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Nanomaterials as an Environmental Sustainability Choice for Wastewater Treatment: A Review

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Keywords:
Carbon nanotubes; Metal oxide; Wastewater; Nanotechnology; Water Contaminants; Zero-valent.

Highlights:

- *Wastewater treatment selectivity and efficacy can be enhanced using nanomaterials.*
- *Harmful elements in wastewater harm the aquatic and terrestrial ecosystems wellness.*
- *Nanocomposites can enhance the long-term treatment of wastewater.*
- *Nanomaterials effectively eliminate heavy metals, dyes, and organic pollutants.*
- *Commercialization and affordability are required to widely adopt nanotechnology.*

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Abstract: Water is the fundamental element required for life on Earth and a critical resource for human civilization. Meeting worldwide demand for clean, inexpensive water remains a serious concern, as billions of people continue to lack access to safe drinking water. Annually, millions of people die as a result of contaminated water that contains bacteria, viruses, arsenic, and lead. With limited water supplies, wastewater purification has become increasingly crucial. Companies worldwide are adopting innovative technologies to treat wastewater before releasing it back into the environment, moving away from conventional methods. Among these innovations, nanomaterials are the subject of much investigation due to their unique characteristics. Many studies on wastewater treatment have been conducted; however, few have explicitly examined the kinds of nanomaterials employed. This review evaluates recent developments in a range of nanomaterials used in wastewater treatment. Recent advancements in nanotechnology are emphasized, with particular attention paid to the physicochemical characteristics of free nanomaterials, such as metal oxides, carbon-based nanomaterials, and nanoparticles of precious metals. Researchers studying nanotechnology will have interesting prospects in the future as they investigate the methods and efficacy of these materials in eliminating various pollutants.

المواد النانوية كخيار للاستدامة البيئية لمعالجة مياه الصرف الصحي: مراجعة

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الخلاصة

الماء هو العنصر الأساسي للحياة على الأرض، ومورد حيوي للحضارة الإنسانية. ولا يزال تلبية الطلب العالمي على مياه نظيفة ورخيصة مصدر قلق بالغ، إذ لا يزال مليارات البشر يفتقرون إلى مياه شرب آمنة. يموت ملايين البشر سنويًا نتيجة تلوث المياه بالبكتيريا والفيروسات والزرنيخ والرصاص. ومع محدودية إمدادات المياه، تتزايد أهمية تنقية مياه الصرف الصحي. وتتبنى الشركات حول العالم تقنيات مبتكرة لمعالجة مياه الصرف الصحي قبل إعادتها إلي البيئة، مبتعدةً بذلك عن الطرق التقليدية. ومن بين هذه الابتكارات، تُعدّ المواد النانوية موضوعًا للكثير من البحث نظرًا لخصائصها الفريدة. وقد أُجريت العديد من الدراسات حول معالجة مياه الصرف الصحي، إلا أن القليل منها تناول بوضوح أنواع المواد النانوية المستخدمة. تُقيّم هذه المراجعة التطورات الحديثة في مجموعة من المواد النانوية المستخدمة في معالجة مياه الصرف الصحي. وتُسلّط الضوء على التطورات الحديثة في تكنولوجيا النانو، مع إيلاء اهتمام خاص للخصائص الفيزيائية والكيميائية للمواد النانوية الحرة، مثل أكاسيد المعادن، والمواد النانوية الكربونية، والجسيمات النانوية للمعادن الثمينة. سيكون لدى الباحثين الذين يدرسون تكنولوجيا النانو آفاق مثيرة للاهتمام في المستقبل أثناء بحثهم عن أساليب وفعالية هذه المواد في القضاء على الملوثات المختلفة.

الكلمات الدالة: أنابيب الكربون النانوية؛ أكسيد المعدن؛ مياه الصرف الصحي؛ تقنية النانو؛ ملوثات المياه؛ صفر التكافؤ.

1.INTRODUCTION

Unaltered wastewater remains a significant environmental issue worldwide. Approximately eighty percent of the overall wastewater is dumped into the ecosystem without undergoing any treatment or being reused. As a result, over 1.8 billion individuals depend on water polluted with diverse microbes and disease-causing agents, such as cholera, dysentery, typhoid, and polio [1]. This issue clearly demonstrates the urgent requirement for wastewater treatment. Another significant contributor to pollution is the presence of micropollutants found in effluents originating from wastewater. In addition, wastewater treatment facilities release 3 to 10 billion gallons of raw waste without any treatment each year [2,3]. Nanotechnology is a field of research that addresses methods to interact with components at the atomic and molecular levels. Nanometers, or one-millionth of a millimeter, are the unit of measurement for this technology [4,5]. Additionally, these microscopic particles, in their size, have a series of physical, chemical, and surface-related characteristics that make them useful in various applications and areas. With this technology's help, challenges in medicine, energy, agriculture, and even the environment and the military will be addressed, and effective solutions will be found [6-8]. Nanotechnology has several benefits. It has expanded the industry's potential, for instance, it became feasible to create stain-resistant clothing and for doctors to explore the human body using new, precise cameras produced with this technology to identify ailments [9,10]. For some diseases that are difficult to recover from, including cancer, remedies have been created. This technique allows for the tracking, disposal, or treatment of contaminated cells [11]. Compared to nations without this technology, those that use it to safeguard their national security will be entirely protected. Many companies have experienced cost reductions by reducing the size and weight of their machinery and increasing the surface area of the chemicals they employ, which speeds up reactions, boosts output, and lowers prices [12]. Researchers and scientists who have an affinity for nanotechnology have noted the critical role that this remarkable technology provides in addressing some of the most pressing global issues, such as supplying clean drinking water to the world's growing population [13-15]. Water is a naturally occurring substance on the planet, and both humans and other living organisms must have access to it in its purest form because life would be inconceivable without it [16,17]. Water is vital for all human activity. Every day, agricultural sectors, industries, and homes create enormous amounts of wastewater due to the growing number of people worldwide [18,19]. The expanding population's requirements for water must be supported; however, freshwater supplies are not renewed. According to a report by the WHO/UNICEF Joint Monitoring Programme, [20] freshwater (salt content of less than 1 g/L) is only used in 2.5% of seas and oceans. On the other hand, seventy percent of freshwater (FW) is frozen permanently. Merely 1% of FW is suitable for consumption by humans; about 700 million people worldwide cannot obtain drinkable, clean water [21]. Any category of water influenced by human activity is considered wastewater. According to Nagpal *et al.* [22], wastewater is "water used in any combination of commercial, agricultural activities, domestic, surface running water, industrial, or rainwater drainage, and any flowing or running drainage. Hence, wastewater is a waste product from home, commercial, industrial, or agricultural activity. Depending on where it originates, wastewater has different properties [23]. Residential wastewater produced by residential activities, municipal wastewater produced by public gatherings (also known as sewage), or industrial wastewater produced by commercial or industrial activities are some examples of the many forms of wastewater; therefore, wastewater may also contain a variety of possible contaminants in varying amounts [24-26]. It also commonly refers to the liquid wastes generated from human complex systems, which comprise a variety of contaminants as a result of combining liquid wastes from different sources [27]. Generally, the word "sewage" is often used to refer to a portion of wastewater that has been polluted with feces or urine; however, it is also frequently used to describe all liquid waste [28]. Sewage water is comprised of household and industrial liquid waste dumped into pipelines, sewers, or other structures comparable to them, as shown in Fig. 1 [29]. It may also be dumped into technical pits, where it is then removed by specialized machinery that removes the wastewater and discharges it away [30].

Fig. 1 Wastewater Major Resource [29].

The infrastructure required to move wastewater from its source to the disposal locations or treatment facilities is included in the term "sewage system". This infrastructure comprises pipelines, pumps, filters, channels, and other systems. The Middle East, Africa, Asia, and Latin America are most affected by these problems, although these problems are present elsewhere [31]. The data are startling: 2.1 billion people reside in residences lacking sufficient access to clean water for consumption, while at least one month of the year, 4 billion people experience extreme shortages of water [32,33]. Consequently, in these impacted areas, water purification must be implemented. The quality of water, which can be produced with current technology to treat it, is no longer sufficient to suit both human and environmental demands [34,35]. It is a challenge for technology organizations, development, and research to produce affordable alternative wastewater treatment approaches with minimal environmental impact requirements. To treat wastewater as effectively and affordably as possible, it is essential to select the most effective method and resource. Therefore, when choosing a wastewater treatment technique, it is important to take its efficacy, ability to reuse materials, eco-friendliness, and cost into account [36,37]. The opportunity for alternative wastewater treatment systems is provided by nanotechnology. Because of the distinctive physicochemical characteristics of its nanomaterials, nanotechnology is currently becoming a widely used technique in several fields of environmental treatment [38]. A variety of nanomaterials is currently under investigation for the eradication of both inorganic and organic pollutants. However, the water resources administration may make more cost-effective use of nanotechnology [39-41]. It has been claimed that different nanomaterials may efficiently eliminate inorganic anions, microorganisms, heavy metals, and organic contaminants. Several investigations demonstrated that nanoparticles have significant potential for utilization in water and treatment of wastewater [42-45]. The urgent need for practical and long-lasting solutions to the problems of water pollution and scarcity makes the investigation of nanomaterials in wastewater treatment essential. Traditional wastewater treatment techniques include drawbacks, such as low removal efficiency, secondary pollution production, and high energy costs. Nanomaterials present viable solutions to these problems by increasing resource recovery, lowering energy usage, and improving treatment efficiency. Gaining knowledge about how nanoparticles affect wastewater treatment is crucial to the advancement of the field and the creation of cutting-edge, eco-friendly technology [46-48]. Nanoparticles are currently being utilized in a variety of applications, such as photocatalysis, membrane filtration, and adsorption. Metal-based nanoparticles are frequently employed for pollution removal by catalytic degradation and adsorption processes, including silver (Ag), titanium dioxide (TiO_2), and iron oxide (Fe_2O_3, Fe_3O_4). Because of their superior catalytic activities and adsorption abilities, they can effectively remove pathogens, heavy metals, and organic pollutants from wastewater streams [49,50]. Compared to their bulk equivalents, nanocomposites-composite materials of nanoparticles scattered within a matrix material-offer improved characteristics and multifunctionality. Nanocomposites are used in wastewater treatment for catalytic reactors, adsorbent materials, and membrane manufacturing. Graphene-based nanocomposites, including reduced graphene oxide and graphene oxide, demonstrated water permeability, chemical stability, and mechanical strength, making them highly attractive for use in membrane applications [51,52]. The nanocomposite membranes are excellent choices for wastewater treatment applications due to their pollutant rejection characteristics and exceptional fouling resistance. Furthermore, polymer-based nanocomposites, which combine metal oxides and zeolites as nanoparticles with polymer matrices, such as polymeric membranes and adsorbent resins, provide improved selectivity and adsorption capabilities for the removal of pollutants in wastewater treatment processes [53,54]. On the other hand, Nanocatalysts aid in the oxidation or reduction reactions that break down organic contaminants, producing less toxic byproducts or completing the mineralization process. Platinum nanoparticles, Palladium nanoparticles, and gold nanoparticles are examples of metal-based nanocatalysts that demonstrate strong catalytic activity, as well as selectivity against particular organic contaminants, allowing for effective degradation in mild environments [55,56]. Furthermore, metal oxide-based nanocatalysts are commonly used for photocatalytic elimination of harmful organic substances and pathogen disinfection in wastewater treatment. These nanocatalysts include manganese oxide nanoparticles, titanium dioxide nanoparticles, and cerium oxide nanoparticles. By generating reactive oxygen species from solar or ultraviolet light, they could improve the safety and cleanliness of water by oxidizing organic contaminants and pathogenic microbes [57,58]. Interestingly, many toxins found in wastewater may be identified and eliminated using nanotechnology. Non-biodegradable heavy metals endanger the ecosystem since they are extremely poisonous and hurt the lives of plants, animals, and other living things. Thus, metal oxides (Zn, Ti), polymer, ceramic nanowires, carbon nanotubes, polymer membranes, and nanopowder can overcome this issue [59]. Nanotechnology also plays a significant role in practical materials, including nanofibers, carbonaceous, dendrites, and nanoclays [60]. However, zero-valent metal nanoparticles (ZVI), metal oxide nanoparticles, nanocomposites, and Carbon nanotubes (CNTs) are the key materials for the treatment of wastewater that have received the most research to date [61-63]. This review mainly examines some of the recent developments and uses of nanotechnology in the wastewater treatment sector, with a special focus on the main problems and the possible use of these technologies in tackling issues related to wastewater treatment systems.

2.CATEGORIES OF CONTAMINANTS IDENTIFIED IN WASTEWATER

The importance of wastewater treatment is highlighted in protecting human and community health from diseases and epidemics. From an environmental health perspective, the main dangers in wastewater are represented by organisms, i.e., animals, bacteria, single-celled plants, and plants, in addition to many other contaminants present in them, which leads to the occurrence of diseases and epidemics of both humans and animals [64]. Figure 2 illustrates the major types of contaminants present in wastewater [65].

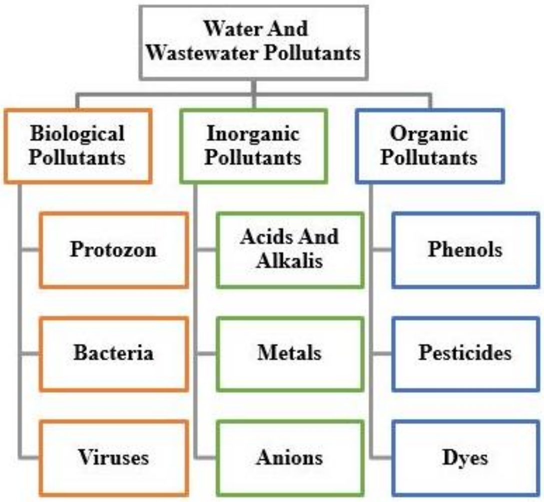

Fig. 2 Types of Contaminants in Wastewater [66].

Among the most important contaminants present in wastewater are the following:

2.1.Biological Contaminants

They are among the most significant forms of pollutants in wastewater, detrimental to the ecosystem. They must be removed urgently since they are hazardous to both human life and other living beings [66,67]. Several sectors, such as automated slaughterhouses, generate various kinds of harmful bacteria, whereas other industries, like starch and yeast factories, establish fungi and parasites [68]. Moreover, Biological contamination includes viruses, parasites, and bacteria that cause watery illnesses such as hepatitis, polio, dysentery, schistosomiasis, and cholera [69]. Blackwater is the term for toilet-generated water [70]. It includes human faces and urine and, if improperly handled, can result in waterborne illnesses (Table 1) [71].

Table 1 Pathogens in Wastewater and Their Resistance to Chlorine Treatment.

Bacteria	Chlorine resistance	Viruses	Chlorine resistance	Protozoa	Resistance to chlorine
Acinetobacter spp.	Low	Hepatitis A	Moderate	*Balantidium coli*	High
Klebsiella spp.	Low	Hepatitis E	Moderate	*Acanthamoeba castellani*	High
Aeromonas spp.	Low	Norovirus	Moderate	*Naegleria fowleri*	Low
Leptospira spp.	Low	Poliovirus	Moderate	*Blastocystis Hominis*	High
Burkholderia	Low	Rotavirus	Moderate	*Cyclospora Cayetanensis*	High
Legionella pneumophila	Low	Sapovirus	Moderate	*Cryptosporidium parvum*	High
pseudomallei	Low	Adenovirus	Moderate	*Microsporidia*	Moderate
Pseudomonas aeruginosa	Moderate	Enterovirus	Moderate	*Giardia lamblia*	High
Campylobacter coli	Low	Astrovirus	Moderate	*Entamoeba Histolytica*	High
Francisella tularensis	Moderate	Echovirus	Moderate	*Sarcocystis spp.*	High
Escherichia coli pathogenic	Low	Coxsackie virus A	Moderate	*Giardia duodenalis*	High
Mycobacterium spp. (non-tuberculous)	High	Coxsackie virus B	Moderate	*Toxoplasma gondii*	High
E coli enterohaemorrhagic	Low	Helminths		*Giardia Intestinalis*	High
Helicobacter pylori	Low	*Schistosoma spp.*	Moderate	_	_
Salmonella spp.	Low	*Fasciola spp.*	High	_	_
Salmonella paratyphi	Low	*Dracunculus medinensis*	Moderate	_	_
Salmonella typhi	Low	*Ascaris lumbricoides*	Unknown	_	_
Shigella spp.	Low	Free-living nematodes	High	_	_
Staphylococcus aureus	Moderate	_	_	_	_
Tsukamurella spp	Unknown	_	_	_	_
Toxic cyanobacteria	Low				
Yersinia enterocolitica	Low	_	_	_	_
Vibrio cholera	Unknown	_	_	_	_

2.2. Chemical Contaminants

Chemicals comprise a significant amount of the wastewater generated by industrial processes and certain household consumption. Employing standard biological treatment techniques, it is difficult to eliminate these contaminants [72,73]. There are two categories of chemical pollutants:

2.2.1. Organic Substances

The most significant pollutants include industrial hydrocarbons, oils, pesticides, phenols, proteins, and organic pollutants produced by different commercial and industrial operations [74]. Organic pollution in water depends on the nature of the organic matter itself, whether it is biodegradable or not, and its decomposition degree [60]. Organic substances that deteriorate water quality pose serious risks to both marine organisms and a healthy human population [75]. Organic water contaminants mostly consist of food manufacturing waste, such as fats, oils, and compounds that require oxygen. Petroleum hydrocarbons, which include fluids (motor oil), hydrocarbons (gasoline, diesel, and jet fuel), and byproducts of fuel combustion, disinfection byproducts (DBPs) like chloroform present in drinking water that have undergone chemical sterilization, VOCs from inappropriate storage like commercial solvents, pesticides, which are a wide variety of organohalides, and other chemical substances. Forestry activities', i.e., leftover tree and bush waste, organic contaminants tolerant to environmental deterioration are referred to as organic pollutants [76,77]. Since these organic molecules are highly stable, they are capable of withstanding adverse conditions without degrading. The impact of organic pollution has many effects on the ecosystem in which it resides. The most important effects that organic materials have on water include the effect on the exchange and balance of dissolved oxygen in water, the chemical properties and properties of waterways, construction and demolition products, and the diversity of aquatic organisms [78].

2.2.2. Inorganic Substances

Inorganic contaminants are compounds that cannot be broken down by biological processes; they frequently come from industrial, agricultural, and domestic sources [79]. These pollutants move into water systems both directly and indirectly. They range from salts to heavy metals like lead, mercury, and arsenic to nitrates, phosphates, and sulfates [80]. These contaminants may remain for long periods, damaging aquatic ecosystems and human health. Important contributors to this contamination include untreated wastewater, precipitation from agricultural processes, and industrial wastewater. Understanding their origins and how they affect human lives and the environment is crucial [81]. Human health is severely impacted by exposure to inorganic pollutants by ingestion or interaction with polluted water (82). Many of these contaminants, including lead and mercury, are neurotoxins that hurt children's mental growth and function [83]. Some of them, like arsenic, can trigger cancer. These contaminants have worrying consequences for the ecosystem because these compounds might be hazardous to aquatic life and damage ecosystems. Aquatic organisms' biological accumulation of heavy metals interrupts food systems, putting whole genera and biodiversity under threat [84,85].

3.CHARACTERIZATION AND SYNTHESIS OF NANOPARTICLES

Based on their chemical structure, nanoparticles (NPs) can be divided into several classes, such as metallic NPs, consisting of copper, silver, and gold particles among other metals; Carbon-based NPs, made up of carbon particles with different structural arrangements, like graphene. Various features, including chemical and physical, primarily determine the suitability of NPs for a particular application, such as shape, surface area, and size [86]. The techniques employed to characterize NPs depend on the kind of material being used. There are many different types of microscopes available, such as probe, optical, and X-ray, to characterize nanoparticles. Scanning electron microscopy, among other techniques, is used for topological, crystal, imaging, and chemical investigation. To generate nanomaterials, bottom-up and top-down methods can be applied. Covalent or ionic bonds are used in the bottom-up strategy, whereas the top-down approach weakens Vander Waal's forces. Using the top-down approach, big items or clusters are broken down into little particles [87,88]. Top-down synthesis methods are required to generate particles with a diameter of less than a micron. Top-down methods are essentially easier and depend on breaking down or removing bulk components to create the desired shape with the necessary properties. In contrast, the bottom-up method advances to nanomaterials by passing through tiny, targeted particles (Fig. 3) [89]. Industrial NPs manufacturing is still in the early stages of development for many bottom-up methodologies.

4.NANOTECHNOLOGY IN WASTEWATER TREATMENT

According to Priyadarshanee et al. [90], nanomaterials, which generally have dimensions of less than 100 nm, include substances with unique and dramatically altered physical, chemical, and biological characteristics. These materials have new size-dependent characteristics that distinguish them from those that are greater in size, as shown in Fig. 4 [91].

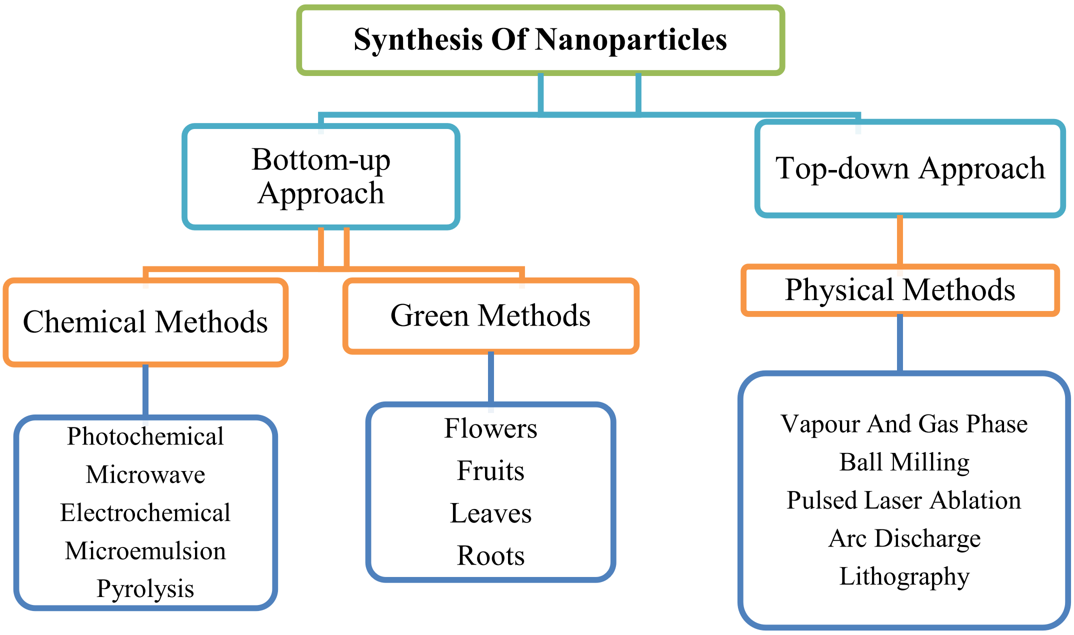

Fig. 3 Synthesis of Nanoparticles Using Various Methods [89].

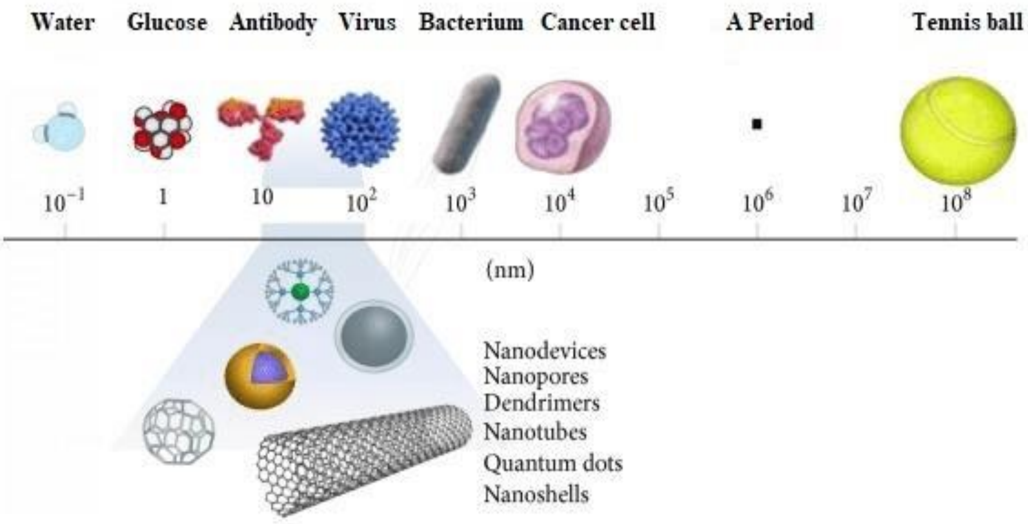

Fig. 4 Nanoparticle Size Comparison with Other Materials of Greater Size [91].

Nanotechnology is anticipated to play a significant role in more effective saltwater desalination, water recycling, and water remediation due to the quick decline of clean water supplies [92-94]. It has long been recognized that the science of nanotechnology has great promise for resolving many problems related to the purification process [95,96]. Techniques for treating water based on nanotechnology, as illustrated in Fig. 5 [89], a range of treatment methods, including membrane filtration, photocatalysis, electrochemical elimination, chemical precipitation, and ion exchange, and other techniques, have been employed to completely and successfully remove contaminated impurities from water and wastewater. Even though these technologies do exist, their application to the treatment of wastewater is restricted for a variety of reasons, such as high maintenance and energy requirements, intricate operational procedures, and a lack of emphasis on the circular economy and sustainability [97,98].

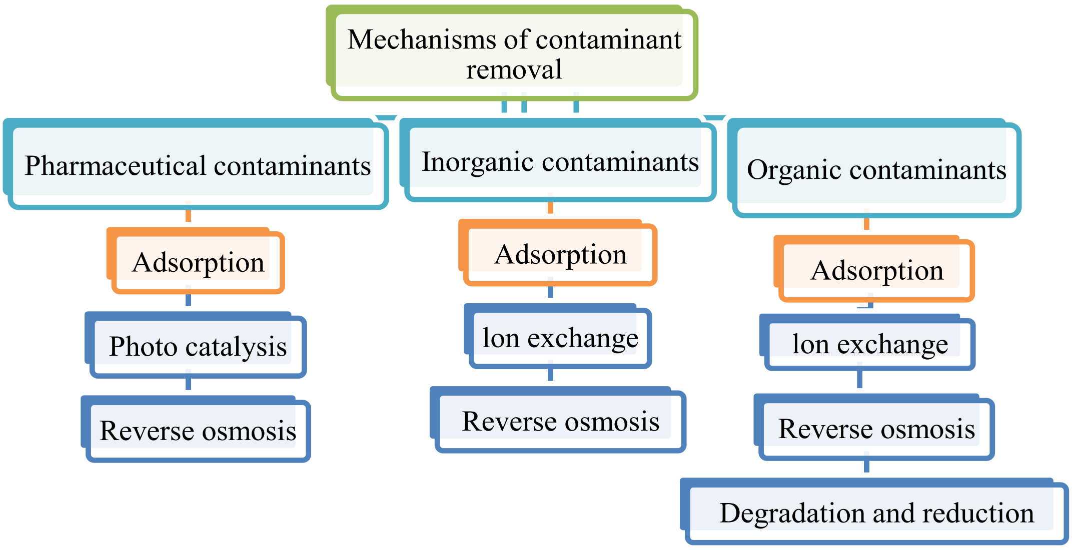

Fig. 5 Techniques for Removing Dangerous Contaminants from Water [89].

The adsorption strategy is among the most popular, well-respected, flexible, and efficient techniques for filtering dangerous pollutants, such as heavy metal ions and dyes. However, its poor efficacy after repeated cycles limits its use in wastewater treatment. Recently, there has been a lot of interest in NPs as adsorbents due to the synthesis of carbon-based and metal polymers. Due to their special qualities and huge surface area, nanoparticles are perfect for the adsorption of dangerous contaminants from wastewater [99,100]. On the other hand, the most intensively explored nanotechnology for wastewater sanitation currently includes nanocomposites, zero-valent iron nanoparticles, metal oxide nanoparticles, and CNTs [101-103]. Water treatment and purification involve the application of several NMs (Fig. 6) [104].

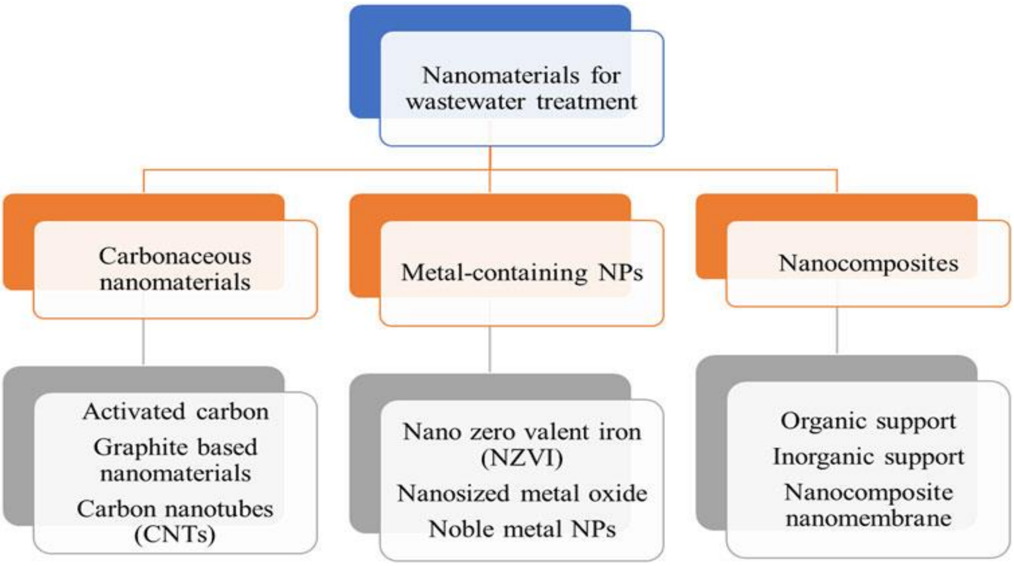

Fig. 6 Diagrammatic Representation of Different Nanoparticles Used in Wastewater Treatment [104].

4.1.Carbon Nanotubes (CNTS)

Carbon-based nanomaterials have attracted significant interest in wastewater treatment today, given the volume of wastewater produced and the vast range of carbon availability in nature. Graphene sheets with a diameter of 1 nm produced in cylindrical rolls are known as carbon nanotubes [105]. CNTs have been investigated for applications in a wide range of fields, including drug delivery, environmental remediation, medical devices, nanocomposites, adsorption, treatment of contaminants, and energy storage. The usage of CNTs is beneficial in the removal of many contaminants from water bodies, such as zinc, copper, lead, benzene, cadmium, and colors, due to their high adsorption capacity and efficiency [106]. Chromium can be eliminated by fusing the magnetic characteristics of iron oxide with the adsorption capabilities of CNT. Combining CNT with other metal materials allows for the modification of its adsorption, mechanical, electrical, and optical characteristics. To give an example, different CNT functionalizations may enhance the quantity of oxygen, nitrogen, or additional clusters on the surface of the CNT, which increases its dispersibility and surface area [107]. It has been demonstrated that graphene-sheeted CNTs with polarized edges can function as electron-dominant π-donors. Briefly, the denser adsorbent's defective area can be occupied by electron donors; however, an extra n-π-EDA reaction may occur, in which donors, that is, electrons from amino or hydroxyl groups, react with the electron-deficient angles of CNT, which can take on the role of acceptors of π-electrons [108]. Membrane technology is another method in which CNTs are employed in wastewater treatment. This technology uses CNTs as an adsorbent and is widely used and extensively studied in the field of water purification and filtration. Using the sieve idea, CNTs can remove a wide range of impurities from an aqueous medium [109]. CNT is an appealing material for membrane filtration of extremely reactive monovalent anions at reduced pH values due to its simplicity of functionalization, high aspect ratio, significant surface area, and rapid movement of water, even faster than the hypothetically expected 4-5 orders of magnitude [110]. Because of its permeability, strength, antifouling properties, and disinfectant properties, it can be employed directly as a filter, improving the performance of other membranes. Groundwater fluoride levels have dropped thanks to the carbon nanotube composite adsorbent. Six percent of CNT generated globally is now being used to clean wastewater [111]. Different investigators have conducted several experiments that have indicated that chemisorption is a major factor in CNTs' ability to eliminate a broad variety of contaminants. It has also been demonstrated that pseudo-second-order kinetics may be used to simulate the adsorption process. The pH value significantly impacts the CNT's adsorption capability. CNTs are grafted onto polymers to enhance their chemical and mechanical strength [112]. The amazing physicochemical features of CNTs have made them the primary subject of investigation into nanotechnology since their discovery. CNTs can be safely employed for treating water [113]. They consist of both multi-walled nanotubes (MWNTs) and single-walled nanotubes (SWNTs), which have several layered tubes and lengths ranging from around 100 nm up to approximately 200 nm [114]. Both SWNTs and MWNTs have been linked to respiratory damage and cytotoxicity in mammalian cells, according to research on the safety of CNTs, as shown in Fig. 7 [115].

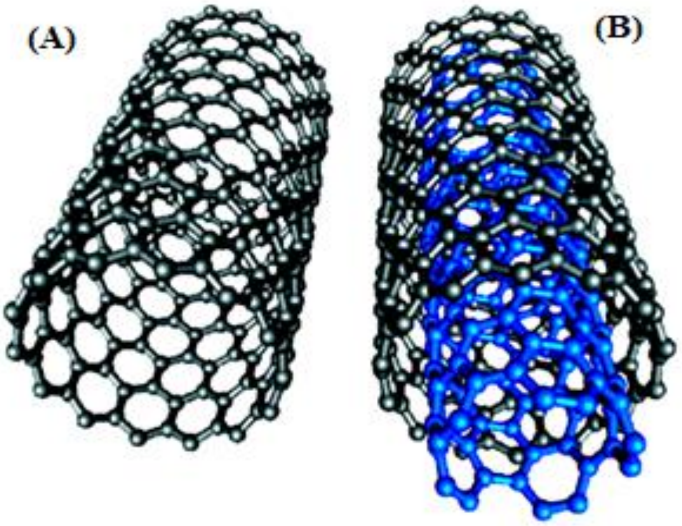

Fig. 7 (A) single-walled Carbon Nanotubes, (B) Multiwall Carbon Nanotubes [115].

CNTs are tubular macromolecules that are arranged in a hexagonal arrangement in the walls of the tubes. The tips of the tubes are enclosed with the help of a configuration resembling a fullerene [116]. Water comprises a variety of impurities, including colors, personal hygiene products, pharmaceuticals, petroleum products, pesticides, heavy metals, and organic substances. These impurities are often poisonous, chemically stable, cytotoxic, and nondegradable [117]. When input levels are high, carbon nanotubes offer the necessary selectivity. These nanotubes may almost eliminate all sorts of water pollutants. The increased specificity of these filters compared to conventional water treatment methods is due to the nanometric permeability of carbon nanotubes [118]. The high cost of CNTs compared to graphite, carbon fiber, black, and clay is an obstacle that limits their use as adsorbents for water filtration [119]. CNTs effectively adsorb a wide range of substances due to several contaminant-CNT interactions, such as H-bonds, Π-Π interactions, electrostatic forces, covalent bonds, and hydrophobic effect, as shown in Fig. 8 [120]. The comparative results of CNTs and their ability to adsorb pollutants are shown in Table 2.

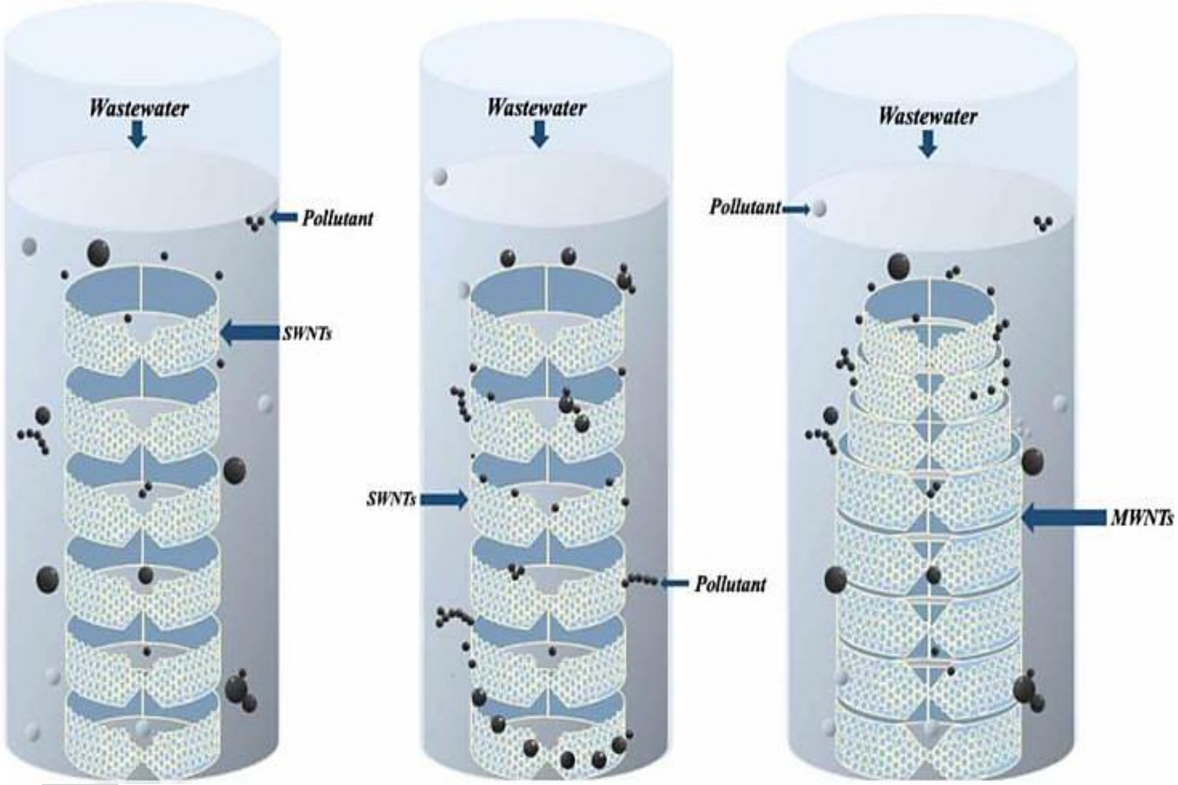

Fig. 8 Schematic Showing the Adsorption Capabilities of Carbon Nanotubes for Wastewater Purification [120].

Table 2 Various Uses of CNTs to Remove Pollutants from Wastewater.

Adsorbent	Pollutants	Adsorption Capacity (mg/g)	References
MWCNTs (16-25 nm diameter)	Pb(II) Ni(II)	201.35± 0.02 mg/g 206.40 ± 0.02 mg/g	[121]
MWCNTs (16-25 nm diameter)	Ni(II) Pb(II)	206.40 ± 0.02 mg/g 201.35± 0.02 mg/g	[122]
Oxidized-MWCNTs	Zn(II) Cu(II)	411.88 mg/g, 416.47 mg/g 411.88 mg/g	
MWCNTs	Cu(II)	364.66 mg/g	
Ag-MWCNTs	Zn (II), Fe (II), Mn (II)		[123]
Pure-MWCNTs	Zn (II), Fe (II), Mn (II)		
PN@TR-CNTs and treated CNTs and	Cu(II), Cd(II), Ni(II), Fe(II) and Pb(II)		[124]
MWCNTs-KOH	As(V), Pb(II)	65.5% ±4.2% 50.7% ±3.4%	[125]
MWCNTS-KOH@NINPS	As(V) Pb(II) Cd(II)	88.5% ± 6.5% 91.2% ± 8.7% 80.6% ± 5.8%	

4.2.Metal Oxide Nanoparticles (MONPS)

A growing amount of interest has been paid to metal oxides due to their outstanding efficacy and affordable price when it comes to removing impurities. Nanosized ferric oxides, cerium oxides, manganese oxides, aluminum oxides, magnesium oxides, and titanium oxides are the perfect nanosized metal oxides [126]. Numerous studies have revealed that metal oxides demonstrate advantageous adsorption towards common pollutants, including phosphate and organics, as well as heavy metals, such as cadmium, uranium, and arsenic, with significant capacity and specificity [127-129]. Table 3 shows the various uses for metal oxide nanoparticles.

Table 3 Various Uses for Metal Oxide Nanoparticles.

Absorbent	Shape And Size (Nm)	Surface Area (m^2/g)	Target Contaminant	References
Maghemite (α -Fe_2O_3)	Partide, 10 Partidle, 10	198 178	Cr (VI), Cu (II), Ni (II)	[130-132]
Magnetite (γ-Fe_2O_4)	Particle, 10-20	-	Cr (VI) Se(V)	[133, 134]
Goethite (α FeOOH)	Needlelike, width – 50, length 200 Needlelike, 1-10	50 -	Cu (II) F	[135, 136]
Hematite (γ-Fe_2O_3)	Partide, 37	31.7	Pb (II), Cd (II), Zn (II), and Cu (II)	[137-139]
Hydrous ferric oxide (HFO)	Partidle	148	F	[140]
Al_2O_3	Partidle, 62-87	42.62	Cd (II), Pb (II), Co (II), and Cr (III)	[141-143]
TiO_2	Partile, 8.3	185.5	Cd (II), Pb (II), Cu (II). Dye, Ni (II), micro-pollutants, Zn (II)	[144-147]
ZnO	Partide, 26	-	Cd (II), Zn (II), and Hg (II)	[148-150]

Among the most prominent metal oxide nanoparticles are titanium oxides, zinc oxides, copper oxides, iron oxides, and silver oxides [151]. Among these nanoparticles, zinc oxide is most commonly used for wastewater treatment technologies, followed by TiO_2 and CuO, which are commonly employed for purification and the treatment process. As they have indicated excellent results in various applications, metal oxide nanoparticles are favored for absorbing organic contaminants and heavy metals [152, 153]. Zinc oxide is considered environmentally friendly due to its biocompatible and non-toxic properties. After treatment, the nanoparticles are easily retrieved and separated, reducing the possibility of environmental contamination. Furthermore, the antibacterial capabilities of ZnO-NPs make them especially well-suited for treating municipal wastewater, as they effectively eradicate any microorganisms that may be present [154]. Researchers have expressed a strong interest in employing them for wastewater treatment due to zinc oxide nanoparticles' increased stability in terms of charge and chemical bonding, as well as their capacity to dissolve in both basic and acidic solutions [155]. There has been evidence that ZnO nanoparticles can effectively reduce fouling by adsorbing and breaking down contaminants, such as phosphorus, from hospital waste. The bioreduction of cations in the precursor salts by enzymes, amino acids, and other biomolecules produced by bacterial cells forms the basis of the biogenic nanoparticle manufacturing mechanism. Red seaweed was utilized as the precursor salt by Mansour et al. [156] in their green synthesis method to create ZnO-NPs. Under varied circumstances, the effectiveness of the produced ZnO-NPs as an adsorbent for the removal of IV2R dye was assessed. In conclusion, zinc oxide (ZnO) is regarded as one of the best metal oxides for wastewater treatment due to its antibacterial qualities, strong photocatalytic activity, chemical stability, and range of application possibilities. Due to these characteristics, ZnO nanoparticles are a convenient and effective option for handling the various problems related to wastewater treatment [157]. However, they are not frequently mentioned, these kinds of nanoparticles, which go by the name of immobilizing transporters, are frequently utilized as support carriers for biosorbents and biological sensors. Their effectiveness has been linked to their chemical and physical characteristics, although they have not been widely used in wastewater treatment (Fig. 9) [158].

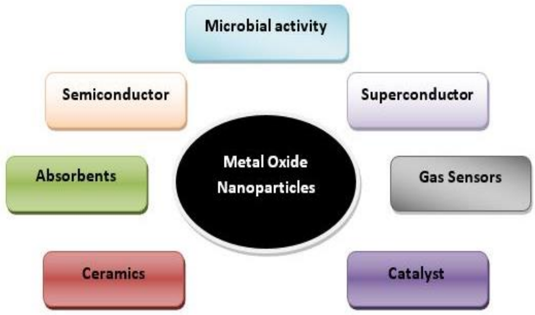

Fig. 9 Metal Oxide Nanoparticles Applications [158].

4.3.Zero-Valent Iron Nanoparticles

Water purification can be accomplished with the use of ZVI [159, 160]. The creation of nanoscale zero-valent iron (nZVI) has significantly increased its reactive properties. As a result of their extensive particular areas, nZVI has numerous unique favorable characteristics, such as a strong reactivity against a variety of pollutants, and extremely small sizes that provide efficient subsurface distribution and injection in aquatic sediments for contamination removal [161]. Previous studies suggest that changing (reducing) the size of ZVI from micron to nanoscale could boost the efficiency variable for Arsenic (V) removal by 1-3 orders of magnitude [162]. As a result, to the iron hydroxide layer, which was demonstrated to be a highly effective adsorbent, nZVI has been extensively utilized as an adsorbent for the elimination of pollutants [163]. A wide range of pollutants that need to be eliminated from wastewater are addressed by nano zero-valent Fe [164]. In contrast, they also have some restrictions, such as their accumulation, which makes it more difficult to separate them from the water system. Despite this issue, there are still approaches to modify micro zero-valent Fe to enhance its efficiency in the treatment of wastewater [165]. Nano-ZVI serves as a valuable metals that assist nano-ZVI in accelerating the decomposition reaction when they are combined in a polymeric membrane system for the breakdown of pollutants like chlorinated chemicals [166]. The comparative results of nZVI and their ability to adsorb pollutants are summarized in Table 4.

Table 4 Application of nZVI for Removal of Pollutants from Wastewater.

Adsorbent	Pollutants	References
Sulfidation of nZVI with a chelator	Acid Red 73 (AR 73)	[167]
nZVI-Cu bimetals	Nitrate	
Hydrotalcite-Supported nZVI	MB	[168]
nZVI	Cr (VI), Hg (II), Cd (II), Pb (II), Ni (II), and Cu (II)	[169]
Nano-sized zero-valent iron	Pb (II), Cd (II)	[170]
	Cu (II), Cd(II), Pb (II)	[171]
	Direct Brown-2 (DB-2)	[172]
	And Direct Red-31 (DR-31)	[173]
	V^{5+}	[174]
	MB	
	Furfural	

5.NANOCOMPOSITES

The majority of the previously mentioned nanomaterials are found as nanoparticles. The widespread use of nanoparticles in water purification comes with several fundamental technological challenges, including accumulation, release into water, separation, and harmful environmental and health effects [175, 176]. The manufacturing of nanocomposite material that gains advantages from the impregnated nanoparticles, as well as the hosts, is a potential way to further the use of nano-particulate materials [177-178]. Consequently, nanocomposite materials might have the potential to link the nanoscopic and mesoscopic scales [179,180]. Currently, it has been considered that nanocomposites would be the best practical way to transfer water nanotechnology from experiments to commercial use. Nanocomposite membranes are potential filtering components that can be constructed from combined polymers and membranes with surface functionalization [180,182]. The majority of the nanofillers used in mixed matrix membranes are inorganic with a considerable surface area and are incorporated into a polymeric or inorganic oxide matrix [174]. An example of nanocomposites is activated carbon nanocomposites, which showed a substantial antibacterial action against *Pseudomonas aeruginosa* and *Staphylococcus aureus* [183].

5.1.Nanocomposites of Organic Supports

Polymers have special properties that make them ideal as supporting materials in wastewater treatment polymer-based nanocomposites (PNCs). These properties include functional groups, remarkable mechanical strength, and porous architectures. Grafting polymerization procedures were utilized to generate PNCs (grafted magnetic nanoparticles) to remove heavy metal ions [184]. Numerous studies have been conducted on the synthesis of PNCs via direct compounding, which involves joining polymers and precursors of NPs directly with NPs. They are created using nucleation and in-situ precipitation techniques. Table 5 summarizes the possible uses and contaminant removal of different nanocomposites.

5.2.Nanocomposites of Inorganic Material

Activated carbon and naturally existing minerals (clay, zeolite) are utilized as inorganic supports for nanocomposites CNTs [198]. Wastewater treatment facilities make substantial use of these adsorbents (Table 6).

Table 5 Using Different Nanoparticles to Remove Pollutants from Water.

Polymeric host	Nanoparticles	Removal	References
Iron (III) oxyhydroxide powders with TEMPO-oxidized cellulose nanofibrils		Removal of fluoride	[185]
Microcomposite employing an ISA and CFA combination		Malachite green	[186]
Iron oxyhydroxide@COF		As (III) up to 98.4%	[187]
Cds/TiO_2		Acid blue dye	[188]
Alginates	Iron oxides	As (50 to 10 ppb) MB, methyl orange	[189]
Polmeric anion exchanger	Hydrated ferric oxide	Phosphate 100 to 5 ppb	[190]
Polyacrylamide		155.0 mg for H(II) 211.4 mg for Pb (II), 147.2 mg for Cd (I)	[191]
Cellulose	Iron Oxyhydroxide	As (III) (99.6 mg) As(V) (33.2 mg)	[192]
Cyclodextrin	Iron oxides	Cu (II)	[193]
Cellulose-Ag		Cr and CD	[194]
-	ZnO NPs	MB dye (76%-95%)	[195]
-	Iron oxide NPs (IONPs) from coal fly ash	Zn (II), Cd (II), Al (II) Cu (II), Cr, Pb (1I), Ni (1I) Mn (II), Co (II), (40%-70%)	[196]
-	Silica NPs	Zn (II), Cd (II), Al (II) Cu (II), Cr, Pb (1I), Ni (1I) Mn (II), Co (II), (40%-90%)	
-	ZnO NPs	MB dye Ampicillin (975)	[197]

Table 6 Various Inorganic Supports Remove Contaminants from Wastewater.

Polymeric host	Nanoparticles	Removal	References
Kaolin/ZnO nanocomposites	Cr(VI), Chloride, Fe(III), BOD, COD	Fe(III): (98%), Cr(VI): (100%), %), BOD: (94%), COD: (95%), Chloride: (78%)	[199]
Magnetite-Zeolite nanocomposite	COD BOD TOC	99.88% 99.96% 99.87%	[200]
Ag-supported-Montmorillonite	Methylene blue dye	81%-95%	[201]
ZnO-decorated halloysite	Methylene blue dye	90%-97%	
Siderite NP-coated sewage sludge and waterworks		Cr with 9,416 mg/g of maximum adsorption value	[202]
Magnetic biochar		Cu (II)	[203]
ZnO-decorated halloysite	Methylene blue dye	90%-97%	[204]

6.CONCLUSION AND FUTURE WORKS

After investigating the impact of various types of nanotechnology on wastewater treatment, including its capacity to remove various pollutants and contaminants, the following conclusions were drawn:

- Water that has been impacted by organic, bacterial, or microbiological pollutants or microbes is referred to as wastewater.
- Wastewater can be further subdivided into sewage and industrial wastewater.
- Nanotechnology is so good at removing contaminants and pathogens in water that it is utilized to make materials that clean

surface water, groundwater, and wastewater.

- It also cleans the soil of heavy metals that prevent plants from absorbing nutrients and water nutrients.
- Nanotechnology may remove salinity from water and purify it of suspended heavy materials more effectively and affordably than reverse osmosis.
- Hazardous effects of environmental nanomaterials should be thoroughly examined, and efforts are required to synthesize those using environmentally friendly methods to reduce their adverse environmental impact.
- The usage of nanomaterials should be governed by regulations and procedures to reduce any negative effects on aquatic life and human well-being.
- These recommendations, standards, and procedures are anticipated to be developed according to the comprehensive knowledge of human experts on the effects of nanotechnology.

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CONFLICT OF INTEREST

The author claims they have no conflicting interests.

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