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# Nanomaterial-Based Dye Removal from Wastewater

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**ABSTRACT**

Dyes represent a significant class of organic pollutants prevalent in various industries, including textiles, leather tanning, cosmetics, and pigment production. These industries extensively utilize dyes to impart color to their products, but the effluents discharged during manufacturing pose substantial risks to both environmental and human health. The untreated or inadequately treated dye-laden wastewater can contaminate water bodies, adversely affecting aquatic life, disrupting ecosystems, and posing health hazards to humans through contaminated water sources. To mitigate the harmful effects of dye-polluted wastewater, it is imperative that such wastewater undergo thorough treatment before being released into the environment. Scientific and technological advancements have paved the way for the development of multiple techniques aimed at removing dyes from both industrial and domestic wastewater. Traditional methods such as adsorption, coagulation-flocculation, oxidation, and biological treatment have been employed with varying degrees of success. Among these methods, the application of nanotechnology has emerged as a particularly promising and innovative approach. Nanotechnology involves the use of nanomaterials, which have unique properties and high surface areas that enhance their ability to adsorb dyes effectively. This method has shown significant potential in improving the efficiency and speed of wastewater treatment processes. The integration of nanotechnology in dye removal processes is anticipated to become a cornerstone in the industry, offering a highly efficient and sustainable solution for purifying dye-contaminated wastewater.

***Keywords:*** Wastewater, Dyes, Nanomaterials, Removal, Nanotechnology, Environment

## Introduction

As the human population and economy grow, the global water demand is rapidly increasing. The combined effects of population growth, changing lifestyles, and the development of industrial cities with large factories are exerting immense pressure on our essential water resources, leading to widespread water stress in many countries. As the population expands, the demand for food rises correspondingly, further straining water resources. Agriculture, which already consumes a significant portion of global freshwater, must increase its production to meet the needs of the growing population. This often results in over-abstraction of water from rivers, lakes, and aquifers, depleting these vital resources. Over-extraction not only threatens the sustainability of water supplies but also harms aquatic ecosystems that depend on stable water levels to support diverse plant and animal life. Additionally, industrialization and urbanization intensify this pressure. Large factories and industrial processes require substantial amounts of water for production, cooling, and waste disposal[1-4]. The establishment of industrial cities often leads to water contamination with chemicals, heavy metals, and other pollutants, rendering the remaining water resources less usable without extensive and costly treatment. Among these, Dyes are a significant class of organic pollutants common in industries such as textiles, pigment production, leather tanning, and cosmetics. These industries extensively use dyes to color their products, but the effluents discharged during production pose significant risks to both the environment and human health[5-7]. Untreated or inadequately treated dye-laden



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wastewater can contaminate water bodies, adversely affecting aquatic life, disrupting ecosystems, and posing health risks to humans through contaminated water sources. To mitigate the harmful effects of dye-contaminated wastewater, it is essential that such wastewater undergo thorough treatment before being released into the environment[8, 9]. Advances in science and technology have led to the development of numerous techniques aimed at removing dyes from industrial and domestic wastewater. Traditional methods such as adsorption, coagulation-flocculation, oxidation, and biological treatment have been employed with varying degrees of success. Among these methods, the application of nanotechnology has emerged as a particularly promising and innovative approach. Nanotechnology involves the use of nanomaterials, which possess unique properties and high surface areas that enhance their ability to adsorb dyes effectively. This method has shown significant potential in improving the efficiency and speed of wastewater treatment processes. The integration of nanotechnology into dye removal processes is anticipated to become a cornerstone of the industry, offering a highly efficient and sustainable solution for purifying dye-contaminated wastewater[9-11].

## DYES

Dyes are organic compounds that can be classified based on their compositions, colors, and uses. They play a crucial role in various industries, especially textiles, food, and cosmetics[12, 13]. The main types of dyes based on different applications are ionic and non-ionic dyes, as detailed in Figure 1. Ionic dyes can be further categorized into two main groups: anionic and cationic dyes. Anionic dyes, also known as acid dyes, carry a negative charge and are commonly used for dyeing protein fibers like wool and silk, as well as nylon. These dyes form ionic bonds with the positive in the fibers, resulting in strong and lasting color. Examples of anionic dyes include direct dyes, reactive dyes, and acid dyes. Cationic dyes, also called basic dyes, carry a positive charge and are particularly effective in dyeing acrylic fibers and some types of modified nylon. These dyes form ionic bonds with negatively charged groups in the fibers. Cationic dyes are known for their bright and vivid colors, but they often have lower light fastness compared to other dye types. They are commonly used in the production of colored paper and dyeing leather[14-16]. Non-ionic dyes, which do not carry an electrical charge, include disperse dyes and solvent dyes. Disperse dyes are primarily used for dyeing synthetic fibers like polyester. These dyes are insoluble in water and are applied as a fine aqueous dispersion. When heated, the dye particles dissolve into the fiber, coloring it from within. Solvent dyes, as the name suggests, are soluble in organic solvents and are used for coloring plastics, gasoline, oils, and waxes. The choice between ionic and non-ionic dyes depends on various factors, including the type of material being dyed, the desired color intensity and fastness, and the specific application requirements. In the food industry, dyes must meet strict safety and regulatory standards. Most food dyes are water-soluble and fall into the ionic category, particularly anionic dyes. The cosmetics industry uses a wide range of dyes, both ionic and non-ionic, depending on the specific product and its intended use[14, 17, 18].

The complex structure of dyes makes them remarkably stable and resistant to environmental conditions. This stability, however, renders them ineffective in the presence of heat, light, microbes, and even oxidizing agents, which poses significant challenges in dye degradation. The robust chemical bonds and structures designed to withstand various conditions also mean that dyes are persistent pollutants. When released into the environment, particularly in water bodies, they pose serious environmental hazards. The presence of colors in water bodies affects the penetration of sunlight, reducing oxygen solubility and thereby diminishing water quality. This can prevent photosynthesis in aquatic plants and disrupt the entire aquatic ecosystem, affecting both plants and animals. In addition to environmental damage, dyes can also cause significant harm to human health. Many dyes are known to be toxic, carcinogenic, or allergenic. Prolonged exposure to these compounds can lead to various health issues, including skin irritation, respiratory problems, and even cancer. As such, the safe management and removal of dyes from industrial effluents are critical[19-21].

Azo dyes, anthraquinone dyes, and triarylmethane dyes, respectively, such as Disperse Red 19[22], Disperse Red 9(1-(methylamino)anthraquinone)[23], and Victoria Pure Blue BO (VPBBO$^+$)[24] (Table 1), are some of the studied and common dyes class in industrial applications. Azo dyes, in particular, are known for their vivid colors and wide range of hues, making them popular in the textile industry. However, their complex molecular structures make them difficult to break down. Anthraquinone dyes are known for their durability and resistance to fading, while triarylmethane dyes are noted for their bright colors. Among these, Researchers have focused extensively on finding effective methods to remove these dyes from wastewater and water reservoirs.

### *Dye Removal Techniques*

A wide range of technologies have been developed and applied for the scavenging of dyes, as shown is it Figure 2, divided into three main categories: biological methods, chemical methods, and physical methods[25].





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Biological methods involve the use of living organisms or their by-products to remove dyes from wastewater. This approach includes biodegradation, where microorganisms such as bacteria, fungi, and algae break down dye molecules into less harmful substances. Enzymatic degradation, a subset of biological methods, leverages enzymes produced by these organisms to catalyze the breakdown of complex dye structures. Additionally, biosorption involves the accumulation of dyes on the surface of biological materials like plant biomass, microbial cells, or agricultural waste. While biological methods are generally considered environmentally friendly and cost-effective, they may be limited by the specific range of dyes they can target and the time required for complete decolorization. Chemical methods encompass a variety of techniques that involve chemical reactions to remove or neutralize dyes. Among these are oxidation processes, such as advanced oxidation processes, which generate highly reactive species like hydroxyl radicals to degrade dye molecules. Coagulation and flocculation are other common techniques, involving the addition of chemicals to aggregate dye particles, making them easier to separate from the liquid. Reduction methods, like chemical reduction, transform dyes into colorless compounds, while electrochemical methods utilize electrical currents to induce redox reactions that break down dyes. Although chemical methods can be highly effective and rapid, they often come with high operational costs and the potential for secondary pollutants. Among these, Physical methods focus on the separation of dyes from wastewater without altering their chemical structure. Adsorption is a widely used physical method, where dye molecules adhere to the surface of solid materials such as activated carbon, nanomaterials, clay, or synthetic polymers. Membrane filtration techniques, including ultrafiltration and nanofiltration, physically separate dye molecules based on size exclusion principles. Other methods, like ion exchange, employ resins to swap dye ions with other ions in solution. Physical methods are generally straightforward to implement and can be highly efficient; however, they often require frequent maintenance and regeneration of the materials used[25-28].

As a result, each of these methods has its advantages and limitations. The choice of technology often depends on various factors, such as the type of dye, its concentration, the volume of wastewater, and regulatory requirements. In many cases, a combination of these methods—known as a hybrid or integrated approach—is employed to achieve optimal dye removal efficiency and meet environmental standards. Meanwhile, nanotechnology represents a cutting-edge frontier in water and wastewater treatment, with the potential to revolutionize the field. As research continues to advance, it is anticipated that nanomaterials will play a crucial role in developing sustainable, cost-effective, and highly efficient treatment solutions. These advancements promise not only to address current environmental challenges but also to pave the way for future innovations in the management of water resources.

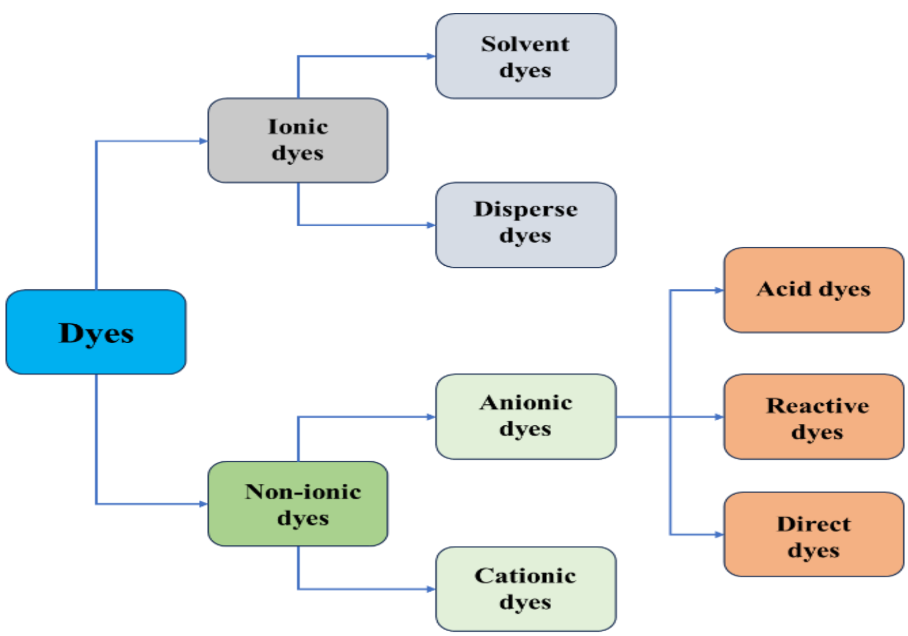


**Fig. 1.** Classification of colors based on their ionic or non-ionic properties.



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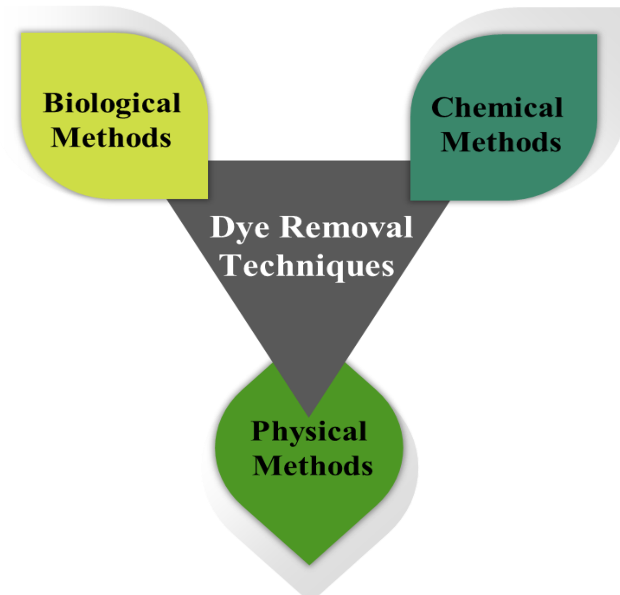
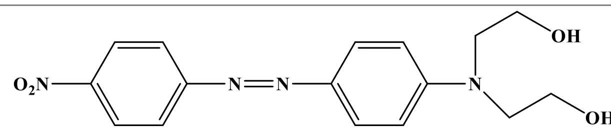
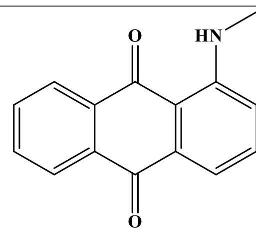
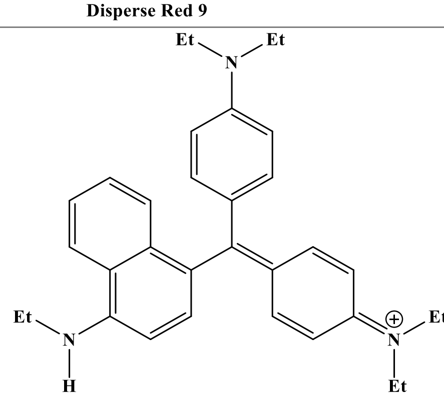



**Fig. 2.** Different types of Dye Removal Techniques.

**Table 1.** The Class of common dyes Molecular structures of Disperse Red 19, Disperse Red 9, and VPBBO⁺.

| Class of common dyes | Example |
| --- | --- |
| **Azo dyes** |  **Disperse Red 19** |
| **Anthraquinone dyes** |  **Disperse Red 9** |
| **Triarylmethane dyes** |  **VPBBO⁺** |





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## Various Nanomaterials In Dye Adsorption

Rapid advancements in recent years have dramatically propelled nanotechnology research, especially in the domain of metallic nanoparticles (NPs). NPs, which range in diameter from 1 to 100 nanometers, possess distinct physicochemical properties that set them apart from bulk materials. These properties include large surface-to-volume ratios, quantum effects, and unique electronic characteristics. The exploration of nanotechnology began in earnest in the 1980s and has since evolved into a cornerstone of modern scientific discovery[29]. This field offers a multitude of possibilities for enhancing systems, materials, and tools with new properties. Its applications span various domains such as agriculture, food processing, environmental management, medicine, and more. In the context of water and wastewater treatment, nanotechnology has provided innovative solutions that address the limitations of conventional methods. Specifically, it has emerged as a cost-effective and efficient alternative for removing pollutants, including toxic metals, organic contaminants, and microorganisms[30, 31].

Different types of nanomaterials have been developed and studied by researchers across the globe(Figure 3). Among these, metal oxide NPs such as titanium dioxide ($TiO_2$), zinc oxide (ZnO), iron oxides ($Fe_2O_3$ and $Fe_3O_4$), and cerium oxide ($CeO_2$) have garnered significant attention. These materials exhibit high reactivity and photolytic properties, making them excellent adsorbents for water purification. Their large surface area and affinity for a diverse range of functional groups enable them to interact effectively with various contaminants, facilitating their removal from water systems[32].

A recent research study focuses on the removal of cationic dyes from simulated wastewater using $Fe_3O_4$ NPs loaded with activated carbon ($Fe_3O_4$@AC NPs). In this work, $Fe_3O_4$@AC NPs were synthesized using the co-precipitation method, which involved the simultaneous precipitation of iron salts and the incorporation of activated carbon. This synthesis method resulted in NPs with a high surface area and magnetic properties, making them easy to separate from the aqueous medium after adsorption. The study demonstrated that $Fe_3O_4$@AC NPs exhibited excellent adsorption behavior towards cationic dyes under optimal process conditions, including pH, contact time, and temperature. Specifically, the maximum adsorption capacities for methylene blue (MB) and brilliant green (BG) dyes were found to be 138 mg/g and 166.6 mg/g, respectively. This indicates a high affinity of the $Fe_3O_4$@AC NPs for these dyes, making them a promising material for dye removal from wastewater. To further evaluate the performance of the $Fe_3O_4$@AC NPs, the researchers compared their efficiency with other synthesized nano adsorbents for cationic dye removal. The results showed that $Fe_3O_4$@AC NPs were more efficient than the other adsorbents tested, suggesting that the combination of magnetic NPs with activated carbon enhances the adsorption capacity. The adsorption data fitted best with the Langmuir isotherm model, which suggests that the adsorption occurs on a homogeneous surface with monolayer coverage. This finding indicates that the dye molecules uniformly occupy the available sites on the surface of the $Fe_3O_4$@AC NPs. Additionally, the kinetics of dye adsorption were analyzed, and it was found that the pseudo-second-order model best described the adsorption process for both MB and BG dyes. This model implies that the adsorption rate is controlled by chemical interactions between the dye molecules and the adsorbent surface. The study also highlighted the reusability of $Fe_3O_4$@AC NPs, as they could be regenerated and reused for several adsorption cycles without a significant loss of efficiency.

These findings underscore the potential of $Fe_3O_4$@AC NPs as an effective and reusable nano adsorbent for the removal of cationic dyes from aqueous solutions. The combination of magnetic properties, high adsorption capacity, and ease of separation makes them a valuable material for environmental remediation. Future research could focus on optimizing the synthesis process, exploring the adsorption mechanisms in more detail, and expanding the application of these nanocomposites to other types of contaminants in water. This work contributes to the ongoing efforts to develop sustainable and efficient technologies for water purification[33].

In another work, humic acid (HA) was used to modify $Fe_3O_4$ NPs, resulting in the development of $Fe_3O_4$/HA for the removal of Rhodamine B (RhB) from water. The $Fe_3O_4$/HA was synthesized through a coprecipitation process, involving the reaction of iron salts with humic acid. This modification aimed to enhance the adsorption properties of $Fe_3O_4$ NPs by introducing additional functional groups and improving stability in aqueous solutions. The characterization of $Fe_3O_4$/HA was conducted using various techniques, revealing important features. Transmission electron microscopy images showed that the $Fe_3O_4$/HA NPs, with approximately 10 nm $Fe_3O_4$ cores, tended to aggregate in aqueous suspensions. This aggregation did not hinder their application, as the magnetic properties of the nanocomposite allowed for easy separation from water. The $Fe_3O_4$/HA exhibited a saturation magnetization of 61.2 emu/g, enabling efficient recovery from aqueous solutions using magnetic separation techniques under low magnetic field gradients. This rapid and simple separation process is a significant advantage for practical applications in water treatment, as it reduces the need for complex and time-consuming filtration methods.





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The study investigated the adsorption capacity of $Fe_3O_4$/HA for RhB, a common organic dye known for its vibrant color and toxicity. The results demonstrated that $Fe_3O_4$/HA could remove up to 98.5% of RhB from water at an optimal pH of 2.53. The high removal efficiency at low pH levels suggests that the $Fe_3O_4$/HA nanocomposite is particularly suitable for treating acidic wastewater. The stability of the adsorbent in low pH environments further highlights its potential for practical applications, as many industrial wastewaters are acidic. Future research could explore the modification of $Fe_3O_4$/HA with different organic compounds or polymers to enhance its adsorption capacity for a wider range of pollutants. Additionally, investigating the recyclability and regeneration methods of $Fe_3O_4$/HA will be crucial for assessing its long-term applicability and cost-effectiveness[34].

In new research conducted in 2023, ZnO NPs were synthesized using a green chemistry approach. This environmentally friendly synthesis method highlights the potential of ZnO NPs in addressing two critical environmental challenges: wastewater treatment and microbial contamination. The study demonstrated that the green-synthesized ZnO NPs were highly effective in capturing and removing Congo Red (CR) dye from wastewater. The NPs were able to achieve a remarkable dye removal efficiency of over 98% within 120 minutes, across a wide pH range from 2 to 10. This broad operational pH range indicates the versatility of these ZnO NPs in varying water conditions, making them a robust solution for real-world applications. Additionally, the antimicrobial properties of the synthesized ZnO NPs were thoroughly evaluated through well-diffusion assays. The results revealed significant inhibitory effects against various bacterial strains. Specifically, the ZnO NPs showed a 34% inhibition rate against Bacillus subtilis (ATCC 6538), 52% against Escherichia coli (ATCC 11103), 58% against Pseudomonas aeruginosa (ATCC 25668), and 32% against Staphylococcus aureus (ATCC 25923). These findings underscore the potential of ZnO NPs as effective antimicrobial agents. The green synthesis method employed in this study not only provides a sustainable and eco-friendly approach to nanoparticle production but also highlights the dual functionality of ZnO NPs. Their exceptional performance in both dye removal and antimicrobial activities positions them as a highly promising material for environmental and health applications[35].

In another work, according to the research conducted, $TiO_2$ NPs were successfully synthesized using a straightforward, rapid, and economically viable flame pyrolysis method. The synthesis process yielded $TiO_2$ NPs with an average particle size of 153 nm and 145 nm, respectively, and a spherical morphology, which is often advantageous for various applications due to the uniformity and consistency of the particles. The flame-synthesized $TiO_2$ NPs demonstrated remarkable dye removal efficiency. Specifically, they achieved a 97.64% removal rate for Methylene Blue dye and a 92.39% removal rate for CR dye. These impressive efficiencies highlight the effectiveness of $TiO_2$ NPs as advanced materials for dye removal, making them a strong candidate for applications in industrial dye removal and wastewater treatment. The potential of these $TiO_2$ NPs extends beyond the current study's scope. With their high removal efficiencies for specific dyes, these NPs hold promise for broader applications, including the removal of textile and industrial colorants. As the textile industry and other industrial processes frequently use synthetic dyes that can be challenging to remove, $TiO_2$ NPs could offer a valuable solution for treating contaminated wastewater and mitigating environmental impact[36].

In one of the new studies on $CeO_2$ NPs, the NPs were successfully synthesized using the co-precipitation method under mild conditions. This synthesis approach is notable for its simplicity and ability to produce high-quality NPs. The resulting $CeO_2$ NPs exhibited a spherical and crystalline morphology, with surface areas ranging from 159.6 to 189.3 $m^2/g$. These surface characteristics are crucial for their effectiveness as adsorbents. The as-synthesized $CeO_2$ NPs were utilized for the adsorptive removal of malachite green dye from aqueous solutions. The efficiency of this process was remarkable; under optimized conditions, approximately 98.0% of malachite green dye was removed within 120 minutes. This high removal rate demonstrates the significant potential of $CeO_2$ NPs in environmental cleanup applications, particularly in treating contaminated water. Kinetic studies revealed that the adsorption of malachite green dye onto $CeO_2$ NPs follows pseudo-second-order kinetics. This suggests that the rate of adsorption is dependent on the number of active sites available on the $CeO_2$ surface and the interaction between the dye molecules and these sites. Isotherm analysis showed that both the Langmuir model and the Sips model could effectively fit the adsorption data. The Langmuir isotherm model, which assumes monolayer adsorption on a surface with a finite number of identical sites, yielded a maximum adsorption capacity of 558.68 mg/g at 313 K. In comparison, the Sips isotherm model, which combines features of both Langmuir and Freundlich models to account for heterogeneous adsorption sites, provided a maximum adsorption capacity of 740.54 mg/g at 303 K. These high adsorption capacities indicate that $CeO_2$ NPs are highly effective adsorbents for malachite green dye, capable of removing large amounts of dye from water. Moreover, the stability and reusability of the $CeO_2$ NPs were evaluated, showing that they remain effective for up to five cycles of adsorption with only a minimal decrease in performance.





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This durability is an essential attribute for practical applications, as it suggests that the $CeO_2$ NPs can be reused multiple times without significant loss of efficacy[37].

As a result, These NPs exhibit high adsorption capacities, efficient separation properties, and potential reusability, making them promising candidates for environmental remediation. The studies also reveal the dual functionality of some NPs, such as ZnO, which also possess antimicrobial properties. The consistent high performance across different NPs and dyes underscores their potential for practical applications in wastewater treatment, particularly in addressing the challenges posed by industrial dyes. Future research should focus on optimizing synthesis methods, exploring broader contaminant removal capabilities, and enhancing the long-term viability and cost-effectiveness of these materials.

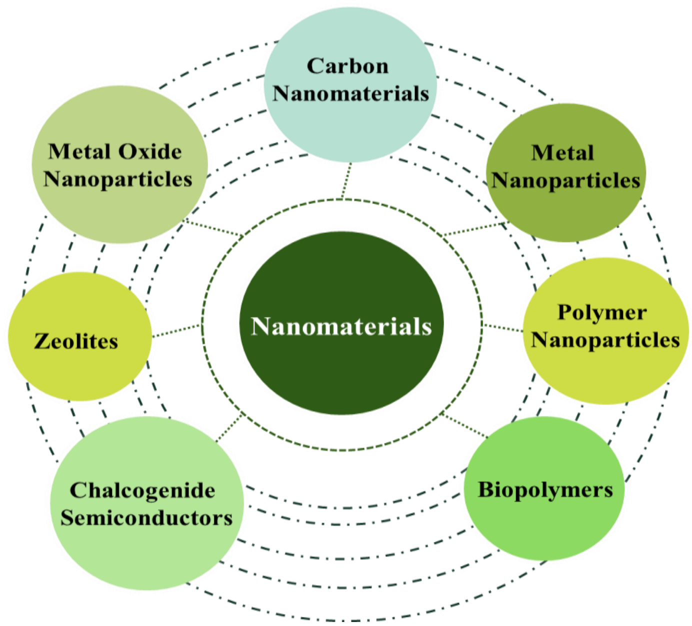


**Fig. 3.** Different types of nanomaterials

## Conclusion

In conclusion, the use of dyes in various industries, while essential, poses significant environmental challenges due to the pollution they cause, particularly in water bodies. Traditional methods for dye removal from wastewater, such as adsorption, have been complemented by the emergence of nanotechnology, offering advanced solutions. The development of nano-adsorbents like $Fe_3O_4$@AC, $Fe_3O_4$/HA, ZnO, $TiO_2$, and $CeO_2$ NPs demonstrates the potential for highly efficient dye removal. These materials not only provide superior adsorption capacities but also offer additional benefits like ease of separation, reusability, and even antimicrobial properties. Future research should focus on optimizing these technologies for broader applications, ensuring their sustainability and effectiveness in real-world scenarios. As industries continue to seek eco-friendly and cost-effective solutions, the role of nanotechnology in water purification is set to become increasingly vital.

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