obstacles compared to the conventional ones [247].

8.4. Other Challenges

The education of nanotechnology is an important area that is often overlooked. This may cause the problems of a lack of capable workers, which will decrease the progress of science and technology developments [248]. There is a growing need to prepare future generations, not only scientists, engineers, and technicians, but also policymakers, communicators, and regulators with good knowledge about the field [249]. The latter groups play a very important role in the commercialization of nanotechnology. The lack of availability is one of the current key factors that stall the dissemination of the developed technology.

9. Conclusions

The water scarcity problem has emerged and worsened in several areas in the past years and continues to threaten most of the human population in other areas. As all living beings' lives are dependent on freshwater availability, technologies for achieving sustainable water resources management to solve the water scarcity problem need to be prioritized. Nanotechnology offers an effective alternative way to reuse and treat contaminated wastewater caused by human activities. Due to its small size, nanomaterials provide several advantages compared to conventional water treatment techniques, i.e., higher efficiency as a result of higher surface area, improved catalytic performance, and several additional properties such as antimicrobial, high conductivity, and self-assembly on surfaces. Nanotechnology effectiveness for treating contaminants in water, including

emerging contaminants, has been studied in the past decades by many researchers, though only very few large-scale applications have been applied. At the moment, there is inadequate information to assess all aspects of sustainability for nanotechnology applications in water treatment; thus, this type of study is needed in the near future to accelerate the application of nanotechnology. Regulations are confirmed to be one of the current challenges for nanotechnology implementation in water resources management, since a comprehensive database for regulatory purposes is still limited. In the future, good collaboration between academia, business, and authorities is needed to accelerate the implementation of nanotechnology for water resources management so its benefit can be utilized for the benefit of mankind.

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