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Next-Generation Nanocomposites for Environmental Remediation: Progress and Future Prospects

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Abstract: Nanocomposites have emerged as effective materials for environmental cleanup owing to their distinctive physicochemical features, elevated surface area, and increased reactivity. This review paper presents a comprehensive overview of nanocomposites used for environmental remediation, focusing on their synthesis, mechanisms, recent advancements, challenges, and future directions. The paper classifies nanocomposites into five primary types which are discussed in detail in this review. Each type offers distinct advantages in pollutant degradation and heavy metal removal through adsorption, photocatalysis, Fenton and Photo-Fenton reactions and membrane filtration. Notably, adsorption and photocatalytic mechanisms, including charge separation and ROS generation, are highlighted for their effectiveness in tackling contamination. Recent advancements in synthesis techniques emphasize green synthesis approaches, heterojunction formation, and surface functionalization to enhance performance. Despite the progress, challenges such as nanoparticle agglomeration, recyclability, toxicity, and environmental impacts persist. Addressing these limitations through innovative strategies is crucial for sustainable application. Future research should focus on developing multifunctional nanocomposites for integrated remediation, leveraging artificial intelligence for material optimization, and designing eco-friendly and biodegradable materials. By overcoming current challenges, nanocomposites hold significant potential to revolutionize environmental remediation strategies.

Keywords: nanocomposites; environmental remediation; adsorption; photocatalysis; heavy metal removal; dye degradation; green synthesis

1. Introduction

Environmental pollution has become a major challenge, posing serious risks to human health, ecosystems, and biodiversity. Rapid industrialization, urbanization, and technological advancements have significantly contributed to increasing levels of pollution. Environmental pollution can generally be classified into air, water, and soil pollution. Among these, air pollution is primarily caused by the discharge of harmful gases and suspended particulate matter originating from industrial operations, transportation systems, and the combustion of fossil fuels. These atmospheric contaminants adversely affect human respiratory health and significantly exacerbate global warming and climate change [1,2]. Air pollution is mainly attributed to the excessive release of toxic gases, including Carbon Monoxide (CO), Nitrogen Oxides (NO_x), Sulfur Dioxide (SO₂), along with fine particulate matter such as PM_{2.5} and PM₁₀. These pollutants are primarily generated from various anthropogenic activities, including industrial emissions from power plants, chemical industries, and manufacturing units; vehicular emissions resulting from the combustion of fossil fuels; and agricultural activities such as the burning of crop residues, which lead to smog formation and hazardous air quality. Long-term exposure to polluted air also accelerates climate change by increasing greenhouse gas concentrations [2].



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Water pollution occurs due to the contamination of lakes, rivers, oceans, and groundwater by toxic chemicals, industrial effluents, agricultural runoff, and domestic waste (Figure 1). Major pollutants include heavy metals such as Lead (Pb^{2+}), Mercury (Hg^{2+}), Chromium (Cr^{6+}), Cadmium (Cd^{2+}), and Arsenic (As^{3+}), which accumulate in the food chain, along with dyes and organic pollutants released from textile and pharmaceutical industries, as well as pathogenic microorganisms originating from sewage and untreated wastewater [3,4]. Contaminated water adversely affects aquatic ecosystems, reduces biodiversity, and causes waterborne diseases such as cholera, dysentery, and hepatitis [5]. Soil contamination mainly results from improper waste disposal, excessive pesticide use, and industrial spills. Pollutants such as plastics, petroleum hydrocarbons, and hazardous chemicals degrade soil fertility, disturb microbial balance, and reduce agricultural productivity [6]. Due to these environmental threats, conventional pollution control methods such as chemical treatment, adsorption, and microbial degradation have been used for decades. However, these methods often suffer from low efficiency, high operational costs, and secondary pollution problems. Therefore, nanotechnology-based approaches have emerged as innovative and sustainable solutions for environmental remediation [7].

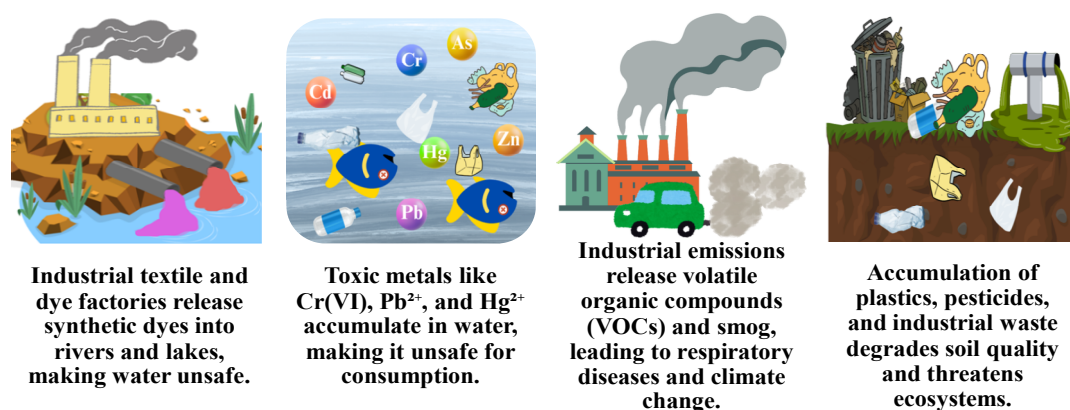


Figure 1. Major Industrial Pollutants and Their Environmental Impact.

Nanocomposites, which consist of nanoparticles integrated with materials such as polymers, Metal Oxides, and Carbon-based nanostructures, exhibit advanced properties, including high surface area, enhanced reactivity, and improved adsorption capability, making them highly efficient for pollutant removal [8]. In recent years, nanocomposite-based materials have attracted significant attention for water remediation due to their superior adsorption capacity, catalytic efficiency, and filtration performance. One of the major applications of nanocomposites in water treatment is the adsorption of heavy metals and toxic substances. Materials such as Graphene Oxide (GO), metal–organic frameworks (MOFs), and chitosan-based nanocomposites demonstrate high efficiency in removing harmful metals like Pb^{2+} , Cd^{2+} , and Cr^{6+} from polluted water [9–11].

Another important application of nanocomposites lies in the photocatalytic degradation of organic pollutants. Nanocomposites based on Titanium Dioxide (TiO_2) and Zinc Oxide (ZnO) effectively degrade pesticides, dyes, and pharmaceutical residues under Ultraviolet (UV) or Visible Light irradiation [12,13]. Furthermore, heterojunction nanocomposites such as TiO_2/CuO and ZnO/GO exhibit superior photocatalytic activity by improving charge separation and electron transfer, thereby enhancing degradation efficiency [14,15]. In addition to adsorption and photocatalysis, membrane filtration using nanocomposite-enhanced membranes has gained considerable attention as an effective water purification strategy [16]. These advanced membranes offer superior permeability, strong fouling resistance, and enhanced selectivity. Polymer-based nanocomposite membranes are widely employed in desalination and wastewater treatment processes due to their excellent structural stability and high separation efficiency [17].

Apart from water remediation, nanocomposites also play a significant role in air purification. Air pollution represents a serious environmental concern, posing substantial threats to both human health and ecological balance. The increasing concentration of atmospheric pollutants, including volatile organic compounds (VOCs), further intensifies this issue. Nanocomposites have emerged as promising materials for air purification because of their remarkable catalytic, adsorption, and antimicrobial properties [18]. One of the most extensively studied applications of nanocomposites in air purification is the photocatalytic degradation of airborne pollutants. TiO_2 -based nanocomposites are highly effective in degrading VOCs, NO_x , and SO_x under sunlight exposure, thereby reducing harmful emissions [19]. Moreover, hybrid nanocomposites such as CeO_2-TiO_2 exhibit enhanced catalytic oxidation activity, improving pollutant degradation efficiency [20]. Carbon-based nanocomposites are also widely

used for gas adsorption applications. Graphene and Activated Carbon nanocomposites demonstrate excellent adsorption capacity for capturing CO₂ and other toxic gases [21]. Similarly, Metal-doped Carbon Nanotubes (CNTs), including Fe-CNTs and Cu-CNTs, exhibit enhanced gas adsorption capability due to their high surface area and abundant active sites, making them highly efficient materials for air purification [22].

In addition to pollutant removal, maintaining air quality also requires effective control of microbial contamination in air filtration systems. Antibacterial coatings based on Silver and Copper nanoparticles embedded within polymer nanocomposites provide an efficient solution for preventing microbial growth [23]. These coatings inhibit bacterial proliferation on filtration surfaces, thereby improving the longevity and hygiene of air purification systems. Ongoing advancements in nanocomposite-based technologies are expected to further improve pollutant removal efficiency and contribute to the development of sustainable strategies for environmental protection and public health safety.

Despite the rapid growth of research on nanocomposites for environmental remediation, the existing literature remains highly fragmented, with most studies focusing on specific materials, pollutants, or individual remediation mechanisms [24–26]. To the best of the authors' knowledge, a comprehensive and critical review that systematically integrates recent advances, underlying mechanisms, key challenges, and future research directions is still lacking. Moreover, issues such as nanocomposite stability, reusability, toxicity, environmental fate, and large-scale applicability are often underreported or discussed superficially in the literature. Therefore, the present review aims to provide a consolidated and up-to-date overview of nanocomposites used for environmental remediation, emphasizing their synthesis strategies, structure–property relationships, and pollutant removal mechanisms. In addition, this review critically analyzes current limitations and emerging challenges while highlighting future prospects, including sustainable design, green synthesis approaches, and real-world implementation. By addressing the gap between laboratory-scale investigations and practical environmental applications, this review provides a comprehensive resource for researchers, policymakers, and environmental engineers involved in developing sustainable pollution mitigation strategies.

2. Types of Nanocomposites for Environmental Remediation

Nanocomposites are a class of advanced hybrid materials in which nanoscale particles are evenly dispersed within a continuous matrix, such as polymers, Metals, or Carbon-based structures.

Depending on their composition and structural features, nanocomposites are generally classified into Polymer-based, Metal-based, Carbon-based, Magnetic, and Hybrid types (Figure 2). Among these, Polymer-based nanocomposites consist of nanoparticles dispersed within polymer matrices, leading to notable improvements in mechanical strength, thermal stability, and adsorption efficiency. As a result, they are extensively used in water treatment applications, especially in membrane filtration and purification systems [27]. Comparison of different types of nanocomposites for environmental remediation is summarized in Table 1.

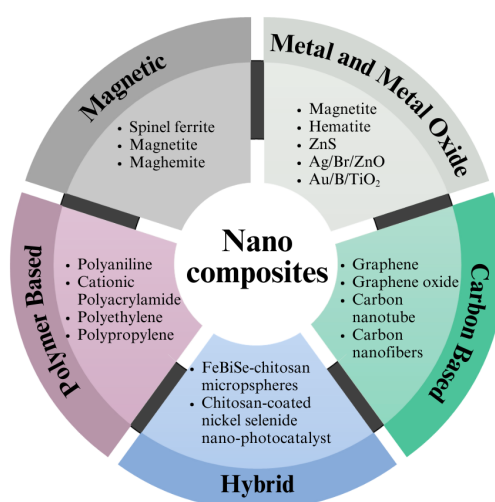


Figure 2. Types of Nanocomposites.

2.1. Metal Oxide-Based Nanocomposites

Metal Oxide-based nanocomposites have emerged as highly efficient materials for environmental remediation, attributed to their extensive surface area, robust chemical stability, and superior catalytic efficiency [28]. Among

Metal Oxide-based nanocomposites, TiO_2 is one of the most extensively investigated photocatalytic materials. TiO_2 nanocomposites are widely employed in the degradation of organic pollutants, dyes, and pharmaceutical waste. Upon exposure to ultraviolet (UV) radiation, TiO_2 produces reactive oxygen species (ROS) that efficiently degrade hazardous contaminants [29]. Recent research indicates that TiO_2 –graphene nanocomposites display enhanced photocatalytic performance under visible light, making them well-suited for conditions with limited UV availability [30]. Another notable Metal Oxide nanocomposite is ZnO, recognized for its potent antimicrobial activity and strong UV-absorbing ability. ZnO-based nanocomposites are widely applied in air filtration and water disinfection, where they effectively eliminate pathogens and pollutants [31]. Furthermore, Cerium Oxide (CeO_2), known for its antioxidant properties, is commonly applied in catalytic converters to reduce air pollution. $\text{CeO}_2/\text{TiO}_2$ hybrid nanocomposites have demonstrated superior degradation of VOCs, highlighting their potential in air purification technologies [32].

2.2. Carbon-Based Nanocomposites

Carbon-based nanocomposites have gained considerable attention in environmental remediation owing to their superior electrical conductivity, large surface area, and strong chemical stability. These unique properties make them highly effective for adsorption-based pollutant removal and catalytic applications. Their ability to efficiently trap contaminants and promote chemical reactions has made them promising materials for wastewater treatment, gas adsorption, and environmental monitoring [33].

Among Carbon-based nanocomposites, GO has been widely explored due to its abundant surface functional groups, which enhance its ability to adsorb heavy metals and organic pollutants [34]. In addition, hybrid materials such as GO– TiO_2 exhibit improved photocatalytic efficiency by combining the strong adsorption capacity of GO with the photocatalytic properties of TiO_2 . A recent study reported that GO– TiO_2 nanocomposites can effectively break down complex organic contaminants under visible light, highlighting their potential for wastewater treatment applications [35].

Furthermore, CNT-based nanocomposites constitute another significant category, distinguished by their large surface area and multifunctional properties. CNTs are extensively utilized in gas adsorption, water purification, and electrochemical pollutant sensing. The integration of magnetic nanoparticles such as Fe_3O_4 , into CNT structures has been found to improve heavy metal adsorption while enabling straightforward magnetic separation after treatment. A study reported that CNT/starch/ Fe_3O_4 nanocomposites achieved high removal efficiency for toxic metal ions such as Pb^{2+} and Cd^{2+} in industrial wastewater [36].

Biochar-based nanocomposites, which are produced from agricultural residues, have gained attention as economical and sustainable materials for environmental remediation. They exhibit strong adsorption capabilities and are especially effective in applications such as soil restoration and water purification [37]. Huang et al. highlighted the potential of biochar-based composites in removing persistent organic pollutants (POPs) from contaminated soils [38].

2.3. Polymer-Based Nanocomposites

Polymer-based nanocomposites have gained considerable attention in environmental remediation due to their improved mechanical strength, high chemical stability, and versatile functional properties. The incorporation of nanoparticles into polymer matrices results in materials with enhanced performance, multifunctionality, and improved physicochemical properties [39]. These nanocomposites show superior efficiency in filtration, pollutant removal, and even biomedical uses. Their ability to merge the flexibility of polymers with the functional advantages of nanoparticles makes them highly effective for a wide range of environmental applications [40].

Among polymer-based nanocomposites, chitosan-based systems have been extensively explored due to their eco-friendly nature and high efficiency in pollutant removal. Chitosan, a biodegradable and non-toxic polymer, possesses excellent adsorption capability, enabling efficient removal of heavy metals and dyes from wastewater [41]. Moreover, chitosan–ZnO nanocomposites display pronounced antibacterial activity, making them well suited for water purification applications [42]. Polyaniline (PANI) and polypyrrole (PPy) nanocomposites are also prominent polymer-based materials used for adsorption and electrochemical sensing of pollutants [43,44]. PANI– TiO_2 nanocomposites have shown improved dye degradation efficiency under visible light, as reported by Jangid et al. making them suitable for treating textile and industrial wastewater [45].

Polymeric membrane nanocomposites are extensively utilized in advanced filtration applications, particularly in desalination and wastewater treatment. By incorporating nanoparticles such as TiO_2 into polyvinylidene fluoride (PVDF) membranes, the resulting membranes exhibit enhanced fouling resistance, increased water permeability,

and improved selectivity. TiO₂-PVDF membranes demonstrated superior filtration performance, proving efficient in eliminating organic pollutants and suspended particles from contaminated water [46].

2.4. Magnetic Nanocomposites

Magnetic nanocomposites have gained considerable importance in environmental remediation owing to their high efficiency and ease of recovery. These materials generally comprise magnetic nanoparticles, such as Magnetite (Fe₃O₄), dispersed within polymeric, Carbon-based, or inorganic matrices. A major advantage of these nanocomposites is their magnetic behavior, which allows for quick and efficient separation from treated water through the application of an external magnetic field. This property significantly reduces secondary pollution and enhances recyclability, making magnetic nanocomposites highly suitable for sustainable environmental applications [47].

One of the most widely studied magnetic nanomaterials is Fe₃O₄. Iron oxide (Fe₃O₄) nanocomposites are especially significant in environmental remediation because of their magnetic characteristics, which allow for easy separation and recovery after adsorption. They are widely used for the magnetic removal of heavy metals and for oil spill remediation in wastewater systems [48,49]. Functionalization of Fe₃O₄ nanoparticles with polymers, Silica, or Carbon materials improves their adsorption capacity and chemical stability. For instance, chitosan-Fe₃O₄ nanocomposites demonstrate excellent adsorption efficiency for toxic metal ions owing to the presence of amino and hydroxyl functional groups, which enhance their chelation ability [50].

Magnetic Graphene-based nanocomposites, such as Fe₃O₄-GO hybrids, combine the high surface area of Graphene Oxide with the magnetic separability of iron oxide nanoparticles. These composites show superior performance in removing organic dyes and pharmaceutical contaminants from wastewater [51]. Additionally, magnetic biochar nanocomposites derived from agricultural waste have gained attention as low-cost and eco-friendly alternatives. By incorporating magnetic nanoparticles into biochar matrices, these composites offer high adsorption capacity for POPs and heavy metals, while allowing easy magnetic recovery after treatment. Their sustainability and economic feasibility make them promising materials for soil and groundwater remediation applications [52].

2.5. Hybrid and Functionalized Nanocomposites

Hybrid and functionalized nanocomposites are advanced materials that combine two or more types of nanomaterials to achieve superior pollutant removal efficiency. By integrating Metal Oxides, Carbon-based materials, magnetic, and polymers, these hybrid systems exhibit unique synergistic effects, enhancing their catalytic, adsorption, and antimicrobial properties. Such multifunctional nanocomposites are highly promising for complex environmental applications [53].

Among the various types, Metal Oxide–Carbon hybrid nanocomposites, such as TiO₂–Graphene and ZnO–CNT systems, are extensively researched. These hybrids markedly enhance both photocatalytic and adsorption performance, making them highly efficient for air and water purification. For instance, TiO₂–Graphene composites exhibit improved activity under visible light, enabling effective degradation of VOCs and organic dyes [54]. Similarly, ZnO–CNT hybrids exhibit superior adsorption properties for heavy metals, ensuring efficient remediation of polluted environments [55]. Polymer-metal nanocomposites, such as chitosan-Fe₃O₄ and PANI-Ag, offer advanced functionality by combining antimicrobial, adsorptive, and electrochemical sensing capabilities. These composites are extensively used in antimicrobial coatings and heavy metal chelation applications [50,56]. A study by Fadhel revealed that chitosan/Ni/Fe₃O₄ nanocomposites demonstrated remarkable removal efficiency for Pb²⁺ and Zn²⁺ from industrial wastewater while preventing microbial growth [57].

Table 1. Comparison of different types of nanocomposites for environmental remediation.

Type of Nanocomposites	Key Materials	Main Applications	Advantages	Reference
Metal oxide—Based	TiO ₂ , ZnO, Fe ₃ O ₄ , CeO ₂	Photocatalysis, heavy metal removal, air purification	High stability, effective in pollutant degradation	[28–32]
Carbon based	Graphene, CNTs, Biochar	Gas adsorption, water filtration, pollutant sensing	Large surface area, high conductivity	[33–38]
Polymer based	Chitosan, polymeric membranes	Dye adsorption, antimicrobial coating, membrane filtration	Biodegradable, flexible, high adsorption capacity	[39–46]
Magnetic Nanocomposites	Fe ₃ O ₄ , γ -Fe ₂ O ₃ , Magnetic Biochar	Heavy metal removal, dye adsorption, oil spill cleanup	Easy magnetic separation, high reusability, reduced secondary pollution	[47–52]
Hybrid Nanocomposites	TiO ₂ –Graphene, Chitosan-Fe ₃ O ₄ , Ag	Multipollutant removal, oil spill cleanup, filtration	Synergistic properties, high efficiency	[53–57]

3. Mechanisms of Environmental Remediation Using Nanocomposites

Environmental pollution has become a critical challenge and conventional remediation techniques often fail to provide efficient and sustainable solutions. To overcome these limitations, nanocomposites have gained significant attention as advanced materials for environmental remediation. These materials remove pollutants through various mechanisms, including adsorption, photocatalysis, advanced oxidation processes (Fenton and Photo-Fenton Reactions), and membrane filtration. Comparison of different environmental remediation using nanocomposites is shown in Table 2.

3.1. Adsorption Mechanism

Adsorption is a commonly employed mechanism in environmental remediation, where contaminants are captured on the surface of nanocomposite materials through physical or chemical interactions (Figure 3). Nanocomposites possessing a large surface area, well-developed porosity, and abundant functional groups exhibit high adsorption efficiency for removing heavy metals, dyes, and various organic pollutants. The process is mainly controlled by electrostatic forces, hydrogen bonding, surface complexation, and in certain cases, covalent interactions between the adsorbent and pollutant molecules [58,59].

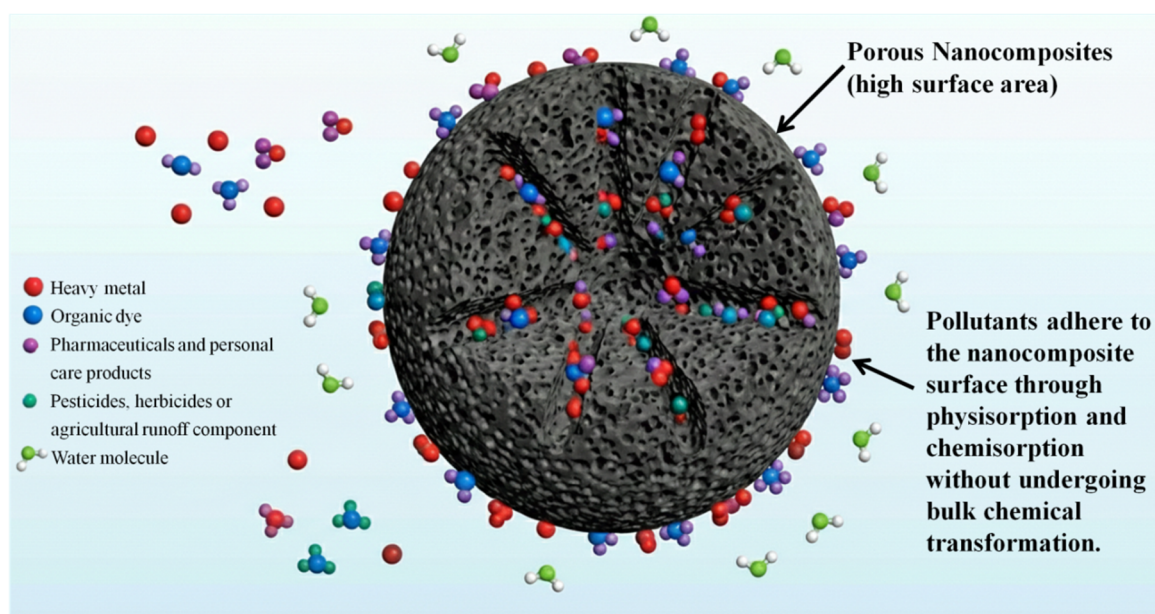


Figure 3. Adsorption Mechanism.

Adsorption efficiency is greatly affected by the surface chemistry and structural features of nanocomposites. Functionalized materials such as GO, biochar, and chitosan-based nanocomposites contain Oxygen- and Nitrogen-rich groups ($-\text{OH}$, $-\text{COOH}$, $-\text{NH}_2$), which promote strong interactions with metal ions and organic pollutants. Moreover, nanocomposites with highly porous and adjustable pore structures such as Activated Carbon, Metal–Organic Frameworks, and Carbon nanotubes, provide a larger number of active adsorption sites, thereby enhancing pollutant removal. Environmental conditions, including solution pH and ionic strength, also play a crucial role, as they influence both the surface charge of the nanocomposite and the chemical form of the contaminants [60–63].

A variety of nanocomposites have exhibited outstanding adsorption performance in water treatment applications. GO-based nanocomposites are widely recognized for their efficient removal of Metal Ions such as Pb^{2+} , Cd^{2+} , and As^{3+} from contaminated water [64]. Chitosan– Fe_3O_4 nanocomposites combine strong adsorption capacity with magnetic separability, allowing effective elimination of dyes and heavy metals along with easy recovery [50]. Likewise, biochar-based nanocomposites have shown significant potential in adsorbing pesticides and pharmaceutical residues from agricultural runoff [38].

3.2. Photocatalysis Mechanism

Photocatalysis is an advanced oxidation process that utilizes light-responsive nanocomposites to generate ROS capable of degrading pollutants into less harmful products (Figure 4).

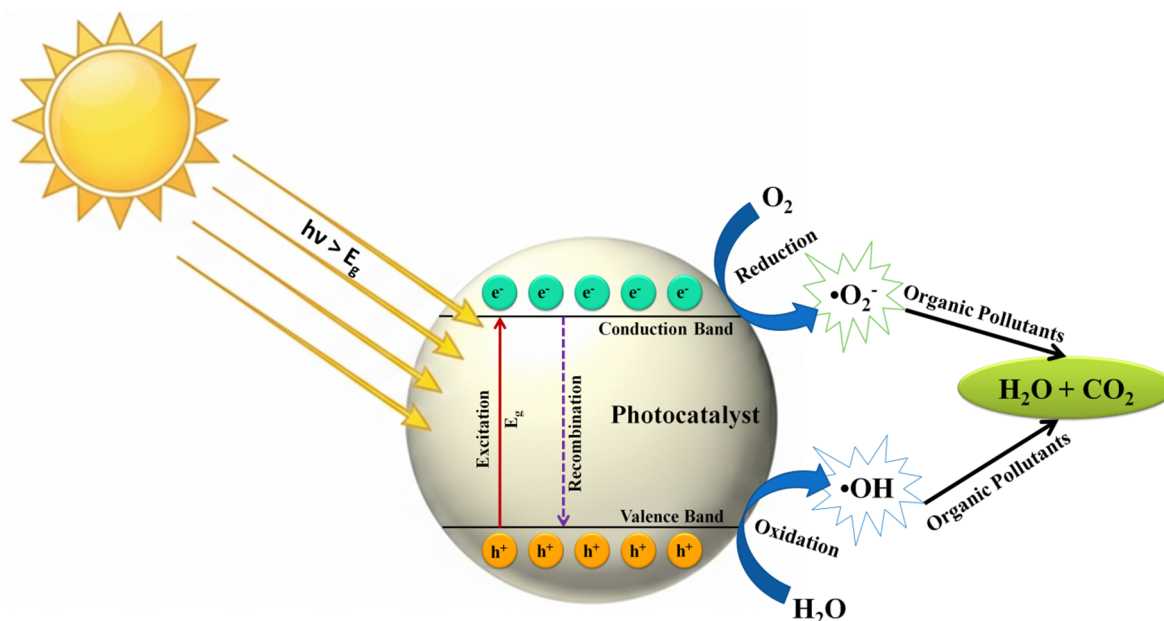


Figure 4. Photocatalysis Mechanism.

Photocatalytic nanocomposites are particularly effective for the removal of organic dyes, pharmaceutical residues, VOCs, and microbial contaminants in water and air purification systems. The photocatalytic process begins when semiconductor-based nanocomposites, such as TiO₂, ZnO, or g-C₃N₄, absorb photons from ultraviolet or visible light, leading to the generation of electron–hole pairs. During excitation, electrons move to the conduction band, leaving vacancies (holes) in the valence band. These charge carriers then participate in surface redox reactions: the excited electrons react with dissolved oxygen to form superoxide radicals ($\cdot\text{O}_2^-$), while the holes oxidize water or hydroxide ions to produce hydroxyl radicals ($\cdot\text{OH}$). These ROS are essential for degrading and mineralizing organic pollutants [65–67].

One of the major limitations of conventional photocatalysts, such as TiO₂, is their wide bandgap, which restricts light absorption to the UV region. To overcome this limitation, nanocomposite engineering strategies such as bandgap tuning, heterojunction formation, and noble metal doping have been employed. Hybrid nanocomposites, including TiO₂–graphene, ZnO–CNTs, and Ag–TiO₂ systems, exhibit improved charge separation and extended light absorption into the visible region, resulting in enhanced photocatalytic efficiency [68,69].

3.3. Fenton and Photo-Fenton Reactions

Fenton and photo-Fenton processes are well-established advanced oxidation methods that operate through the catalytic generation of highly reactive Hydroxyl Radicals ($\cdot\text{OH}$) via the reaction between iron species and hydrogen peroxide (Figure 5).

In the traditional Fenton reaction, Ferrous ions (Fe^{2+}) interact with hydrogen peroxide to produce highly reactive hydroxyl radicals, which can swiftly oxidize a wide range of organic pollutants. The reaction mechanism involves the oxidation of Fe^{2+} to Fe^{3+} with simultaneous formation of hydroxyl radicals ($\cdot\text{OH}$), followed by the photoreduction of Fe^{3+} back to Fe^{2+} , thereby completing the catalytic cycle. However, conventional homogeneous Fenton reactions suffer from drawbacks such as narrow operating pH range, sludge generation, and limited catalyst recyclability [70,71].

To address these issues, nanocomposite-based heterogeneous Fenton catalysts have been developed. Iron Oxide-based nanocomposites, such as Fe₃O₄–Graphene and Fe₂O₃–TiO₂, offer improved catalytic stability, enhanced hydroxyl radical generation, and easy separation from treated water. In photo-Fenton systems, UV or visible light further accelerates the regeneration of Fe^{2+} ions, significantly increasing pollutant degradation efficiency [72,73]. Fenton-based nanocomposites have been successfully applied in the degradation of antibiotics, pesticides, dyes, and phenolic compounds. For instance, Fe₃O₄–Carbon nanocomposites have demonstrated high efficiency in antibiotic degradation, while Iron Oxide–Silica hybrids are effective for phenolic wastewater treatment. Additionally, Cu–Fe₂O₃ nanocomposites have shown enhanced catalytic performance in dye-contaminated wastewater systems [74,75].

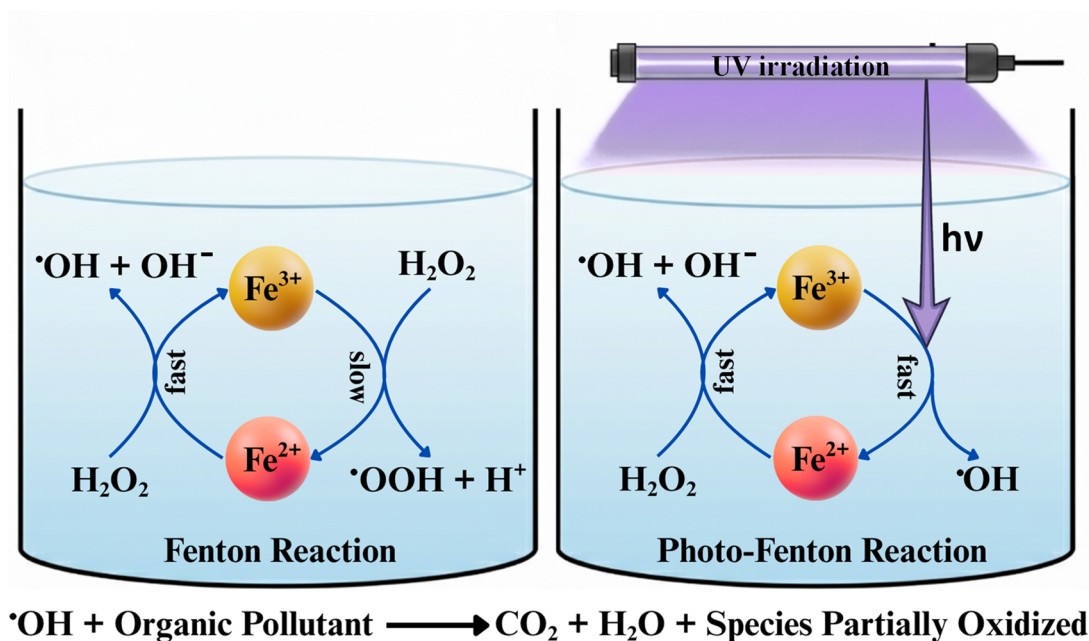


Figure 5. Fenton and Photo-Fenton Reaction.

3.4. Membrane-Based Filtration Using Nanocomposites

Membrane-based filtration is a separation method in which nanocomposite-modified membranes remove contaminants through size exclusion, electrostatic interactions, and chemical affinity (Figure 6). The addition of nanomaterials to the membrane structure enhances permeability, selectivity, resistance to fouling, and mechanical strength [76].

Polymeric nanocomposite membranes, such as PVDF–TiO₂ systems, are widely used in reverse osmosis and ultrafiltration processes for desalination and wastewater treatment [77]. Chitosan–ZnO membranes exhibit antibacterial properties and improved removal of organic pollutants [78]. Carbon-based nanocomposite membranes, including Graphene Oxide and Carbon nanotube-modified membranes, offer high water permeability, excellent salt rejection, and efficient oil–water separation capabilities.

Hybrid nanocomposite membranes further enhance membrane performance by combining multiple functionalities. MoS₂/Ag–TiO₂ hybrid membranes improve antifouling resistance and bacterial inactivation, while Fe₃O₄–polymer membranes enable magnetic-assisted separation and dynamic filtration processes. These membranes have been successfully applied in desalination plants, industrial wastewater treatment, and oil–water separation systems [79,80].

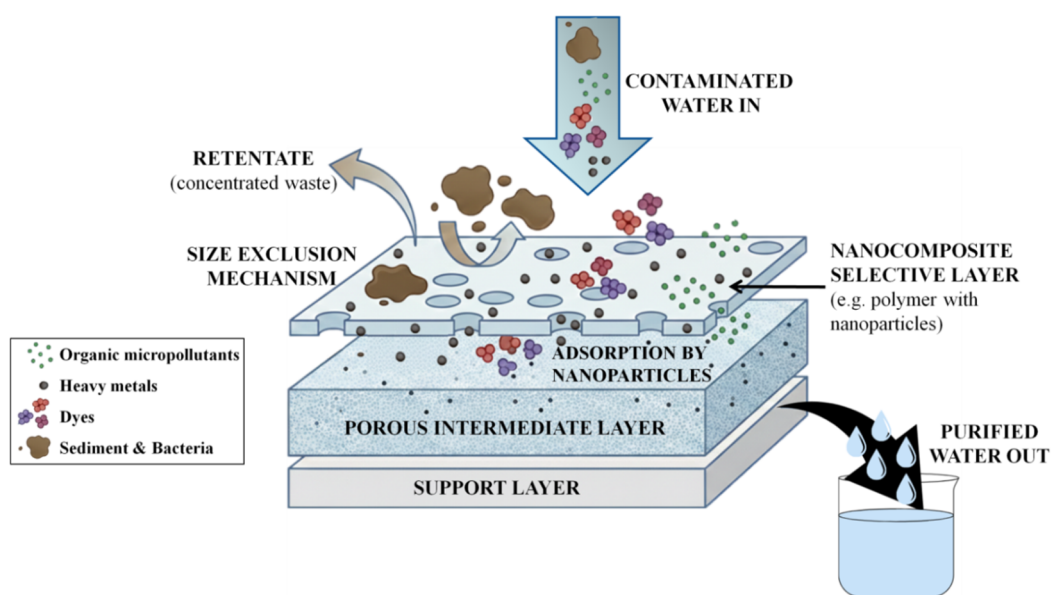


Figure 6. Membrane Based Filtration.

Table 2. Comparison of Different Environmental Remediation Mechanisms Using Nanocomposites.

Remediation Mechanism	Working Principle	Nanocomposites Used	Main Applications	References
Adsorption	Surface binding and pore diffusion	GO, CNTs, biochar, Chitosan, Fe ₃ O ₄	Heavy Metal removal, dye adsorption	[58–64]
Photocatalysis	Light-driven degradation of pollutants	TiO ₂ , ZnO, TiO ₂ -Graphene	Wastewater treatment VOC degradation, Air purification	[65–69]
Fenton & Photo-Fenton	Hydroxyl radical generation via Fe ²⁺ and H ₂ O ₂	Fe ₃ O ₄ , Cu-Fe ₂ O ₃ , Fe ₂ O ₃ -TiO ₂ hybrids	Industrial effluent treatment oil refinery wastewater degradation	[70–75]
Membrane filtration	Selective separation through nanocomposite membranes	PVDF-TiO ₂ , GO membranes	Seawater desalination pharmaceutical waste removal	[76–80]

4. Nanocomposites for Dye Degradation and Heavy Metal Removal

4.1. Dye Degradation

Dye pollution has emerged as a significant environmental issue due to the widespread use of synthetic dyes in industries such as textiles, paper, plastics, and food processing. Dyes including Methylene Blue, Rhodamine B, Congo Red, Malachite Green, and Crystal Violet are typically non-biodegradable and toxic, thereby requiring efficient and reliable removal strategies. Nanocomposites facilitate dye degradation through various mechanisms, including adsorption, photocatalysis, Fenton-like reactions, and Advanced Oxidation Processes (AOPs) [81].

In recent years, extensive research has explored the use of nanocomposites for environmental remediation, with a strong emphasis on dye degradation and the removal of heavy metals from wastewater. Scientists have engineered a diverse array of nanocomposite materials by integrating Metal Oxides, Carbon-based nanostructures, and polymer composites to improve adsorption capacity, catalytic efficiency, and overall stability. For example, TiO₂-based nanocomposites have been extensively explored for the photocatalytic breakdown of organic dyes under UV irradiation, achieving degradation efficiencies of up to 95% [82]. Likewise, GO nanocomposites exhibit exceptional adsorption capacities for dyes such as Methylene Blue and Rhodamine B, attributed to their expansive surface area and strong π - π interactions [83]. Moreover, magnetic nanocomposites like Fe₃O₄ have shown high effectiveness in removing heavy metals through combined adsorption and reduction processes [84].

Bio-nanocomposites have also been explored, leveraging natural polymers like chitosan and cellulose combined with metal nanoparticles to create eco-friendly and sustainable solutions [85]. However, challenges related to regeneration and stability has been reported in several studies, indicating the need for further optimization.

The integration of hybrid nanocomposites, such as TiO₂/GO and ZnO/Ag, has been proposed to enhance light absorption and improve catalytic performance [35,54,86]. Additionally, the functionalization of nanocomposites with amine, thiol, and carboxyl groups has been shown to significantly increase heavy metal adsorption efficiency [87,88].

4.2. Removal of Heavy Metals

The elimination of heavy metals using engineered nanocomposites has gained significant attention due to their high efficiency and versatile functionality. In Chromium removal, especially for Cr(VI), adsorption and reduction are the primary mechanisms involved. The reduction is typically driven by materials such as Fe₃O₄, zero-valent iron (ZVI), and Graphene-based nanocomposites, which facilitate the transformation of highly toxic Cr(VI) into the less harmful Cr(III) state. Additionally, functionalized Metal–Organic Frameworks (MOFs), biochar, and chitosan-derived composites demonstrate strong affinity toward Cr(VI) ions, enabling effective adsorption and removal from aqueous systems [89–93]. For Pb(II) removal, adsorption and precipitation are the most common strategies. Activated Carbon, zeolite, Graphene Oxide, and cellulose-based composites efficiently remove Pb(II) due to their high ion-exchange capacities [94–97]. Moreover, phosphate-functionalized nanocomposites facilitate the precipitation of Pb(II) as insoluble Pb₃(PO₄)₂ [98]. Hg(II) removal is often achieved through reduction and adsorption. Reduction processes typically involve nano-Selenium, Sulfur-doped Carbons, and thiol-functionalized polymers, which convert Hg(II) to (Hg(0)), making it easier to remove [99]. Adsorption, on the other hand, utilizes MOFs, biochar, and Silica-based composites to immobilize Hg(II) through strong binding interactions [100,101]. As(III) removal primarily relies on adsorption and oxidation. Iron-based nanocomposites, such as Fe₂O₃ and Fe₃O₄, demonstrate high selectivity for Arsenic adsorption [102]. Additionally, MnO₂-based composites facilitate oxidation of As(III) to As(V), which is more readily removed by adsorption [103].

4.3. Comparative Analysis of Adsorption Performance of Different Nanocomposites

To critically evaluate the practical performance of nanocomposites for environmental remediation, a comparative analysis of representative adsorption systems was performed using recent studies. The adsorption efficiency of nanocomposites is strongly governed by their surface chemistry, pore structure, functional groups, and pollutant–adsorbent interaction mechanisms. Functional groups containing Nitrogen, Sulfur, and Oxygen atoms provide abundant active sites for coordinating heavy metal ions through electrostatic attraction, surface complexation, ion exchange, and chelation. Consequently, surface-functionalized nanocomposites generally exhibit superior adsorption capacities and selectivity compared with their unmodified counterparts.

Among carbon-based nanocomposites, GO-Fe₃O₄ demonstrated rapid adsorption of Methylene Blue and Rhodamine B because of the combined effects of π – π interactions, electrostatic attraction, and magnetic recovery [83]. Likewise, polymer-functionalized graphene materials exhibited exceptionally high adsorption capacities for heavy metals. For example, poly(*N*-vinylcarbazole) with Graphene Oxide (PVK–GO) achieved an adsorption capacity of 887.98 mg g^{−1} for Pb(II), whereas 4-amino-3-hydrazino-5-mercapto-1,2,4-triazole on Graphene Oxide (AHMT–PRGO) exhibited adsorption capacities of 370.0 mg g^{−1} for Hg(II), 136.2 mg g^{−1} for Cr(VI), and 109.6 mg g^{−1} for Pb(II). These outstanding performances are primarily attributed to the presence of abundant amine, thiol, hydroxyl, and carboxyl functional groups, which provide multiple coordination sites for heavy metal ions [87,96].

Magnetic nanocomposites represent another important class of adsorbents because they combine high adsorption efficiency with simple magnetic recovery. Magnetic nanoparticles functionalized with meso-2,3-dimercaptosuccinic acid (MNP–DMSA) exhibited adsorption capacities of 116.54, 102.73, and 75.48 mg g^{−1} for Pb(II), Ni(II), and Cd(II), respectively, while maintaining excellent selectivity in multi-metal systems through the synergistic action of carboxyl and thiol functional groups [88]. Similarly, magnetic cellulose nanocrystals and a zinc MOF (MCNC@Zn–BTC) demonstrated a Pb(II) adsorption capacity of 558.66 mg g^{−1} and retained more than 80% of its adsorption performance after five regeneration cycles, highlighting its excellent reusability [97]. Greener Graphene Oxide–Ferrosoferric Oxide/Bentonite Nanocomposite (GGOF:B@1:1), a magnetized graphene-based green nanocomposite synthesized using sugarcane juice and bentonite, further demonstrated the capability of simultaneously removing Pb(II) and Cr(VI) from binary metal systems while maintaining efficient magnetic separation and reusability [91]. Magnetic acid-treated activated Carbon (MAC) also showed high removal efficiencies of 96.6% for Pb(II) and 91.4% for Cd(II) in real industrial wastewater, demonstrating the practical potential of magnetic nanocomposites for wastewater treatment [94].

For Chromium remediation, several nanocomposites combine adsorption with simultaneous redox transformation. Ultrasound-assisted nanoscale zero-valent iron on reduced Graphene Oxide (US–nZVI/rGO) removed Cr(VI) through both adsorption and reduction of toxic Cr(VI) to the less toxic Cr(III), resulting in an adsorption capacity of 80.05 mg g^{−1} with rapid removal kinetics [90]. Similarly, the Iron-based MOF into activated Carbon (Fe–BDC@AC) metal–organic framework composite exhibited a maximum adsorption capacity of 100 mg g^{−1} for Cr(VI), while Nickel nanoparticle-impregnated chitosan/sodium-alginate/poly(acrylic acid) hydrogel composite (Ni@CS/Na–Alg/PAAc) hydrogel achieved 74.5 mg g^{−1} owing to its high density of amino and carboxyl functional groups. These studies demonstrate that coupling adsorption with catalytic reduction substantially enhances pollutant removal efficiency [92,93].

Mercury removal remains particularly challenging because of the strong toxicity and persistence of Hg(II) in aquatic environments. Mesoporous Silica nanocomposites such as BIS-3 demonstrated an adsorption capacity of 178.6 mg g^{−1} with complete Hg(II) removal under optimized conditions, owing to their high surface area and Nitrogen-rich adsorption sites. More recently, PySiO₂ silica-based materials have expanded the functionality of nanocomposites by integrating selective Hg(II) adsorption with fluorescence sensing. Although their adsorption capacity (54.04 mg g^{−1}) is lower than that of BIS-3, they offer simultaneous pollutant detection and removal together with excellent selectivity and reusability, making them attractive for real-time environmental monitoring applications [100,101].

Recent developments have also expanded nanocomposite applications beyond adsorption alone. Photocatalytic nanocomposites such as Silver-doped zinc oxide nanoflakes (AZO@400 °C) effectively degraded pharmaceutical pollutants under natural sunlight, achieving degradation efficiencies of 82.28% for Ciprofloxacin and 75.00% for Azithromycin. The enhanced performance resulted from defect engineering, narrowed band gap energy, and efficient generation of reactive oxygen species, including superoxide and hydroxyl radicals [86]. Likewise, Fe₂O₃–Pd nanohybrids and MnO₂/biochar composites (MBC-100) combined adsorption with catalytic oxidation to remove arsenic species from water, illustrating the advantages of multifunctional nanocomposites over conventional adsorbents [102,103].

Overall, the comparative analysis demonstrates that no single nanocomposite is universally superior for every contaminant. Carbon-based nanocomposites generally provide the highest adsorption capacities because of their exceptionally high surface area and abundant functional groups, whereas polymer-functionalized nanocomposites offer excellent selectivity toward heavy metal ions. Magnetic nanocomposites provide the additional advantage of rapid recovery and excellent reusability, making them more suitable for practical wastewater treatment. Silica-based nanocomposites exhibit excellent selectivity for Mercury removal and, in some cases, combine adsorption with sensing functions. Meanwhile, metal oxide-based and photocatalytic nanocomposites offer multifunctionality by coupling adsorption with catalytic degradation or redox transformation of pollutants. Therefore, the selection of an appropriate nanocomposite should be based not only on adsorption capacity but also on pollutant type, regeneration ability, operational stability, selectivity, and overall treatment objectives. A quantitative comparison of representative nanocomposites, including adsorption capacities, removal efficiencies, and major mechanistic advantages, is presented in Table 3.

Table 3. Comparative adsorption performance of representative nanocomposites for environmental remediation.

Nanocomposite	Target Pollutant(s)	Adsorption/Degradation Capacity	Removal Efficiency/Rates	Major Advantages & Mechanism Highlights	Reference
GO-Fe ₃ O ₄	Methylene Blue (MB) Rhodamine B (RB)	MB: 100 mg g ⁻¹ RB: 80 mg g ⁻¹	~100% for MB in 1 min	Ultra-fast dye removal via planar π - π and electrostatic interactions. Fe ₃ O ₄ nanoparticles expand interlayer spacing (0.82→1.11 nm) Rapid magnetic recovery without filtration.	[83]
AZO@400 °C	Ciprofloxacin (CPF) Azithromycin (AZI)	Degradation Rates (k): CPF: 0.00651 min ⁻¹ AZI: 0.01077 min ⁻¹	CPF: 82.28% (240 min) AZI: 75.00% (120 min) (under natural sunlight)	Narrowed bandgap (3.07 eV) enhances solar light absorption. Lattice defect engineering facilitates generation of reactive species ($\bullet$ O ₂ ⁻) and ($\bullet$ OH ⁻) High surface-area nanoflake morphology with short charge transport paths.	[86]
AHMT-PRGO	Hg(II) Cr(VI) Pb(II)	Hg(II): 370.0 mg g ⁻¹ Cr(VI): 136.2 mg g ⁻¹ Pb(II): 109.6 mg g ⁻¹	High removal efficiency across all target heavy metals	Amine/thiol multidentate chelation centers (N, S, O). Exceptional selectivity for Hg(II) in complex metal mixtures. Fast equilibrium (30–60 min for Pb/Hg and high reusability (5 cycles).	[87]
MNP-DMSA	Pb(II) Ni(II) Cd(II)	Single System: Pb(II): 116.54 mg g ⁻¹ Ni(II): 102.73 mg g ⁻¹ Cd(II): 75.48 mg g ⁻¹ Ternary System: Pb(II): 64.50 mg g ⁻¹ Ni(II): 53.90 mg g ⁻¹ Cd(II): 27.18 mg g ⁻¹	High multi-metal removal efficiency	Dual functional groups (–COOH and –SH) minimize competitive ion binding. Magnetic core enables rapid isolation from treated solution. Highly monodispersed nanosize (~8.24nm).	[88]
US-nZVI/rGO	Cr(VI)	80.05 mg g ⁻¹ (Ultrasonic) 78.01 mg g ⁻¹ (Unassisted)	80.05% in 15 min (~65% in 1 min)	Ultrasonic pretreatment cleans oxide shell and accelerates Fe ²⁺ release. Synergistic physical adsorption and chemical reduction (Cr(VI) → Cr(III)). High tolerance across acidic to alkaline environments pH 9).	[90]
GGOF:B@1:1	Pb(II) Cr(VI)	Single System: Pb(II): 32.84 mg g ⁻¹ Cr(VI): 5.17 mg g ⁻¹ Binary System (1:1): Pb(II): 27.50 mg g ⁻¹ Cr(VI): 25.10 mg g ⁻¹	High performance in simultaneous binary mixtures	Green synthesis using sugarcane juice and bentonite clay. Magnetically separable via magnetite nanoparticles. Reusable over 4 cycles using 0.1M acid eluent.	[91]

Table 3. Cont.

Nanocomposite	Target Pollutant(s)	Adsorption/Degradation Capacity	Removal Efficiency/Rates	Major Advantages & Mechanism Highlights	Reference
Fe-BDC@AC	Cr(VI)	100.0 mg g ⁻¹ (Langmuir maximum)	85% at 25 ppm in 55 min	MOF impregnation in cinnamon-stick-based activated carbon avoids fine-powder limitations. Dual action: electrostatic attraction/ion exchange + redox reduction to Cr(III). Fast equilibrium (~50 min) and recyclable over 5 cycles.	[92]
Ni@CS/Na-Alg/PAAc	Cr(VI)	74.5 mg g ⁻¹ (Nanocomposite) 58.06 mg g ⁻¹ (Base hydrogel)	Optimal capacity achieved at pH 8	In-situ Ni nanoparticle formation increases surface area (63.6 m ² /g) and pore volume. Crosslinker-free gamma irradiation synthesis. Strong electrostatic uptake via amine and carboxyl groups.	[93]
MAC	Pb(II) Cd(II)	Pb(II): 86.2 mg g ⁻¹ Cd(II): 49.8 mg g ⁻¹	Pb(II): 96.6% Cd(II): 91.4% (in real wastewater)	Nitric acid activation increases active surface sites. Magnetite (Fe ₃ O ₄) addition enables magnetic separation. Proven effective in treating real battery manufacturing wastewater.	[94]
PVK-GO	Pb(II)	887.98 mg g ⁻¹	High removal efficiency at near-neutral pH	Exceptionally high capacity due to dense oxygen functionalization (COOH, -OH). Reaches adsorption equilibrium within 90 min. Combines GO surface area with PVK dispersion stability and antimicrobial properties.	[96]
MCNC@Zn-BTC	Pb(II)	558.66 mg g ⁻¹	>80% retention after 5 recycling cycles	Rapid adsorption equilibrium reached in 30 min. Magnetic separation achieved within 30 s (S _m = 41.42 emu/g). Synergy between green cellulose nanocrystals, magnetite, and carboxyl-rich MOF.	[97]
BIS-3	Hg(II)	178.6 mg g ⁻¹	100% up to 900 mg L ⁻¹ initial concentration	High porosity (296 m ² /g) and optimal nitrogen content (4.27%). Ultra-fast kinetics (equilibrium in 30 min). Stable and efficient under strongly acidic conditions (pH 2.0).	[100]
PySiO ₂	Hg(II)	54.04 mg g ⁻¹	High removal efficiency (LOD: 0.29 µM/0.058 ppm)	Chelation-free design with dual functionality (simultaneous fluorescence sensing & adsorption). High selectivity with strong fluorescence quenching (KSV = 2 × 10 ⁶ M ⁻¹). Effective in real aquaculture water samples across 4 cycles.	[101]
Fe ₂ O ₃ -Pd	As(III) As(V)	~82 mg g ⁻¹	~90% (synthetic water) 93% (real mine tailings)	Pd catalyzes in-situ oxidation of toxic As(III) to As(V), quadrupling capacity over pristine iron oxide. Broad working range (pH 2–11). Outperforms base oxide in complex real mining wastewater matrices.	[102]
MBC-100	As(III)	4.8 mg g ⁻¹ (10× higher than raw biochar)	94.6% in simulated groundwater (reduces As to <10 µg L ⁻¹ WHO limit)	MnO ₂ oxidizes toxic As(III) to As(V) (leaving only 5.9% residual As(III)). Sustainable matrix utilizing rice husk agricultural waste. Dual mechanisms: surface complexation and surface precipitation.	[103]

5. Recent Advances in Nanocomposite Synthesis

Recent advances in nanocomposite synthesis primarily focus on enhancing remediation efficiency, long-term stability, selectivity toward target contaminants, and practical applicability under real environmental conditions. In this context, researchers have increasingly emphasized sustainable design strategies, including green synthesis routes, strategic doping, heterojunction engineering, and surface functionalization. These approaches improve catalytic activity, adsorption capacity, and recyclability while simultaneously reducing environmental risks associated with toxic reagents, secondary pollution, and energy-intensive fabrication processes. Consequently, modern synthesis strategies aim not only to optimize nanocomposite performance but also to align with principles of environmental sustainability and green chemistry. Some important nanocomposite synthesis techniques and their applications are summarized in Table 4.

5.1. Green Synthesis Approaches

Green synthesis constitutes an eco-compatible and sustainable strategy for the fabrication of nanocomposites, employing biological resources such as plant extracts, microorganisms, and biopolymers. In contrast to conventional physicochemical methods often reliant on elevated temperatures, hazardous solvents, and toxic reducing agents, green synthesis mitigates environmental impact while enhancing biocompatibility and safety. The presence of naturally occurring biomolecules during synthesis facilitates controlled particle growth, surface stabilization, and functionalization, leading to nanocomposites with enhanced stability and remediation performance. As a result, green synthesis has emerged as a promising strategy for developing eco-friendly nanocomposites for pollution control applications.

5.1.1. Plant-Mediated Synthesis

Plant-mediated synthesis has emerged as one of the most widely adopted green approaches for nanocomposite fabrication. This approach is favored because of its procedural simplicity, economic viability, and scalability for large-scale production. Plant extracts are rich in diverse bioactive constituents such as flavonoids, polyphenols, alkaloids, terpenoids, and tannins, which act as intrinsic reducing, capping, and stabilizing agents during synthesis. These phytochemicals facilitate the transformation of metal ions into nanoscale structures, while simultaneously inhibiting particle agglomeration and enhancing surface properties [104,105].

Nanocomposites prepared via plant-assisted methods often display enhanced catalytic and adsorption performance, primarily owing to the retention of residual functional groups on their surface. For instance, Silver and Gold nanoparticles synthesized using extracts from neem, green tea, and aloe vera have exhibited enhanced catalytic performance along with pronounced antimicrobial and antioxidant properties [106–108].

Within the realm of environmental remediation, plant-derived nanocomposites composed of Fe_2O_3 , ZnO , and TiO_2 have demonstrated remarkable efficiency in heavy metal adsorption as well as in the photocatalytic degradation of dyes and other organic effluent. The environmentally benign nature of this synthesis route, coupled with its improved functional performance, makes it a promising strategy for large-scale applications in pollution control [109,110].

5.1.2. Microbial-Assisted Synthesis

Microbial-assisted synthesis employs microorganisms like bacteria, fungi, and algae to produce nanocomposites through biological reduction mechanisms. Microbes are capable of reducing metal ions via enzymatic activity, metabolic processes, and extracellular secretions, leading to the formation of stable nanostructures. Bacterial species like *Bacillus* and *Pseudomonas* produce enzymes and metabolites that facilitate nanoparticle formation, while fungi such as *Aspergillus* and *Fusarium* provide extensive surface area and high metal tolerance, enabling efficient nanocomposite synthesis [111–113].

Microbially synthesized nanocomposites often exhibit narrow size distribution, good crystallinity, and enhanced surface reactivity. Magnetite (Fe_3O_4) and Silver-based nanocomposites synthesized using bacterial and fungal cultures have shown high efficiency in pollutant adsorption, catalytic degradation, and magnetic recovery. Moreover, microbial synthesis offers benefits including reduced energy requirements, ease of large-scale implementation, and the generation of minimal toxic residues, rendering it a highly appealing approach for sustainable environmental remediation technologies [114–116].

5.1.3. Biopolymer-Based Synthesis

Biopolymer-assisted synthesis employs naturally derived polymers such as chitosan, cellulose, starch, and alginate as templates, stabilizers, or functional matrices in the fabrication of nanocomposites. These biopolymers contain a rich abundance of functional groups that enable strong interactions with metal ions and pollutants, thereby enhancing adsorption capacity and material stability. In addition, biopolymer-supported nanocomposites exhibit improved mechanical strength, biodegradability, and biocompatibility [117,118].

Among various biopolymers, chitosan has received particular attention owing to its abundant amino and hydroxyl functionalities, which provide excellent chelation ability for heavy metal ions. Chitosan-based nanocomposites doped with Metal or Metal Oxide nanoparticles have exhibited exceptional efficiency in heavy metal uptake, dye elimination, and antimicrobial effectiveness [119].

5.2. Doping and Heterojunction Formation for Enhanced Performance

To enhance the photocatalytic, electronic, and adsorption properties of nanocomposites, doping and heterojunction formation have emerged as effective material engineering strategies. These modifications play an important role in tuning the electronic structure, narrowing band gaps, improving charge separation efficiency, and increasing surface reactivity, thereby significantly improving the overall performance of nanocomposites in environmental remediation applications.

5.2.1. Doping in Nanocomposites

Doping refers to the intentional incorporation of foreign metallic or non-metallic atoms into the lattice of nanomaterials to modify their optical, electrical, and catalytic properties. Through controlled doping, defect sites and localized electronic states are introduced, which improves light absorption, charge carrier mobility, and catalytic activity [120].

Metal Doping

Metal doping is a widely employed strategy in semiconductor-based nanocomposites, where transition metals like Fe, Cu, Ag, and Au are incorporated into materials such as TiO₂, ZnO, and g-C₃N₄. The introduction of additional energy states within the band structure enhances light absorption and suppresses the recombination of photogenerated electron–hole pairs. As a result, metal-doped nanocomposites display superior photocatalytic and overall catalytic efficiency. For instance, Ag-modified TiO₂ nanocomposites have demonstrated markedly improved performance under visible light irradiation, making them highly effective for degrading organic dyes and wastewater pollutants [121–125].

Non-Metal Doping

Non-metal doping entails the incorporation of elements such as Nitrogen, Sulfur, Phosphorus, and Boron to tailor the band structure and electronic properties of nanocomposites. These dopants effectively modify the valence and conduction band positions, thereby enhancing charge separation and electron transport. Nitrogen-doped g-C₃N₄ has shown remarkable photocatalytic efficiency due to improved light absorption and reduced recombination of charge carriers. Overall, doping strategies not only enhance photocatalytic efficiency and charge transfer dynamics but also improve the thermal and chemical stability of nanocomposites, making them highly suitable for water treatment and environmental remediation applications [126–130].

5.2.2. Heterojunction Formation

Heterojunction formation involves coupling two or more semiconductors with compatible band structures to facilitate efficient separation and migration of photogenerated charge carriers. This approach significantly reduces electron–hole recombination and extends light absorption, leading to enhanced photocatalytic efficiency. Various heterojunction architectures have been developed to improve nanocomposite performance [131,132].

In Type-I heterojunctions, charge carriers are confined within a single semiconductor, leading to moderate enhancement in photocatalytic activity, as observed in CdS/ZnO systems [133]. In contrast, Type-II heterojunctions promote directional migration of electrons and holes between two different semiconductors, effectively suppressing recombination; TiO₂/g-C₃N₄ heterojunctions are a well-known example. Z-scheme heterojunctions represent an advanced design inspired by natural photosynthesis, where strong redox potentials are preserved through efficient charge transfer pathways [127,132].

5.3. Surface Functionalization and Hybridization

Surface functionalization and hybridization are additional strategies employed to further enhance the selectivity, stability, and pollutant interaction capability of nanocomposites. These modifications enable tailored surface chemistry and multifunctionality, thereby improving remediation efficiency under complex environmental conditions.

5.3.1. Surface Functionalization

Surface functionalization refers to the alteration of nanocomposite surfaces through the incorporation of specific functional groups such as –COOH, –NH₂, –OH, and –SH, or by the attachment of biomolecules. These modifications enhance surface reactivity, improve dispersion stability, and strengthen the affinity toward target pollutants. As a result, functionalized nanocomposites exhibit superior adsorption capacity and selectivity [134].

For example, amino-functionalized Graphene Oxide shows strong affinity toward heavy metal ions such as Pb(II) and Hg(II), making it highly effective for wastewater treatment [135]. Similarly, thiol-functionalized Silica nanoparticles selectively bind Mercury ions, resulting in enhanced removal efficiency from contaminated water sources [136].

5.3.2. Hybridization of Nanocomposites

Hybridization involves combining different classes of nanomaterials, such as Metal Oxides, Carbon-based materials, and polymers, to form multifunctional nanocomposites with improved physicochemical properties [53]. Magnetic hybrid nanocomposites, such as Fe₃O₄/Graphene Oxide systems, allow efficient magnetic separation and recovery after pollutant removal [137]. Polymer-based hybrids, including chitosan/ZnO nanocomposites, exhibit enhanced antibacterial and photocatalytic activity [138], while Carbon-based hybrids such as Graphene/TiO₂ composites show improved photocatalytic degradation of organic pollutants due to extended light absorption and enhanced charge transport [139].

Table 4. Important Nanocomposite Synthesis Techniques and Their Applications.

Synthesis Techniques	Key Features	Examples	Applications	References
Green synthesis (Plant based)	Uses plant extracts reducing agents	Neem, Green Tea, Aloe vera	Photocatalysis, heavy metal removal	[104–110]
Microbial synthesis	Uses microorganisms (bacteria, fungi, algae)	<i>Bacillus</i> , <i>Aspergillus</i>	Pollutant adsorption, catalytic degradation	[111–116]
Biopolymer-based synthesis	Uses natural polymers (chitosan, cellulose)	Chitosan/ZnO	Heavy metal removal, Biocompatibility	[117–119]
Metal doping	Incorporates transition metals for improved activity	Ag-TiO ₂ , Cu-ZnO	Light absorption, catalytic enhancement	[121–125]
Non-metal doping	Uses elements like N, S for band-gap modifications	N-doped g-C ₃ N ₄	Enhanced charge separation and improved stability	[126–130]
Heterojunction formation	Combines semiconductors to improve charge transfer	TiO ₂ /g-C ₃ N ₄ , BiVO ₄ /Graphene	Photocatalytic efficiency, redox reactions	[131–133]
Surface functionalization	Modifies surface with functional groups	Graphene Oxide-NH ₂	Selective metal adsorption (Pb, Hg), stability	[134–136]
Hybridization	Combines different nanomaterials for synergy	Fe ₃ O ₄ /Graphene Oxide, Chitosan/ZnO	Pollutant removal, antibacterial activity	[137–139]

6. Challenges and Limitations in Nanocomposite Applications

Nanocomposites have transformed environmental remediation owing to their high surface area, adaptable properties, and remarkable efficiency in pollutant removal. Nevertheless, despite their promise, several obstacles limit their large-scale application, including particle agglomeration, difficulties in recyclability, potential toxicity, and economic constraints (Table 5). Addressing these limitations is crucial for advancing nanocomposite applications from laboratory research to real-world environmental solutions.

6.1. Nanoparticle Agglomeration and Stability Issues

A key limitation in the use of nanocomposites for environmental remediation is the propensity of nanoparticles to agglomerate. Due to their high surface energy and strong van der Waals forces, nanoparticles tend to cluster together. This aggregation reduces the effective surface area and, in turn, reducing the availability of active sites, leading to diminished performance and a consequent decline in adsorption capacity and catalytic performance. Such instability directly limits the efficiency and long-term applicability of nanocomposites in real environmental systems. Several factors contribute to nanoparticle agglomeration. The high surface energy of nanoparticles drives aggregation as a means of minimizing free energy. Electrostatic interactions between charged particles further promote clustering, especially under unfavorable dispersion conditions. Additionally, variations in solution pH and ionic strength, particularly in the presence of dissolved salts, can destabilize nanocomposites, resulting in precipitation or sedimentation. Long-term storage also poses stability issues, as prolonged aging often leads to structural degradation and performance loss [140,141].

6.2. Recyclability and Regeneration

Although nanocomposites demonstrate excellent pollutant removal efficiency, their recyclability and regeneration remain significant challenges for sustainable application. Repeated usage cycles often lead to a gradual loss of performance due to structural degradation, fouling, or leaching of active components. These issues increase operational costs and limit large-scale implementation. Several factors contribute to poor recyclability. Repeated adsorption–desorption cycles can cause physical and chemical damage to the nanocomposite structure,

reducing its lifespan. In metal-based nanocomposites, leaching of metal ions like Ag, Cu, or Fe not only decreases catalytic efficiency but also introduces secondary contamination risks. Additionally, fouling by organic pollutants or biofilm formation can block active sites, further diminishing performance [142].

6.3. Toxicity and Environmental Concerns

Despite their effectiveness, nanocomposites raise important toxicity and environmental safety concerns due to their nanoscale size and high chemical reactivity. The uncontrolled release of nanoparticles into ecosystems may result in bioaccumulation, cytotoxicity, and long-term ecological damage. These risks necessitate careful assessment before widespread environmental deployment. Certain nanomaterials, including Silver and Zinc Oxide nanoparticles, have been reported to accumulate in aquatic organisms, leading to toxic effects. Leaching of toxic metal ions like Cr, Pb, Hg, and Ag from nanocomposites can contaminate water sources and pose serious health risks. Furthermore, interactions between metal oxide nanoparticles and biological systems may generate ROS, causing oxidative stress, DNA damage, and cellular toxicity [143–145].

6.4. Scalability Challenges

Despite notable success at the laboratory scale, the large-scale fabrication and commercialization of nanocomposites remain impeded by substantial economic and technical constraints. One of the primary obstacles is the difficulty in maintaining consistent particle size, morphology, and physicochemical properties during scale-up. Variations in synthesis conditions can lead to batch-to-batch inconsistencies, ultimately affecting adsorption capacity, catalytic activity, and long-term stability. Furthermore, many synthesis techniques, including hydrothermal, sol–gel, and chemical vapor deposition (CVD), are difficult to scale continuously while maintaining product quality and reproducibility [146,147].

6.5. Cost Analysis and Limitations of Nanocomposites

The economic feasibility of nanocomposites is a critical factor governing their transition from laboratory research to industrial-scale environmental remediation. Although nanocomposites generally exhibit superior adsorption capacities, rapid reaction kinetics, and high selectivity toward pollutants, their commercial deployment is often constrained by the relatively high costs associated with raw materials, synthesis methods, and post-treatment recovery. Carbon-based nanomaterials such as GO, CNTs, and MOFs remain considerably more expensive than conventional adsorbents because of complex synthesis procedures and purification requirements. In contrast, Metal Oxide nanocomposites based on TiO_2 , ZnO , and Fe_3O_4 are comparatively economical and have demonstrated better prospects for large-scale wastewater treatment owing to their abundant availability and established synthesis technologies [148,149].

The synthesis route significantly influences the overall production cost of nanocomposites. Conventional methods such as hydrothermal synthesis, CVD, and sol–gel processing generally require elevated temperatures, prolonged reaction times, and sophisticated instrumentation, leading to higher energy consumption and capital investment. Conversely, green synthesis approaches employing plant extracts, microorganisms, and agricultural waste significantly reduce chemical consumption and processing costs while minimizing environmental impacts. These sustainable approaches are increasingly regarded as economically attractive alternatives for future industrial production [150,151].

Operational expenses must also be considered when evaluating the economic viability of nanocomposites. These include catalyst regeneration, membrane replacement, energy requirements for photocatalytic processes, and recovery of nanomaterials after treatment. Magnetic nanocomposites based on Fe_3O_4 provide an important advantage because they can be rapidly separated using an external magnetic field, thereby reducing operational costs and facilitating repeated reuse. Nevertheless, gradual performance deterioration after multiple regeneration cycles may still increase long-term treatment expenses [152,153].

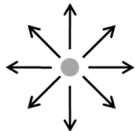
Table 5. Summary of Challenges and Limitations of Nanocomposites.

Challenges	Description
Agglomeration	Nanoparticles cluster due to Van der Waals forces
Recyclability	Reduced efficiency after multiple uses and structural damage
Toxicity and Environmental Concerns	Nanomaterials cause bioaccumulation and cytotoxicity
Scalability and Cost	High material and production costs, batch variability

7. Future Prospects and Research Directions in Nanocomposites

Nanocomposites have exhibited significant promise in environmental remediation, especially in wastewater treatment and pollution mitigation. However, to maximize their real-world applications, future research must focus on multifunctionality, sustainability, advanced computational techniques, and large-scale implementation (Table 6). Emerging technologies such as AI, biodegradable materials, and regulatory frameworks are shaping the next phase of nanocomposite development. This section explores key future directions that can improve the effectiveness, expand scalability, and promote the sustainability of nanocomposites in environmental remediation.

Table 6. Advancements and Future Strategies in Nanocomposite Research.

Future Prospects	Key Focus	Strategies/Approaches
 Multifunctional nanocomposites	Removing multiple pollutants simultaneously	Hybrid photocatalysts, magnetic–biological hybrids, self-regenerating materials, and multi-pollutant removal systems
 AI and machine learning integration	Optimizing synthesis and performance prediction	Predictive modeling, automated synthesis optimization, real-time pollution monitoring, and data-driven materials discovery
 Eco-friendly and biodegradable nanocomposites	Reducing environmental toxicity and enhancing sustainability	Green synthesis, biodegradable polymer composites, waste-derived nanomaterials, and self-decomposing nanocomposites
 Industrial application and policies	Commercialization and regulatory compliances	Cost reduction, quality control, safety assessments, certification, and public–private partnerships

7.1. Multifunctional Nanocomposites for Integrated Remediation

The future of nanocomposite-based environmental remediation is strongly focused on the development of multifunctional materials capable of simultaneously addressing diverse classes of pollutants. Traditional nanomaterials are typically engineered to target a single contaminant, limiting their effectiveness in complex and mixed wastewater systems. In contrast, next-generation multifunctional nanocomposites are designed to combine multiple remediation processes such as adsorption, photocatalysis, antimicrobial action, and redox reactions within a single platform. These integrated systems are crucial for the efficient removal of heavy metals, organic dyes, pharmaceuticals, pesticides, and emerging pollutants like microplastics.

Recent advancements highlight several key innovations in multifunctional nanocomposite design. Hybrid photocatalysts formed by coupling semiconductors such as TiO_2 and BiVO_4 with Carbon-based materials such as Graphene Oxide and Carbon nanotubes demonstrate improved photocatalytic degradation of pollutants under visible light, owing to enhanced charge separation and broader light absorption capabilities [14,30,54,72,154]. Magnetic–biological hybrid nanocomposites, particularly Fe_3O_4 -based systems combined with biopolymers such as chitosan or starch, offer dual benefits of high adsorption efficiency and facile magnetic recovery, along with improved biodegradability [36,50]. Furthermore, the development of self-regenerating nanocomposites capable of self-cleaning or catalytic reactivation significantly enhances material longevity and cost-effectiveness. Designing single nanocomposite systems that can simultaneously remove dyes, antibiotics, and pesticides represents a critical step toward advanced and compact wastewater treatment technologies.

7.2. Artificial Intelligence and Machine Learning in Nanocomposite Optimization

The integration of AI and ML into nanomaterials research is emerging as a transformative approach for accelerating nanocomposite design, synthesis, and performance optimization. Traditional experimental methods rely heavily on trial-and-error processes, which are time-consuming and resource-intensive. AI-driven models, in

contrast, can process large datasets to predict material properties, optimize synthesis parameters, and guide rational nanocomposite design with significantly reduced experimental effort.

AI and ML have demonstrated broad applicability in nanocomposite research. Predictive modeling techniques can estimate adsorption capacity, photocatalytic efficiency, stability, and reusability based on physicochemical properties and structural features. Automated synthesis optimization using machine learning algorithms enables precise control over reaction parameters like temperature, precursor concentration, and reaction time, leading to improved reproducibility and performance. Additionally, AI-powered sensing systems integrated with nanocomposites allow real-time pollutant detection and adaptive remediation responses. Data-driven material discovery further facilitates the identification of novel nanocomposites with superior remediation capabilities by mining existing material databases. The incorporation of AI and ML is expected to significantly reduce research timelines while enhancing the efficiency and scalability of next-generation nanocomposites.

7.3. Eco-Friendly and Biodegradable Nanocomposites

Sustainability has become a central concern in nanotechnology, particularly due to the potential toxicity and persistence of certain nanomaterials in the environment. To address these concerns, future research is increasingly focused on the development of eco-friendly, biodegradable, and renewable nanocomposites that minimize long-term ecological and health risks.

A range of sustainable approaches has been investigated for the development of nanocomposites. Green synthesis methods utilizing plant extracts, bacteria, and fungi avoid the use of toxic chemicals and help minimize environmental impact [111]. Biodegradable polymer-based nanocomposites, incorporating materials such as cellulose, starch, chitosan, and alginate, offer enhanced sustainability while maintaining high remediation efficiency [36,78,93,117,137]. The transition toward eco-friendly nanocomposites is essential for ensuring regulatory compliance, environmental safety, and long-term applicability of nanotechnology-based remediation systems.

7.4. Industrial-Scale Applications and Policy Regulations

Despite significant advancements at the laboratory scale, the large-scale commercialization of nanocomposites for environmental remediation remains limited due to economic, technical, and regulatory barriers. Bridging the gap between academic research and industrial deployment requires coordinated efforts in scalable manufacturing, safety validation, and policy development.

Key challenges in industrial-scale applications include high production costs associated with energy-intensive synthesis methods and advanced raw materials. Maintaining material consistency and quality control across large production batches remains a major concern, as performance variability can undermine industrial reliability. Additionally, environmental and health safety issues necessitate comprehensive toxicity assessments before regulatory approval. The lack of standardized international guidelines for nanocomposite use in water treatment further complicates large-scale adoption.

To address these issues, regulatory frameworks are being developed by organizations such as Environmental Protection Agency (EPA), REACH, and ISO to establish toxicity thresholds, disposal protocols, and safety standards for nanomaterials. Certification and compliance based on environmental impact assessments will be essential for future deployment. Furthermore, strengthened collaboration among academia, industry, and policymakers through public-private partnerships can accelerate technology transfer and commercialization. Establishing clear global regulations and sustainable production strategies will be crucial for integrating nanocomposites into real-world environmental remediation systems.

The advancement of nanocomposites in environmental remediation depends on the integration of multifunctional material design, AI-driven optimization, sustainable synthesis methods, and large-scale industrial deployment. The integration of AI, biodegradable materials, and scalable manufacturing strategies will accelerate the transition of nanocomposites from laboratory research to practical applications. With continued advancements, nanocomposites are poised to play a transformative role in global pollution control and sustainable environmental management.

7.5. Real-Life Applications and Industrial Implementation

Although numerous nanocomposites have demonstrated exceptional pollutant removal efficiencies under laboratory conditions, successful translation into real-world environmental remediation requires pilot-scale validation, economic feasibility, and regulatory approval. In recent years, several nanocomposite systems have progressed toward practical implementation in wastewater treatment, air purification, and environmental monitoring. Metal oxide nanocomposites such as TiO_2 , ZnO , and Fe_3O_4 have been incorporated into photocatalytic reactors, membrane filtration units, and adsorption columns for treating textile effluents, pharmaceutical

wastewater, and mining discharge because of their excellent stability and high removal efficiencies. Carbon-based nanocomposites, including GO and Activated Carbon hybrids, have also been integrated into advanced filtration systems for removing heavy metals, dyes, pharmaceutical residues, and emerging contaminants [151,155].

Industrial wastewater generated from textile dyeing, electroplating, leather processing, mining, and pharmaceutical manufacturing represents one of the most promising application areas for nanocomposite technologies. Magnetic nanocomposites have attracted considerable industrial interest because they enable rapid magnetic recovery after adsorption, thereby reducing sludge generation and simplifying process operation. Similarly, nanocomposite membranes are increasingly being investigated for desalination, membrane bioreactors, and advanced wastewater reclamation owing to their superior permeability, fouling resistance, and long operational lifespan [156].

Despite these advances, several challenges continue to hinder widespread industrial implementation. The reproducibility of nanocomposite synthesis on a large scale, long-term material stability in complex wastewater matrices, catalyst deactivation, membrane fouling, and variability in contaminant composition remain significant technical limitations. Furthermore, regulatory concerns regarding nanoparticle release, life-cycle assessment, environmental toxicity, and disposal protocols must be addressed before commercialization. Consequently, future industrial deployment will require standardized production methods, comprehensive safety assessments, and internationally harmonized regulations governing nanomaterial manufacturing and environmental applications [149,153].

Collaborative efforts involving academia, industry, and regulatory agencies are expected to accelerate technology transfer from laboratory research to commercial environmental treatment systems. Integration of green synthesis, biomass-derived materials, artificial intelligence-assisted process optimization, and circular economy principles will further improve the sustainability and commercial viability of nanocomposite-based remediation technologies [149–151].

8. Conclusions

This literature review highlights recent progress, challenges, and future prospects of nanocomposites in environmental remediation. Metal- and Carbon-based nanocomposites have gained significant attention for their effectiveness in addressing water pollution, heavy metal removal, and the catalytic breakdown of organic contaminants due to their combined adsorption and photocatalytic properties. Studies indicate that nanocomposites offer superior adsorption and catalytic performance compared to conventional materials. Advanced synthesis techniques such as hydrothermal, sol–gel, and chemical vapor deposition enable the development of materials with high surface area, porosity, and functionalization, enhancing their remediation efficiency. Functionalized and hybrid nanocomposites have shown strong potential in degrading persistent pollutants like dyes, pesticides, and pharmaceutical residues.

Despite these advancements, challenges such as scalability, cost, environmental safety, and long-term stability limit their widespread application. Future progress will depend on innovative, sustainable, and scalable approaches to improve their practical implementation. With continuous progress in materials science, surface engineering, and green chemistry, the development of next-generation nanocomposites with tailored functionalities and minimal environmental impact is anticipated. Moreover, the integration of computational modeling and machine learning can significantly aid in designing more efficient and sustainable materials.

Author Contributions

S.A.: Writing—original draft, methodology, preparation of figures and tables, visualized the study, writing—review and editing. H.S.: Writing—original draft, investigated the study, literature survey, data collection. V.G.: Writing—original draft, investigated the study, literature survey, data collection. R.K.S.: Supervision, Conceptualization, Validation. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

Given the role as Journal Editor, Prof. Rakesh Kumar Soni had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

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