

# Nano-Enabled Remediation Of Industrial Wastewater: Performance, Mechanisms, And Risk Assessment Of Engineered Nanomaterials

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Engineered nanomaterials are considered avenues for overcoming the complicated problem of remediating industrial wastewater since they allow high effectiveness in removing a wide range of contaminants under controllable conditions. This paper is a critical review of the use of metal- and metal-oxide nanoparticles, carbon-based nanomaterials, and polymeric nanocomposites to treat real and simulated industrial effluents that contain heavy metals, synthetic dyes, pharmaceuticals, and mixed ionic species. The usual methods for getting rid of contaminants, such as adsorption, ion exchange, redox transformation, photocatalysis, and membrane separation based on size or charge, have been examined using standard models (like Langmuir and Freundlich for adsorption, and pseudo first and second order for kinetics) to connect the features of nanomaterials to how fast and effectively they can perform. The case studies chosen for the textile, pharmaceutical, tannery, and electroplating industries have demonstrated how nano-enabled processes work in realistic operating conditions compared to conventional adsorbents and catalysts in terms of efficiency, contact time, and reusability. The paper talks about ways to reuse materials (like chemical, heat, solvent-based, and magnetic methods), how to use nanomaterials in different treatment processes, and important design factors like size, cost, waste management, and energy needs. The focus is on environmental risks, including the possible release of nanoparticles, their transformation and fate in actual matrices, ecotoxicity and bioaccumulation issues, and the new role of life cycle assessment in evaluating nano-enabled technologies. Lastly, the main research gaps and future directions are outlined, with an emphasis on safe-by-design materials, readily recoverable nano-adsorbents, pilot and full-scale experiments in real effluents, and interconnection with digital tools and circular economy solutions that are centred around recovering resources and metals.

**Keywords:** engineered nanomaterials; industrial wastewater; adsorption; photocatalysis; nanocomposite membranes; regeneration; environmental risk; life-cycle assessment; safe-by-design; circular economy.

## 1 Introduction

Explosive industrialisation has given rise to the release of complex streams of wastewater that include dyes, heavy metals, pharmaceuticals, and other enduring organics, and they are deadly to both aquatic ecosystems and human health (Lu and Astruc, 2020; Suleiman et al., 2024).

Some of the main sources of these harmful substances are industries like textiles, pharmaceuticals, tanneries, petrochemicals, and electroplating, which often release wastewater that has high levels of chemical oxygen demand (COD), biological oxygen demand (BOD), and heavy metals that exceed legal limits. Synthetic dyes are especially bad due to their complex aromatic structures and high stability, which causes colour pollution, light penetration, and possible mutagenic and carcinogenic effects (Yadav et al., 2024; Yaseen & Scholz, 2019). Non-biodegradable and potentially bioaccumulating heavy metals, like cadmium, chromium, lead, and nickel, may cause kidney damage, neurological disorders, and other types of cancers (Suleiman et al., 2024; Ubaid et al., 2023). The presence of pharmaceutical residues in waste from industries and hospitals leads to problems like hormone disruption, antibiotic resistance, and long-term toxicity, making industrial wastewater one of the biggest environmental challenges in today's chemistry and environmental science.

The usual methods for treating wastewater, like physical and biological treatments, often don't work well for removing small amounts of dyes, heavy metals, and pharmaceuticals, especially when these contaminants are mixed together or present in low concentrations. Engineered nanomaterials are effective tools for modern wastewater treatment because they have a large surface area, adjustable surface properties, and unique electronic features, which help them interact better with and react to pollutants. Nano-oxides, carbon-based nanomaterials, and nanocomposites have a high adsorption capacity and higher kinetics with both cationic and anionic pollutants due to adsorption capacities, as surface complexation, electrostatic interactions, and  $\pi$ - $\pi$  stacking with their surfaces can be used as adsorbents (Suleiman et al., 2024). Semiconducting nanomaterials, including  $\text{TiO}_2$ ,  $\text{ZnO}$ , and doped compounds, are used in photocatalytic reactions to form reactive oxygen species during light irradiation, which are used to oxidise and mineralise recalcitrant organics (e.g., dyes, pharmaceuticals) (Lu and Astruc, 2020). Nanomaterial-modified membranes have a better ability to allow liquids to pass through, choose what to filter, and resist buildup, which helps overcome some problems with traditional membrane methods when treating strong industrial wastewater.

The engineered nanomaterials used in wastewater treatment can be made using different methods, including physical, chemical, or environmentally friendly processes like the sol-gel technique, co-precipitation, hydrothermal synthesis, and methods involving plants or microorganisms. Even though the way nanomaterials are made greatly affects their size, shape, structure, and surface features, which in turn influence how well they can adsorb and work as photocatalysts, discussing these production methods in detail is not the focus of this work. Instead, these structural and surface features are linked to how well they perform in real or test industrial wastewater systems, including how effectively they remove contaminants, their reaction speeds, how many times they can be reused, and their stability during use. At the same time, there is more and more evidence that using nanomaterials in treatment processes can create new environmental problems, like the release of nanoparticles into treated water, harm to ecosystems, and issues with downstream biological treatment. Hence, understanding the balance between high treatment performance and possible adverse effects is necessary for the responsible deployment of nano-enabled technologies in the management of industrial wastewater (VeilleNanos, 2023; Hilaris, 2024).

It is against this background that the current paper has four interrelated goals, which jointly inform its objectives and contribution. First, it will critically analyse the performance of various engineered nanomaterials, such as metal and metal-oxide nanoparticles, carbon-based nanomaterials, and nanocomposites, to remove dyes, heavy metals, pharmaceuticals, and other organic pollutants from industrial wastewater with a specific emphasis on quantitative parameters. such as the removal efficiency, adsorption capacity, photocatalytic activity, and reusability under realistic conditions of operation. Second, it aims to explain the controlling mechanisms behind nano-enabled adsorption, photocatalysis, and membrane-based processes by analysing pollutant-surface interactions, radical formation, and charge transfer, as well as how important operational variables (pH, ionic strength, co-existing ions, and mixed contaminants) influence these mechanisms. Third, the paper looks at the risks to the environment and human health from using engineered nanomaterials to clean industrial wastewater, especially how nanoparticles might be released into treated water, their potential harm to ecosystems and ability to build up in living organisms, and how they could affect future biological treatment processes and microbial communities. Lastly, it aims to identify important areas where more research is needed and suggest future steps for creating safe and effective nanomaterials, as well as for incorporating nano-enabled processes into sustainable treatment systems while considering their entire life cycle, regulatory issues, and the need to balance the benefits of technology with long-term environmental safety.

## **2 Classes of nanomaterials used in industrial wastewater treatment**

Among the most popular engineered nanomaterials that are used in the treatment of industrial wastewater are those that are typically categorised into three broad groups: metal and metal oxide nanoparticles, carbon-based nanomaterials, and polymeric or composite nanomaterials, each possessing distinct physicochemical properties that define their correct application in the adsorption, photocatalysis, and membrane-based separation processes (Zhang et al., 2016). The nanoparticles made from metals and metal oxides, like zero valent iron (nZVI), iron oxides, titanium dioxide (TiO<sub>2</sub>), zinc oxide (ZnO), manganese oxides, copper oxides, and alumina, have very large surface areas and short paths for movement, providing many active spots to connect with pollutants. Their strong redox and photocatalytic potential allows reducing toxic metal ions, such as Cr (VI), to the less mobile Cr (III) and oxidising a broad spectrum of organic pollutants, like dyes, phenols, and pharmaceuticals (Ahmed et al., 2022). In many cases, these materials can be superparamagnetic, like Fe<sub>3</sub>O<sub>4</sub> and similar iron oxides, which allows for easy collection of the treated water using a magnetic field and makes it possible to reuse them, offering an advantage over traditional granular or powdered sorbents.

The second important group is carbon-based nanomaterials, which include single- and multi-walled carbon nanotubes (CNTs), graphene, graphene oxide (GO), reduced graphene oxide, carbon dots, and graphene quantum dots. The characteristic features of these materials include very high surface areas, mesoporous or hierarchical pore structures, and delocalised  $\pi$  electron systems that facilitate strong  $\pi$ - $\pi$  stacking with aromatic dyes and pharmaceuticals and can interact in many different ways, including hydrophobic attraction, hydrogen bonding, and surface complexation (Lu and Astruc, 2020, p. 1; Zhang et al., 2021). Their surface can be

easily changed by oxidation, heteroatom (N, S, P) doping, or polymer grafting to adjust hydrophilicity, surface charge, and the density of functional groups (such as -COOH, -OH, and -NH<sub>2</sub>) and enhance adsorption capacity and selectivity to a particular contaminant (Lu and Astruc, 2020). Carbon-based nanomaterials are also mechanically strong and chemically stable, which means they can preserve their structure and function in the acidic, basic, or saline conditions common to most industrial effluents. Their ability to conduct electricity makes them useful as supports in systems that treat water using electrochemical and photocatalytic methods (Lu and Astruc, 2020; Zhang)

Thirdly, there are polymeric nanomaterials, which include synthetic polymers as well as natural or biopolymeric systems. Polysulfone (PSF), polyvinylidene fluoride (PVDF), polyamide, and polyacrylonitrile are synthetic polymers that are commonly used due to their high film-forming capacity, mechanical stability, and chemical resistance (Abooali et al., 2024; Zulkifli et al., 2024). Phase inversion, interfacial polymerisation, and surface modification can be used to optimise water flux, solute selectivity, and fouling resistance by controlling their porosity, pore size distribution, and surface hydrophilicity (Abooali et al., 2024; Zulkifli et al., 2024). Additional functionality is provided by biopolymers, like chitosan, cellulose, and alginate, due to the presence of a large number of reactive groups (-NH<sub>2</sub>, -OH, -COOH), which give intrinsic adsorption and flocculation properties towards dyes and metal ions and permit the synthesis of beads, gels, and films to be used in sorption-based treatment (Hussain et al., 2024).

When these polymer matrices are used to create polymeric nanocomposites and nanomembranes by mixing them with inorganic nanofillers, including metal oxides or CNTs along with graphene derivatives or other nanoparticles, the resulting nanoproducts tend to exhibit properties that are better than those of the components (Abooali et al., 2024; Hussain et al., 2024; Zulkifli et al., 2024). The dispersed nanofillers may enhance the hydrophilicity of membranes, regulate their surface roughness, and add new functional groups or catalytic centers, which results in enhanced water permeability, contaminant removal, and a decrease in organic matter or biofilm adsorption (Abooali et al., 2024). Nanofillers (silver, ZnO, or TiO<sub>2</sub>) are also used in certain designs, allowing membranes to serve as physical barriers and at the same time as active reaction sites to degrade pollutants (Abooali et al., 2024; Hussain et al., 2024). Recent work on PSF- and PVDF-based nanocomposite membranes with ZnO, TiO<sub>2</sub> or graphene oxide, such as, has been shown to have improved hydrophilicity, pure water flux, dye and heavy metal rejection and long-term stability over unmodified membranes, showing how thoughtfully designed hybrid structures can solve multiple treatment problems in a single unit (Abooali et al., 2024; Zulkifli et al., 2024). Overall, the size of the particles or fibres, their surface area, pore structure, surface treatments, properties of semiconductor band gaps (for photocatalyst systems), and strength all determine how each type of nanomaterial can be used in processes like adsorption, photocatalysis, and membrane separation in combined industrial wastewater treatment systems.

**Table-1: Classes, examples, properties, and roles**

<b>Class of nanomaterial</b>	<b>Representative examples</b>	<b>Key physicochemical properties relevant to treatment</b>	<b>Main roles in industrial wastewater treatment</b>
Metal and metal-oxide nanoparticles	Fe and Fe <sub>3</sub> O <sub>4</sub> nanoparticles, nZVI, TiO <sub>2</sub> (anatase/rZnO), MnO <sub>2</sub> , CuO, Al <sub>2</sub> O <sub>3</sub>	Exceptionally high surface area per unit volume, as well as high volume-to-surface area ratio; high redox activity, enabling the reduction of metals (e.g., Cr (VI) to Cr (III) and the degradation of organic pollutants; adjustable surface charge by pH and surface functionalization; numerous systems can be made superparamagnetic, permitting magnetic separation; semiconductor band gaps (e.g., TiO <sub>2</sub> and ZnO) can be used in photocatalysis in either the UV or visible light (Ahmed et al., 2022)	High-capacity adsorption of the heavy metals and selected organic pollutants; catalytic or photocatalytic degradation and mineralisation of dyes, phenols, pharmaceuticals, and other stubborn organics; disinfection and inactivation of microorganisms; application as nano adsorbents or catalysts in fixed bed, fluidised bed, or slurry reactors to polish industrial effluents (Ahmed et al., 2022; Zhang et al., 2016).

Carbon-based nanomaterials	Single- and multi-walled CNTs, graphene, graphene oxide (GO), reduced GO, carbon dots, graphene quantum dots	Very large surface area and mesoporosity; delocalised $\pi$ electron systems that facilitate $\pi$ -stacking with aromatic dyes and pharmaceuticals; tunable surface chemistry by oxidation, heteroatom doping, or polymer grafting; high mechanical strength and chemical stability at acidic, alkaline, or saline conditions; and high electrical conductivity, which can be used in electrochemical and photocatalytic reactions (Lu and Astruc, 2020; Zhang et al., 2021).	High-performance organic contaminants (dyes, pharmaceuticals, pesticides) and, in certain instances, metal ion adsorbents; scaffolds and supports of catalytic nanoparticles and semiconductor photocatalysts; functional fillers in mixed matrix membranes to increase water flux, solute selectivity, and fouling resistance; active materials in electrochemical treatment, capacitive deionisation, and integrated sensing-treatment systems (Lu and Astruc, 2020; Zhang et al., 2021).
Polymeric nanomaterials	Polysulfone (PSF), PVDF, polyamide (NF/RO active layers), polyacrylonitrile, chitosan, cellulose, alginate	Fine film-forming properties and processability into asymmetric or thin-film composite membrane; variable porosity and pore size distribution through phase inversion or interfacial polymerization; variable hydrophilicity and surface charge through monomer choice and subsequent synthetic modification; good mechanical and chemical stability; biopolymers have high functional group density ( $-\text{NH}_2$ , $-\text{OH}$ , $-\text{COOH}$ ), which offers inherent sorption	Bases to be used as pressure-driven membrane processes (microfiltration, ultrafiltration, nanofiltration, reverse osmosis) to treat various industrial effluents; adsorbents and flocculants (especially chitosan and modified cellulose) to remove dyes, metals and suspended solids; scaffolds to immobilise inorganic nanoparticles, enzymes, or microbial cells in hybrid and bio-nano treatments (Aboali et al., 2024; Hussain et al., 2024)

		and flocculation properties (Abooali et al., 2024; Hussain et al., 2024; Zulkif et al., 2024)	
Polymeric nanocomposites and nano-membranes	PSF/GO, PSF/TiO <sub>2</sub> , PSF/ZnO, PVDF/CNT, biopolymer–metal-oxide hybrids, PSF/PANI–ZnO membranes	Add flexibility and processability of polymers with the high reactivity and surface area of inorganic nanofillers, better hydrophilicity and altered surface roughness, frequently resulting in higher water flux and reduced fouling, extra sorption sites and catalytic centres furnished by nanofillers, possible antibacterial activity and enhanced mechanical strength, controlled pore structure and surface charge that allows more selective contaminant rejection (Abooali et al., 2024; Hussain et al., 2024; Zulkifli et al., 2024)	High-performance nanocomposite membranes with the ability to concurrently adsorb and filtrate dyes and metal ions; selective removal of multivalent ions and organic micropollutants; antifouling and antibacterial surfaces that can be used in long-term operation in severe industrial wastewaters; multifunctional treatment modules in which size exclusion, adsorption, and catalytic degradation can be carried out in the same membrane-based operation (Abooali et al., 2024)

### 3 Removal mechanisms and kinetics

#### 3.1 Heavy metals: Adsorption, ion exchange, reduction, isotherms and kinetics

For heavy metal ions like Pb (II), Cd (II), Cr (VI), and Cu (II), specially designed nanomaterials mainly clean up contaminants by sticking to them (adsorption), swapping ions (ion exchange), and changing them chemically (reduction) when possible (Gao et al., 2019; Xu et al., In ion adsorption, the hydrated metal ions are the ones that form inner-sphere or outer-sphere complexes with functional groups present on the surface of the nanomaterial (e.g., -COOH, -OH, -NH<sub>2</sub>), whereas in ion exchange, the counter-ions on the sorbent surface (e.g., H<sup>+</sup>, Na<sup>+</sup>, or Ca<sup>+</sup>) are replaced by metal ions in solution (Gao et al., 2019). Partial reduction of

the very toxic Cr (VI) to the less harmful Cr (III) and other chemical reactions that happen with nZVI and iron-oxide-based nanomaterials are key to completely removing these metals, usually followed by adsorption or precipitation. The pore structure, surface charge, and surface area of nanomaterials have a high impact on metal uptake capacity and affinity, and, in most cases, an increase in a specific surface area and appropriate functionalisation increases binding (Gao et al., 2019; Xu et al., 2022).

The Langmuir and Freundlich isotherm models are the most widely used methods to understand how heavy metals stick to nanomaterials, showing the relationship between the concentration of the metal in balance and the amount of metal that attaches to each unit of the material. The classical Langmuir isotherm is a monolayer adsorption that assumes that the surface is homogeneous with finite sites of equal energy. It is formulated.

$$q_e = \frac{q_{\max} K_L C_e}{1 + K_L C_e}$$

In this equation,  $q_e$  is the theoretical monolayer capacity ( $\text{mg g}^{-1}$ ),  $C$  is the concentration of the solute at equilibrium ( $\text{mg L}^{-1}$ ),  $q_{\max}$  is also the theoretical monolayer capacity ( $\text{mg g}^{-1}$ ), and  $K_L$  is The Freundlich isotherm is empirical and describes adsorption on heterogeneous surfaces.

$$q_e = K_F C_e^{1/n}$$

$K_F$  ( $(\text{mg g}^{-1}) (\text{L mg}^{-1})^{-1}$ ) is the Freundlich constant and  $1/n$  is the heterogeneity factor (Rahman et al., 2022). Most studies of nano-iron oxides and other nano-adsorbents to remove Pb (II) and Cu (II) give excellent fits to both models, with Langmuir tending to do better and give maximum capacity values in the tens to hundreds of  $\text{mg g}^{-1}$  range (Xu et al., 2022; Kinoti et al., 2024). The details of these balances are very affected by the characteristics of nanomaterials, such as their surface groups, how much they clump together, and the presence of other ions in the solution.

The pseudo-first-order and pseudo-second-order rate equations are the most commonly used methods to explain how heavy metals stick to nanomaterials, helping us understand the steps that limit the rate and whether the process involves chemical or physical bonding. It is common to write the pseudo-first-order model (Lagergren model).

$$\frac{dq_t}{dt} = k_1 (q_e - q_t)$$

which integrates to

$$\ln (q_e - q_t) = \ln (q_e) - k_1 t$$

where  $q_t(\text{mg g}^{-1})$  is the adsorption capacity at time  $t$  (min),  $q_e$  is the equilibrium capacity, and  $k_1(\text{min}^{-1})$  is the pseudo-first-order rate constant (Rahman et al., 2022). The pseudo-second-order model can be stated as

$$\frac{dq_t}{dt} = k_2(q_e - q_t)^2$$

which integrates to

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

where  $k_2(\text{g mg}^{-1})$  is the pseudo-second-order rate constant (Rahman et al., 2022; Gao et al., 2019). In many systems with nanomaterials and heavy metals, the kinetic data fits the pseudo-second-order model better than the pseudo-first-order model, suggesting that the speed of the process is limited by the chemical bonding or sharing of electrons between metal ions and the surface functional groups. Nanomaterials can have high external surface area and short diffusion; the paths and beneficial surface charge are likely to enhance the initial adsorption rate and reduce the time to reach equilibrium, making it shorter than with traditional sorbents (Gao et al., 2019).

### 3.2 Synthetic dyes and organic contaminants: Photocatalysis and advanced oxidation

Nanomaterials can remove synthetic dyes and other organic pollutants through both adsorption and advanced oxidation processes (AOPs), specifically heterogeneous photocatalysis using semiconductor nanoparticles like TiO and ZnO or nanocomposites containing these semiconductor nanomaterials (Lu and Astruc, 2020). When the semiconductor nanomaterials are exposed to UV or visible light, they absorb photons that have enough energy to excite electrons, causing them to jump from the valence band to the conduction band, which leaves behind positively charged holes. These newly formed electrons and holes could then react with water and oxygen that are already on the surface to make reactive oxygen species (ROS), such as hydroxyl radicals (OH), superoxide radicals (O), and hydrogen peroxide. These ROS can break down complex dye molecules and other organic compounds into smaller intermediates and eventually into CO and HO (Lu and Astruc, 2020). The balance between how much ROS is produced and how often the electron-hole pairs recombine, along with the properties of the nanomaterials (like band-gap width, crystallinity, particle size, surface defects, and dopants or co-catalysts), is crucial for effectively breaking down pollutants using photocatalysis.

Dye and organic materials need to stick to the surface of the photocatalyst as a necessary first step in most nano-enabled systems, which increases the amount of pollutants around the active sites and helps with electron transfer. Heterostructured photocatalysts made from carbon-based nanomaterials (like CNTs and graphene) and semiconductor nanoparticles are often used to help carbon act as an electron sink, which helps keep charges separate and reduces recombination, mainly to improve quantum efficiency and degradation rates. The band-gap engineering can be achieved by adding certain elements (like nitrogen to titanium oxide) or by working with a semiconductor that has a smaller band gap to allow better light absorption in

the visible range, which is particularly helpful when using sunlight. The overall speed and ability to remove dye will depend not just on how well the dye sticks to the surface (which can still be described using Langmuir or Freundlich isotherms) but also on how well the photocatalyst works, the strength of the light, and how well materials move around in the reactor.

The breakdown of dyes and organic pollutants using nanomaterials typically behaves like a simple first-order reaction according to the Langmuir-Hinshelwood model, especially when the starting concentrations are low. The rate law takes the form.

$$\ln \left( \frac{C_0}{C_t} \right) = k_{app} t$$

The rate law is expressed as follows: Increased surface area, enhanced light absorption within the range of the wavelengths of interest, greater charge separation, and suitable surface functionalisation of nanomaterials are all involved in increasing the "k" values and rates of mineralisation (Lu and Astruc, 2020).

### **3.3 Salts and mixed contaminants: Nanofiltration and nano-enabled membranes**

Nanofiltration (NF) and other advanced membranes remove substances, including salts and mixed ionic contaminants, from industrial brines and complex waste using nanomaterials. They do this mainly by blocking particles based on their size and charge. The radii of membrane pores in nanofiltration typically range from approximately 0.3 to 1 nm, facilitating the passage of monovalent ions while excluding multivalent ions and larger solutes, which are rejected due to their dimensions and configurations when hydrated (Emamjomeh et al., 2022). Donnan exclusion is caused by surface charge on the membrane, which can be generated by ionisable functional groups or charged nanomaterials embedded within it. It causes repulsion between co-ions (of the same charge as the membrane surface) and partitioning between counter-ions based on charge neutrality, affecting the rejection of salts like NaCl and Na<sub>2</sub>SO<sub>4</sub> (Emamjomeh et al., 2022). Recently, it has been proposed that dielectric exclusion, the thermodynamically low-permeability membrane pores, can be the primary controlling factor in ion selectivity, especially in Cl<sup>-</sup>/SO<sub>4</sub><sup>2-</sup> separation.

Functionalisation of nanomaterials in NF and associated membranes varies the pore architecture, roughness, hydrophilicity, and charge of the NF and alters steric and electrostatic rejection (Abooali et al., 2024; Zulkifli et al., 2024). Hydrophilic nanofillers like graphene oxide and metal oxides can create more pathways for water to flow and reduce clogging, while the presence or absence of charged or polar groups on the surfaces of nanomaterials influences how certain ions are excluded from passing through. The nanocomposite membrane can be used to combine size and charge filtering with the ability to absorb and break down contaminants, which is useful in systems with both salts and organic pollutants, like when photocatalytic nanoparticles are added to the selective layer. The movement of salt and ions through the NF membranes is usually explained by more complex equations, rather than

simple ones, but how quickly things move depends a lot on changes in the size of the pores, the complexity of the path, and the charge on the surface of the nanomaterials.

#### 4 Textile dye wastewater: Case studies and comparative performance

Textile wastewater is usually compounded with reactive dyes, azo dyes, and disperse dyes, as well as surfactants, salts, and auxiliary chemicals. It is thus difficult to achieve full decolorisation and mineralisation of wastewater using traditional wastewater treatment techniques (Jeliani et al., 2023; Mourad et al., 2024). Recent nano-enabled systems using TiO<sub>2</sub> and ZnO, as well as hybrid composites, have been shown to effectively remove a great deal of dye and COD in real textile effluent over relatively short irrigation durations, and the catalyst in such systems is often highly reusable (Mourad et al., 2024; Raza et al., 2024). As an illustration, research on photocatalytic treatment of industrial textile wastewater using C- and S-doped TiO<sub>2</sub> nanoparticles on Reactive Blue 19 and Red 76 dyes showed that the dye decolorisation was  $\approx 100\%$  and there was a significant reduction in COD within 60 minutes of visible light irradiation at an optimal catalyst dose of 1.6 g L<sup>-1</sup> (El Alfy et al., 2019). In another study a modified clay/TiO<sub>2</sub>/ZnO hybrid nanocomposite on real textile effluent attained approximately 91 per cent of colour removal and 94% of COD removal at pH 5.5, an adsorbent dose ratio of 0.55 grams, and 75 minutes of contact time, with a maximum sorption capacity of approximately 660 mg g<sup>-1</sup> (Mourad et al., 2024). Equally, optimal performance of the green synthesis of ZnO nanoparticle produced from *Eleocharis dulcis* to treat raw textile wastewater under solar photocatalysis conditions was about 87% decolorization and 100% COD removal at pH 7, 60 minutes of solar radiation, a dose of ZnO of 2 g/L, and a fixed percentage of influent colour concentration and this illustrates the potential of biogenic nano ZnO in the real outside setting (Mourad et al., 2024)

Adsorption-based systems combined with photocatalysis can provide better performance and effectiveness for treating dye-laden textile wastewater. An example of these is carbon nanotube/TiO<sub>2</sub> (CNT/TiO<sub>2</sub>) nanocomposites, which capitalise on a broad photocatalytic region of the light spectrum and the high adsorption capacity of CNTs for azo dye removal (He et al., 2020). MWCNTs/TiO<sub>2</sub> nanocomposites were found to be more effective as a microfluidic treatment option than pure TiO<sub>2</sub> by mediating a higher rate of decolorisation and enhancing mineralisation at an acidic pH because the CNT phase led to a higher CNT-adsorption and CNT-electron transfer rate, thus lowering the rate of electron-hole recombination (He et al., 2020). Recently, the nZVI-SiO-TiO nanocomposite made at low pH showed it could completely remove and break down methylene blue dye, and it kept over 90% effectiveness even after being used 5 times in a row, showing it works really well and stays stable for treating wastewater with dye (Saini et al., 2024). These nano-enabled systems commonly remove dyes and COD by benchmarking against rival adsorbents like activated carbon, with the use of nano-enabled structures often achieving comparable or superior colour and COD removal in shorter contact times and allowing the in situ degradation of dyes instead of transferring the dye to a secondary phase (Jelani et al., 2023; Mourad et al., 2024).

**Table-2: Performance of selected nano-enabled systems versus conventional materials for textile dye wastewater treatment.**

Study / effluent type	Treatment material / process	Key operating conditions (pH, dose, time, light)	Performance metrics (dyes/COD)	Reusability / notes
El-Alfy et al. (2019) – Industrial textile wastewater with RB-19 and RR-76 dyes went	C-doped, S-doped, and C,S co-doped TiO <sub>2</sub> NPs (photocatalysis)	pH ≈ 1; catalyst dose 1.6 g L <sup>-1</sup> ; visible light; 60 min irradiation	≈100% decolourisation of RB-19 and RR-76; COD reduction up to ~87–89% depending on dopant	Catalyst-recovered and reused treated effluent also demonstrated much less toxicity toward rotifers and artemia.
Mourad et al. (2024) – Real textile effluent weapon online +1	Modified clay/TiO <sub>2</sub> /ZnO hybrid nanocomposite (adsorption/photocatalysis)	pH 5.5; adsorbent dose 0.55 g; contact time 75 min; optimized via RSM (batch)	≈91% color removal; ≈94% COD removal; maximum sorption capacity ≈660 mg/g <sup>-1</sup>	Proposed material that is effective in actual effluent; possible reuse plans are discussed, making it possible to use it in irrigation.
Mourad et al. (2024) – Raw textile wastewater (solar) iwaponline	Green ZnO-ED NPs (solar photocatalysis)	pH 7; ZnO-ED dose 2 g L <sup>-1</sup> ; 10% influent color; 60 min solar exposure	≈87% decolourisation ; 100% COD removal under optimized conditions	ZnO-ED Nps made out of plant extract; solar operation under conditions of realism in the outdoor environment.
He et al. (2020) synthetic azo dye wastewater pubs. rsc+1	MWCNTs/TiO <sub>2</sub> nanocomposite (adsorption + photocatalysis, microfluidic system)	Near-neutral pH; composite loading optimized; UV illumination; short residence times (minutes-scale)	The MWCNTs/TiO <sub>2</sub> nanocomposite exhibits enhanced decolourisation and	CNTs improve adsorption and electronic transfer; a system of continuous treatment by

			mineralisation compared to TiO <sub>2</sub> alone, as well as enhanced apparent rate constants.	means of microfluidics.
Journals use conventional benchmarks, which encompass various textile effluents. uni-lj+1	Activated carbon adsorption or coagulation–flocculation	pH 5–8; adsorbent doses commonly 1–10 g L <sup>-1</sup> ; contact times 60–180 min; no light irradiation	Colour and COD removal is usually 60–80%, according to dosage; insufficient mineralisation; used carbon needs to be regenerated/disposed of.	The process is vigorous and extensively used, primarily for transferring dyes into the solid phase, resulting in increased levels of sludge generation and a significant time commitment.

## 5 Regeneration methods and reuse performance

Chemical, thermal, solvent-based, or magnetic separation-assisted methods are generally used to regenerate nanoadsorbents and nanophotocatalysts. Many chemically amenable chemoluminescence systems can be regenerated using either acid or base washing (e.g., 0.1 N HCl, HNO<sub>3</sub>, or NaOH) or using chelating agents (e.g., EDTA) to de-absorb heavy metals from functionalised magnetic nanoparticles, and many of these systems can retain over 90% of their original adsorption capacity after three to five regeneration cycles (Li et al., 2016; Zhou et al., 2016; Zhang et al., 2020). One such example is the Fe<sub>3</sub>O<sub>4</sub>@Me<sub>6</sub>TREN magnetic nanoparticles, which selectively remove heavy metals, can be successfully regenerated by EDTA Na solutions, exhibit stable adsorption behaviour after 3 cycles, and can be readily regenerated by a magnetic field (Zhang et al., 2020). On the same note, magnetically engineered nanoadsorbents that can absorb and release Pb(ii) and Pd(ii) have been engineered with regeneration using dilute nitric acid, which has shown the capacity to retain about 80%–90% of the initial capacity in numerous adsorption and desorption operations (Kumar et al., 2022).

Thermal regeneration is commonly used on carbon-based and select inorganic nanomaterials, where moderation heating in either air or an inert gas depletes organics on the surface but needs to be well regulated to prevent sintering and surface area loss (Li et al., 2016). Carbon-based nanomaterials can release their water-repelling organic compounds into alcohols or other organic liquids. Sometimes, magnetic separation helps recover them, but this usually needs chemical washing to restore their active sites. Overall, many nanoadsorbents can be

reused effectively for about 5 to 10 cycles, but they tend to lose some effectiveness over time, which needs to be evaluated individually.

### **5.1 Process integration in treatment trains**

Practically, when applied as multi-stage treatment trains, nanomaterials are most useful but not when presented as an isolated process. This is often done by adding more nano adsorbents or nano coagulants after the usual steps of coagulation, flocculation, and sedimentation to clean up any leftover dyes, metals, or pharmaceuticals, which reduces the amount of nanomaterials needed and makes it easier to regenerate them (Abdel Shafy & El Khateeb, 2013, as cited in Fouda et al.). Built wetlands can be used with nanoparticle-based coagulation to treat blackwater: first, sediment and horizontal flow wetlands remove most of the suspended solids and biodegradable materials, and then a nanoparticle coagulation step using  $\text{Fe}_3\text{O}_4$  further improves the removal of COD, BOD, and TSS so that the water can be reused without any restrictions. Nanomaterials are now being used in biological treatment as tiny carriers or helpers to improve anaerobic digestion and biogas production, or as surfaces that prevent bacteria buildup in membrane bioreactors.

Nanomaterials can be used as mixed fillers in NF/RO membranes, as thin layers that help with reactions on the membrane surfaces, or as materials that help reduce fouling in membrane systems before treatment. By combining these methods, we can use size/charge exclusion along with adsorption and catalytic degradation, leading to better removal efficiency and a longer life for the membrane compared to just using regular polymeric membranes. Simultaneously, treatment trains should be designed to minimise the release of nanoparticles into effluents; polishing steps, such as sand filtration or secondary membranes, should be included in the treatment train design to trap free particles before discharge (Ahmed et al., 2022; Omran et al., 2024).

### **5.2 Practical design considerations: Scalability, cost, sludge, and energy**

The fact that some nanomaterials, namely CNTs, derivatives of graphene, and noble metal or complex oxide nanoparticles, are costly to produce and that production methods are energy-intensive and require specialised equipment are some of the biggest obstacles to full-scale adoption (Ahmed et al., 2022; Omran et al., 2024). Recent reviews note that to enhance feasibility, they require green and low-cost routes of synthesis (e.g., biogenic or waste-derived starting materials), modular reactors that use very few nanomaterials, and designs that are easy to recover and reuse (Omran et al., 2024).

Under both operational considerations, operationally, nanomaterials are capable of reducing or increasing the sludge volume with respect to their application: when used as high surface area adsorbents or catalysts, they might result in a lower volume of chemical sludge than their conventional metal salts; however, when used as coagulation boosters or when they aggregate, nanomaterials may increase the quantity of nano-containing sludge, which then has to be managed in a safe manner (Ahmed et al., 2022; Li et al., 2016). Another important point is the amount of energy needed, especially in processes like photocatalysis and using membranes, which may require UV/visible lamps, high pressure, or aeration; using nano processes with solar energy or low-pressure membrane systems can help reduce energy use. Finally, the

design should consider the potential dangers of nanoparticles to the environment and their buildup: we need to think about using safe materials, effective ways to capture and reuse them, and clear rules for handling used nanomaterials.

## **6 Environmental risks, toxicity, and life-cycle aspects**

### **6.1 Potential release from treatment systems**

Released nanoparticles Engineered nanoparticles used in processes like adsorption, photocatalysis, or membranes can be found as separate particles, clumps, or pieces of materials that have come off nano Research shows that some engineered nanoparticles in water treatment systems are still attached to their original materials (like membranes or coatings), but some do end up in the wastewater and sludge. Wastewater treatment plants can collect and also release nanoparticles, as they remove a lot of them into sludge but still let some small amounts go into the water when they discharge treated wastewater. For nano-enabled membranes, studies show that while better flow and resistance to clogging can reduce operational challenges, the production and potential release of nanomaterials during use and disposal would have a bigger effect on the overall environmental impact.

### **6.2 Ecotoxicity and bioaccumulation in aquatic systems**

Ecotoxicological studies have suggested that engineered nanoparticles can cause acute and chronic toxicity in diverse aquatic organisms such as bacteria, algae, invertebrates and fish. It has been reported to cause a decrease in survival, growth, and reproduction, as well as sublethal responses, including oxidative stress, membrane damage, inflammation, genotoxicity, and altered behaviour (Sharma et al., 2023; Liu et al., 2010). Systematic reviews show that freshwater and marine organisms consume nanomaterials at different levels in the food chain, leading to the buildup of these materials in their bodies, such as in the gills, liver, and brain, and this can be passed along through the food web. Some metal oxide nanoparticles can lead to high bioaccumulation rates, reaching up to about 80-86 in certain tests, while others like CuO may accumulate less but still significantly, highlighting the need to evaluate each case individually. These results highlight that using nanotechnology in water treatment should be combined with steps to prevent nanoparticles from escaping and to manage leftover nanomaterials safely.

### **6.3 Transformation, aggregation, and environmental fate**

Nanoparticles are not always pure when released into natural waters or treatment systems; they aggregate, dissolve, and change in form and on the surface, affecting their mobility and toxicity. Parameters affecting aggregation and heteroaggregation of suspended solids are heavily dependent on water chemistry parameters, i.e., pH, ionic strength, and presence of natural organic matter, and ultimately determine whether nanoparticles stay in the water column, settle in sediments, or associated with biota (Sharma et al., 2023; Omran et al., 2024). Nanoparticles of metals can disperse and be partly dissolved, releasing the metal ion because of toxicity, and surface oxidation or sulfidation may diminish or maximise the effects of toxicity based on conditions (Sarkar et al., 2024; Wang et al., 2024). The research papers on the fate and transport of nanoparticles in the aquatic environment highlight that these dynamic

changes present a challenge to risk assessment because the species encountered by organisms are sometimes aged, coated, or transformed nanoparticles rather than the originally engineered nanoparticles (Sarkar et al., 2024; Sharma et al., 2023). It is thus crucial for the individual to be aware of the aggregation behaviour and transformation pathways in real matrices, such as wastewater, sludge, and receiving waters, to model long-term exposure and develop safer nano-enabled processes.

#### **6.4 Life-cycle assessment of nano-enabled treatment technologies**

Life cycle assessment (LCA) is a theory that offers a systematic approach to analysing the cradle-to-grave environmental effects of nanotechnology-enabled water treatment, including the extraction of raw materials and nanomaterial processing for device production, operation, and end-of-life disposal (Chew et al., 2020; Wiesner et al., 2020). It has been shown that using dynamic LCA for nanomembranes can help save energy and reduce chemical use, but these benefits might be offset by the negative effects from making nanomaterials, and there are also concerns about how to dispose of them at the end of their life. The new ideas about sustainability in nano-enabled water treatment focus on looking at performance, safety, and environmental impact at every step of the process, from getting raw materials to production, use, and disposal, and using this information to choose materials and designs that are safe from the start. Recent European initiatives, including material flow analysis, life cycle inventory, LCA, and life cycle costing, aim to identify environmental hotspots and economic bottlenecks for nano-enabled technologies, while social impact assessment captures community and regulatory aspects (Nanaqua, 2024). In your paper, it would serve you well to quickly define these LCA concepts as well as highlight the necessity of expediency in balancing efficiency of removal against resource consumption, emissions and long-term ecological safety, which would clearly distinguish this paper from previous studies that focus only on the product's application prospects.

### **7 Study implications**

The paper has a few distinct practical implications in the design and enhancement of industrial wastewater treatment in actual environments. Engineers and plant operators can design a toolkit based on mechanism synthesis, kinetic performance, and sector-specific performance. When professionals can link the features of nanomaterials (like surface area, functional groups, and band gap) to specific pollutants and how they cause pollution (such as adsorption, photocatalysis, and membrane separation), they can select the best materials and conditions for treating wastewater from textiles, pharmaceuticals, or metals instead of just guessing. Information from case studies and isotherm/kinetic analysis can provide the sizes of contactors/reactors needed, expected equilibrium performance, required contact time

The focus on regeneration, reuse, and environmental hazards can assist the stakeholders in shifting from high-level removal in the lab to deployable and less hazardous technologies. The emphasis on safe-by-design, readily recoverable (magnetic or immobilised) nanomaterials is an indication of practicable pathways to reduce nanoparticle release and enable the management of used materials, which is essential for regulatory approval and occupational

health. The study provides a method to evaluate nano-enabled options against advanced traditional treatment by looking at costs and effects for each meter treated, using life cycle analysis, economic factors, and process performance to guide investment decisions and policy talks about the actual advantages of nanotechnology in handling industrial wastewater.

## **8 Scope of future research**

Future research on nano-enabled industrial wastewater treatment should focus on testing these methods in real situations using closely monitored laboratory batch systems. This will require long-term experiments with different loads, pH, and salinity levels, while systematically This would require long-term tests at variable loads, pH, and salinity levels, with systematic reporting of removal efficiencies, the decline in flux, fouling behaviour, regeneration success, energy use, chemical consumption, and unit treatment costs, as well as direct comparisons to the best available conventional technologies. Parallel to this, safe-by-design nanomaterials and nanoadsorbents that integrate high performance with easily recoverable results, such as magnetic cores, immobilisation on stable polymeric or mineral scaffolds, or integration into mechanically stable beads and membranes, along with standardised test procedures for leaching, ecotoxicity, and regeneration stability across more than one regeneration cycle, are strongly desirable.

Meanwhile, it will be essential to incorporate nanotechnology with digital solutions and circular economic ideas to implement them sustainably. The design and real-time control of nano-enabled unit processes can be supported by mechanistic and data-driven models, such as kinetic modelling, computational fluid dynamics, and machine learning-based optimisation, which reduce the efforts of experimentation and increase the resilience of the nano-enabled processes to changing industrial conditions. Systems of the future must clearly aim for resource recovery. Combining life cycle assessment and techno-economic analysis early in the design process will help identify setups that are most likely to deliver the best overall environmental and economic benefits, ensuring that nano-enabled treatment technologies provide real sustainability advantages instead of just the high removal rates seen in labs.

## **9 Conclusion**

The innovative nanomaterials that have been engineered have reinvented the industrial wastewater remediation process, making it quicker, more selective, and more compact than most traditional methods. Metal and metal oxide nanoparticles, carbon-based nanomaterials, and nanocomposite membranes have tunable surface chemistry, high specific surface areas, and very high removal efficiencies for heavy metals, synthetic dyes, pharmaceuticals, and mixed ionic contaminants, which can be achieved with minimal contact times and often at reduced dosages compared to their bulk counterparts as adsorbents or catalysts. They help the nano-enabled membrane effectively capture and break down tough pollutants that are difficult to treat using standard methods like coagulation, activated carbon, or single-stage membrane processes. Industry can enhance decontamination levels by incorporating such materials into treatment Trains, including polishing adsorbents, catalytic reactors, or mixed matrix membranes, can often create opportunities for water reuse.

Meanwhile, the field should clearly strike a balance between high performance and environmental and human health safety and more general life cycle sustainability. The same nanoscale characteristics that cause nanoparticles to react more intensely raise this issue. Release is a concern because engineered nanomaterials can be toxic to the environment, accumulate in living organisms, and change over time in natural water and sludge. Valid, safe-by-design materials that are easy to recover (e.g., magnetic or immobilised materials), stable under typical operating and regeneration conditions, and proven low-risk in standardised ecotoxicity and leaching studies should therefore be the focus of future research, and pilot and full-scale applications in practical industrial effluents need to be further developed. Coupling nano-enabled processes and digital tools to model and optimise processes, while incorporating them into circular economy systems for resource recovery and pollutant removal, will be crucial for ensuring that the next generation of nanotechnologies can deliver viable, measurable improvements in treatment outcomes and overall environmental sustainability.

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