Int. J. Nano Dimens., 14 (1): 1-28, Winter 2023

REVIEW ARTICLE

Nanotechnology in environmental sustainability and performance of nanomaterials in recalcitrant removal from contaminated Water

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Received 14 July 2022; revised 10 August 2022; accepted29 August 2022; available online 30 August 2022

Abstract

In this review article, the implementations of nanomaterials such as metal oxides and their composites, carbon nanotubes, dendrimers, and polymer nanocomposites for wastewater decontamination have been discussed. The nanomaterials have a lot of potential, due to their high pollutant sensing ability and larger surface area. They are ideal for the removal of harmful heavy metals and also eradicate severe infections spreading microorganisms, organic waste and inorganic contaminants from the environment. The article reviews recent developments in waste water treatment using various nanomaterials. Nanotechnology has resulted in a variety of effective nano techniques for environmental remediation such as photocatalysis, nano-adsorption and nano-filtration, which are more accurate to eradicate recalcitrant. Novel semiconductor photocatalysts, nano-adsorbents, nano-composites, and other nanostructures have been used to achieve maximal performance at a low cost. This review provides the techno-functional applications of nanomaterials for wastewater remediation.

Keywords: *CNTs; Dendrimers; Nano Absorption; Nanocomposite; Nanofiltration; Nano Material; Photocatalysis; Recalcitrant Removal; Wastewater Remediation.*

How to cite this article
Jabeen S., Ahmad N., Bala S.H., Bano D., Khan T. Nanotechnology in environmental sustainability and performance of nanomaterials in recalcitrant removal from contaminated Water. Int. J. Nano Dimens., 2023; 14(1): 1-28.

INTRODUCTION

Environmental pollution is a matter of concern and a topic of serious discussion globally. Pure drinking water and breathable air are exceptionally important for all living beings [1]. Nowadays environmental pollution (air, water and soil pollution) has dramatically increased because of unexpected population growth in urban areas and exuberating industrial development. As a result, toxic substances like poisonous gases, fumes, smoke, industrial waste, hazardous chemicals, and organic waste etc. have been released into the environment as shown in Fig. 1. In recent years nanomaterials have received much attention in the area of environmental sustainability and remediation [2]. The field of nanotechnology is a new technological advancement that is based on the incredibly small size of substances [3,4]. Scientists are exploring nanotechnology for environmental remediation [5]. The use of nanomaterials like synthetic mordenite nanocrystals in environmental conservation and sustainability has been explored to eradicate Ti (III) and As (III) from water [6]. It has evolved as an adaptable scaffold, competent in providing systematic, cost-effective and environmentally-friendly solutions [7]. Nanotechnology is critical in the development of smart materials that are effective in sensing and destroying dangerous chemical contaminants in the environment [8].

Polluted water from separate sources generally releases hazardous and toxic contaminants, such as organic compounds, arsenic, pesticides and poisonous colours from textile industries in the form of dyes. Organic dyes have very dangerous and harmful effects on human beings leading to

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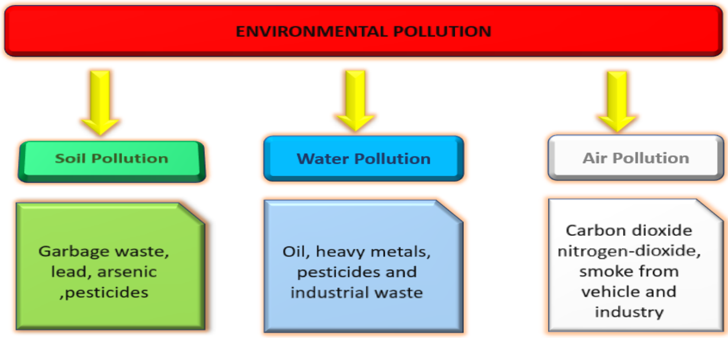

Fig. 1. Classification of pollution.

contact dermatitis, respiratory diseases, hair fall, irritation to mucous membranes etc. [9-10]. These dyes are highly photostable and have complex aromatic structures and are not removed naturally from wastewater [11]. Nanomaterials eradicate recalcitrant dyes via advanced and cheap nano-technological methods [12]. Water pollution is also caused by industrial waste, hospital waste, chemical and oil waste, and household waste [13-14]. Different sources of pollution and their effects are elaborated in Table 1. The World Health Organization (WHO) has reported that around 1.69 billion people die annually after consuming contaminated water and 3.99 billion people suffer from waterborne diseases [15]. The criterion for the selection of nanotechnological intervention for the remediation is based on the type of pollutants found in the contaminated water. Eradication of hazardous molecules from the environment with the help of $CuWO_4/gC_3N_4$ nanocomposite exhibited a relatively high visible light absorption region and the band gap shifted from 2.77 to 2.53 eV, when an unstable and low band-gap $CuWO_4$ was composited with gC_3N_4 to achieve tuning of the visible light responsiveness and stability of $CuWO_4$, removal of reactive orange (RO16) with the help of biomaterial of cross-linked chitosan-tripolyphosphate/TiO_2 nanocomposites (CCTPP/TiO_2 NC) and MgO/C_3N_4 nanocomposite, [16-18]. The objective of this review is to discuss different nanostructured materials and methodologies for the eradication of environmental pollutants. Therefore, the main goal of this review is to elaborate detailed information about nanostructured materials and methodologies, which are used in environmental remediation. Additionally, the mechanisms of different methodologies are also explained, such as photocatalytic concepts, adsorption, nano-filtration process and their applications for environmental remediation. Furthermore, recent expansions and upcoming research prospects on these methodologies for environmental applications are also addressed.

NANOTECHNOLOGY AND ITS APPLICATION IN ENVIRONMENTAL CLEAN-UP

Some nanoparticles like semiconductive nanomaterials (TiO_2 and WO_3), metals with zero valencies (Fe, Cu, Zn), and metallic nanocomposites (Au/Ag, Fe/Pd) perform a crucial part in environmental sustainability given their

Table 1. Different water pollutants and their adverse effects on human life.

S.No.	Origin of pollutant	Sources of pollution	Effect	Reference
1	Industrial waste	Organic dyes, metals, pesticides, oils etc	Water and air pollution	[19]
2	Domestic waste	Kitchen waste, sewage, toilet and bathroom waste etc.	Waterborne diseases like jaundice, abdominal cramps	[20]
3	Organic waste	Azo Dyes, polyaromatic hydrocarbons, detergents and herbicides	Threat to aquatic life, dysgenic, endocrine-related disease, mutagenicity etc.	[21]
4	Agriculture waste	Urea and different types of chemicals used in crop-yielding, fertilizers	Contaminate fresh water directly	[22]
5	inorganic waste	Heavy metals, inorganic salts, and mineral acids	Disaster for aquatic flora and fauna, acidity, hardness	[23]

super collaborative response with impurities like aromatic dyes, toxic heavy metallic contaminants, and pesticides etc. [24-26]. The common working mechanisms of nanomaterials are nano-adsorption and photocatalytic degradation [27-28]. Nanotechnology has been used for the eradication of Co (III) from waste water, and dyes, medicines, phenols, organic waste, and pesticides are other contaminants that can be removed from waste water based on nanotechnological techniques [29-30]. In manufacturing industries where hazardous metals such as Cd, As, Cd, Pb and chlorinated compounds spread due to landfills and leakage in underground storage is another serious concern [31]. Table 2 summarizes the applications of nanotechnology in waste water remediation.

For the treatment of wastewater, nanotechnology has emerged as a smarter, cheaper and latest way of purification [39]. Different methods like chemical, physical and biological are used for the eradication of contaminants [40]. Photocatalytic methods are very effective for the eradication of recalcitrant biodegradable waste, organic contaminants, toxic elements and inorganic impurities dissolved in water [41].

NANOMATERIALS FOR WASTEWATER REMEDIATION

Many technological interventions have been made to treat waste water. In recent decades, numerous nanomaterials have been synthesized and applied for waste water treatment [42-44]. During the Biannual Ecotoxicology Meeting 2016 (BECOME) held in Livorno (Italy) [45], the convened topic was "Eco-friendly Nanotechnology: state of the art, future perspectives and ecotoxicological evaluation of Nano remediation applied to contaminated sediments and soils" [46]. Nano remediation was the main topic of discussion at the convention and the following points were agreed upon -

1. Safety of the ecosystem is important when NMs deliberated on Nano remediation;
2. Anticipating the safety arrangement of nanomaterials for environmental remediation is compulsory.
3. Environmentally friendly, feasible and inventive nanomaterials are developed and promoted by agencies which have the capacity for recalcitrant removal from the environment.

Some important nanomaterials used for waste water remediation are depicted in Fig. 2.

Nanocomposites

Nanocomposites are a kind of materials in which a nanomaterial integrates into a matrix of excellent materials. They show tremendous improvement in hardness, surface area, thermal and electrical conductivity and mechanical strength. A nanocomposite is a combination of two and more materials in which at least one is a nanomaterial with different physical and chemical properties [47-48]. Different types of nanocomposites used for wastewater remediation are shown in Fig. 3.

PNC (polymer nanocomposite)

A polymer nanocomposite is simply a blending of a polymer medium with different nanoparticles [49]. Nanoparticles such as metal and their oxides, semiconductive materials (TiO_2, ZnO, WO_3) [50], metal with zero valencies, metallic composite (Fe/Ni, Au/Ag) [51], with polymers like PVA (polyvinyl alcohol), cellulose acetate phthalate (CAP) [52], cellulose, gelatine, hyaluronic acid

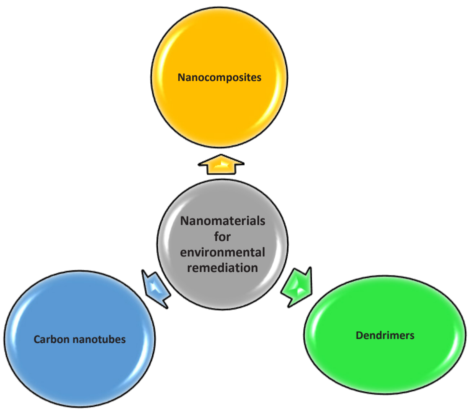

Fig. 2. Nanomaterials for environmental remediation.

Table 2. Applications of nanotechnology in waste water remediation.

S.No.	Target pollutant	Mechanism & Method	Nanomaterial used	Comparative result	Reference
1	Heavy metals anion, organic pollutants	Adsorption	Magnetic graphene oxide (MGO), Reduced graphene oxide(rGO)	The maximum adsorption capacities of MGO were 252 mg/g for TC, 234 mg/g for Cd (II) and 14 mg/g for As(V).	[32]
2	Organic and inorganic substances	Nanofiltration	SiO_2-modified nanocomposite	The rejection order of both M0 and M4 for different salts was Na_2SO_4 > $MgSO_4$ > $MgCl_2$ > NaCl. The MWCO of the NF membrane can be adjusted by changing the quantity of HGPN-SiO_2 added according to the actual demands.	[33]
3	Dichlorination/removal of Trichlorophenol	Reduction, adsorption	Biomass-Derived mesoporous Carbon-supported Sulphide nanoscale zerovalent Iron	TCP 100% removal procedure was well described by a Langmuir adsorption model and pseudo-second-order model	[34]
4	Organic pollutants such as RhB dye degradation	Photocatalysis	CeO_2/Bi_2MoO_6	The RhB degradation efficiency of 100% in 75 min, which was considerably higher than those of pristine CeO_2 (26.8%) and Bi_2MoO_6 (80.3%).	[35]
5	Heavy metals, organic pollutants, degradation of MO (coloured dye) and isoniazid (colourless pollutant)	Encapsulation, Photocatalysis	Black Cu-doped TiO_2 nanoparticles (BCT) encapsulated within hierarchical flower-like NiAl-layered double hydroxide (LDH). BCT/LDH	BCT/LDH composites exhibited high stability even after five successive runs, with no significant loss in the activity and exhibited 97% degradation.	[36]
6	Organic pollutant Antibiotic sulfachlorpyridazine.	Adsorption and oxidation	Ni@NCNTs (nickel encapsulation and doping of nitrogen)	98.9% degradation was obtained. The mechanistic insight of catalytic reaction for PS activation was investigated by EPR and quenching experiments, showing that radical ($SO_4^{-\bullet}$ and $^{\bullet}OH$) and non-radical reactions were involved in the activation process	[37]
7	Organic dyes MB and Indigo carmine	Photocatalysis	Composite nanofibers using TiO_2, carbon nanotubes (CNT) and polyacrylonitrile.	The constancy studies showed that the photo-degradation competence remained constant at 99% after five sequential cycles. The renewal studies with 15 mg TiO_2 NPs and 5 mg CNT (the minimum photocatalyst concentration) exhibited the maximum degradation at pH 6 organic dye solution.	[38]

(HA) [53], poly-lactic acid (PLA) [54] etc. can form PNCs. The detailed structure of PNCs is given in Fig. 4 showing that the nanoparticle is completely coated with a polymer matrix and forms a new and improved composite with the properties of both materials generated as PNCs [55].

Types of PNCs

The common polymer nanocomposites are -

(a) Polymer/ceramic nanocomposite

Polymer-ceramic nanocomposites have high power density and quick charging-discharging capacity and are commonly used in pulsed power technology. They are used for making environment-friendly energy storage devices, in which energy is stored over a long period and is effective in the application of wastewater [56].

(b) Inorganic/organic polymer nanocomposite

These nanocomposites are commonly organic polymer composites merged with inorganic nanoscale materials. They have blended properties of the inorganic substance like their firmness

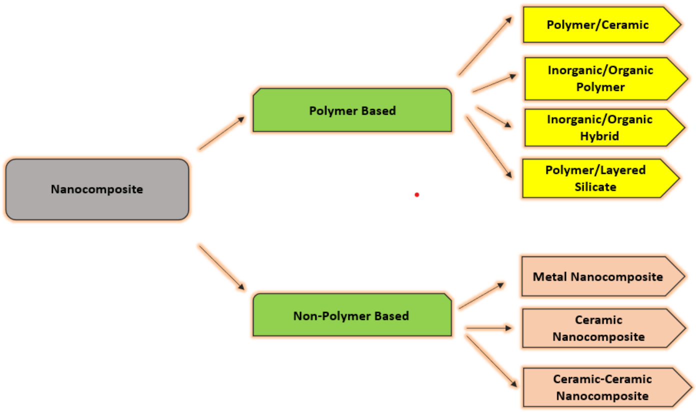

Fig. 3. Different types of nanocomposites.

and thermal conductivity and the qualities of organic polymers like elasticity, insulation and processability [57].

(c) Inorganic/organic hybrid

Organic polymer medium when merged with inorganic units gives new and improved organic-inorganic amalgam constituents. These constituents exhibit exceptional properties like upgraded physical and machine-driven characteristics of the polymer arrangements [58].

(d) Polymer/layered silicate nanocomposite

These nanocomposites have high power-driven and thermal characteristics as compared to other macro composites. PLS nanocomposite was effectively employed for use of the FDM procedure [59].

Applications of polymer nanocomposites

PNCs have an array of applications as discussed in Table 3. PNCs can remove dense metal ions and organic pollutants [60-61] and oil from water [62]. Through adsorption and degradation, PNCs can remove pollutant dyes. Different applications of PNCs (Fig. 5) have been reviewed such as the removal of contaminant dyes and organic pollutants, scaffold for tissue engineering, removal of heavy metals, pollution sensing, recovery of oil spills, gene delivery, and novel catalysis etc.

(a) Removal of pollutant dyes and organic components

The existence of recalcitrant organic contaminants, and extremely harmful non-biodegradable dyes in wastewater, causes serious ecological disturbance [63]. rGO-SiW nanocomposite has been found to exhibit high catalytic performance for wastewater remediation with MB and Rhodium blue dyes [64].

(b) Scaffold for tissue engineering

A scaffold is a crucial element for bone and tissue formation [65]. The scaffold provides mechanical stability to the implant tissues and their proliferation, space for cell growth etc. [66]. A nanocomposite scaffold made up of collagen/hydroxyapatite is commonly used for bone manufacturing [67].

(c) EM radiation absorption

Pollution from electromagnetic (EM) radiation decreases the performance of devices and has a prejudicial effect on human health [68]. 2D MXene (Ti_3C_2Tx) filled polyvinylidene fluoride (PVDF) polymer nanocomposite has shown a shielding

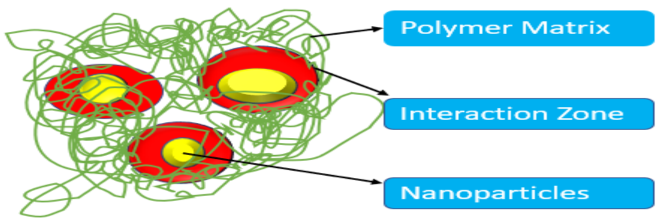

Fig. 4. Structure of PNCs.

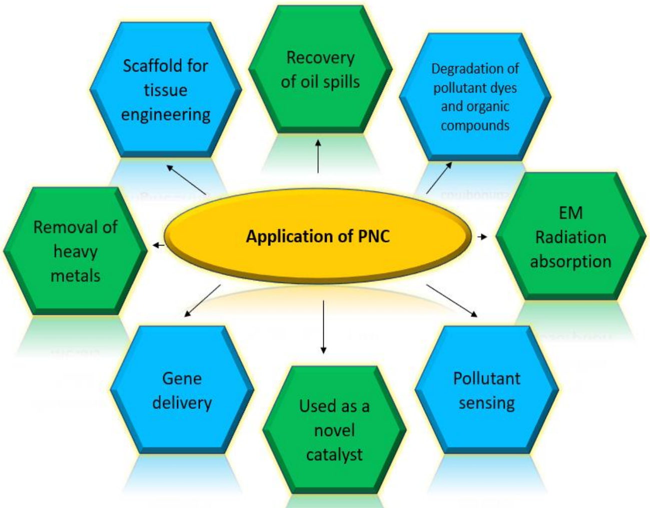

Fig. 5. Various applications of PNCs.

effect (SE) of 48.47 ± 3.5 dB against harmful electromagnetic radiations [69].

(d) Pollutant Sensing

Poly-3-hexylthiophene (P_3HT)/Graphene nanocomposite has been shown to detect the presence of ammonia gas at room temperature [70].

(e) Recovery of oil spills

Oil spills cause extensive distress to the environment and harm the flora and fauna due to oil leakage [71]. Polyethene and PVC blended polystyrene nanofibrous sorbents are generally used for the prevention of oil spills [72].

(f) Used as a novel catalyst

PNCs are utilized as nano-photocatalysts for environmental remediation. Pt@PPy (Polypyrrole)–PANI nanocomposites are used for the electro-oxidation of methanol [73].

(g) Gene delivery

Various types of graphene composites made up of reduced graphene oxide (rGO), and nano-graphene oxide (NGO, graphene oxide) have extensive medical applications. However, rGO is very commonly utilized as a nanomaterial for the intracellular transport of drugs and genes [74].

(h) Eradication of dense metal ions

Heavy metals like Pb, Cu, Zn and Cd are not biodegradable and cause harmful effects due to their accumulation in living organisms. Magnetic chitosan nanocomposite has been found to remove heavy metals from water [75-76].

Non-Polymer-based nanocomposite

Non-Polymer dependent nanocomposites for waste water remediation are mostly inorganic nanocomposites and are classified into three types [86] as shown in Fig. 3.

Metal-Matrix nanocomposite

These nanocomposites are generally found as amalgams or as the arrangement of core-shell assemblies. They are widely used because of their extraordinary catalytic properties and modification in the optical characteristics that are associated with specific metals [87]. Metal and metal oxides are mostly chosen for wastewater remediation studies due to their high reactivity. Ti, Cu, Al and Zn are the common metals used for the purpose (Fig. 6). They have promising characteristics to form metal matrix nanocomposites and they are promising catalytic agents for the dilapidation of contaminants. Metal oxide nanocomposites have a significant role as catalysts in various oxidation reactions and display durable catalytic responsiveness for contaminant particles and alter these contaminants into environment-friendly materials [88-89].

(a) ZnO NPs

ZnO NPs carry strong photocatalytic properties because their near UV spectral absorption possesses straight and broad band gaps showing tremendous oxidation ability [90-92]. ZnO NPs are very much compatible with microorganisms

Table 3. Different nanoparticles and polymer matrices used to form PNCs and their applications.

S.No.	Nanoparticle	Polymer matrix	Application of PNCs/Target pollutant	Comparative result	References
1	TiO_2	PVDF/PMMA	Congo Red and Tartrazine	Showed an outstanding removal of Congo Red with 99% removal and 81% for Tartrazine.	[77]
2	Cu	Chitosan	Detection of the traces of lead in water via sensing ability	The LOD results of the invented sensor in drinking water, mining wastewater, and soil leachate samples were 0.72 ppb, 1.12 ppb, and 1.01 ppb, respectively. Similarly, the RSD for 10 consecutive measurements of the invented sensor in consuming water, mining wastewater, and soil leachate samples were 0.65 %, 1.93 %, and 8.75 %, respectively. The minimal interfering in the presence of other heavy metal ions was observed in the detection of lead ion traces using the fabricated sensor.	[78]
3	Cu (II)	Chitosan magnetic composite CTS@SiO_2@Fe_3O_4	RBR (Reactive Brilliant Red)	The maximum adsorption amount of CTS-Cu@SiO2@Fe_3O_4 reached 880.84 mg/g at pH 4	[79]
4	Cu (II)	Chitosan/ alumina nanocomposite	Aromatic amines from water	Maximum adsorption capacities were 84 and 61 mg/g.	[80]
5	TiO_2	Polypyrrole (PPy)	MB	The MB dye was degraded by PPy-TiO_2 nanocomposite under solar light irradiation. The fraction removal of dye degradation was higher (93 %) in PPy-TiO_2 nanocomposite	[81]
6	NiO	PANI	MB	PANi-NiO photocatalyst degraded 76% of MB	[82]
7	zirconium (IV) selenophosphate	Chitosan-Gelatin	Dye pollutant (Rhodamine-B dye), heavy metal ion removal	84% of RD-B dye was degraded and followed pseudo-first order kinetics.	[83]
8	ZnS	Chitosan-g-poly(acrylamide)	CR and MO dyes	After 2 h of irradiation, 75% of congo red dye was degraded and 69% of methyl orange was degraded after 4 h of simulated solar irradiation.	[84]
9	Ag_3PO4	Nitrogen-doped graphene (NG)/Poly(3-hexylthiophene) (P_3HT) composite	Rhodamine-B dye	The degradation efficiency of RhB using Ag_3PO_4/NG/P3HT at the irradiation time of 40 min decreases from 100% to 97%, 91% and 90% during the four cycles test.	[85]

[93]. Bonding with microorganisms makes them appropriate for waste water remediation. ZnO NPs can absorb large light quanta and a broader array of solar spectra as compared to other semiconducting oxides of metals [94]. The photodegradation ability of ZnO NPs gets improved by metal doping, adding cationic and anionic dopants and co-dopant etc. [95].

(b) Titanium NPs (TiNPs)

They are suitable for waste water treatment because they are comparatively less expensive, resistant to corrosion, and stable [96]. To pre-concentrate and remove dense metal ions from polluted water, TiO_2 nanoparticles may be utilized as solid-phase extraction (SPE) packing materials [97]. Diazinon is an organophosphate pesticide that is found in groundwater [98] and is generally treated as a hazardous constituent. Nanocomposites of titanium dioxide (TiO_2) with Fe show incredible diazinon subtraction competence [96]. Primary dyes detected in the wastewater include Rhodamine B, methylene blue, and malachite green. A hybrid nanocomposite scheme compounding UV/TiO_2 with polyvinylidene fluoride (PVDF) membrane has been developed to remove Rhodamine B dye up to 95% [100]. TiO_2 nanoparticles have a key role in the removal of xenobiotic ingredients from water, like pesticides, dyes, and hazardous compounds, and hence have a wide range of applications in wastewater treatment [101]. Synthesized montmorillonite–kaolinite/ TiO_2 can remove heavy metallic impurities (Pb (II), Fe (III)and Cd (II)) from polluted water using the TiO_2 nanocomposites [102]. Synthesized TiO_2 nanowires can also remove heavy metals from wastewater by hydrothermal method [103].

(c) Copper NPs (CuNPs)

CuO is used as a catalyst, gas sensor etc. [104].

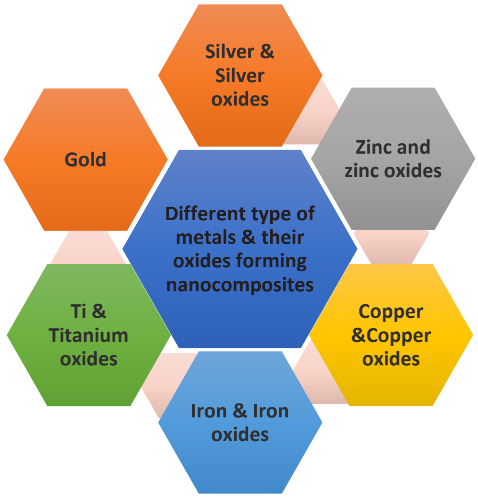

Fig. 6. Different types of metal and metal oxide nanoparticles forming MMNCs.

In the wastewater system, liberated Cu (II) ions from nanoparticles interact with the bacterial cytoplasm and cause cell wall damage [105]. The interaction of the liberated Cu (II) ions with the DNA nucleoid of the CuO nanoparticles can disrupt the DNA helical helix [106]. Oxidative stress is the most recent hypothesised mechanism of the disruption. Reduced oxidation species (ROS) generated by CuO NPs [107], harm the bacterial DNA, depending on the capability of CuO NPs' breakdown rate [108].

(d) Iron NPs

The application of iron-based nanoparticles has considerably increased in recent years [109]. Iron-based nanomaterials have recently demonstrated exceptional sorption potential due to their large surface area, magnetic properties, and high aperture capacity [110]. Nanocomposites such as paramagnetic constituents (Fe_2O_3) with CNTs were discovered and found to be effective in eradicating harmful heavy metals [111]. FeO NPs are magnetized in addition to possessing a large surface expanse, appreciable nano-adsorption capabilities, and a high rate of responsiveness [112]. When FeO NPs are exposed to an external magnetic field, they quickly aggregate, making extraction from an aqueous solution easy. The nanoparticles lose their magnetic moment after the removal of the external magnetic field, but few of them due to their super paramagnetic characteristics can be re-dispersed. Magnetite (Fe_3O_4) and its oxidation equivalent maghemite (Fe_2O_3) are examples of FeO NPs that have superparamagnetic characteristics [113].

(e) Silver NPs (AgNPs)

Ag nanoparticles (AgNPs) show powerful antimicrobial activity against an extensive range of bacteria, viruses [114] and fungi. As an effective antimicrobial representative, AgNPs have been broadly used for water purification [115-116]. The capacity of AgNPs to adhere to the microbial cell wall [117] results in structural alterations in the cell membrane, boosting its penetrability. Free radicals can also be generated when AgNPs interact with bacteria [118]. AgNPs can disrupt cell membranes and are supposed to trigger cell death. They can interact with bacterial nucleoids and abolish the bacterial cytoplasm and nucleoids [119]. AgNPs have been used effectively in wastewater treatment and the PES-Ag NPs membranes have exhibited to have potential antibacterial activity and might be used to treat waste water [120].

Applications of metal and metal oxide nanocomposites (MONCs)

The MONCs are usually used as adsorbents, nano-photocatalysts and nano-sensors to eradicate environmental contaminants. The nanostructured materials offer a huge surface expanse and high responsiveness, making them extremely useful for water purification and sensing contaminants. **Table 4** summarizes metals and their oxides nanoparticles and their applications for waste water remediation.

Ceramic nanocomposite (CNCs)

CNCs are assorted materials where an additional phase is embedded inside a ceramic medium [135]. They are associated with rigidity, high-temperature consistency, and tremendous strength with exact personalized characteristics (hardness and self-healing), dependent upon the behaviour of the emphasizing phase [136]. Fibres stable at temperatures above 1000 °C can be used as CNCs [137]. CNCs are widely used in the medical, aviation, and automobile industries [138].

Ceramic-ceramic nanocomposite

These composites are known for their capacity to withstand pressure [139]. These pressures are moulded due to the modification in the compaction rate of the two-component powders into a ceramic frame and a change in the thermal expansion coefficient (CTE) of the densified ceramic [140], like the laminate composites of zirconia-porcelain in dental crowns [141].

Carbon Nanotubes

Carbon nanotubes are hollow cylindrical tubes made up of hexagonally arranged carbon atoms and covered by fullerene-like structures [142]. The adsorption surface area of CNTs increases due to their porous structure. In conjugation with other materials, their hydrophobic properties, and electronic interaction increase. CNTs nanomaterial-based sensors show exceptional optical, chemical, electrical and physical properties for the detection of pollutants in water [143].

Types of CNTs

The unique structure of CNTs shown in Fig. 7 can be divided mainly into single-walled nanotubes

Table 4. Metal and metal oxide Nanocomposites and their applications for wastewater remediation.

S.No.	Metal and metal oxide nanocomposites	Applications and target pollutants	Comparative result	References
1	MWCNT/Al_2O	Eradicate Reactive Red 198 and Blue 19 dyes	The removal efficiency was 91.54% and 93.51%, respectively.	[121]
2	Fe_2O_3/SiO_2	Eradicate MB (methylene blue) and Congo red dyes under visible light	The photocatalytic degradation competence of about 88% for both methylene blue and Congo red in 180 and 240 minutes of reaction duration was obtained.	[122]
3	Fe_3O_4-TiO_2/rGO	Fenton's like catalyst remove methylene blue and remove Atrazine	The decolouration efficiencies were nearly 73% in the first 2 cycles and gradually decreased to 70% in cycle 8.	[123]
4	Fe-TiO_2/rGO	Remove rhodium B in existence of Xe lamp	The maximum elimination rate was 91% and was obtained when the concentrations of graphene oxide and iron were 5% and 3% respectively, at pH 6 and a nanocomposite dosage of 0.6 g/L. The concentration of rhodamine B was 20 mg/L, and the irradiation time was 120 minutes.	[124]
5	TiO_2-ZrO_2	H_2 evolution from water splitting	The composite revealed prominent performance, with the total hydrogen yield after 8 h being 23.7 μmol.	[125]
6	3D hierarchical flower-like TiO_2	Remove phenol in presence of a UV Lamp	The removal percentage was 93%. Before irradiation, the suspension was continuously agitated in the dark for 60 minutes to allow phenol to reach adsorption equilibrium on the surface of the photocatalyst.	[126]
7	TiO_2/ZnO/CuO	Remove phenol in presence of a UV Lamp	78% phenol removal was obtained at a 6-hour irradiation time.	[127]
8	g-C_3N_4/anatase TiO_2	Eliminate enrofloxacin (ENFX)	Photocatalyst decomposed ~98.5% ENFX after 60 minutes.	[128]
9	CuO-ZnO	Remove Arsenite, Dyes and heavy metals from wastewater	The removal competence was 60% on 12 h of irradiation with the catalyst concentration of 0.33 g L^{-1}, 100% with 0.67 g L^{-1} and 1.0 g L^{-1} on 10 hours and 8 hours of irradiation.	[129]
10	Ag_2S-NiO-ZnO	Rhodium B used a halogen lamp as a light source	The removal competence was 95%	[130]
11	Ni/Al_2O_3	Eradicate electrolytic filths from water	The removal competence was 83%	[131]
12	Co/Cr	Co/Cr co-doped ZnO nanomaterials are used for the effective removal of numerous anionic carbon-based contaminants	668.68 mg g^{-1} for Direct Red, 300.33 mg g^{-1} for congo red, 418.95 mg g^{-1} for Evans Blue and 754.47 mg g^{-1} for methyl blue, respectively. For methyl orange and tetracycline hydrochloride, the maximum adsorption capacities were 1057.90 mg g^{-1} and 874.46 mg g^{-1}.	[132]
13	Fe/MgO	Used for dense metal ions and colourant dye elimination.	1476.4 mg g^{-1} for Pb (II) and 6947.9 mg g^{-1} for MO	[133]
14	Al/CNT	Used for the efficient removal of bisphenol AF and metribuzin	The maximum adsorption concentrations were 274 mg/g for BPAF and 213 mg/g for Metribuzin.	[134]

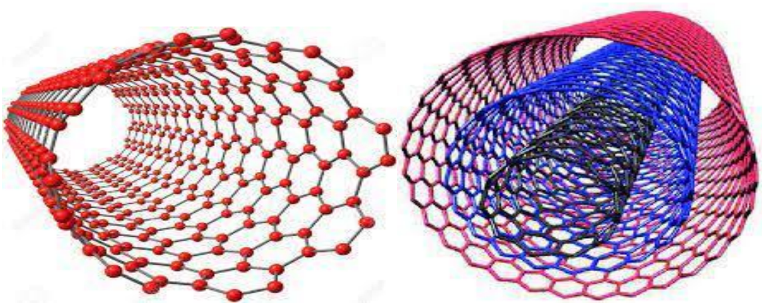

Fig. 7. 3D structure of carbon nanotubes (Image source is internet) (1) single-walled and (2) multi-walled CNTs.

(SWNTs) and multi-walled carbon nanotubes [144].

Single-walled carbon nanotubes

The single-walled CNTs own a tubular nanostructure with a high characteristic proportion moulded by rolling up solitary graphene pieces into a tubular form. Electrostatic attraction promotes cationic dye adsorption at regulated pH. Single-walled CNTs are one of the most promising adsorbents for waste water remediation [145].

Multi-walled carbon nanotubes

The multi-walled CNTs contain a concentrical assembly of more than 2 graphene sheets in the arrangement of a roll with an interlayer space of around 0.35 nm. They form a variety of shapes depending on the production method. MWNTs can absorb more near-infrared radiation (NIR) radiation as compared to single-walled carbon nanotubes (SWNTs). The multi-walled carbon nanotubes are superior to single-walled carbon nanotubes**.** The MWNTs with magnetic nanoparticles make it possible to decolourize cationic colourant dyes such as methylene blue and jenus green B etc. CNTs rooted in chitosan beads are more efficient colour removers [146-147].

Application of CNTs

Physio-chemical characteristics of CNTs are given in Fig. 8 which can be explored for ecological applications (nano-adsorbent, nano-catalyst, nano-filters, and nano sensors). Table 5 summarizes various applications of CNTs in wastewater remediation.

(a) Adsorbent

The elementary characteristics of CNTs like large surface extents and tremendous thermal constancies make them excellent for adsorbing pollutants from wastewater. PNCs show effective adsorption capacity against poisonous agents in wastewater such as Pb and Cd, and aromatic compounds [148]. There are four potential adsorption sites (Fig. 9a-9d) in the CNTs showing tremendous performance against pollutants [149-150].

(b) Transdermal drug delivery

The possible practice of carbon nanotubes (CNTs) for generating advanced drug delivery systems has been rising day by day in the research field with some auspicious results. CNT shows promising results as an antimicrobial, anti-cancer anti-inflammatories, and antihypertensive, and now use as a transdermal drug [151]. Instead of CNT, Chitosan (Csn) and polyvinyl alcohol (PVA) also have excellent mechanical strength properties and can be encapsulated with citral (Cil) into nanoemulsions (NEs) and applied for the treatment of infected wounds and ointments produced from ZnO/Chsn/Citl nanoparticles (NPs) are used to treat the infected wounds. [152-153].

(c) Oil spill management

CNTs possess a high oil adsorption tendency, and are super-hydrophobic oil sorbents due to their intrinsic nano-surface and permeable structure with excellent moistening surface and are extremely good for oil spill management [154].

(d) Sensor properties

CNTs are considered for environmental sensing applications due to their extraordinary properties including non-metallic nature, superior thermal, chemical and structural stability etc. [155].

(e) Membrane's filter

CNT membrane filters are a highly effective remediation source for recalcitrant pollutants present in wastewater, due to their high stability and considerably large surface area [156].

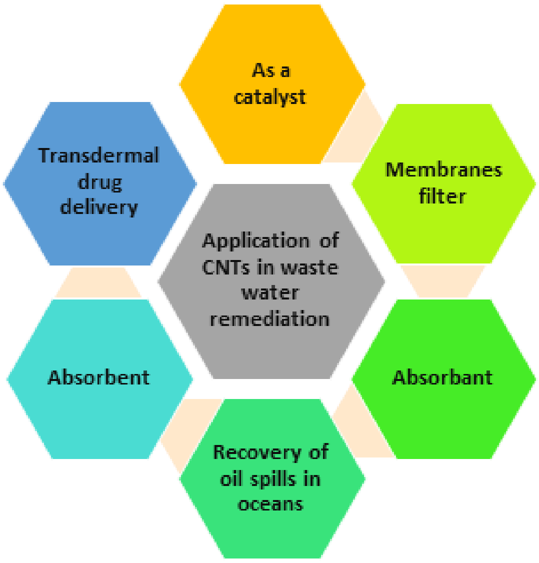

Fig. 8. Different applications of CNTs in waste water remediation.

(f) Catalyst

CNTs as a catalyst are also effective in wastewater remediation due to their graphite-like assembly enabling backing of metals, rich in mesopores, large surface extent, tremendous mechanical strength and electrical and thermal properties [157].

Dendrimers

The name dendrimer is derived from the Greek term dendron (tree) and meros (part) [168]. Every branched assembly originates from the fundamental central unit termed a dendron. Dendrimers are characteristically 2 nm to 20 nm in width and can be separated into three different sections: the central unit termed as the core, the internal interior (or branches) and the edge surface (periphery groups) as shown in Fig. 10. It is commonly used for the separation of metal ions in wastewater remediation and is favourable as a biodegradable chelating representative [169]. The connectivity of dendrimers through magnetic constituents allows the quick removal of impurities from the waste water [170]. Magnetic chains simplify the recovering phase departure by eradicating steps like filtration and centrifugation. It also synergizes inclusive elimination by ceasing the generation of secondary waste and boosting the

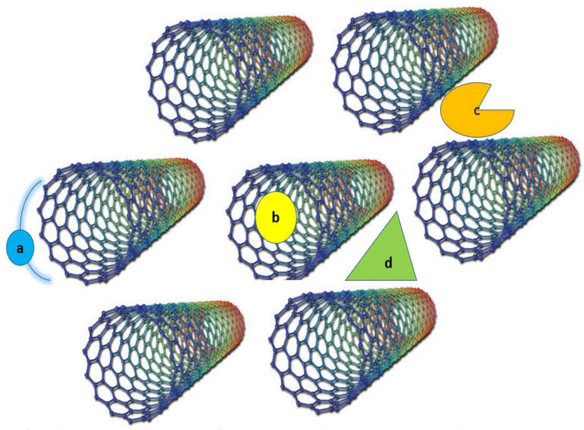

Fig. 9. Some adsorptive locations of pollutants and areas of contact with carbon nanotubes. 9(a), Exposed surface locations or the visible surface position of CNTs which adsorb impurities in water, 9(b), Internal sites existing in the hollow assembly of carbon nanotubes have a tremendous capacity to adsorb impurities. 9(c), External grooves existing on the side-line surface of the nanotube packs a V-like structure and show tremendous adsorption potential and 9(d), the interstitial networks that exist between the separate nanotubes are simply accessible for the adsorbate particles.

Table 5. Various applications of recalcitrant pollutant eradication using different carbon nanotubes.

S.No.	Nanomaterial of CNTs	Application	Comparative result	References
1	POTCe(III) T@CNTnanocomposite(poly)(o-toluidine) Ce(III)tungastate@CNT)	Sensor for highly hazardous Pb (II)	The selective coefficient value for Pb (II) was 0.016	[158]
2	PAMAM/CNT	Absorbent for heavy metals (Ni (II), Zn (II), As (III), Co (II)) from wastewater	About 90% of metal adsorption was found using 0.03 g/L nanocomposite dosage in a solution containing 100 mg/L metal ion concentration	[159]
3	WO_3/CNT nanocomposites	Photocatalytic removal of tetracycline (TTC) and pharmaceutical wastewater treatment	Eradicated 100% TTC at pH 9.0 and in pharmaceutical wastewater removed 83.7% and 90.6 % of TOC and COD, after 220 minutes of reaction time.	[160]
4	POSS-CNTs-CS	Dye Adsorbent for Wastewater	Eradicated 314.97 mg/g CR dye	[161]
5	Hydroxylated and carboxylated carbon nanotube membranes, COOH-CNT membrane, OH-CNT membrane	Removal of zinc from wastewater	The eradication capacity of Zn^{2+} through f-CNT membranes was above 98% for the synthetic water and over 70% for real wastewater effluents	[162]
6	Ag-ZnO/CNT	Eradication of acid orange dye (AO) via photocatalysis	The decolourization effectiveness of AO7 gradually reduced from 98% to 93.5 and 87% with increasing initial dye concentration from 20 mg/L to 30 and 40 mg/L.	[163]
7	CuO/CNTs	Eradication of Direct Red 31 and Reactive Red 120 dye	Dye degradation was 89 % and 87 % for DR31 and RR120, respectively.	[164]
8	PHB (Polyhydroxyl butyrate -CNT	Removal of heavy metals from waste water using the Electroplating method	Successfully removed 15.11% and 15.92% of Fe, 78.06% and 77.95% of Ni, 98.68% and 99.34% of Cd, 99.44% and 98.85% of Pb, 82.91% and 83.08% of Cu, 21.80% and 18.34% of Zn, 99.80% and 98.19% of Cr, and 99.99% and 99.95% of As.	[165]
9	CNTs/L-cys@GO/SA (carbon nanotubes/graphene oxide/sodium alginate)	Adsorption of Ciprofloxacin (An antibiotic pollutant from wastewater)	The adsorption capacity of CNTs/L-cys@GO/SA was 160.2 mg/g, close to the primary adsorption capacity of 181 mg/g.	[166]
10	polypyrrole/CNTs-$CoFe_2O_4$	Removal of organic contaminants from wastewater	Nearly 100% of MEB was removed after 30 minutes at 1.0 g/L catalyst, 4.0 mM PMS and 50 mg/L MEB solution	[167]

eradicating capability of the composite [171].

Applications of dendrimers in waste water remediation

Dendrimers have several applications (Table 6) in waste water management like metal encapsulation for catalysis [172], and sensor (polyamidoamine) dendrimers for recalcitrant contaminants [173].

NANOTECHNIQUES FOR THE REMOVAL OF WASTE FROM THE ENVIRONMENT

A wide range of treatment techniques (Fig. 11) have been examined for environmental remediation [179] of which a few important techniques are photocatalysis, nano-adsorption and nano-filtration.

Photocatalysis

The photocatalytic mechanism is the current evolution in the field of wastewater remediation used to eradicate hazardous contaminants which ruin environmental sustainability and are a major threat to mankind [180]. Photocatalysis is a method by which the synthesis and modification of a substance take place. Due to photocatalysis, the rate of a chemical reaction speeds up and the involvement of nano photocatalysts in presence of UV and Visible light remains consistent and unaffected during the entire process [181]. Nanomaterials such as titanium dioxide (TiO_2), tin dioxide (SnO_2), zinc oxide (ZnO), and cupric oxide (CuO), are favourable substances for the degradation of pollutants via photocatalysis and show promising characteristics as nano-photocatalysts because of their size-tuneable physicochemical characteristics and cost-effectiveness. Semiconductive behaviour promotes metal oxides as superior nano-photocatalysts for environmental sustainability [182-184]. Advanced

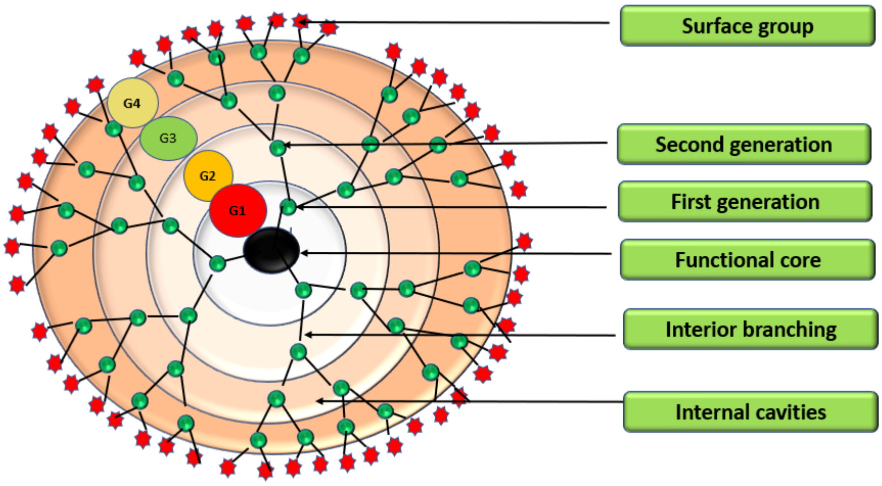

Fig. 10. Structure of dendrimer.

oxidation processes have been demonstrated to be efficient and impressive mechanisms including photocatalysis, O_3/H_2O_2/UV and Fenton oxidation [185]. Photocatalysis is efficient in the removal of contaminants without generating toxic by-products [186].

Mechanism of photocatalysis

A Nano photocatalyst such as TiO_2 absorbs light approximately equivalent to or larger than TiO_2 band gap thickness. It conveys to electron-hole pairs **(e^- –– h^+).** Mainly, h^+ in the valence band (VB) interacts with H_2O (surface-bound) to produce the OH radicals and at the same time, e^- in the conduction band (CB) generates the superoxide radicals as described in chemical equations below 1- 6 [187].

$$TiO_2 + h\nu\ (\text{Photon}) \rightarrow TiO_2\ e^-(CB)/h^+(VB) \quad (1)$$

$$O_2 + e^- \rightarrow {}^{\cdot}O_2^- \quad (2)$$

$$H_2O + h^+ \rightarrow {}^{\cdot}OH + H^+ \quad (3)$$

$$\text{Colorant Dye + Holes} \rightarrow \text{oxidation product} \quad (4)$$

$$\text{Colorant Dye + electrons} \rightarrow \text{reduction product} \quad (5)$$

$$\text{Dye+ hydroxyl radicals} \rightarrow \text{degradation product} \quad (6)$$

In photocatalytic degradation, a pollutant is split into several by-products. The possible pollutant dilapidation mechanism in the presence of light is summarized in Fig. 12.

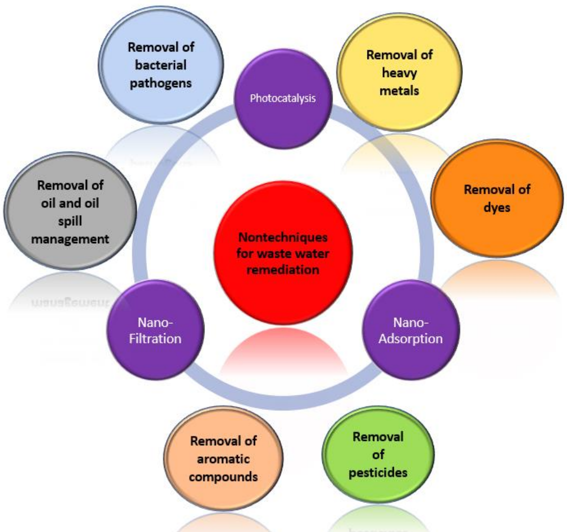

Fig. 11. Techniques to eradicate recalcitrant contaminants from wastewater.

Table 6. Dendrimer-based nanoparticles and their applications in wastewater remediation.

1	Dendrimer/titania nanohybrid	Removal of phenol	The removal competence was ~85% at a phenol concentration of 20 mg/L.	[174]
2	Silica-gel/PAMAM dendrimer hybrid	Capable of removing Cr (III) from aqueous solution	The absorption capacity amino-terminated adsorbents were above 90%, while that of ester-terminated adsorbents was higher than 85%	[175]
3	Carboxyl-terminated hyperbranched poly(amidoamine) dendrimers grafted superparamagnetic nanoparticles (CT-HPMNPs)	Novel adsorbent for removing Hg (II) from aqueous systems	The maximum removal efficiency of 73% and 75% was obtained at 1.5 and 2.0 g L^{-1} of adsorbent dosage for synthesized nanocomposites	[176]
4	PAMAM magnetic dendrimer	Eradication of naphthalene from waste water	The NAP eradication competence was 93- 100%.	[177]
5	ZrO2@GO-gen2-Aza (hydrophilic nano ZrO_2 encapsulated GO-based PAMAM dendrimers (up to 2nd generation) tethered with Aza group	Removal of arsenite from waste water AsO_3	The maximum removal efficiency was 80.54 mg g^{-1}	[178]

Applications of photocatalysis

Photocatalytic degradation has received much attention for toxic organic pollutants, and removal from wastewater because of their notable physicochemical properties [188]. Different types of nano- photocatalysts and their preparation methods are summarized in Table 7. Nanocomposites of photocatalytic TiO_2 and ozonated graphene were prepared and used for the photocatalytic degradation of methylene blue, methyl orange and ketoprofen using UV irradiation [189].

Drawbacks of the photocatalysis process

1. This method is very costly and involves a complex process.

2. Formation of toxic by-products takes place showing a negative impact on the environment [197].

Nano-adsorption

The Adsorption procedure has been one of the greatest operative techniques using nanomaterials to eradicate substantial metal ions in contaminated water [198]. However, the nano-adsorption method is particularly effective than the conservative method [199]. Nanomaterials have a tremendous capacity to remove toxic elements like Arsenic from drinking water when Fe $(OH)_3$ is infused with Ti nanoparticles and polymer material [200]. Few nanomaterials have also shown antimicrobial activities. AgNPs, zeolites, and CNT-based nanocomposites, etc., have numerous properties like mild oxidizing nature, and inertness to water [201-202].

Mechanism of nano-adsorption

Adsorption is a surface phenomenon in which a contaminant called adsorbate is gathered at the periphery of the adsorbent (Fig. 13). Adsorbate and adsorbent molecules intermingle through interactive forces [203]. Interactive forces are of two types, (1) **Chemical interactive forces** which are responsible for chemisorption leading to the formation of a durable chemical bond, in which sharing and transfer of electrons take place between the adsorbate and adsorbent molecules [204]**.** (2) **Physical interactive forces, which** are responsible for physisorption that is caused by feeble attractive forces between adsorbate and adsorbent [205].

Applications of adsorption in waste water management

Nano adsorbents are highly effective in wastewater remediation because the larger surface extent in their matrix makes them appropriate for diverse methodological applications such as chemical sensors, water refinement, drug distributions, etc. [206]. Polymer-based nano-adsorbents have a tremendous capacity for the

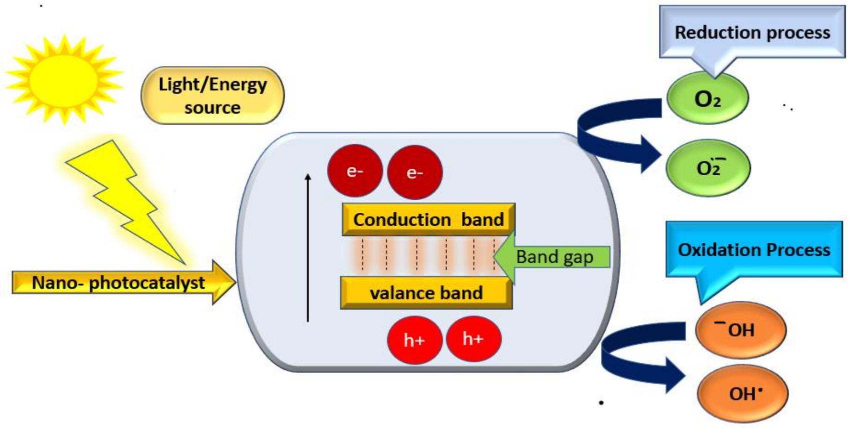

Fig. 12. Mechanism of photocatalysis using nano photocatalyst.

removal of metal ions, peroxides, and microbes from water/wastewater as shown in Table 8.

Drawbacks of nano-adsorption in waste water management

1. It cannot eradicate the contaminants.
2. Some other challenges include poor mechanical stability, production scalability and operational duration of material etc. [213 -214].

Nano-filtration

Nanofiltration is a pressure-driven membrane procedure that lies between ultrafiltration and reverse osmosis in terms of its ability to discard molecular or ionic species. Nanomembrane separation procedures are the best accessible procedures for wastewater remediation [215]. The overall procedural expenses of nano-filtration can be attained at optimum pressure and the driving pressure has a linear relation with the environmental effect [216]. Nanomembrane filtration technology has advantages over old and conventional separation technologies and is the best alternative for wastewater remediation [217].

Mechanism of nano-filtration

Nano-filtration is a process (Fig. 14) in which contaminated water after applying pressure passes through a semipermeable membrane [218]. The inlet stream has two different separate portions, the first one is permeated which is the clean and filtered percentage of the stream and the other one is retentate which is the excluded non-filtered percentage [219]. Nano-filtration has successfully shown effective elimination of organic contaminants, viruses, bacteria, colloids, bivalent ions and up to 90% monovalent ions [220].

Applications of nano-filtration

Nano-filtration has a wide range of applications particularly in waste water remediation [221]. One of the greatest features of nano-filtration membranes is their capability to filter mono-valent ions **(Fig. 14).** The process can be useful for the filtration of Na_2SO_4 and other impurities like viruses, bacteria and protein etc. Nano-filtration

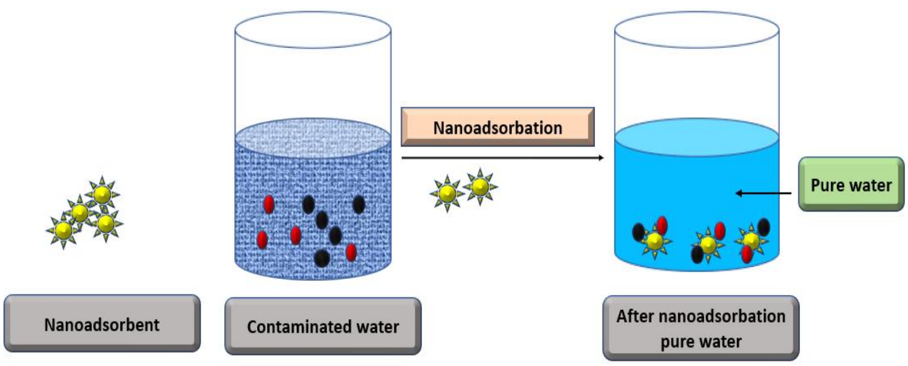

Fig. 13. Nano-adsorption process for wastewater remediation.

Table 7. Preparatory methods and applications of nano-photocatalysts in the removal of recalcitrant pollutants from wastewater.

S.No.	Nano photocatalyst	Preparation method	Target pollutant	Comparative result	References
1	ZnO/CuO	Sono-coprecipitation synthesis	Parathion	The removal percentages after 100 minutes were 60.16%, 78.13%, and 80.75% at photocatalyst dosages of 0.5 g/L, 1 g/L, and 1.5 g/L respectively.	[190]
2	α-MoO_3-WO_3/CdS	The physical solid-state method was performed in 18 mm stainless steel balls in one step	Banned production of Hydrogen and total organic contaminants (TOC) via photocatalytic degradation	The removal percentage after 6 h of solar-harvesting was75%	[191]
3	Flowerlike p-BiOI/n-$ZnFe_2O_4$	Solvothermal synthesis	Removal of acid orange 7	The removal percentage of AO7 after irradiating 3 h under visible light was about 95.7, 90.8, 80.7, and 78% for 15, 20, 25, and 30 ppm of AO7 dye.	[192]
4	TiO_2/ ONLH	A simple hydrothermal method	Typical pharmaceuticals	The degradation rates of propranolol in pure water, tap water, lake water, river water, and wastewater effluent after 30 minutes were 98.7%, 95.5%, 88.9%, 86.1%, and 90.9%	[193]
5	of ZnO/W/Ag	Combustion method	Dye removal	The removal percentage of dye was 78.8%	[194]
6	Cd-doped TiO_2	Sol-gel synthesis	Acid orange	95 % of dye degradation was obtained after 120 minutes of treatment.	[195]
7	ZnS photocatalyst	Co-precipitation method	Dye removal	The removal rate for MB, XO, MO, and MR were 78.41%, 81.22%, 90.90% and 95.10% after 120 minutes of reaction	[196]

membrane procedures are frequently accessible by numerous industrial processes, such as organic manufacturing, fabrics industries, metallic industry, tissue and paper, pharmacological and bioengineering applications, and basically for wastewater remediation **(Table 9).** The reported applications mainly include:

1. Textile industries, biochemical and organic manufacturing industries for the elimination of colourant dyes and other poisonous chemicals.
2. Detoxification of food productions (dairy, fluid processing, liquor, non-veg food, soda products, meat processing, etc.
3. Eliminations of heavy Metals, metal refining industries and leather industry.

Drawbacks of nano-filtration

1. An expensive procedure. Additionally, the implementation of nano-filtration in manufacturing industries application is still under development.
2. Fouling and blocking are the main glitches in any membrane separation, but nano-filtration is more complex because the interactions lead to fouling at the nano-scale.
3. It is a preferred technique for the removal of monovalent ions as compared to bivalent ions [227].

ADVANTAGES AND DISADVANTAGES OF NANOTECHNOLOGY TO REMOVE WASTE FROM THE ENVIRONMENTAL SECTORS

The main objective of using nanotechnology in the environmental sector is to eradicate contaminants from wastewater, and sense hazardous gases in the air [228]. The methods discussed above are very useful to eradicate contaminants from the environment, but they have their own merits and demerits, which are discussed in Table 10.

APPLICATIONS OF NANOTECHNOLOGY IN VARIOUS FIELDS

The branch of nanotechnology is predicted to expand in the coming years, and the different applications of nanotechnology are summarized in Table 11.

FUTURE PROSPECTS

A futuristic approach is needed to improve the

Table 8. Different nano-adsorbents used for wastewater remediation.

S.No.	Nano-adsorbent	Treatment in water	Comparative result	References
1	Carbon-based nano-adsorbents	Remediate Ni (II), Pb (II), Cu (II), and Cd (II) ions, due to high surface area, and outstanding chemical confrontation	The results showed that the adsorption equilibrium time was reached within 90 minutes for all four metal ions.	[206]
2	Regenerable magnetic chitosan	Removal of dye	The magnetic nanoparticles containing SCS showed high removal ability (over 50%) of MB	[207]
3	Transition Metal Oxide Nanowires nano-adsorbant	Rare earth elements from wastewater	Transition metal oxide nanowires absorbance was 1000 mg/g of rare earth elements with 93% recyclability.	[208]
4	Nanoclay	Eradication of heavy metals, colourants, hydrocarbons and other pollutants from wastewater	Nanoclay deduced ~85-90% colourants within 10-60 minutes	[209]
5	Graphene oxide nano-adsorbent	Eradication of arsenic and some additional dyes	The maximum adsorption capacities were 51.64 and 124.69 mg/g for As (III) and As(V)	[210-211]
6	Nano-metal oxide	Different kinds of dense metal ions and organic toxins	FeSiMnOx microjets were able to remove more than 98% and 94% (n=3) of Cd (II) and Pb (II) ions	[212]

quality of water globally which is also linked to the development of flora and fauna and climate change [240]. The need for and consumption of fresh and clean water is increasing speedily. In current years, the usage of nanomaterials in water remediation methodology has amplified significantly [241]. The unique and exceptional characteristics of nanomaterials like size-dependability on the nanoscale, promote the development of innovative and technological materials for effective wastewater remediation processes [242] such as nanomembranes, nano-adsorbents, nano-catalysts, layering nanomaterials, and nano-sensors [243-244]. Nanocomposites are preferred because of their accumulation behaviour and variability over nanoparticles. The huge probable potential of nanomaterials in various verticals and sectors of research and development and applications is giving promising, and socio-economic benefits [245-246]. While these technical parameters and methodologies make a foundation stone to achieve a way toward a scalable and sustainable future for generations. To make this happen, a comprehensive technical analysis and research are required to link laboratory-scale and industrial applications.

CONCLUSION

The article covers all aspects of nanotechnology as well as environment clean-up. Many notable methods have been discussed in light of environmental nanotechnology to remove waste and contaminants from the environment. These traditional processes have several advantages and disadvantages. Various photocatalysts such as metal oxide nanoparticles and nanocomposites such as CNTs, dendrimers and polymer nanocomposites are more popular in the market for environmental remediation to overcome the issues. This review delivers an up-to-date explanation of current progress in the arena of nanomaterials utilizes for water remediation. Here different methodologies for waste water remediation have been discussed such as photocatalysis, nano-filtration and nano-adsorption. The photocatalysis method is a new one to emerge in the last two decades and eradicates problems caused by environmental pollution. The evolution of new super aqua-phobic surfaces and coatings has improved the possibility of nano-

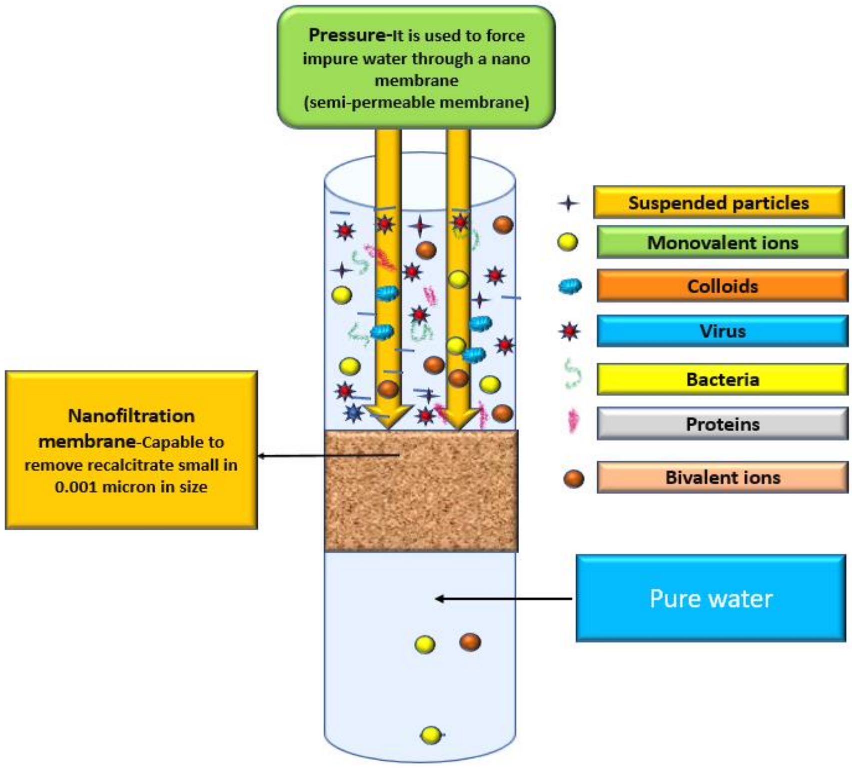

Fig. 14. Pictorial representation of nano-filtration.

Table 9. Different nanofiltration membranes and their application in wastewater remediation.

S.No.	Nanofiltration membrane	Application	Comparative result	References
1	NF270 membranes	Eradication of herbicide namely 2-methyl-4-chlorophenoxyacetic acid (MCPA)	The NF270 showed 71.3% rejection for MCPA	[222]
2	GO composite loose membranes	Removal of dyes/salts	92.9% rejection for Methyl blue (MB) and 98.8% rejection for Congo red (CR) 94.3% of Na_2SO_4, 97.6% of $MgSO_4$, 98.3% of $MgCl_2$ and 99.0% of NaCl	[223]
3	Yttria-stabilized ZrO_2(8YSZ NF)	Removal of pesticides	The maximum removal rate was 89%	[224]
4	Chitosan/cellulose acetate composite	Removal of copper	The refusal for copper was 81.03% at 506.5 kPa applied pressure.	[225]
5	Carboxylated graphene oxide-incorporated polyphenylsulfone	Eradication of heavy metal ions	The maximum elimination rates were >98% and ~80% for the anions and cations	[226]

Table 10. Advantages and disadvantages of nanotechnological methods in environmental remediation.

S.No.	Methods	Types	Advantage	Disadvantage	Reference
1	Chemical	• Photocatalysis	• Very fast process • Eradicates the contaminants completely • Extremely effective	• Costly • Formation of toxic by-products takes place • Very complex and tough process	[229-230]
2	Physical	• Nano-adsorption • Nano-filtration	• Very quick and fast process • Effective method • Does not generate toxic by-products	• Cannot eradicate the contaminants completely • Pore blocking takes place • Stability issues with the membrane	[231-232]

Table 11. Various industries using nanotechnology.

S.No.	An industry where nanotechnology used	Application of nanotechnology	Example	Reference
1	Cosmetics	For the development of make-up removers, facemasks, anti-ageing creams, sun screens lotion and other liquid-based beautifying creations.	ZnO and TiO_2	[233-234]
2	Construction	Paints, Nano steel, self-cleansing glass	Silicon dioxide is used for ceramic coating and Graphene is used as an anti-corrosive coating	[235]
3	Medicine	Tissue engineering, Drug delivery, and cancer therapy decreased the bacterial colonization and healing of wounds infected with methicillin-resistant Staphylococcus aureus	CEO-NLCs and gold/perlite nanocomposite using Urtica dioica extract	[236-237]
4	Environment	Remediation, pollution prevention and sensing	Carbon nanotubes (CNTs), metal ions with zero valencies and Ultrafine Ag/ZnO Nanotetrapods nanomaterial etc.	[238-239]

photocatalytic reactors with high merit. The cost-effective and large-scale development of the photocatalysis phenomenon contributes to green engineering and hence a healthier living. Nano-adsorption is another competent and widely-used procedure which can eradicate or diminish organic and inorganic contaminants without generating by-products or toxic intermediates. Numerous nano-adsorbents can also be used, like nanometal oxides, zeolites, and polymeric nano-adsorbents, because of their exclusive properties like large surface area, steadiness and bacteriological effect. New studies can be adopted with these materials like chemical stabilization and surface adaptations to advance their applications in wastewater remediation. Lastly, nano-filtration membranes are used because of their advanced salt refusal rates and water absorbance, larger pore size, positive surface charges and advanced hydrophilicity. These advanced membranes display tremendous potential for water softening, wastewater treatment and separation and purification of active, pharmaceutical molecules. Overall, the capability of eradication of toxic metal ions, colourant dyes, and germs from the environment by nanomaterials and their efficiency has made them one of the significant emerging materials.

CONFLICT OF INTEREST

The authors have no competing interests.

ACKNOWLEDGEMENTS

The authors are thankful to Prof. A.R. Khan, Head, Department of Chemistry, Integral University, Lucknow and the R&D cell of the University for providing the manuscript communication number (IU/R&D/2022-MCN0001454).

ABBREVIATIONS

CNTs	Carbon nanotubes
SWCNTS	Single-walled carbon nanotubes
MWCNT	Multiwalled carbon nanotubes
PNCs	Polymer nanocomposites
WHO	World Health Organization
MGO	Magnetic Graphene oxide
rGO	Reduce graphene oxide
Ni@NCNTs	Nickel encapsulation and doping of nitrogen in carbon nanotubes
BCT	Black Cu-doped TiO_2 nanoparticles
LDH	Layered double hydroxide
PVA	Polyvinyl alcohol
CAP	Cellulose acetate phthalate
HA	Hyaluronic acid
PLA	Poly lactic acid
EM	Electromagnetic
PLS	Polymer layer silicate
FDM	Fused deposition modelling
MB	Methylene blue
PVDF	Polyvinylidene fluoride
PANI	Polyaniline
CR	Congo red
MO	Methyl orange
RBR	Reactive brilliant red
SPE	Solid-phase extraction
DNA	Deoxyribonucleic acid
FeO NPs	Iron oxide nanoparticles
CNC	Ceramic nanocomposites
CTE	Thermal expansion coefficient
POT	Poly ortho toluidine
PAMAM	Poly(amidoamine)
POSS	Polyhedral oligomeric silsesquioxanes
CS	Chitosan
SA	Sodium alginate
PVA	Polyvinyl acetate
PHB	Poly hydroxy butyrate
CT-HPMNPs	Carboxyl-terminated hyperbranched poly(amidoamine) dendrimers grafted with superparamagnetic nanoparticles
UV	Ultra violet
NF	Nanofiltration
EIP	Electrospray interfacial polymerization
TTC	Tetracycline
SPE	Solid phase extraction
ROS	Reactive oxygen species
PVDF	Polyvinylidene fluoride
RO16	Reactive orange 16
CEO-NLCs	Caraway essential oil- loaded into nanostructured lipid carriers
NAP	Naphthalene

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