Applications of Nanocomposites in Removal of Dyes from Wastewater: A Critical Review

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Abstract: Contamination of water by synthetic dyes due to industrial activities is a pressing environmental issue. These dyes are toxic, nonbiodegradable, and pose severe risks to ecosystems and human health. Nanocomposite materials are increasingly recognized for their outstanding capacity to eliminate synthetic dyes from wastewater. By combining exceptionally large surface areas with customizable surface chemistry and catalytic properties, composites such as graphene oxide, zinc oxide, and silver nanoparticles can remove dyes through both adsorption and light-driven degradation processes. Although studies often report removal efficiencies above 90%, real-world implementation is challenged by high production costs, difficulties in scaling up, and concerns over nanoparticle release into the environment. To address these hurdles, researchers are developing greener, more scalable fabrication methods like microwave-assisted synthesis—to reduce energy consumption and improve material uniformity. At the same time, process optimization models are being applied to fine-tune reaction conditions and enhance performance under practical treatment scenarios. This comprehensive review provides valuable insights into the current state and future prospects of nanocomposite-based dye removal techniques for sustainable wastewater treatment.

***Keywords**: nanocomposite, dyes, mechanism, wastewater, dye removal.*
UNSDG Goals: SDG 3, SDG 6, SDG 9, SDG 12, SDG 13

1. INTRODUCTION

Flocculation, filtration, chemical oxidation, and activated carbon adsorption have been employed to address dye pollution (Mittal et al., 2016). In industries like textiles and leather, a lot of synthetic dyes are used, and they often end up in wastewater. People generally initiate the cleanup of contaminated water through coagulation and flocculation processes. The procedure employs some supplementary chemicals to create dye particle clumping which allows them to settle down. The techniques demonstrate limited success at water cleanup although the outcome is prone to failure with high dye content or large water volumes.

The dye removal through microfiltration and reverse osmosis presents effective performance yet comes with high financial costs. The devices must consume substantial energy to operate effectively according to Crini et al. (2006). The treatment process removes color yet produces dangerous byproducts as its main disadvantage (Farhan et al., 2023). Activated carbon adsorption exists since a long time. The process functions properly yet proves quite expensive to maintain. According to Deng et al. (2013) regenerating spent carbon along with its subsequent reactivation remains a challenging and expensive process (Deng et al., 2013).

Because of these drawbacks, scientists have started looking at new materials, and one of the most interesting options is nanocomposites (Bogue, 2011). These are materials where tiny nanoparticles are combined with another substance to form a stable structure. They've shown a lot of promise in removing dyes from wastewater (Rustembekkyzy et al., 2024; Omanović-Mikličanin et al., 2020).

Nanocomposites can work in a few different ways. The most common are adsorption and photocatalysis. In adsorption, the dye sticks to the surface of the nanocomposite, which has a large surface area and active sites that attract the dye (Omidvar et al., 2017). In photocatalysis, light activates the material, and that produces highly reactive species that break the dye molecules apart (Al-Rawashdeh, Allabadi, & Aljarrah, 2020). Some systems even use both methods together these hybrid systems are more efficient and are being looked at for real-world use (**Figure 1**) (Mittal et al., 2016).

Synthetic dyes, especially from the textile and food industries, are very hard to remove using traditional methods because they're made to be stable and resist breakdown (Ahmad & Kumar, 2010). That's where nanocomposites really shine.

Some examples are pretty impressive. For instance, nanocomposites based on biochar have removed up to 99% of dyes in lab experiments (Rustembekkyzy et al., 2024). MXene-based nanocomposites are another group showing great results. Their high surface reactivity and conductivity make them very good at dye degradation (Palani et al., 2023).

Other types like layered double hydroxides (LDHs) and metal-organic frameworks (MOFs) are also getting attention because they have a high capacity to capture dyes, they're strong, and they can be reused several times (Silva & Gomez, 2024; Nelson et al., 2024; Sonawane et al., 2021) (**Table 1**).

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This paper takes a closer look at the potential of nanocomposites in dye removal. It covers the different kinds, how they work (**Figure 2**), and some newer ways of making them like microwave-assisted synthesis (Mostafa et al., 2020). It also looks at the challenges we still need to deal with, like how to use them on a larger scale, improve their performance, and make sure they're safe for the environment (Farhan et al., 2023; Fahim et al., 2024).

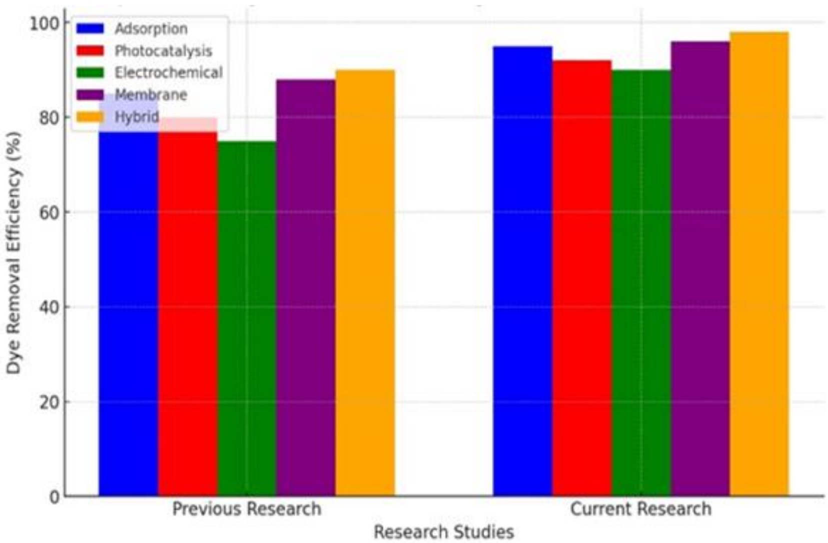


Figure 1. Comparison of dye removal efficiency: previous vs. current research

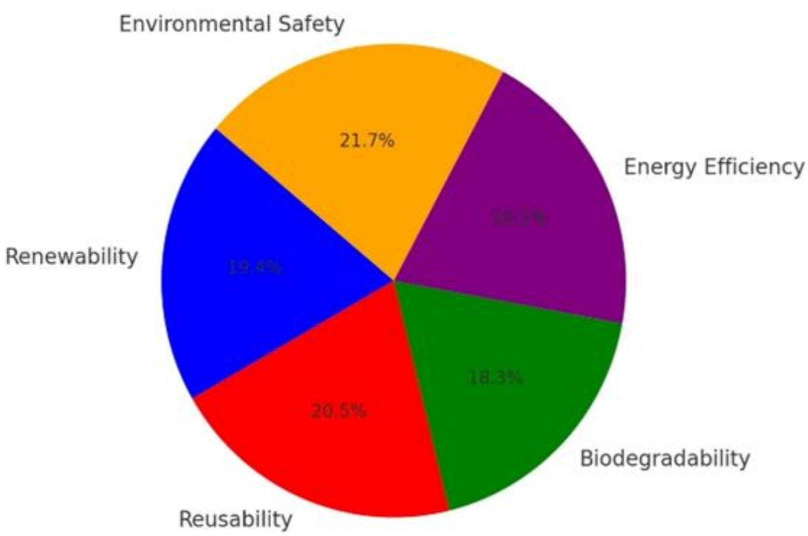


Figure 2. Sustainability comparison of nanocomposite method

TYPES OF DYES

Dyes are classified into various types, as shown in **Figure 3**, and their impact on health and the environment is shown in **Table 1**. Acid dyes contribute to aquatic toxicity, leading to reduced oxygen levels in water and harm to aquatic organisms. Long-term exposure has been associated with skin irritation and allergic reactions in humans (Bhatnagar & Sillanpää, 2010). Example: Acid red 88. These dyes are water-soluble anionic compounds that are commonly used in dyeing protein-based fibers, such as wool, silk, and nylon. They require an acidic medium to ensure strong bonding with the fabric and are valued for their good lightfastness. However, their release into water bodies leads to serious environmental pollution because of their high stability and persistence (Bhatnagar & Sillanpää, 2010).

Basic dyes are positively charged and readily bind to negatively charged substrates, such as acrylic fibers and wool. Although they produce vibrant colors, their high solubility leads to increased bioavailability, making them toxic to aquatic organisms.

They have been reported to cause DNA damage, cellular toxicity, and mutagenic effects in aquatic organisms. Exposure to cationic dyes has also been linked to respiratory and skin disorders in industrial workers (Mittal et al., 2016).

Direct dyes are water-soluble pigments that can be directly applied to cellulose fibers, such as cotton and rayon, without requiring a mordant. Although easy to apply, they exhibit moderate wash fastness and are prone to leaching, leading to persistent coloration in water bodies. They have been linked to skin sensitization, allergic reactions, and dermatitis in humans. The release of these dyes into water bodies disturbs aquatic ecosystems by blocking light penetration, which negatively affects photosynthetic organisms (Camargo et al., 2009).

Vat dyes are water-insoluble and must undergo chemical reduction before being applied to fabrics. After application, they were oxidized back to their original state, ensuring exceptional durability and wash fastness. However, their production and processing generates hazardous waste, including aromatic amines and sulfides, which are highly toxic to aquatic life and have carcinogenic effects on humans (Mittal et al., 2016). Their production is energy intensive and contributes to high carbon emissions (Mishra & Militky, 2013).

Disperse dyes bioaccumulate in fish tissues, disrupt endocrine functions, and alter reproductive systems in aquatic life. Some disperse dyes have been identified as potential carcinogens and mutagens that pose serious health risks upon prolonged exposure (Chong et al., 2015).

Azo dyes can be broken down into carcinogenic amines under anerobic conditions, posing serious health risks, including bladder cancer and genetic mutations. They have been detected in groundwater sources, raising concerns regarding drinking water contamination. Azo dyes represent the largest category of synthetic dyes and are distinguished by the presence of azo (−N = N-) functional groups. They are extensively utilized in textiles, food, and cosmetics; however, their high environmental persistence and potential toxicity raise significant concerns (Palani et al., 2023).

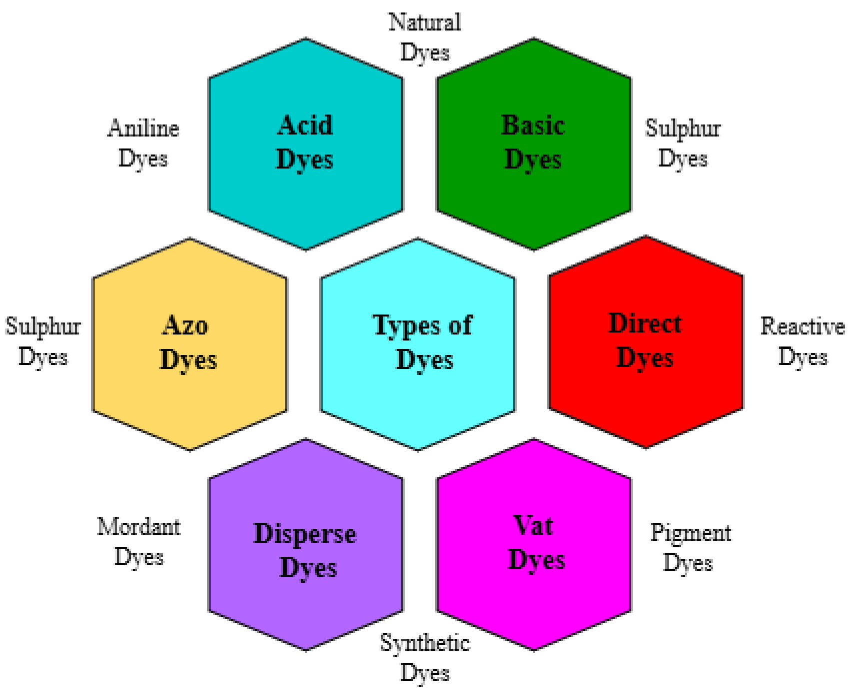


Figure 3. Different types of dyes used in various industries

Table 1. Different Types of Dyes and Impact on Health and Environment (Ahmad & Kumar, 2010; Palani et al., 2023; Mittal et al., 2016)

Different types of Dye	Solubility in aqueous medium	Environmental impact	Health effects	Example
Acid dyes	high	high aquatic toxicity	skin irritation, allergies	acid red 88
Basic dyes	high	mutagenic effects	DNA damage, respiratory issues	methylene blue
Reactive dyes	high	persistent and cytotoxicity	kidney/liver damage	reactive red 120
Direct dyes	moderate	water pollution, bioaccumulation	skin sensitivity	direct blue 86

Vat dyes	Low	carcinogenic by-products	cancer risk	indigo
Disperse dyes	Low	bioaccumulation, endocrine disruption	reproductive toxicity	disperse blue 56
Azo dyes	high	groundwater contamination	bladder cancer, genetic mutations	Congo red

CLASSIFICATION OF NANOCOMPOSITES

Nanocomposites are categorized based on their matrix materials (**Figure 4**), which influence their structures and functionalities (**Table 2**) (Nambiar et al., 2024). Below are the major types of nanocomposites used for dye removal.

Nanocomposites represent an innovative class of materials with tunable properties and multifunctional structures that offer enhanced performance across various environmental applications (Rajani et al., 2021).

Polymer Matrix Nanocomposites

While going through some studies, I noticed that when tiny particles nanoparticles are added to a polymer, the material turns out to be stronger and more reusable. Not just that, but it does a surprisingly good job at removing dyes from water. Polymers like chitosan, polyaniline, and PEG are often used because they have chemical parts that help them hold onto dye molecules. Plus, they're not harmful, which is obviously a good thing for environmental use. One example that stuck with me was a material made by mixing chitosan and graphene oxide. In lab tests, it managed to clean out over 95% of Congo red dye from water, which honestly sounds pretty impressive to me. (**Figures 5, 6**) (Mittal et al., 2016). It really makes you think how far this kind of material could go if used on a large scale.

Metal Matrix Nanocomposites

Researchers have found that when you mix metals with extremely tiny particles, the resulting materials become much tougher and better at doing certain chemical reactions. These special mixtures can play a big role in cleaning up dye-contaminated water. One example that's been widely explored involves using silver-based materials not just because they help break down dye molecules, but also because they can stop the growth of harmful microbes during the treatment process. Another interesting type uses materials that respond to magnets. This means once they've done their job in the water, they can be pulled out easily using a magnetic field. That makes the process more convenient and helps prevent leftover materials from polluting the water further. Thanks to these smart features, these metal-based composites are becoming a strong option for water purification tasks (Sun et al., 2017). Fe_3O_4@SiO_2-Ag nanocomposites have demonstrated 98% (**Figures 5, 6**) degradation of methylene blue in aqueous solutions (Ren, Y., Abbood, H. A., He, F., Peng, H., & Huang, K., 2013).

Ceramic Matrix Nanocomposites

When scientists mix small particles with ceramics, they get materials that are not only tougher but also better at handling heat. These materials are really useful for cleaning up dye from water. For instance, a mix of titanium dioxide (TiO_2) and zeolite has been found to work really well at breaking down dyes when exposed to UV light, turning the harmful chemicals into safer by-products (**Figures 5, 6**). Another combo, TiO_2-ZnO, has shown it can get rid of 92% of azo dyes in just two hours of UV exposure (Chong et al., 2015).

Hybrid Nanocomposites

When it comes to getting rid of dyes from dirty water, hybrid nanocomposites are kind of like the all-in-one solution. They're made by mixing different materials together so they can do multiple things at once like grabbing the dye, breaking it down with light, and helping with chemical reactions. This makes them super useful for treating wastewater that has a bunch of different stuff in it. What's cool is that scientists can actually tweak their structure like how porous they are or how they interact with water to make them work even better. One really impressive example is the graphene oxide and palladium (GO/Pd) combo. It's been able to clean up about 97% of dyes like methylene blue and rhodamine B, thanks to how good it is at breaking those dyes down through oxidation (**Figure 5, 6**) (Omidvar et al., 2017).

MOF-Based Nanocomposites

MOFs, or Metal–Organic Frameworks, have been getting a lot of attention because of how their structure works like a sponge full of little pockets that can grab onto specific things, like dye molecules. This makes them perfect for cleaning up water that's polluted with dyes. The cool thing is that they can also help break down those dyes, not just hold onto them. Recently, scientists have started mixing these MOFs with graphene to make them even stronger and longer-lasting, so they work better in real-life water treatment systems. One example is Fe-MOF (iron-based MOFs), which has been shown to remove almost 98% of a dye called Acid Red 88 by simply attracting it and trapping it (**Figure 5 and 6.a**). Depending on the MOF's structural configuration and surface area, removal efficiencies can range from 95% to 99% (**Figure 7.b**). These developments are paving the way toward more cost-effective and scalable solutions for industrial wastewater treatment (Farhan et al., 2023).

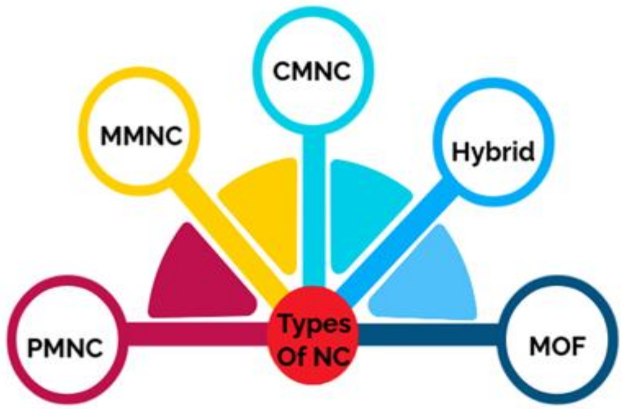


Figure 4. Overview of Nanocomposite Types Utilized for Dye Removal from Wastewater

Table 2. Summary of Nanocomposite Variants and Their Efficiency in Dye Removal Applications (Al-Rawashdeh, Allabadi, & Aljarrah, 2020; Rustembekkyzy et al., 2024; Farhan et al., 2023)

Nanocomposite type	Best for removing	Efficiency (%)	Advantages	Challenges
Polymer-based	anionic dyes	85–95	biocompatible, flexible	lower stability
Metal-based	cationic dyes	90–98	high reactivity, antimicrobial	costly synthesis
Ceramic-based	azo dyes	85–92	thermal stability, durable	limited adsorption capacity
Hybrid	mixed dye effluents	95–99	multiple mechanisms	complex synthesis
MOF-based	Acid/Reactive dyes	95–99	high porosity, reusability	scalability issues

Abbreviations: MOF metal–organic framework.

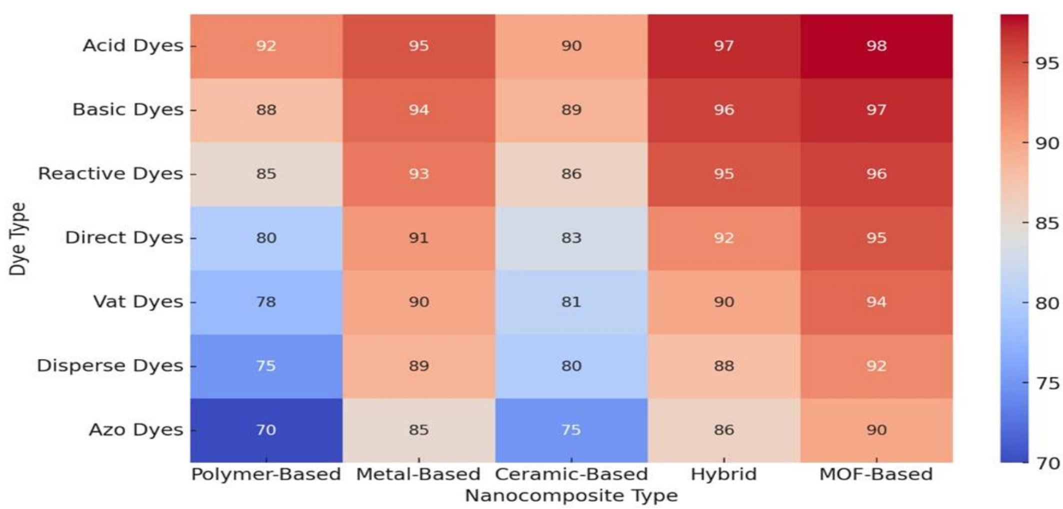
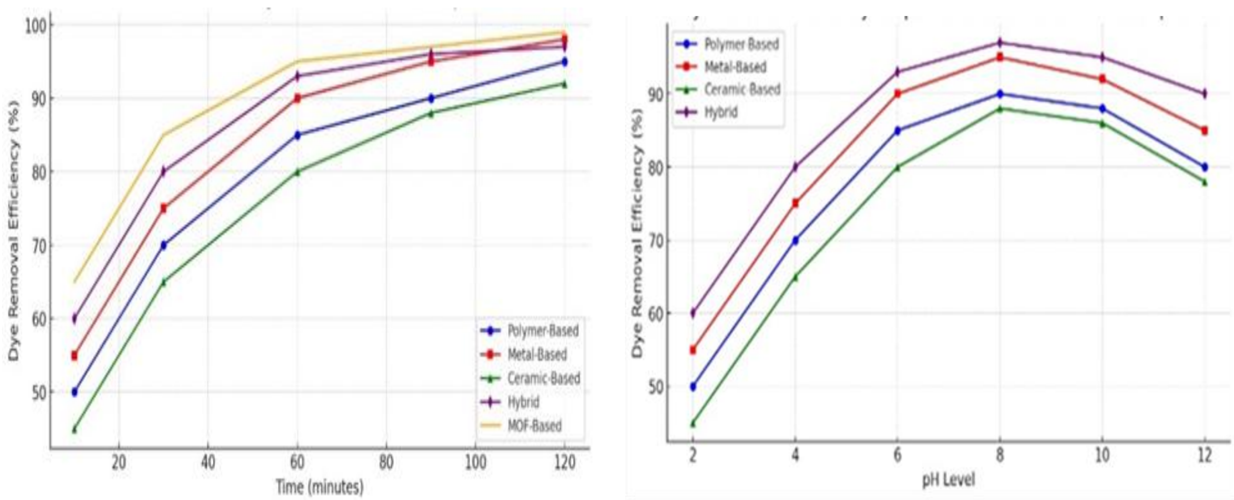
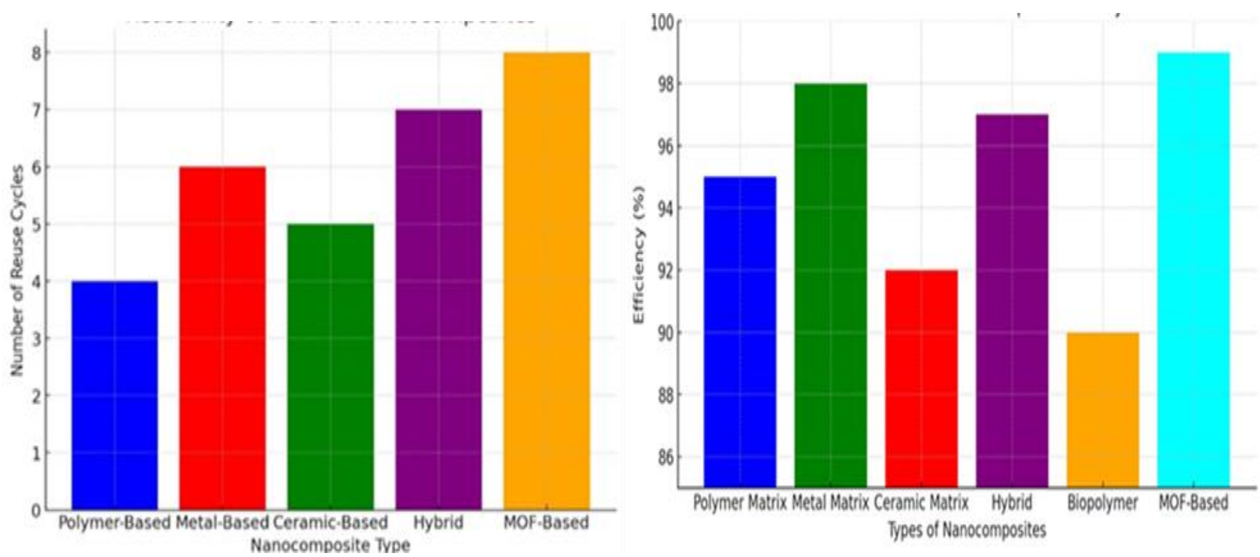


Figure 5. Removal efficiency of various nanocomposites for dye



(a) **(b)**

Figure 6. (a) Time vs. efficiency for Different nanocomposites **(b)** Dye Removal Efficiency vs. pH Level



(a) **(b)**

Figure 7. (a) Number of Reuse Cycle vs. nanocomposites Type **(d)** Efficiency vs. types of nanocomposites

REMOVAL TECHNIQUES BY NANOCOMPOSITES

Adsorption

Adsorption remains one of the most widely adopted and effective techniques for removing dyes from wastewater, primarily due to its operational simplicity, cost efficiency, and reliable performance. The mechanism through which dyes get removed from this setup (**Figure 8**) proves to be fascinating. The dye molecules do not vanish but instead bond with nanocomposite surfaces through electrostatic force pulling as well as hydrogen bonds and van der Waals forces and potentially pi-pi stacking interactions according to Al-Rawashdeh and team (2020). The adsorption process works differently for each dye type. The adsorption strength depends upon water acidity or basicity conditions as well as temperature combined with waiting time and initial dye concentration (Mittal et al., 2016). The adsorbent's ability to adjust according to various wastewater settings makes it suitable for multiple wastewater types.

The scientific community has focused on developing graphene oxide (GO) and hydrogels and MOFs together with chitosan-based composites as well as additional research materials. Hydroxyapatite-based nanocomposites proved effective for removing dyes from wastewater according to Pai and other authors (2021). The great dye-gathering abilities of these materials stem from their extensive surface areas combined with adjustable active sites and adjustable porosity levels (Mohammadzadeh Pakdel et al., 2022). According to Oyewo and others (2020) the dye trapping efficiency increases substantially because of these properties.

They provide a compelling illustration. The combination of GO chitosan nanocomposites exhibits superior Congo red dye removal capability at over 97% efficiency within half an hour based on the data displayed in **Figure 13** (Camargo et al., 2009). This discovery becomes more amazing when analyzed (Camargo et al., 2009).

However, even though adsorption is highly effective (**Table 3**), there are a few challenges. One of the biggest issues is regenerating spent nanocomposites. Honestly, taking the adsorbed dyes off the material can be a real headache, and it doesn't come cheap either. Additionally, because adsorption mostly deals with surface interactions, it might not completely break down the dye pollutants. This means you might need additional steps to fully treat the water (Deng et al., 2013). Nevertheless, when coupled with complementary techniques such as photocatalysis, adsorption can contribute to more efficient and sustainable dye removal strategies (Farhan et al., 2023).

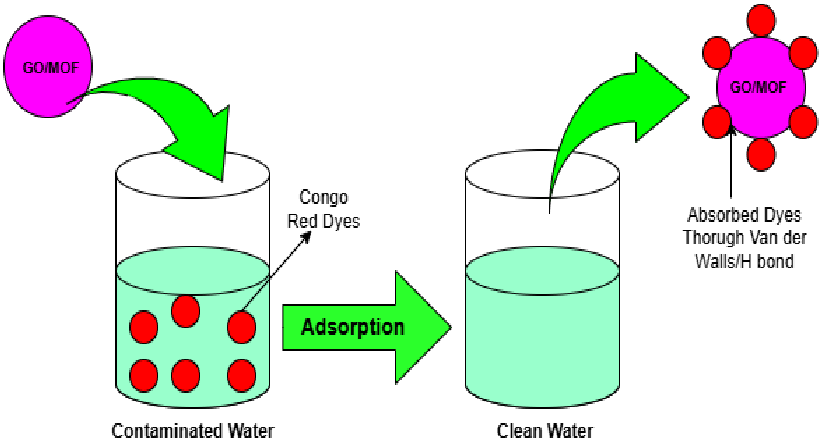


Figure 8. Removal of dyes by nanocomposites from water through Absorption

Photocatalysis

Photocatalysis is an advanced oxidation process that employs semiconductor nanocomposites such as ZnO, TiO_2, and Ag/ZnO to degrade dye pollutants when exposed to light (Chong et al., 2015). During this process (**Figure 9**), ROS such as hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet -}$) are generated, which break down complex dye molecules into harmless by-products, such as carbon dioxide and water (Rustembekkyzy et al., 2024).

The effectiveness of photocatalysis depends on multiple factors, including the light intensity, catalyst composition, reaction time, and presence of oxidizing agents (Palani et al., 2023). Among the various nanocomposites, TiO_2-ZnO hybrids have shown high photocatalytic efficiency, achieving up to 92% degradation of Reactive Red 120 under UV light within 120 min, proving their strong potential for wastewater treatment (**Figure 13**) (Singh et al., 2013; Mittal et al., 2016).

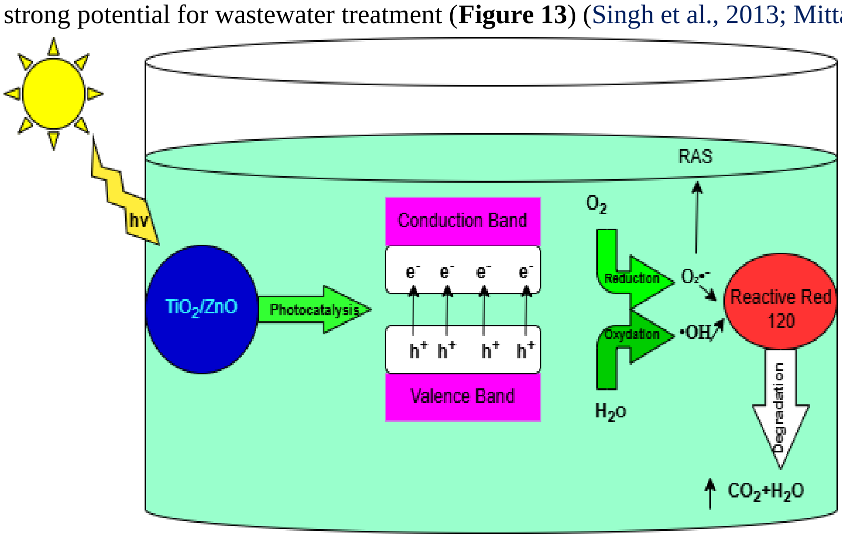


Figure 9. Photocatalytic dye removal from water using nanocomposites

A major advantage of photocatalysis is its ability to completely mineralize dye molecules and eliminate secondary waste products. However, challenges such as catalyst stability, limited visible-light absorption, and photocorrosion hinder their large-scale application (**Table 3**) (Farhan et al., 2023). Recent advancements in doped semiconductor nanocomposites, plasmonic photocatalysts, and heterojunction structures have significantly improved photocatalytic efficiency and durability (Omidvar et al., 2024). Additionally, coupling photocatalysis with adsorption techniques enhances dye removal rates, ensuring that both dissolved and surface-bound pollutants are efficiently treated. Looking ahead, there's a real need for researchers to refine the way catalysts are made making them more efficient and better suited to work under natural light, like sunlight. At the same time, it's important to develop systems that aren't just effective in the lab but can actually be used on a larger scale without costing a fortune. These improvements could bring us a step closer to using photocatalysis in everyday wastewater treatment (Al-Rawashdeh, Allabadi, & Aljarrah, 2020).

Electrochemical Oxidation

Electrochemical oxidation is considered one of the more advanced methods available today for breaking down dye pollutants, especially those that don't respond well to traditional treatment techniques. In simple terms, this process uses electricity to trigger chemical reactions that help dismantle stubborn dye molecules, turning them into safer, non-toxic substances (Farhan et al., 2023). When voltage is applied (**Figure 10**), it sets off a chain of reactions mainly at the anode where dye compounds begin to oxidize. Alongside that, highly reactive substances like hydroxyl radicals (•OH) are produced, which further speed up the breakdown of complex dye structures. Nanocomposites play a key role here, especially those made with metal-doped carbon or Fe_3O_4-based materials. These boost how effectively electrons are transferred during the process, making the whole system work better (Ren et al., 2013). That said, the efficiency of this method doesn't just depend on the materials used. Factors like the type of electrodes, how much voltage is applied, and the composition of the electrolyte solution all influence how well the treatment performs (Mittal et al., 2016).While the method is promising offering nearly complete dye breakdown with minimal risk of leaving behind harmful residues it's not without challenges. For example, making sure the electrodes stay stable over time and dealing with the energy costs are two hurdles that need to be overcome before this can be rolled out on a bigger, more practical scale (**Table 3**).

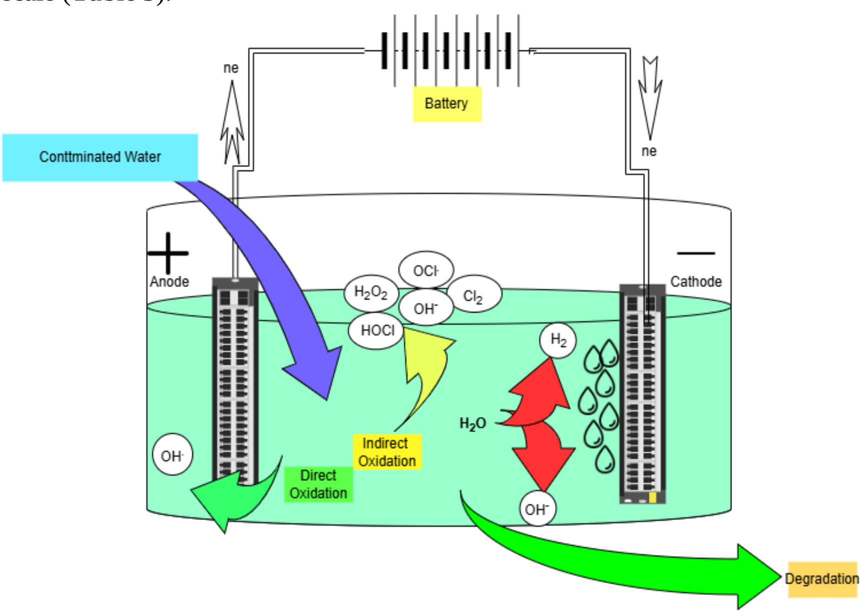


Figure 10. Removal of dyes by nanocomposites from water by Electrochemical Oxidation

Membrane Filtration and Separation

Membrane filtration is a widely recognized and efficient technique for dye removal, where membranes enhanced with nanocomposites facilitate the selective separation of dye molecules through mechanisms like size exclusion, charge repulsion, and adsorption. This method works really well in filtration systems like nanofiltration and ultrafiltration (**Figure 11**), where the membrane does the job by separating dye molecules based on pore size and how the dyes interact with the surface of the membrane (Mittal et al., 2016). By adding nanocomposite materials into these membranes whether they're made of polymers, ceramics, or metals the filtration gets a lot better. This boosts things like how easily water can pass through, makes the membrane stronger, and helps it resist fouling (Farhan et al., 2023). Magnetic nanocomposites, especially Fe_3O_4-based ones, are really helpful here. They trap the dye, and once you apply a magnetic field, they can be pulled out easily, which keeps the water from getting polluted again (Ren et al., 2013). Also, graphene oxide (GO)-based membranes are great at choosing which dyes to reject. Their surface charge can be tweaked, so they can block both positive and negative dyes. Membranes made from layered double hydroxides are also showing good results they're really good at catching dyes and getting rid of them efficiently. Additionally, metal-organic framework (MOF)-integrated membranes have demonstrated remarkable dye removal efficiencies (**Table 3**), achieving removal rates above 95%, depending on their structure and functionalization (Omidvar et al., 2017). This method is highly scalable and well-suited for large-scale wastewater treatment. However, challenges like membrane fouling, clogging, and high energy consumption need to be addressed to enhance the long-term performance and cost-effectiveness of the process (Al-Rawashdeh, Allabadi, & Aljarrah, 2020).

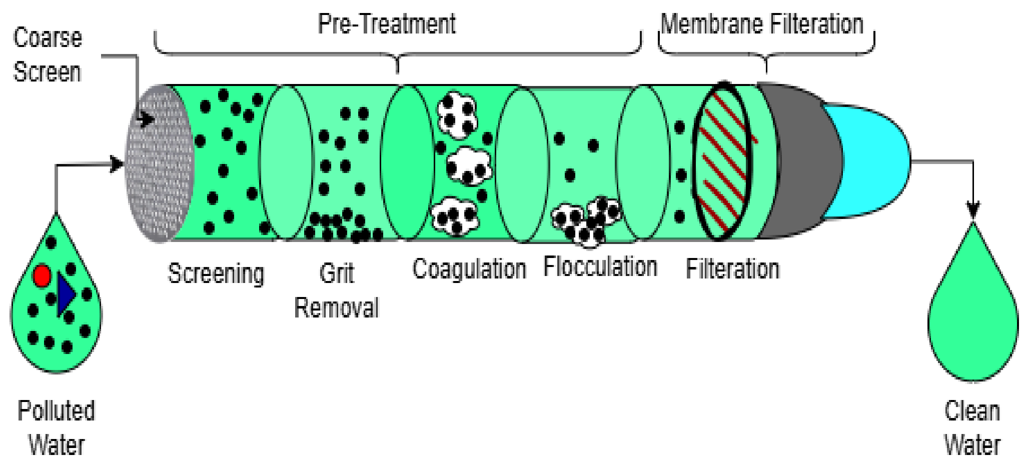


Figure 11. Removal of dyes by nanocomposites from water through Membrane Filtration and Separation

Hybrid Approaches

Hybrid approaches integrate two or more dye removal techniques, such as adsorption, photocatalysis, electrochemical oxidation, and membrane filtration, to achieve a higher removal efficiency and sustainability. These multifunctional nanocomposites possess dual functionalities (**Figure 12**), enabling simultaneous dye adsorption, catalytic degradation, and charge-driven separation, making them highly effective for wastewater treatment (Omidvar et al., 2017).

Among the most extensively researched hybrid nanocomposites, GO/TiO_2 composites, as well as rGO–TiO_2/Fe_3O_4 systems, demonstrate a high adsorption capacity and photocatalytic activity, achieving nearly 98% dye removal (Banerjee et al., 2018; Hayati et al., 2013) for pollutants such as rhodamine b and methylene blue (**Figure 12**). Similarly, Ag/ZnO hybrids leverage the surface plasmon resonance effect of AgNPs, enhancing visible-light-driven photocatalysis and electron transfer, which accelerates dye degradation (Farhan et al., 2023).

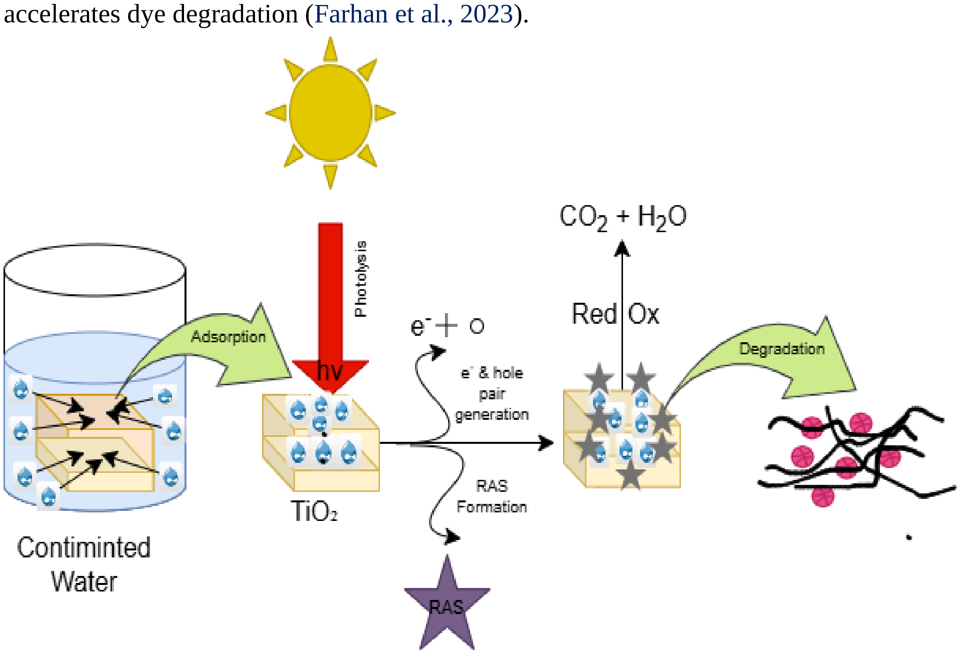


Figure 12. Removal of dyes by nanocomposites from water through Absorption and Photo catalysis (Hybrid approaches)

Additionally, MOF-polymer nanocomposites combine high porosity and selective adsorption with redox-active sites, thereby improving dye separation and degradation in complex wastewater matrices (Palani et al., 2023).). Magnetic nanocomposite hybrids (e.g., $Fe_3O_4@SiO_2-TiO_2$) enhance dye removal by adsorbing pollutants, while allowing magnetic separation, reducing secondary contamination, and improving recyclability (Sun et al., 2017., Ren, Y., Abbood, H. A., He, F., Peng, H., & Huang, K., 2013). By combining adsorption with photocatalysis or electrochemical oxidation, hybrid nanocomposites greatly improve the dye removal efficiency, stability (**Table 3**), and reusability, making them a cost-effective and scalable solution for industrial wastewater treatment (Mittal et al., 2016).

Table 3. Comparison of Dye Removal Techniques (Chong et al., 2015; Deng et al., 2013; Omidvar et al., 2017)

Technique	Mechanism	Efficiency (%)	Advantages	Limitations
Adsorption	surface binding	85–97	simple, cost-effective	requires regeneration
Photocatalysis	oxidation	90–98	complete mineralization	light dependency
Electrochemical	redox reaction	85–95	no secondary waste	high energy consumption
Membrane filtration	size exclusion	90–99	high selectivity	membrane fouling
Hybrid methods	multiple	95–99	high efficiency, sustainable	expensive setup

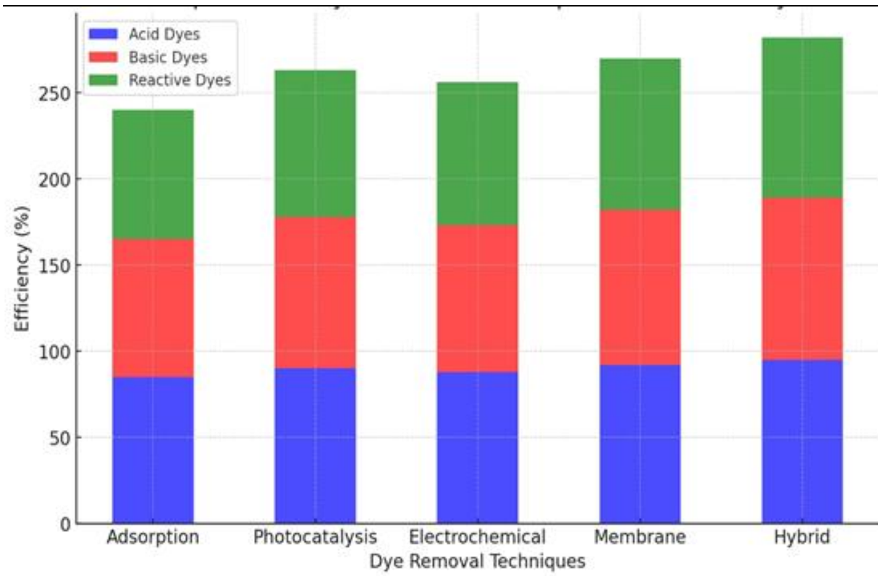


Figure 13. Effieciency of different dyes removal techniques

MECHANISMS OF DYE REMOVAL USING NANOCOMPOSITES

Electrostatic Interactions

Electrostatic interactions play a fundamental role in dye removal by nanocomposites, particularly polymer-based and metal-doped nanomaterials (**Table 2**). This mechanism relies on attraction between oppositely charged species. Cationic dyes, such as methylene blue (**Table 1**), are effectively adsorbed onto negatively charged nanocomposites, while anionic dyes, such as Congo red, interact with positively charged surfaces. The strength of electrostatic interactions is influenced by factors such as the pH, ionic strength, and surface functionalization of the nanocomposites (Mittal et al., 2016).

For instance, polyaniline-based nanocomposites have shown strong electrostatic interactions with anionic dyes, achieving removal efficiencies exceeding 95% (Oyewo et al., 2020). Similarly, functionalized graphene oxide nanocomposites, with their negatively charged oxygen-containing groups, exhibit a high affinity for positively charged dyes, making them highly effective adsorbents (Al-Rawashdeh, Allabadi, & Aljarrah, 2020). Electrostatic adsorption depends mostly on the pH value of the water. Under acidic water conditions particular functional groups located on nanocomposites develop outstanding capability to draw negatively charged dyes. Electrostatic adsorption proceeds differently when water becomes more alkaline because the functional groups will drop their protons thus enabling dye attraction of cationic compounds (Camargo et al., 2009). However, applying high salt levels to wastewater creates issues. Both nanocomposites and dye molecules experience disrupted electrostatic forces due to salt presence. The efficiency levels decrease when materials successfully do their job of pollutant removal. The development of nanocomposites with environment-sensitive surface charge regulation is currently researched by scientists to improve efficiency in wastewater dye removal. Researcher Farhan et al. (2023) gave these materials adaptive capabilities which allows them to remove dyes from various water conditions (p. 368).

The charge-based attraction stands as the key factor which enables this method to succeed. The principle behind the method reveals how dyes with positive charges get attracted to negative sites whereas those with negative charges gravitate toward positive sites. This effect becomes strongest with nanocomposites prepared from polymers and metal-doped materials given they possess special functional groups that strengthen the attraction level (Mittal et al., 2016). At the same time, pH along with salt content and surface design influence the process. The strong electrostatic interaction of polyaniline nanocomposites makes them highly effective in pulling out methyl dyes according to Oyewo et al. (2020). The removal process becomes less effective when water contains excessive numbers of other ions because they cause interference.

Hydrogen Bonding and pi-pi force

Two forces namely pi-pi interactions and hydrogen bonding serve as the main functions behind the ability of Graphene oxide (GO) and carbon nanotubes and hydrogels to remove dyes from solutions. The surface of GO and carbon nanotube composites attracts dyes through the mechanism of pi-pi stacking interactions. According to Ates, Eker, and Eker (2017) the strong attraction occurs when molecule electrons in the dye interact with electrons on material surfaces. The dyes with aromatic structures like azo dyes or anthraquinone dyes generate excellent affinity during this technique. The dye absorption power of chitosan hydrogels comes from their ability to bond using hydrogen bonds. The hydrogel's hydroxyl (–OH), amine (–NH2) as well as carboxyl (–COOH) functional groups easily connect with dye functional groups which enables hydrogels to effectively extract dyes from wastewater. This interaction facilitates efficient dye adsorption, with studies demonstrating up to 98% removal of methylene blue (MB) in a short contact time (Ren et al., 2013). However, competitive adsorption in complex wastewater, influenced by pH, ionic strength, and temperature variations, can reduce efficiency. To enhance adsorption, surface functionalization, polymeric coatings, and metal nanoparticle incorporation have been explored to improve stability and reusability (Farhan et al., 2023).

Photocatalytic Oxidation

Photocatalytic oxidation is a highly advanced process that employs semiconductor nanocomposites to produce ROS, thereby facilitating the degradation of dye pollutants. This mechanism (**Figure 9**) operates by exciting electrons in semiconductor materials such as ZnO, TiO_2, and Fe_3O_4 when exposed to UV or visible light. When high-energy photons strike the nanocomposite surface, they generate electron-hole pairs. These charge carriers then interact with oxygen and water molecules, leading to the formation of hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet-}$), which break down complex dye molecules into nontoxic by-products such as carbon dioxide and water (Chong et al., 2015; Rustembekkyzy et al., 2024). The advantages of photocatalysis in dye molecule breakdown include full degradation of dyes along with an avoidance of secondary pollutants often produced by other treatment systems. Several problems remain before full implementation can be achieved. Researchers face major challenges to maintain catalyst stability while improving their visible light absorption performance and overcoming issues like photocorrosion particularly during large-scale application (Farhan et al., 2023). Research developments show great advancements in recent times. Three advanced solutions involving doped semiconductor nanocomposites and plasmonic photocatalysts and heterojunction structures have enhanced the strength and dependability of photocatalysis according to Omidvar et al., 2017. Photocatalysis when combined with adsorption has proven to be an intelligent solution because it successfully removes dissolved stains as well as those present on surfaces (Mittal et al., 2016). Research should develop both light-sensitive catalyst structures and economical plant applications for real-world wastewater treatment facilities (Al-Rawashdeh, Allabadi, & Aljarrah, 2020).

Ion Exchange and Redox Reactions

Wastewater dye elimination benefits tremendously through the implementation of nanocomposites which demonstrate genuine breakthrough potential for dye treatment. Nanocomposites operate mainly using redox reactions together with ion exchange.

The attachment of dye molecules happens across the surface of nanomaterials predominantly those containing metal oxides or surface modifications. The existing ions of the nanocomposite relocate with the existing ions that are floating in water solution from dye molecules. The removal of negatively charged anionic dyes becomes effective through this method because dye particles easily exchange with surface-bound hydroxide groups. The ion exchanging abilities of several metal oxides such as manganese dioxide (MnO_2), cerium oxide (CeO_2), and iron oxide (Fe_3O_4) work exceptionally well in the removal process due to their rapid and efficient ion transfer capabilities (Farhan et al., 2023).

The electron transfer mechanism stands as the primary approach in redox reactions instead of other processes. The dye molecules can be degraded into harmless fragments or converted into removal-friendly structures through this mechanism. Nanocomposites combination of silver nanoparticles (AgNPs) shows exceptional performance in the field. AgNPs activate TiO_2 materials into potent catalysts that can degrade even persistent dyes such as azo compounds which normally prove difficult to break down. The strong oxidizing power of AgNP-TiO_2 composites allows them to eliminate about 97% of azo dyes within short treatment periods according to research by Omidvar et al. (2017).

Various aspects such as the dye type together with the surface chemistry of nanocomposites and treatment parameters determine the effectiveness of these processes. Both redox reactions and ion exchange methods demonstrate high performance but researchers need to watch for metal leaks and unwanted secondary reactions during operations. Surface engineering advancements together with stabilizer technologies enable researchers to solve several encountered issues. The latest advances in nanocomposite development make them a growing reliable and eco-friendly technology for large-scale wastewater treatment (Ren et al., 2013).

Size Exclusion and Membrane Mechanisms

The process of membrane filtration through industrial wastewater facilities operates as a highly effective method for deleting dye compounds. Nanomaterials used together with this process enhance its operational efficiency. The membrane separation system functions as a refining filter that holds back powerful dye particles and permits pure water molecules and tiny substances to move forward. Therefore membranes enhance treated water quality (Ren et al., 2013).

Membrane efficacy depends on three aspects including pore size dimensions and membrane surface charges and the nature of water molecules. Graphene oxide (GO)-based membranes function exceptionally well for water filtering since they maintain water passage while stopping the progression of dyes. Studies have proven that GO membranes achieve a complete removal rate of dyes present in textile wastewater (Palani et al., 2023). The membranes obtain additional value through the addition of nanomaterials such as TiO_2 and ZnO and Fe_3O_4 which delivers protecaiton against surface fouling in addition to improving mechanical durability and chemical decay resistance (Farhan et al., 2023).

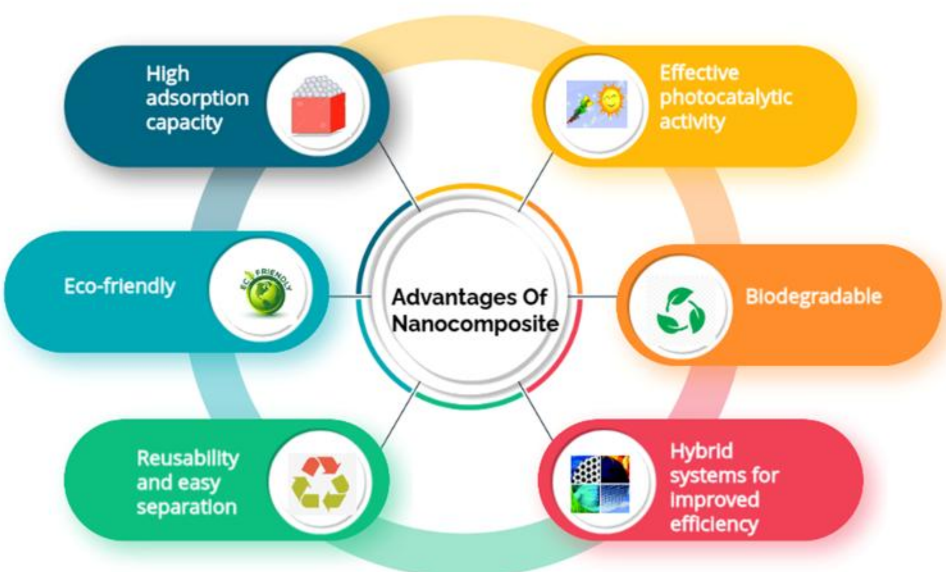


Figure 14. Several advantages of nanocomposites over traditional dye removal techniques

Surface charge plays an essential role in addition to the size of the membrane pores. Membranes which embody negative surface charges generate an electrostatic repulsion effect that helps to select desired molecules. The combination of magnetic Fe_3O_4 nanomaterials with membranes leads to improved efficiency and simplifies recovery processes as well as reuse operations which decreases operational expenses and reduces secondary pollution (Mittal et al., 2016).

Challenges: Membranes can become clogged over time, reducing filtration efficiency. However, ongoing research is making progress through the development of hybrid nanocomposite membranes and self-cleaning surfaces. Future efforts should focus on designing membranes that are not only more effective but also more affordable and durable for large-scale industrial applications (Omidvar et al., 2017).

ADVANTAGES OF NANOCOMPOSITES IN DYE REMOVAL

Nanocomposite-based dye removal methods are becoming really popular because they work well and are flexible, offering a great alternative to older wastewater treatment techniques. Additional research must focus on the improvement of existing methods because they currently need refinement for better effectiveness.

Nanocomposites bring a lot of benefits when compared to traditional dye-removal methods (Rajani et al., 2021) (**Figure 1**). Their large surface area and specially designed active sites make them much more efficient at adsorbing dyes than older materials like activated carbon (Al-Rawashdeh, Allabadi, & Aljarrah, 2020). Moreover, semiconductor-based nanocomposites, such as ZnO and TiO_2, facilitate the photocatalytic breakdown of dyes into nontoxic products when exposed to UV and visible light, making them a sustainable option for wastewater treatment (Chong et al., 2015). Magnetic nanocomposites, like Fe_3O_4-based materials, allow for easy recovery and multiple reuse cycles, helping reduce operational costs and improving sustainability (**Figure 2**) (Ren et al., 2013). Hydrogels and biopolymer-based nanocomposites provide eco-friendly alternatives, reducing the risk of secondary pollution (Oyewo et al., 2020). Additionally, synergistic hybrid systems that combine adsorption and photocatalysis significantly improve overall dye removal efficiency, making them highly effective (**Figure 14**) for wastewater treatment applications (Omidvar et al., 2017).

Challenges in Nanocomposite-Based Dye Removal

While nanocomposite-based dye-removal techniques show great promise, they also face several challenges. A major concern is the high synthesis cost, as the production of advanced nanocomposites involves complex fabrication processes that require precise control of various parameters (Rustembekkyzy et al., 2024). Scalability is another issue, as maintaining uniform properties during large-scale industrial applications proves difficult (Farhan et al., 2023). Nanocomposites are pretty effective, but there are a few issues to keep in mind. The nano-composite materials become difficult to capture the dyes because they have a tendency to stick together after being added to water systems (Mittal et al., 2016). The small particles within these composites pose environmental risks because their long-term release into the environment may actually generate additional issues while failing to address previous water contamination difficulties. The effectiveness of nanocomposites varies depending on the dye type they need to treat. These specific nanocomposites demonstrate excellent performance with individual dyes although they yield underwhelming results for coping with combined industrial wastewater (Palani et al., 2023).

Future Research Directions

The notable potential of nanocomposites in wastewater treatment faces challenges regarding expenses and large-scale manufacturing methods. Omidvar et al. (2017) advises on the potential solution of wastewater remediation through plant extract and biopolymer production that uses green methodologies. The effectiveness of nanodevices can be enhanced when protective coatings and structural improvements are added to particulate surfaces. Using these enhancements over time makes the device more durable which ultimately leads to elevated sustainability and decreased operational costs (Ren et al., 2013).

Technology advancement combined with nanocomposites enables additional unique opportunities. Advanced high-tech filtration systems and nanoreactors have the ability to boost process treatments effectively while managing the required energy consumption according to Farhan et al. (2023). Process efficiency can go up while monitoring and adjustment controls become possible with the implementation of artificial intelligence technology.

Research on nanocomposite long-term effects together with their influence on water ecosystems represents vital information for analysis (Rustembekkyzy et al., 2024; Dai et al., 2019). Water pollution contains dyes in addition to heavy metals and organic chemicals which create direct environmental damage (Dai et al., 2019). The wastewater treatment benefits from hybrid nanocomposites that possess both fundamental characteristics.

CONCLUSION

Nanocomposites have essential wastewater treatment characteristics because their combination of big surface areas and powerful photoactivity operation with flexible design features. Wastewater dye removal functions best through these materials when compared to normal treatment technologies. Different arrangement approaches between adsorption and photocatalysis and ion exchange help obtain better dye removal efficiency from wastewater by nanocomposites.

Several advantages exist for this technology although multiple problems still require solutions. Sustainable fixes need to lower material expenses together with solving operational growth limitations and ensuring material durability in environmental applications. The field of academic research produces advancements in eco-friendly sustainable methods for product generation together with hybrid nanocomposite structures and improved filtration systems which enhance the practical adoption of these materials. Future nanocomposite research must improve material strength through the development of new approaches for material recycling. Research value would increase if scientists managed to remove various contaminants beyond dyes through their exploration. Enhanced efficiency becomes possible through real-time control systems along with monitoring functions because of automation through machine learning and AI integration into technological systems.

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REFERENCES

Ahmad, R., & Kumar, R. (2010). Adsorptive removal of congo red dye from aqueous solution using bael shell carbon. Applied Surface Science, 257(5), 1628–1633. https://doi.org/10.1016/j.apsusc.2010.08.111

Al-Rawashdeh, N. A. F., Allabadi, O., & Aljarrah, M. T. (2020). Photocatalytic activity of graphene oxide/zinc oxide nanocomposites with embedded metal nanoparticles for the degradation of organic dyes. ACS Omega, 5(43), 28046–28055. https://doi.org/10.1021/acsomega.0c03608

Ates, M., Eker, A. A., & Eker, B. (2017). Carbon nanotube-based nanocomposites and their applications. Journal of Adhesion Science and Technology, 31(18), 1977–1997. https://doi.org/10.1080/01694243.2017.1295625

Banerjee, S., Benjwal, P., Singh, M., & Kar, K. K. (2018). Graphene oxide (rGO)-metal oxide (TiO_2/Fe_3O_4) based nanocomposites for the removal of methylene blue. Applied Surface Science, 439, 560–568. https://doi.org/10.1016/j.apsusc.2018.01.140

Bhatnagar, A., & Sillanpää, M. (2010). Utilization of agro-industrial and municipal waste materials as potential adsorbents for water treatment: A review. Chemical Engineering Journal, 157(2–3), 277–296. https://doi.org/10.1016/j.cej.2010.01.007

Bogue, R. (2011). Nanocomposites: A review of technology and applications. Assembly Automation, 31(2), 106–112. https://doi.org/10.1108/01445151111117683

Camargo, P. H. C., Satyanarayana, K. G., & Wypych, F. (2009). Nanocomposites: Synthesis, structure, properties and new application opportunities. Materials Research, 12(1), 1–39. https://doi.org/10.1590/S1516-14392009000100002

Chong, M. N., Tneua, Z. Y., Poh, P. E., Jin, B., & Aryal, R. (2015). Synthesis, characterisation and application of TiO_2–zeolite nanocomposites for the advanced treatment of industrial dye wastewater. Journal of the Taiwan Institute of Chemical Engineers, 50, 288–296. https://doi.org/10.1016/j.jtice.2014.12.013

Crini, G. (2006). Non-conventional low-cost adsorbents for dye removal: A review. Bioresource Technology, 97(9), 1061–1085. https://doi.org/10.1016/j.biortech.2005.05.001

Dai, M., Zhou, G., Ng, H. Y., Zhang, J., Wang, Y., Li, N., Qi, X., Miao, M., Liu, Q., & Kong, Q. (2019). Diversity evolution of functional bacteria and resistance genes (CzcA) in aerobic activated sludge under Cd(II) stress. Journal of Environmental Management, 250, Article 109519. https://doi.org/10.1016/j.jenvman.2019.109519

Fahim, M., Shahzaib, A., Nishat, N., Jahan, A., Bhat, T. A., & Inam, A. (2024). Green synthesis of silver nanoparticles: A comprehensive review of methods, influencing factors, and applications. JCIS Open, 16, Article 100125. https://doi.org/10.1016/j.jciso.2024.100125

Farhan, A., Zulfiqar, M., Samiah, Rashid, E. U., Nawaz, S., Iqbal, H. M. N., Jesionowski, T., Bilal, M., & Zdarta, J. (2023). Removal of toxic metals from water by nanocomposites through advanced remediation processes and photocatalytic oxidation. Current Pollution Reports, 9(3), 338–358. https://doi.org/10.1007/s40726-023-00253-y

Mishra, R., & Militky, J. (2013). Nanocomposites. Journal of Materials Processing Technology, 213(4), 647–654. https://doi.org/10.1080/00405000.2013.812266

Mittal, H., Maity, A., & Ray, S. S. (2016). Gum karaya based hydrogel nanocomposites for the effective removal of cationic dyes from aqueous solutions. Applied Surface Science, 364, 917–930. https://doi.org/10.1016/j.apsusc.2015.12.241

Mohammadzadeh Pakdel, P., Peighambardoust, S. J., Arsalani, N., & Aghdasinia, H. (2022). Safranin-O cationic dye removal from wastewater using carboxymethyl cellulose-grafted-poly(acrylic acid-co-itaconic acid) nanocomposite hydrogel. Environmental Research, 212(Pt B), Article 113201. https://doi.org/10.1016/j.envres.2022.113201

Mostafa, M. H., Elsawy, M. A., Darwish, M. S. A., Hussein, L. I., & Abdaleem, A. H. (2020). Microwave-Assisted preparation of Chitosan/ZnO nanocomposite and its application in dye removal. Materials Chemistry and Physics, 248, Article 122914. https://doi.org/10.1016/j.matchemphys.2020.122914

Nambiar, R. B., Perumal, A. B., & Sadiku, E. R. (2024). Advances in nanocomposites: Preparation, characterization, properties, and applications. Molecules, 29(24), Article 5924. https://doi.org/10.3390/molecules29245924

Omanović-Mikličanin, E., Badnjević, A., Kazlagić, A., & Hajlovac, M. (2020). Nanocomposites: Brief review. Health Technology, 10 (1), 51–59. https://doi.org/10.1007/s12553-019-00380-x

Omidvar, A., Jaleh, B., & Nasrollahzadeh, M. (2017). Preparation of the GO/Pd nanocomposite and its application for the degradation of organic dyes in water. J. Colloid Interface Sci, 496, 44–50. https://doi.org/10.1016/j.jcis.2017.01.113

Oyewo, O. A., Elemike, E. E., Onwudiwe, D. C., & Onyango, M. S. (2020). Metal oxide-cellulose nanocomposites for the removal of toxic metals and dyes from wastewater. International Journal of Biological Macromolecules, 164, 2470–2487.https://doi.org/10.1016/j.ijbiomac.2020.08.074

Pai, S., Kini, M. S., & Selvaraj, R. (2021). A review on adsorptive removal of dyes from wastewater by hydroxyapatite nanocomposites. Environmental Science and Pollution Research, 28(10), 11835–11849. https://doi.org/10.1007/s11356-019-07319-9

Palani, G., Trilaksana, H., Sujatha, R. M., Kannan, K., Rajendran, S., Korniejenko, K., Nykiel, M., & Uthayakumar, M. (2023). Silver nanoparticles for wastewater management. Molecules, 28(8), Article 3520. https://doi.org/10.3390/molecules28083520

Rajani, A., Chauhan, P., & Dave, P. Y. (2021). Nanocomposites: A new tendency of structures in nanotechnology and material science. Journal of Nanoscience and Technology, 7(1), 21–26. https://doi.org/10.30799/jnst.315.21070103

Ren, Y., Abbood, H. A., He, F., Peng, H., & Huang, K. (2013). Magnetic EDTA-modified chitosan/SiO_2/Fe_3O_4 adsorbent: Preparation, characterization, and application in heavy metal adsorption. Chemical Engineering Journal, 226, 300–311. https://doi.org/10.1016/j.cej.2013.04.059

Rustembekkyzy, K., Sabyr, M., Kanafin, Y. N., Khamkhash, L., & Atabaev, T. Sh. (2024). Microwave-assisted synthesis of ZnO structures for effective degradation of methylene blue dye under solar light illumination. RSC Advances, 14(26), 16293–16299. https://doi.org/10.1039/D4RA02451F

Singh, S., Barick, K. C., & Bahadur, D. (2013). Fe_3O_4 embedded ZnO nanocomposites for the removal of toxic metal ions, organic dyes and bacterial pathogens. Journal of Materials Chemistry A, 1(10), 3325–3333. https://doi.org/10.1039/C2TA01045C

Sonawane, G. H., Patil, S. P., & Sonawane, S. H. (2021). Nanocomposites and their applications. In Y.-W. Mai & Z.-Z. Yu (Eds.), Nanocomposites: Volume 1: Synthesis, structure, properties and new application opportunities (pp. 1–20). Elsevier. https://doi.org/10.1016/B978-0-08-101971-9.00001-6

Sun, Z., Yao, G., Liu, M., & Zheng, S. (2017). In situ synthesis of magnetic $MnFe_2O_4$/diatomite nanocomposite adsorbent and its efficient removal of cationic dyes. Journal of the Taiwan Institute of Chemical Engineers, 71, 501–509. https://doi.org/10.1016/j.jtice.2016.12.013

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