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CRITICAL REVIEWS

A critical analysis of the nanotechnology-based approach in textile wastewater treatment

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Abstract

The textile industry includes processes such as the design, manufacture, and distribution of textiles, fabrics, and clothing, all of which result in the production of large amounts of waste. Among the most serious issues to be concerned about is the presence of synthetic dyes, heavy metals, and toxic chemicals in the wastewater. Nanotechnology has emerged as a cutting-edge technology that has demonstrated exceptional capabilities in the treatment of wastewater. Nanoparticles outperform other new technologies in terms of producing superior results, owing to their large surface area and other diverse characteristics. As a new approach to dye removal from wastewater, nanopowders and carbon nanotubes can be purified, functionalized, and used as an absorption material to remove dyes from the wastewater. An investigation into the nanotechnologies in the treatment of textile wastewater is the subject of this review. Following a brief introduction to nanomaterials, synthesis, different types of adsorptions, and the development of nanoparticles towards the remediation of dyes in textile effluent are discussed. Moreover, it brings together the most recent breakthroughs in nanotechnology for dye adsorption in textile industry effluent.

Keywords Effluent · Textile · Nanoparticles · Dyes · Treatment

Introduction

The most regrettable consequence of rapid industrial development is pollution, which occurs as a result of the discharge of waste or effluent into water bodies. There are many different types of industrial effluents, including conventional effluents such as suspended solids, pathogens, oils, fats, and greases, as well as non-conventional effluents such as metallic substances such as silver or arsenic or copper or lead or mercury or a variety of other heavy metals. Besides these common effluents, toxic herbicides and pesticides such as polychlorinated biphenyls (PCBs), ammonia, phosphate, and other toxic substances are released. The environmental impact of various industries is detailed in Table 1.

Textile industry

Many studies have reported the generation of various solid and water effluents at various stages in the textile industry, which are summarized in Table 2 and discussed further. As a result of the dyeing process used in the production of textiles, textile effluents have the highest environmental impact of any of the industries involved. Arsenic, formaldehyde, lead, and mercury are among the poisonous chemicals used in textile dyeing, and macrophytes can only survive for 2 days on textile effluent due to the toxicity of the chemicals used in dyeing. Cotton, one of the major raw materials, contributes an eco-friendly textile; however, the notable environmental impacts arise from the application of agrochemicals such as pesticides and fertilizers which are utilized during typical production of cotton, and therefore, the seepage of these toxic substances from the textile fields as effluent contaminates aquifers and other water bodies. Fungicides and insecticides are used to treat non-organic cotton, which is genetically modified and treated with them. In the textile industry, there are several stages that must be completed, as depicted in Fig. 1. These stages include fibre preparation (preparation of fibres), spinning of yarn (sizing), weaving,

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Table 1 Impact of various industries on the environment

Industries	Source of effluents	References
Electric Power Plants	Condensation of the steam produces wastewater effluents	[1]
Nuclear Power Plants	Pressurized water reactor (PWR) and boiler water reactor (BWR) release the effluents	[2]
Petroleum Industries	Liquid and gaseous pollutants are produced	[3]
Chemical Industries	Release highly concentrated with organic and inorganic toxic pollutants	[4]
Iron and Steel Industry	Generated from coke oven by-product plant	[5]
Food Industries	High COD and BOD content of water makes it toxic	[6]
Leather Industries	Tanning agent Cr(III) salt acts as effluents	[7]
Paper and Pulp Industries	Huge quantities of biomass are generated at each stage	[8]

*COD: Chemical Oxygen Demand; BOD: Biochemical Oxygen Demand

Table 2 Solid and water effluents produced in textile industry

Process	Water effluents	Solideffluents	References
Fibre preparation	No water effluents	Fibre waste Packaging waste	[9]
Yarn spinning	No water effluents	Cleaning and packaging (sized yarn)	[10]
Sizing	BOD and COD	Fibre lint Unused starch-based sizes	[11]
Desizing	Lubricants and antistatic compounds	Fibre lint and yarn waste	[12]
Scouring	Disinfectant, insecticide, residues, NaOH, and spent solvents	No solid effluents	[13]
Bleaching	H_2O_2 and stabilizers	No solid effluents	[14]
Singeing	Exhaust gases (small amount)	No solid effluents	[11]
Heat setting	Volatilization of spin finish agents	No solid effluents	[10]
Printing and finishing	Solvent, acetic acid, and contaminants	Trimmings	[12]

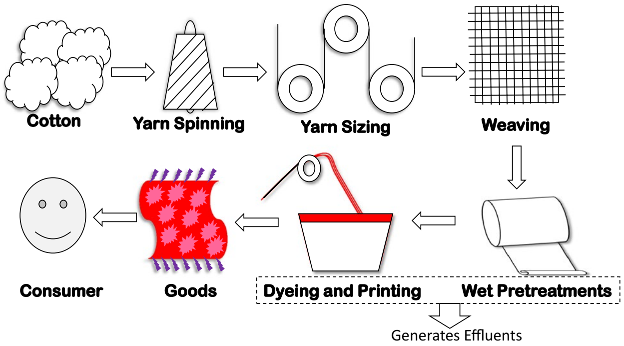

Fig. 1 Different stages involved in the textile industries

knitting (tufting), desizing (scoring), singing (bleaching), mercerizing (heating), dyeing, and finishing.

Dyeing process

Throughout the dyeing process, 10–15 per cent of the dyes are discharged into the environment, resulting in an effluent that is highly coloured and visually unappealing. The high thermal and photo stability (the ability to absorb and reflect sunlight entering the water) of dyes, as well as their resistance to biodegradation, allow them to remain in the environment for a longer period. As described in Table 3,

Table 3 Toxicity of different dyes in textile effluents

Type	Dyes	Toxicity	References
Acid	Sunset Yellow and Methyl Orange	Carcinogenic	[15]
Cationic	Methylene Blue and Rhodamine-6G	Carcinogenic	[16]
Direct	Congo Red and Direct Red 23	Bladder cancer	[17]
Reactive	Reactive Red 120 and Reactive Red 198	Dermatitis	[16]

a number of studies report on the toxicity of various dyes employed in the manufacturing process.

Finishing process

Fabric finishing process involves the release of formaldehyde, silicon, polyethylene, and other lubricating resins into air. These toxic vapours containing heavy metals and other harmful substances remain suspended in air and thereby cause pollution [18]. In addition, the coating materials that are used contribute to air pollution.

Conventional methods of treatment of textile effluents

Karli Gold et al. [19] investigated the efficacy of precipitation and coagulation methods for removing arsenic, fluoride, and phosphorus that are abundant in textile wastewater. There were reports of short detention times for these methods, but the formation of aggregates during separation was a major source of concern. Additionally, Praveena et al. [20] investigated the Fenton process, which treated the BOD and COD of the effluent. That method was reported to be applicable for both soluble and insoluble coloured contaminants, but its higher cost was a major source of concern for the research team.

Ozone, a strong oxidizer, degrades toxic textile effluent compounds, especially azo dyes. In this aspect, the literature by Rivero et al. [10] provided an explanation and examples on eradication of dyes such as Crystal Violet, Rhodamine B, Reactive Red 120, and Acid Orange 20 through ozonation method. Nevertheless, this approach has its limitation to remove dispersed dye from textile wastewater as its scavenging effect is susceptible to various factors including oxidation time and concentration of disperse dye suspension. Randall et al. [21] conducted research on the use of adsorbents such as activated carbon, peat, silica gels, and coal ashes for the elimination of a variety of dyes; however, it was a significant challenge due to the high cost of the regeneration process. Gosavi et al. [22] directed a study on typical methodologies corresponding to homogeneous photolytic chemical process using ultraviolet (UV) lamp, H_2O_2, O_3, etc., for the degradation of dyes, dissolved solids, chlorine, and other toxic heavy metals that exist in textile effluent. Moreover, studies focusing on biological treatment using fungal species such as *Aspergillus flavus* and *Fusarium oxysporum* for textile effluent decolourization have been reported [23]. However, these cutting-edge techniques made it possible to recover and repurpose used chemicals, but they required a time-consuming purification process.

Nanotechnology in textile industries

Nanotechnology in wastewater treatment has improved the efficiency of all the processes than the conventional methods. Nanoparticles (NPs) are synthesized by the following methods as described further for the effluent treatment.

General Synthesis of nanoparticles for broad applications

Several methodologies have been established to fabricate diverse varieties of nanoparticles. Of which, certain techniques are discussed with brief description in Table 4.

Production of nanoparticles for textile fibres

Attritor milling and air jet milling

Fibroin protein, which is derived from silk fibres, has been widely used in advanced biomaterial applications for a long time. As shown in Fig. 2, this method involved degumming the silk cocoons and chopping the extracted silk fibres prior to the attritor and jet milling the silk fibres into snippets. According to Praveena et al. [20], there are two types of attritor milling: dry milling and dry—wet milling, with the wet process being preferred because it causes less colour change. Dry milling is also an option. Creating ultrafine silk powder with a particle size of around 700 nm on a volume-based basis is a feasible option. A volume-based particle size analysis is a more accurate method of determining the relative effectiveness of milling techniques, which is particularly important when evaluating scale-up production. Consequently, pre-treatments are required to produce fine non-degraded nanopowders of high purity.

Spray milling and agitation bead milling

In this technique, there are several steps that must be completed sequentially, including wetting of particle surfaces in a liquid medium. Size reduction by mechanical means of solid particles that are either flocculated, agglomerated, aggregated, or crystalline in nature is performed. Surfactants or dispersants can be used to stabilize the newly reduced NPs in the dispersion by preventing re-agglomeration and re-aggregation. A nanoparticle dispersion is a homogeneous distribution of materials in a liquid phase that has been created by mixing nanoparticles. High-quality dispersions are typically stable and have a long shelf life, as well as the ability to resist sedimentation.

NPs could be packed closely together in this method to provide superior grinding and milling of the product, which is a significant advantage. This is accomplished primarily through the shear force applied to the solids in the slurry as

Table 4 Outline of different approaches for synthesis of nanoparticles

Type	Method/mechanism	Advantages	Disadvantages	NPs synthesized by the method	Application in textile effluent treatment	References
Physical	**Laser absorption** wherein a focused laser beam is applied to the surface of a solid target material in an atmospheric medium after the laser beam has been focused on the target material	Simple technique to generate reliable NPs in broad category of dispersing media aside from metal precursors and reductants	Occurrence of laser-induced cavitation bubbles; high energy consumption	Metal oxide NPS such as TiO_2, SiO_2, Al_2O_3, and Fe_2O_3 together with silver and gold NPs	Adsorption dyes such as Methylene Blue and Acid Brown 43 from the wastewater	[24]
	High-energy ball milling, a mechanical process where a powder mixture is subjected to high-energy collisions to produce nanocrystalline metals	Inexpensive process; generates fine nanopowder of particle size < 10 microns	Eventuality of particle agglomeration and residual strain in crystallized phase	ZnO NPs, CeO_2 nanocomposites	Photocatalytic degradation of toxic organic dyes such as Rhodamine B, Methylene Blue, Reactive Red 84, and Methyl Violet	[25]
Chemical	**Microemulsion** involves dissolving surfactant molecules in organic solvents, which results in the formation of reverse micelles, which are spheroidal aggregates of surfactant molecules	Low viscous and thermodynamically stable	Narrow ability to resolve in substances with high melting points	Magnetite NPs	Catalytic removal of Methyl Violet and chromium	[26]
	Chemical vapour deposition, where a wafer (or substrate) is subjected to one or more volatile precursors, which respond or degrade on the surface of the wafer to generate the desired deposit	Applicable for the production of amorphous or crystalline nanopowders with controllable particle sizes and a homogeneous size distribution	High cost of equipment	Carbon nanotubes and TiO_2 nanomaterials	Adsorption of Rhodamine B and heavy metals including Zn(II) and Cu(II)	[21, 27]
Biological	**Microorganism-assisted biogenesis**, where microbial cells capture the metal ions and reduce them to NPs through series of enzymatic steps	NPs synthesized using microbes possess polydisperse nature	Time-consuming procedure that involves microbial sampling, isolation, and culturing	Metal NPs such as Au, Ag, Co (III), Cr (VI), and Mn (IV)	Removal of azo dyes such as Direct Blue-1, Methyl Red, and Reactive Black-5	[28]
	Bio-template-assisted biogenesis, a green synthesis approach employing plant-based extracts for NPs production	Simplicity and rapidity	Chemicals utilized for phytoextraction is toxic and non-biodegradable that restricts bulk synthesis of NPs	Metal NPs such as Ag, Au, Cd, Pt, and Pb	Adsorption of Vat Black 25, Disperse Blue 56, etc.	[29]

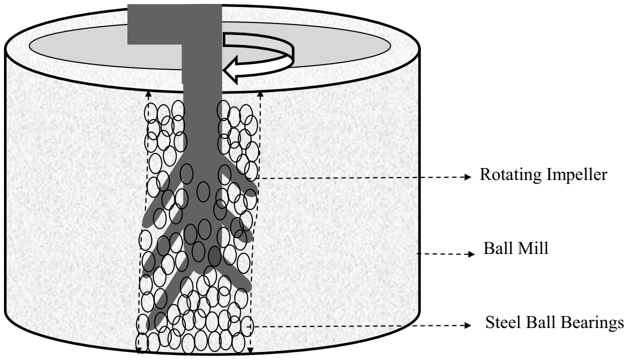

Fig. 2 Attritor milling

they pass through the spacers in the beads as the solid particle in the slurry and the beads move at different speeds relative to one another. With the circulating cooling system, the optimal operating temperature can be maintained efficiently. The feed pump is equipped with an inverter-controlled transmission motor, which allows for the most efficient material feeding possible.

Freeze drying

This method, also known as lyophilization method, involves the removal of water from a frozen sample through the processes of sublimation and desorption while the sample is kept under vacuum. The freeze drying of nanoparticles aids in the preservation of a solution's homogeneous properties as well as the attainment of the desired particle size. In terms of improving the long-term stability of colloidal NPs, this is an excellent technique. Pure water forms ice crystals when the liquid suspension cools down to a certain temperature. In addition to maintaining the core properties of the product, freeze-dried nanoparticles have several other advantages such as particle size, a short reconstitution time, and stability.

Nano spray drying

It has been reported by Baptista et al. [30] that they developed a granulation method that can be used to produce low dusty granules from a suspension of NPs. Once the granules had been spray dried, they were ideally suited for further processing into finished goods while still retaining the enhanced qualities supplied by the nanoparticles. The nano spray dryer is a type of spray dryer that is used to develop particles that are in the nanosize. The drying gas is introduced into the system through a heater in this method. A fine droplet distribution with a limited size distribution is sprayed into the drying chamber by the spray head, which is controlled by the spray head. When the droplets dry, they solidify and become solid particles. The electrostatic particle collector is responsible for separating these solid particles. The exhaust gas is filtered before being directed to a fume hood for further processing. The temperature of the inlet air is controlled by a temperature sensor. Evaporation of solvent occurs because of the contact between the hot inlet air stream and the spray.

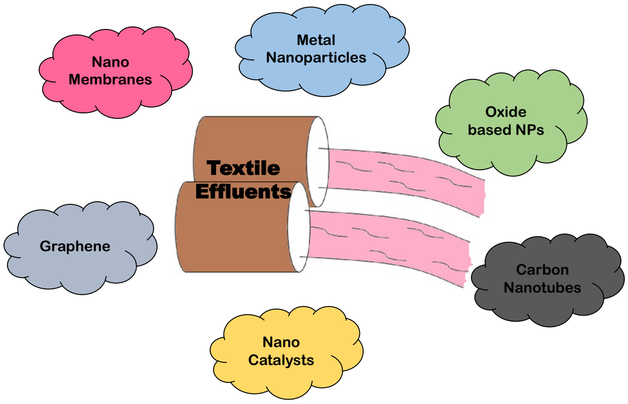

Fig. 3 Types of nanoparticles in textile effluent treatment

Nanoparticles in textile effluent treatment

Nanoparticles are primarily used in the colour removal of textile dyes and the treatment of textile effluents, which are two of the most common applications. As illustrated in Fig. 3, a wide variety of nanoparticles is employed for this purpose, each of which is distinct in terms of its physicochemical properties. Aside from their non-toxicity and high adsorption capacity, which allows them to adsorb contaminants at low concentrations, nanoparticles (NPs) are utilized as an adsorbent for the removal of heavy metals. Adsorbed contaminants are removed easily from the surface, and therefore, the spent nanoadsorbent could be retrieved, renewed, and recycled numerous times via different strategies such as filtration, supercritical fluid desorption, and magnetic separation [31, 32].

In 2016, Joshi et al. [33] demonstrated the degradation of pollutants in wastewater using nanocatalysts. Catalysts based on Fenton are used for many applications, including improving the chemical oxidation of organic materials with antimicrobial properties. In addition, the increased surface area of NPs allows them to have greater chemical activity and adsorption capacity, which is important for the successful adsorption of heavy metals on their surfaces. NPs including activated carbon, carbon nanotubes, graphene, manganese oxide, titanium oxide, zinc oxide, ferric oxides., etc., are being employed intermittently for metal adsorption from textile effluent [34]. Various studies which reported nanoparticles as adsorbent for the removal of different dyes are listed in Table 5.

Metal nanoparticles

Additionally, metal NPs are used for decolourization of the coloured effluent. Because of their dipole–dipole interactions, these particles have a strong tendency to aggregate [37]. A wide range of nanosized metal or metal oxide-based materials, as well as inorganic nanomaterials, is used for the removal of dyes. These materials include nano zerovalent iron (109), nano zerovalent zinc (110), magnetic Fe_2O_3 (111), magnesium oxide (MgO) (112), titanium dioxide (113), and zinc oxide (114), which have a large surface area and specific affinity. Metal oxides are environmentally friendly materials because of their low solubility and low environmental impact. Recently, Nizamuddin et al. [38] proved that these particles are exceptionally successful at removing an array of pollutants from the environment. These pollutants included nitrates, organochlorine pesticides, heavy metals, and dyes. For example humic acid is used to coat Fe_3O_4 NPs in order to remove Rhodamine B from the solution. In this instance, humic acid prevented the oxidation of Fe_3O_4 NPs and increased the stability of the compound. The use of magnesium oxide, as destructive adsorbents for the removal of a wide range of harmful compounds, has become increasingly popular due to their strong surface reactivity and adsorption capacity.

Oxide-based nanoparticles

Nonmetals and metals are the most common sources of oxide-based nanoparticles (NPs), which are inorganic nanoparticles. TiO_2, dendrimers, zinc oxides, magnesium oxide, composites, manganese oxide, and ferric oxide are examples of particles, which are different types of materials that are frequently utilized for the removal of dangerous contaminants from wastewater. These include titanium oxides, dendrimers, composites, and ferric oxides. For the elimination of heavy metals from water-based systems, it was discovered by Premkumar [39] that utilizing oxide-based nanoparticles might be a highly efficient and cost-effective nanoadsorbent for heavy metal removal. The application of surface modification techniques improved their stability and efficiency in water. High BET surface area, low environmental effect, low solubility, and the absence of secondary contaminants separate oxide-based nanoparticles from other types of nanoparticles. They are employed in a wide range of applications.

Nanomaterial catalysts are used in textile effluent treatment to aid in the chemically oxidizing organic pollutants, which is a process known as chemical oxidation. A wide spectrum of inorganic and organic pollutants found in wastewater can be degraded by nonmetal nanoparticles (NPs) produced from magnificent metals such as gold, platinum, and palladium (Pd). Pd may be able to offer careful removal of pollutants such as chloro-hydrocarbons by acting as a catalyst. The Pd-based nanocatalyst (Pd/Fe_3O_4) that has been synthesized exhibits high hydro de-chlorination and the ease with which the nanocatalyst may be recovered from effluent using magnetic separation.

Nickel oxide NPs

These are the most often utilized NPs for dye effluent decolourization. Instrumental investigations usually demonstrate the attachment of degraded dye compounds to NPs. Namrata Datta Ray et al. [40] found that roughly 98 per cent of the colour was removed while the COD was reduced. Batool et al. [17] employed Reactive Blue 21 as a standard dye and polyvinylpyrrolidone (PVP) as a stabilizer for keeping NPs away from clumping together.

Iron oxide NPs

Due to their appropriate magnetic characteristics, low cost, chemical inertness, and low toxicity, iron-based NPs, notably magnetite (Fe_3O_4) and hematite (Fe_2O_3), are the most widely utilized magnetic NPs for water treatment in the textile industry. Iron oxide nanoparticles have demonstrated promising results in the removal of arsenic from water. As a result, they may become cost-effective materials for removing arsenic from water. Ferric oxide is a low-cost material for metal adsorption due to its natural occurrence and simple manufacturing procedure. Nizamuddin et al. [38] shown that iron oxide NPs are an environmentally friendly substance that may be directly applied to a contaminated environment with minimal secondary contamination. pH, temperature, adsorbent dosage, and incubation duration are all factors that influence heavy metal adsorption on Fe_2O_3

Table 5 Nanoadsorbents used in the removal of textile dyes

Adsorbents	Adsorbate	Efficiency	References
Fe_3O_4 NPs	Acridine Orange	0.056 (mol/g)	[35]
HA—Fe_3O_4	Coomassie Brilliant Blue R-250, Congo Red	0.082 (mol/g)	[36]
Rice straw charcoal/MgO nanocomposite	Reactive Blue 221	27.78 mg/g	[16]
Magnetite/reduced grapheme oxide	Rhodamine B	16.2 mg/g	[36]
MgO nanoflakes	Malachite Green and Congo Red	–	[16]

NPs. Modification of nanoadsorbents demonstrates significant affinity for simultaneous removal of many contaminants from wastewater, including Cr^{3+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Cd^{2+}, and Pb^{2+} [41].

Manganese oxide NPs

Manganese oxide nanoparticles have been used as both adsorbents and catalytic materials. The oxidation of dissolved organic pollutants by Mn oxide surfaces has been used to degrade dissolved organic contaminants on a wide scale. Manganese oxide has demonstrated promising results in columns for removing pollutants such as diclofenac and oestradiol using both biotic and abiotic methods. These NPs with higher surface area and a polymorphic structure, according to Brunauer–Emmett–Teller (BET). In the past, it has been used to remove a variety of heavy metals from wastewater, such as arsenic. The manganese oxides include nanoporous/nanotunnel manganese oxides and hydrous manganese oxides, which is produced by combining $MnSO_4$ and alumina. MnOs that have been treated with H_2O and NaClO solution are the most often used modified MnOs. Inner-sphere formation, which can be represented by the ion-exchange process, is typically responsible for the elimination of heavy metals such as lead(II), cadmium(II), and zinc(II) in aqueous solutions (II). When divalent metal metals are adsorbing on the surface of manganese oxide, they go through a two-phase process: external surface adsorption of metal ions and intraparticle diffusion of divalent metal metals.

Zinc oxide NPs

Pad-dry-cure was used to bind the ZnO NPs to a 100% cotton woven fabric after they had been created using a wet chemical process and allowed to dry. It is utilized to make the textile substrate more useful. Because of its antibacterial qualities, zinc NPs have been used in the textile sector as a potential alternative for preventing infectious infections. Furthermore, they have great UV-blocking characteristics. Because of its highly permeable nanostructure and wide BET surface area, zinc oxide is an excellent heavy metal adsorption material.

Magnesium oxide NPs

Magnesium oxide (MgO) nanoparticles are employed to eliminate various heavy metals from contaminated aquatic system discharged by the textile industry. The MgO microsphere has a unique shape that can boost adsorption affinity for heavy metal removal from textile effluents. Different forms of nanoparticle morphological modifications were carried out to boost the adsorption capacity of MgO, including rods, belts, fishbone fractal nanostructures generated, wires, and nanotubes.

Carbon nanotubes

Through adsorption, carbon nanotubes (CNTs) could eliminate heavy metals and various organic pollutants from wastewater produced by the textile industry. A magnet can be used to easily collect magnetically modified carbon nanotubes (CNTs) from wastewater or used medium because of their high dispersion capabilities. The surface modification of CNTs improves their overall adsorption ability as reported by Novoselova et al. [42]. Acid treatment of CNTs was performed with a variety of acids, including HNO_3, $KMnO_4$, H_2O_2, H_2SO_4, and HCl [43]. The contaminants on the surface of CNTs are removed by acid treatment. In addition, it introduces additional functional groups to the surface of CNTs, increasing their adsorption capacity for wastewater.

Another technique to improve the surface features of CNTs is to graft functional groups onto their surface. The method can be accomplished in a variety of ways, including chemical change, plasma treatment, and microwave treatment. However, Jeon et al. [44] demonstrated that plasma technique is one of the better ways since it requires less energy and is environmentally beneficial. Furthermore, CNTs treated with metal/metal oxides as MnO_2, Al_2O_3, and iron oxide show promising results in the heavy metals removal.

Graphene nanoadsorbents

1. Graphene is a carbon allotrope with unique characteristics which cause it ideal for various environmental uses. In the realm of carbon nanomaterials, GO is a two-dimensional carbonaceous material produced by chemically oxidizing a graphite sheet. The Hummers approach, in which hydrophilic groups are incorporated into grapheme oxide and a particular oxidation process is required, is the most frequent method for the synthesis of grapheme oxide [45]. These functional groups improve heavy metal adsorption from contaminated water. GO is gaining popularity as an adsorbent in effluent treatment on the basis of its distinct properties including low weight, high surface area, and stability. GO has two distinct characteristics on comparison with other nanomaterials.
2. A 2-D single sheet GO is optimal for heavy metal removal because it provides the greatest amount of surface area.
3. It has a straightforward production process that involves chemical exfoliation (the application of a caustic chemical or acid, such as alpha-hydroxyl acid) of graphite

without the use of a metallic catalyst or a sophisticated equipment.

Furthermore, because GO already has a hydrophilic functional group, and hence, further treatment is not required. Heavy metals removal from effluents is particularly efficient with graphene and its various composites.

Nanocatalysts

Nanocatalysts are used for various purposes, particularly for semiconductors, in the treatment of textile effluents, which are discussed in detail below [46]. For effluent treatment, different types of nanocatalysts, including photocatalysts and electrocatalysts, are used [47]. Catalysts based on ferrite for better chemical oxidation of organic contaminants and antibacterial effects.

Nanomaterials as photocatalysts

Using nanoparticles in photocatalytic processes, which are based on the contact between light and nanoparticles and have a wide spectrum of photocatalytic activity for a variety of pollutants, is becoming increasingly popular. Photocatalysts are usually made up of semiconductor metals that can breakdown a wide range of insistent organic pollutants found in textile effluents, including dyes, detergents, insecticides, and volatile chemical compounds.

The photoexcitation of electrons in the catalyst is the basic operating mechanism of photocatalysis. The hydroxyl radicals present in these catalysts oxidize the organic contaminants into water and degradation products. TiO_2 is one of the most extensively used photocatalysts, according to Pekakis et al. [48], as a result of its strong reactivity when exposed to UV light and its chemical stability. CdS NPs have been widely utilized to remediate wastewater containing industrial dyes.

Nanomaterials as electrocatalysts

The use of nanomaterials as electrocatalysts improves fuel cell performance by allowing for a bigger surface area and more unchanging catalyst spreading in the reaction medium. Baer et al. [49] used a variety of nanomaterials to demonstrate their high potential for removing heavy metals from textile effluents. The hybrid electrocatalyst was discovered to have smaller dispersed particles, resulting in a high catalytic reduction of 4-nitrophenol due to effective dioxygen process.

Nanomaterial-based Fenton catalyst

The Fenton reaction has been extensively used for effluent treatment to oxidize organic contaminants. Sol–gel and auto-combustion methods can be used to create nanoferrites with regulated distribution, crystalline size, and chemical structure. According to Schafe et al. [50], the presence of metals in these nanomaterials alters the stability and redox characteristics of ferrites, hence increasing catalytic efficiency. Fenton catalysts made of magnetically separable nanoparticles of iron oxide can be utilized to remove a variety of contaminants. This suggests that these nanocatalysts are resistant to pollutant and organic intermediate product oxidation when used in an uncontrolled manner.

Nanomembranes

Membrane filtration technology used for synthesizing nanomaterials is one of the most effective solutions among the present sophisticated textile effluent treatment systems [51]. On comparison with conventional methods, this methodology is extremely economic, efficient, and simple to implement. Aside from particle separation from wastewater, the chemical breakdown of organic foulants is aided by nanomembranes. One-dimensional nanomaterials such as nanotubes, nanoribbons, and nanofibres are used to make these membranes. Heale et al. [52] used carbonaceous nanofibres to create a membrane for selective filtering and reported effective heavy metal removal under high pressure. A macroscopic disc-like titanate-nanoribbon membrane with linked nanoparticles and negatively charged bodies can also improve the capturing capability of NPs and other small molecules, as demonstrated in this study.

Electrospun nanofibre membranes

Electrospun nanofibre membranes: When compared to existing conventional procedures, this technology is a low-cost, lightweight, and energy-efficient process. Nanofibres were used in the treatment of textile wastewater, particulate microorganisms, and salt by Zahrim et al. [53].

These membranes could be used to pre-treat textile effluents before they go through the RO or ultra-filtration stages of treatment. Toxic heavy metals have also been removed using electrospun membranes. As a result of the high operational pressure, high flux, and low-energy requirements, the use of nanofibre membranes in textile effluent treatment for the effective removal of salts from water (desalination process) has been demonstrated to be a successful technology [54, 55].

Hybrid nanomembrane

Baer et al. [49] constructed hybrid membranes to incorporate additional capabilities such as adsorption, photocatalysis, or antibacterial properties. This can be accomplished by adjusting the hydrophilicity, porosity, mechanical stability, and

Table 6 Outcomes, benefits, and future perspectives of nanomaterials in textile effluent treatment

Category		Nanomaterials	Targeted contaminants in textile effluent	Superiority over other conventional treatment resources towards the intended pollutants	Future prospects	References
Nanoparticles	Metal-based	Nano bimetallic materials such as Fe, Cu, and zerovalent metal NPs such as Al, Zn, and Ni	BOD, COD, TSS (total suspended solids), and total phosphorus	Reduced NPs dosage, contact time, cost of synthesis; safe disposal with removal efficiency of 87%	Attempts implying entrapment of NPs in biopolymer material could be executed to remove heavy metals from effluent	[58]
	Oxide-based	MgO-NPs; Al_2O_3-NPs; FeO-NPs; hematite NPs	Heavy metals such as Pb, Co, Cr, Ni, and Cd	Increased surface area, low concentration, readily detachable after treatment, chemical stability, and ease of interaction with adsorbents with removal effectiveness of 75–87%	Research studies are in need for economical method of synthesis and broad scale analysis for metal oxide NPs	[59]
Nanotubes		Surface modified/multiwalled carbon nanotubes (CNT)	Basic dyes including Methyl Violet, Basic Orange dye, and other pigments	High porosity, increased number of reactive sites, and ion-exchange property of these nanotubes makes it a productive adsorbent in the aspect of elevated and selective adsorption capacity together with transient equilibrium time with the dye removal efficiency of 98%	Examinations are required in terms of toxicity shown by CNT and hazards involved in discharge of these nanotubes in effluent treatment equipment	[60]
Nanocatalysts		Photocatalysts involving ZnO-NPs and TiO_2 NPs	Azo dyes such as Yellow Reactive 4 and Direct Blue 71 together with heavy metals	Improved photocatalytic performance through rapid recombination of electron hole pairs and narrow light response range with greater decolourization efficiency	Research activities relying on novel fabrication of ternary mixed oxide systems for photooxidative degradation of dyes are required	[61]
Nanomembranes		Polyether/gelatin nanomembrane; acrylic grafted nanomembrane	Rhodamine B, Acidic Red 88, Acidic Red 14, and Acidic Red 18	Matrix with enhanced hydrophilicity and porosity with dye adsorbing efficiency ranging from 80 to 95%	While membrane fouling is a major issue, explorations involving enhancement of nanomembrane resistivity (for instance, surface-grafting based polymers) and incorporation of anti-fouling convertors, etc., are in need	[62, 63]
Nanoclays		Fibrous nanoclay minerals such as montmorillonite, zeolite, halloysite, saponite, sepiolite, bentonite, laponite, and hydrotalcite	Anionic dyes and heavy metals in textile effluent	Increased surface area and cation exchange capacity of these nanoclays makes it highly beneficial for textile effluent treatment	Future applications rely on studies aiming at degree of desorption of dye molecules from adsorbent surface	[64]

Table 6 (continued)

Category	Nanomaterials	Targeted contaminants in textile effluent	Superiority over other conventional treatment resources towards the intended pollutants	Future prospects	References
Nanofibres	Chitosan-based electrospun nanofibres	Acid Blue-113, Direct Red 81, and Direct Red 180	These types of nanofibres could be modified into various nanocomposites and films that facilitates ease wastewater treatment	Efforts for increasing adsorption–desorption cycle capacity of nanofibres are essential in future works	[65]
Nanowires	α-MnO2 micronests composed of nanowires	Congo Red	Improved surface complexation and electrostatic interaction between its functional groups and dye molecules with separating efficiency of 65%	Regenerative property of MnO_2 nanowires has to be examined for a sustainable and low-cost adsorption process; together with the inquiry on equivalence between crystal structure and pore size that accounts for adsorption of multivalent ions present in textile effluent	[66]
Nanoflakes	CuO, NiO nanoflakes	Malachite Green and Methyl Orange	Better photocatalytic activity and spontaneous adsorption capacity with the efficiency of > 90%	Challenges concerning commercialization such as functioning duration, fabrication versatility, and stability have to be inscribed in future studies	[67]
Nano-emulsions	Nano-emulsion comprising reverse micelles of CTAB (Cetyl trimethylammonium bromide) surfactant	Acid Blue 25 and other anionic dyes	Reduced equilibration time and surfactant concentration with maximum amount of dye removal up to 85%	Safe disposal strategies of emulsions could be concentrated in subsequent studies	[68]
Nanosheets	Graphene oxide (GO) nanosheets; boron nitride nanosheets	Rhodamine B and other cationic dyes	Higher homogeneous binding sites on the surface that corresponds to increased colour removal efficiency up to 95%	While production of GO nanosheets involves high cost, studies aiming at facile GO synthesis on large-scale basis is needed to achieve an economical method of dye removal	[69, 70]

Table 6 (continued)

Category	Nanomaterials	Targeted contaminants in textile effluent	Superiority over other conventional treatment resources towards the intended pollutants	Future prospects	References
Nanogels	Cellulose-based nanogel; nano-carbon xerogel	Reactive Red 195, Cd (II), Methylene Blue, and Rhodamine B	Highly porous, biodegradable, and cost-effective nanomaterial showing target removal efficiency of 93%	Future works focusing on adsorption of nanogels onto porous carbon is needed to understand their texture and surface chemical nature that are responsible for their adsorption capacity towards dye molecules	[71]
Nanodots	Nitrogen-doped carbon dots	Dye molecules such as Methyl Orange, Reactive Black, and Remazol Brilliant Blue	Increased catalytic activity with the presence of $NaBH_4$ exhibiting high dye detoxification efficiency	Investigations on chemical groups existing on surface of carbon nanodots is required to recognize its photoluminescence mechanism that aids in photodegradation of organic dyes (under UV–visible irradiation) present in textile effluent	[72]
Nanoceramics	Hydroxyapatite-based nanoceramics	Rhodamine, Malachite Green, and heavy metals such as Pb and Cd	Recyclable, magnetic-enabled, and high adsorptive nanomaterial for abatement of pollutants in textile wastewater	Studies directing aggressive pollutant adsorption in the presence of biomolecules, and other toxic contaminants have to be focused for extensive application	[73]

charge density of membranes. Filtration and adsorption processes can be combined for the removal of lead and nickel from effluents by employing impregnated polysulphone with zeolite nanoparticle membrane. Simple changes in the membrane fabricating circumstances and the period of evaporation of the casting film could improve the sorption capacity and hydraulic permeability of the membrane.

Beta-cyclodextrins

Rivero et al. [10] recently explored the importance of beta-cyclodextrins in the textile industry and shown their ability to create fabrics that release chemical compounds such as scents and antibacterial agents. Osmotic separation is used to extract phenolphthalein and fuchsin acid. A nanoprecipitation approach was used to investigate the ability of beta-cyclodextrins to self-organize into NPs in various solvents.

Outcomes and benefits of nanoparticles in textile effluent treatment

Nanoparticles exhibit phenomenal efficiency in textile wastewater purification because of its high reaction rate, vast productivity, reduced energy, and time consumption. Nanomaterials have been utilized to remove colour, heavy metals, and hazardous compounds from effluent, in addition to increasing the functionality of textiles. Techniques such as photocatalytic degradation, adsorption, and nanomembrane filtration have gained interest as significant approach to get rid of dye pollutants from textile effluent; for which nanoparticles including TiO_2 [56], Fe_3O_4 (Prem Kumar et al. [39]), CuO [57], and FeO (Nizamuddin et al. [38]) are being employed that proves to be an efficient, feasible, and environment-friendly proposal for decolourization and abasement of textile dye molecules at industrial scale. Furthermore, there are stipulations for surface modifications on NPs in order to achieve large productivity, and therefore, nanomaterials provide an enormous design for potable water globally.

Environmental benefits and future prospects

From diverse technologies that are accessible, application of nanomaterials manifests a sustainable way to treat textile wastewater. Unlike other methodologies, there are different recovery, regeneration, and safe disposal opportunities for the spent nanoadsorbents which paves the way for resource reutilization, feasible waste management, and advanced economy of environmental sustainability. For instance, a recent study conducted by Ninad et al. 2022 [32] has demonstrated the potential of nanoporous textile sludge-based adsorbent towards effective dye removal till six reuse cycles. Despite these merits, the increased high surface-to-volume ratio which is the fundamental principle of nanomaterials to adsorb pollutants leads to particle agglomeration that, in turn, results in uneven distribution of NPs; hence, it is essential to have a future study that aims at perceiving the stability between firmness and surface activity of NPs that aid its interaction with contaminants in effluent.

Table 6 portrays the overall results, substantial benefits, and additional opportunities of certain nanomaterials in textile effluent treatment.

Conclusion

Water is one of the most significant needs for life on this planet. There are some areas where people are unable to get access to water for their fundamental and economic needs because of lack of infrastructure. In such sectors, nanotechnology is being considered as an economic, convenient, and environmentally method of wastewater reduction. It has proven to be highly effective in the removal of micro- and macro-pollutants, and it has the potential to make significant advancements in the future. Different sizes of nanoparticles, such as nanosized metals and nanofiltration membranes, have been shown to be successful in the detection, removal, and destruction of contaminants, while also requiring less time and energy to do the task. Because of their fast rate of response, nanoparticles demonstrate tremendous efficiency. The nanomaterials provide enormous potential for water revolutions, particularly in the areas of decentralized water and seriously degradable contaminants, among other things. As a result, the many applications of nanoparticles can present a significant offer in terms of providing pure water to people all over the world.

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Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

Data availability The authors confirm that the data supporting this study are available within the article.

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