Introduction

Water is a precious natural resource and its quality availability is essential for the survival of living creatures on the earth. However, rapid industrialization is continuously degrading the quality of water due to addition of large amounts of pollutants into the water bodies.\(^1,2\) Water pollutants have appeared as threats to entire biosphere, so their removal has become essential. The different types of water pollutants along with their sources and impact are given in Table 1.

According to recent UN report,\(^3,4\) reliable access of clean and affordable water is one of the most basic humanitarian goals, and is a major global challenge for the 21st century. The fundamental requirements for water purification is appropriate materials with high separation capacity, low cost, porosity, and reusability.\(^5,6\) In this regard, nanotechnology provides an opportunity to develop advanced materials for effective water purification by optimizing their properties like hydrophillicity, hydrophobicity, porosity, mechanical strength, and dispersibility.\(^7\) Nano particles having high surface area, can contribute a lot in water purification but its agglomeration restricts its use.\(^8\) However, agglomeration can be minimized by converting nanomaterials to nanocomposites. In this review, different types of nanocomposites, their preparation and properties have been discussed. Emphasis has been given on polymer nanocomposite and their use for water purification.

Nanocomposite

Nanocomposites are multi-phaseic materials, in which at least one of the phases shows dimensions in the nano range (10–100 nm). Now-a-days nanocomposite materials have emerged as suitable alternatives to overcome limitations of different engineering materials. They are reported to be the materials of 21st century. Nanocomposite materials can be classified, according to their dispersed matrix and dispersed phase materials.\(^9\) The classification of nanocomposite is illustrated in Figure 1.

Among different nanocomposites, polymer-based nanocomposite (PNCs) have become a prominent area of current research and development. PNCs have lot of advantageous properties such as film forming ability, dimensional variability, and activated functionalities.\(^10,11\) The importance of materials can be recognized from the continuous increasing rate of publications in leading journals, which is presented in Figure 2.

Abstract

In recent years, polymer nanocomposites (PNCs) have attracted the attention of scientists and technologists in water purification due to improved processability, surface area, stability, tunable properties, and cost effectiveness. PNCs showed fast decantation ability with high selectivity to remove various pollutants. This review provides up-to-date information about the importance of PNCs in the removal of metal ions, dyes, and microorganism from polluted water. The general methodology for preparation and properties of nanocomposites with reference to PNCs is given. Different adsorption isotherm and kinetic models along with thermodynamic parameters for adsorption have been discussed.

Keywords

Polymer nanocomposite, Water purification, Adsorption models, Kinetic models

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Preparative methods

Number of methods has been used for the preparation of polymer nanocomposites. A brief summary of different methods and their comparison for the preparation of nanocomposites are given in Table 2. However, the designing of correct preparation technique is very critical to obtain nanocomposite with desirable properties.

The PNC prepared from inorganic materials (metals and metal oxide nano-particles) using in situ polymerization and composite formation shows excellent sorbent properties and are also suitable as catalysts, sensors, reducing agents, and bactericides. Shukla et al.23 has synthesized zinc oxide polyaniline nanocomposite with improved interface. The resulting hybrid nanocomposites exhibited thousand times better electrical conductivity due to synergistic effects. The integration of dispersed phase into a dispersed medium was done by both approaches (ex-situ or in-situ). Many times nano particles were also functionalized prior to dispersion in the matrix. The basic objective was to improve the compatibility, ion exchange, and surface interaction. Luo et al.24 prepared ionic liquid coated Fe3O4@chitosan@graphene oxide (GOIL-Fe3O4@CS@GO) by dissolving one gram of tetraoctylammoniumbromide in 15 mL methanol. Further, 1.0 g of Fe3O4@CS@GO was taken in a round bottom flask, dissolved in ionic liquids and sonicated for 2 h with a 15 min intermittent time interval. The resulting solution was filtered and washed with methanol. Thus, obtained ionic liquid impregnated Fe3O4@CS@GO was found suitable for dye removal. The maximum adsorption capacity for methylene blue was 262 mg/g. The preparation and application of Ionic liquid-Fe3O4@CS@GO for removal of MB is illustrated in Scheme 1.24

A semiconductor–conductor tubular nanocomposite in a 60 mm thick alumina template membrane with 200 nm diameter pores were prepared. TiO2 tubules were synthesized within the pores of the alumina membrane by sol–gel process before they were subjected to thermal treatment. Polypyrrole wires were then grown inside the semiconductor tubules by using chemical polymerization method. The conducting polymer enhanced the electrical conductivity of the material, and increased the photo-efficiency of TiO2-polypyrrole nanocomposites as a photocatalyst.25

Characterization of nanocomposite

The important techniques used for the characterizations of PNCs are thermal analysis (TGA, DTA, DSC, TMA, and DMA), microscopic techniques (SEM, TEM, and AFM), spectroscopic techniques (FT–IR, Raman) and X-ray diffraction techniques. The presence of polymer matrix improves the processibility of a non-polymeric constituent and the thermal stability of polymer is also improved significantly. Thermal analytical techniques have frequently been used for this purpose.26

Scanning electron microscopic methods provide images of surface, which are associated with sample properties like homogeneity, roughness, porosity, etc. The images are also used to get information about compatibility and lattice mismatch. The other microscopic techniques are scanning probe microscopy (SPM) and scanning tunneling microscopy (STM). They are indispensable in characterizing PNCs.27 The AFM uses a sharp tip to scan across the sample and appropriate to evaluate roughness of morphology.28,29 The transmission electron microscopy (TEM) allows qualitative understanding about the internal structure, spatial distribution of the various phases,
and views of the defective structure through direct visualization of PNCs, in some cases of individual atoms. Another important tool is wide angle X-ray diffraction pattern, which provides the crystallinity and lattice structure of nanocomposite. Small-angle X-ray scattering (SAXS) is typically used to observe structures of the order of 10 Å or larger. The wide angle X-ray diffraction (WAXD) patterns and corresponding TEM images of three different types of nanocomposites are presented in Figure 3. A closer observation of the micrograph at higher magnification revealed that each dark line often corresponds to several clay layers.

PNCs exhibit newer physical and chemical properties than the individual constituents. It depends on interactions between dispersed phase and matrix, here polymers are considered to be a good host material due to processibility. FT–IR and Raman spectra are widely used to investigate these types of interactions. Figure 4 clearly indicates that as the concentration of Ag in Ag/PMMA nanocomposites increases, the peak shifted to lower wave numbers indicating strong interactions between the constituents.

Properties

Addition of nanoparticles in polymer matrix improves the polymer properties and produce PNCs with desired properties. Catalytic, adsorption, and mechanical properties of PNCs are generally used for the purification of water. These properties of PNCs are briefly discussed below.

Catalyst

Large number of metal, metal oxide, and sulfides have been used as catalysts for purification of water and waste water both in the presence and absence of light. Number of catalytic degradation of different pollutants like nitrogen contain compounds, dyes, and residual organic compounds have been reported. Some catalysts also produce reactive oxygen species (ROS), which enhances the catalytic rate. Heterogeneous catalysis among different metal compounds like TiO₂, ZnO, Fe₂O₃, CdS, GaP, and ZnS are reported for water decontamination due to their ionic surface interaction and modified surface tension. Among different catalysts, titanium dioxide and zinc oxide (ZnO) have received the greatest importance due to their low cost, high photo catalytic activity, and stability. They have been used as a photocatalyst for speeding up many redox reactions on their surface. An example of photocatalytic activity of ZnO/PMMA nanocomposite has been discussed by Mauro et al. for degradation of phenol and methylene blue. The result illustrated in Figure 5 indicates drastic enhancement in catalytic properties due to incorporation of ZnO in PMMA.

Generally, on irradiation with UV light, these oxides generated holes and released electrons, which reacted with H₂O and O₂ molecules, and adhered on the surface. In result, it produces highly reactive oxygen species (ROS) such as peroxides, superoxide, hydroxyl radicals, and singlet oxygen. ROS are capable to degrade organic water pollutants like dyes efficiently. Generation of ROS also has antibacterial effect due

Table 2  Different methods used for preparation of nanocomposites

| Methods                      | Advantages                                      | Disadvantages                      | Examples                                                                 | References |
|------------------------------|-------------------------------------------------|------------------------------------|--------------------------------------------------------------------------|------------|
| Solution casting             | Scalable                                        | Impurity                           | PMMA titanium dioxide nanotube, zeolitic imidazolate framework-8          | 12,13      |
| Melt compounding             | Economical, flexible formulations               | Agglomeration                      | High energy                                                              | 14         |
| Intercalation                | Organized structure                             | Dispersion                         | Reinforce polylactide (PLA) nanocomposites                               | 15         |
| In situ polymerization       | Micro-indentation, liquid phase processing, agglomeration free matrix | Costly, time consuming             | Carbon nanotube/polymer composite                                         | 16         |
| Sol-gel                     | Compatibility and unique properties             | Higher reactivity                  | Polyethylene-octene elastomer (POE)                                      | 17         |
| Spinning                     | Good Interaction, interfacial interaction       | Costly                             | Ethylene vinyl acetate/graphene oxide (EVA/GO)                           | 18         |
| Template synthesis           | Synergistic effects                             | Control dispersion                 | Cellulose/ PMMA                                                          | 19,20      |
| Phase Separation             | Functionalization                               | Uncontrolled formation             | Carbon nanotube/cellulose acetate(CNT/CA) nanocomposite                  | 21         |
| Electrochemical Synthesis    | Synthesized under moderate conditions, that is, at room temperature and ambient pressure | Reactions are confined to the surfaces of the working electrodes         | Conducting polymers-CNT/Pd, Pt, Au/γ-Fe₂O₃/WO₃                          | 22         |
to oxidative stress in an aqueous condition, for example, the hydroxyl radical is responsible for the inactivation of Escherichia coli. However, there are limitations because of the effects on human health and ecosystems due to their release, stability, dissolution, and retention time. In this regard, PNCs have attracted maximum attention. Titania/PMMA nanocomposite has been prepared by electrochemical anodization. The nanocomposite has been tested for inactivation of Escherichia coli as a model organism. Sankar et al. studied antimicrobial effect of silver embedded aluminum oxyhydroxide–chitosan nanocomposite. This composite is capable to control sustained release of silver ions (40 ± 10 ppb) in natural drinking water for an extended volume of water passing through it due to the formation of abundant −O and −OH functional groups on chitosan surface. A new class of photocatalyst is g-C₃N₄, which increases the photocatalytic activity of semiconductor. Beside this g-C₃N₄ has large surface area to adsorb large variety of synthetic organic pollutant and toxic ions. Therefore, carbon nanosheet (CNS) nanocomposites with multi-adaptable features is a good technique to increase the application of semiconductor nanomaterials in the area of photocatalyst. Many semiconductor photocatalysts such as BiOCl, BiVO₄, Bi₂MoO₆, Bi₂WO₆, In₂S₃, CuO₂, SrTiO₃, TiO₂, WO₃, ZnO, and Ag/AgBr have been used to couple with g-C₃N₄ for the synthesis of CNS nanocomposite. TiO₂ has been widely used for waste treatment, water splitting, air purification, and self-cleaning of surfaces because of its unique photocatalytic property. TiO₂ has also been incorporated in various membrane matrices to provide photocatalytic activities. Rahimpour et al. studied the effect of UV radiation on the performance of TiO₂/PES nanocomposite membrane and found that UV irradiated TiO₂/PES membrane had higher flux and enhanced fouling resistance when compared to the system without UV radiation. They attributed this enhancement to
the photocatalysis of TiO₂ under UV radiation. Damodar et al. obtained a superior membrane with enhanced permeability and antibacterial activity.

**Adsorption behavior**

Polymer nanocomposites are known for highly tunable adsorption behavior due to the presence of nano particles with high surface area in the polymer matrix. Optimized adsorption behavior of nanocomposites make them suitable for different technical applications like chemical sensor, water purification, drug delivery, and fuel cell technology. PNCs have extensively been used for adsorptive removal of various toxic metal ions, dyes, and microorganism from water/waste water. Khare et al. has prepared chitosan, carbon nanofibers (CNFs)- supported iron (Fe)-oxide nanoparticles (NPs) and polyvinyl alcohol nanocomposite film with improved adsorption capacity. The materials show a high metal uptake (80 mg per g of chitosan/Fe-CNF composite), and explored for efficient removal Cr(VI) from water under dynamic conditions (Figure 6).

However, in the course of adsorption many secondary pollutants are also generated. Thus, in order to overcome the problem of secondary pollutants, PNCs have been used as adsorbents for water purifications. A series of binary, tertiary, and even quaternary PNCs have been made to develop appropriate level of adsorption behavior. Mittal et al. have reported that addition of nano SiO₂ in acrylamide hydrogel improves the monolayer adsorption capacity of acrylamide hydrogel to 1408.67 mg g⁻¹. They prepared nano silica and gum karaya grafted with poly (acrylic acid acrylamide) (GK-cl-P(AA-co-AAM) nanocomposite containing hydrogel for adsorptive removal of methylene blue (MB) from aqueous solutions. Their findings indicated that, grafted copolymerized gum karaya hydrgel could be used as an eco friendly and efficient adsorbent for the removal of methylene blue dye from industrial wastewater (Figure 7). However, the complete separation of the adsorbent particles from the treated water still remains a challenge in batch mode of purification.

Another important strategy to optimize adsorption behavior is to synchronize hydrophobic and hydrophilic behavior in composite matrix. A novel hydrophilic–hydrophobic optimized magnetic interpenetrating polymer networks (IPNs) of poly (methyl acryloyldiethylenetriamine)/polydivinylbenzene (PMADETA/PDVB) was synthesized by interpenetration of polydivinylbenzene (PDVB) networks in the pores of the magnetic poly (glycidyl methacylate) (PGMA) networks. Initially, PGMA networks were transformed to poly (methyl acryloyl diethylenetriamine) (PMADETA) networks by an amiation reaction. The adsorption of a molecule depends on ionic or surface interaction, which needs selective interaction site. PNCs are most appropriate substrate for this purpose. Poly (acrylamide–styrene sodium sulfonate) containing titanium oxide (TiO₂/(P(AAm–SSS)) obtained by in-situ intercalative polymerization of co-poly acrylamide (PAAm) and styrene sodium sulfonate (SSS) in the presence of TiO₂ nanoparticles were prepared, which showed improved metal ions (Cs⁺, Co²⁺, and Eu³⁺) adsorption with sorption capacity upto 120, 100.9 and 85.7 mg/g, respectively. Another important aspect about the use of PNCs in water purification is biodegradation. In this regard, biopolymers like polysaccharide has enormous potentials due to its world wide availability. Sun et al. has prepared biodegradable polysaccharide-based nanocomposite
Another important characteristic of nanocomposites is anisotropy, which aligns the mechanical properties in composites. In this regard, carbon-based composite have played a significant role in the development of PNCs. The dispersion of carbon nanotube in PMMA matrix increases the mechanical properties of PMMA. The results have indicated that the improvement depends on surface interaction between carbon nanotube and polymer chain. The young modulus of PMMA changes from 2.86 to 3.99 GPa; yield stress from 2.86 to 35.06 MPa due to addition of CNT in PMMA matrix. Carbon nanotubes (CNTs) have also attracted intense attention of scientists working in various disciplines due to its exceptional electrical, mechanical, and thermal properties. These properties have made CNTs as outstanding materials for a range of technical applications including adsorbents. Wheat xylan/poly(acrylic acid) nanocomposite hydrogel containing Fe3O4 nanoparticles has been reported for 90% removal of MB by adsorption. The interpenetrating nature and super-magnetic behavior of hydrogel is further responsible for better adsorption. The materials are having environmental importance and widely covered in green chemistry and also referred as green nanocomposites.

**Mechanical properties**

Processability, stability, and end use of a PNCs depend on its mechanical strength. The interaction among polymer and non-polymeric constituents strongly influences this property. The interaction between constituents particles of composite not only influences mechanical behavior of the neat resin but also increases the value-added properties, which were not present in the pure polymer. Another important characteristic of nanocomposite is anisotropy, which aligns the mechanical properties in composites. In this regard, carbon-based composite have played significant role in the development of PNCs. The dispersion of carbon nanotube in PMMA matrix increases the mechanical properties of PMMA. The results have indicated that the improvement depends on surface interaction between carbon nanotube and polymer chain. The young modulus of PMMA changes from 2.86 to 3.99 GPa; yield stress from 2.86 to 35.06 MPa due to addition of CNT in PMMA matrix. Carbon nanotubes (CNTs) have also attracted intense attention of scientists working in various disciplines due to its exceptional electrical, mechanical, and thermal properties. These properties have made CNTs as outstanding materials for a range of technical applications including adsorbents. Wheat xylan/poly(acrylic acid) nanocomposite hydrogel containing Fe3O4 nanoparticles has been reported for 90% removal of MB by adsorption. The interpenetrating nature and super-magnetic behavior of hydrogel is further responsible for better adsorption. The materials are having environmental importance and widely covered in green chemistry and also referred as green nanocomposites.
The mechanical properties of polymer hydrogels obtained via crosslinking of polyacrylamide (PAM) and chromium acetate has been significantly enhanced due to addition of silica nano particles. It is understood that addition of nano-silica into polymer/chromium acetate crosslinking systems produces composite polymeric network through coordination polymerization. The silica particles are dispersed into the polymer matrix due to small size, and produces high-toughness, wear-resisting, and good-stability to enhance mechanical strength and deformation reversibility of nanocomposites. The mechanical properties are directly related to concentration of silica, while hydrogel without silica is brittle. The compression strength of composite hydrogel was seven time higher than that of pure hydrogel.

Application of polymer nanocomposites for water purifications

Different types of PNCs are currently being explored for usage in purification of water. The prime reason for the use of PNCs in any applications lies in their unique properties, which is different from their counterparts. Different PNCs used in water purifications technology are shown in Figure 8.

Methods of water purification

Different methods used for water purifications are recently been reviewed by Singh et al. and are also tabulated in Table 3. These methods are mainly categorized on the basis of separation techniques like physical adsorption, chemical degradation, and biological treatment. All the methods have some advantages and disadvantages but no single process is able to purify the water adequately. Thus, combination of processes are recommended to insure adequate quality of water. The research findings have indicated that serious efforts are required to integrate different techniques like adsorption–biological treatments to enhance biodegradation of dye stuffs and reduce the sludge formation.

Table 3 Important water purification processes

| Methods                        | Advantages                                                                 | Disadvantages                                                                                     |
|--------------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Conventional methods          | Adsorption: The most effective adsorbent, great, capacity, produce a high-quality treated effluent | Ineffective against disperse and vat dyes, the regeneration is expensive and results in loss of the adsorbent, non-destructive process |
| Coagulation and Flocculation  | Simple, economically feasible                                               | High sludge production, handling and disposal problems                                             |
| Established Methods           | Membrane separations: Removes all dye types, produce a high-quality treated effluent | No loss of sorbent on regeneration, effective                                                    |
| Ion-exchange                   | Oxidation: Rapid and efficient process                                      | Economic constraints, not effective for disperse dyes                                            |
| Emerging technology           | Advanced oxidation process: No sludge production, little or no consumption of chemicals, efficiency for recalcitrant dyes | High energy cost, chemicals required, Economically unfeasible, formation of by-products, technical constraints |
| Biodegradation                 | Economically attractive, publicly acceptable treatment                     | Slow process, necessary to create an optimal favorable environment, maintenance and nutrition requirements |
| Microbial treatment           | Ecofriendly                                                                  | Scaling up, slow, difficult to standardize                                                        |
the adsorbent and adsorbate molecules are both physical and chemical. Physical adsorption is reversible in nature. While, if the attraction forces is due to chemical bonding, it is difficult to desorb the chemisorbed species from the adsorbent surface. Ion exchange technique also shares various common features along with adsorption. Ion exchange is a reversible chemical process in which an ion from solution is exchanged for a similar charged ion attached to an immobile solid particle or composite film. The polymer-based nanocomposite bears superior properties for metal decontamination in different forms like candle, mat, membrane, beads, etc. The nanocomposite-based adsorbents were prepared by infusing the inorganic nanoparticles onto the polymers such as alginate, cellulose, porous resins, and ion-exchangers. To avoid issues caused by the ultra-fine particle size such as transition loss and excessive pressure drops, porous PNCs adsorbents or ion exchangers have proved to be an ideal hybrid adsorbents, due to their excellent mechanical strength and adjustable surface chemistry which is because of polymeric support. Qiu et al. prepared nano iron oxide loaded polystyrene with strong sorption behavior. The presence of counter ion affects the adsorption behavior in the removal of metal ions from an aqueous solution. It is due to the formation of tertiary complex around the composite. FeO nanoparticles coated with polyethyleneimine (PEI) polymer were intercalated between sodium rich montmorillonite (MMT) layers under acidic conditions (pH 2). The composite was used as a magnetic sorbent for the adsorption of Cr(VI). At pH 2, amine groups of PEI were protonated and intercalated between MMT platelets by cationic exchange as shown in Scheme 2.

A superadsorbent composite was synthesized by copolymerization of acrylic acid on bentonite powder. The composite was found suitable for removal of different heavy metals with \( q_{\text{max}} \) values 1666.67 for Pb\(^{2+}\), 270.27 for Ni\(^{2+}\), and 416.67 mg/g for Cd\(^{2+}\) (Figure 9).

Further, basic problem of nanoparticles is their stabilization in appropriate oxidation state. Rastogi et al. encapsulated nano size nickel (II) oxide prepared through eutectic melt in urea formaldehyde resins. Agglomeration free NiO and CuO encapsulated urea formaldehyde nanocomposite was formed and was found suitable for efficient removal of As(III) (80%). Chitosan and its nano derivatives are reported as a good adsorbents for the removal of water contaminants. An comprehensive review on the issue has been published by Shukla et al. covering most of its technical and scientific aspects. Further, the addition of magnetic particles in composite make an advantageous feature for efficient purification of water. Chitosan-based magnetic composites show improved adsorption rate and better adsorption efficiency for removal of various pollutants. Their recovery process is also very simple and easy. Shi et al. prepared magnetic chitosan nanocomposites on the basis of amine-functionalized magnetite nanoparticles. These nanocomposites were used to remove heavy metal ions. The interaction between chitosan and heavy metal ions are reversible, which means that those ions can be removed from chitosan in weak acidic deionized water with the assistance of ultrasound radiation. On the basis of the above referred reason, synthesized magnetic chitosan nanocomposites were used as a useful recyclable tool for heavy metal ions removal.

The inorganic particles immobilized membranes were found to remove toxic contaminants from water. Titania poly

### Table 4 Different types of metallic pollutant and suitable adsorbents

| S. No | Radioactive pollutants | Adsorbent | References |
|-------|------------------------|-----------|------------|
| 1     | Uranium                | Chitin/chitosan complex | 77          |
| 2     | Thorium (IV)           | Polymethacrylic acid-grafted chitosan/bentonite composite | 78          |
| 3     | Am (III) and Cr (III)  | 2,6-bistriziny/pyridine | 79          |
| 4     | Thorium (IV)           | Polyvinyl alcohol/titanium oxide | 80          |
| 5     | Uranium                | PVA/TEOS/APTES hybrid nanofiber | 81          |
| 6     | Sr, Cd                 | Nafion 120, Polycrylicamide-bentonite composite | 82          |
| 7     | UO\(_2\)^{2+}, Ti\(^{4+}\), Pb\(^{2+}\), Ra\(^{2+}\), and Ac\(^{3+}\) | PAN/zeolite | 83          |
| 8     | Thorium                | PAN/peptide complex | 84          |
| 9     | Thorium (IV)           | Poly(methacrylic acid-grafted chitosan/bentonite | 85          |
| 10    | Cesium, cobalt, and Europium ions | TiO\(_2\)/Poly(acrylamide–styrene sodium sulfonate) | 86          |

**Figure 9** Adsorption isotherm for different heavy metal ions on PNC

**Removal of heavy metal ions**

Most of the surface and ground water are contaminated with many heavy and radioactive metals due to anthropogenic sources or geological reasons. These metal ions are accumulated in the biosphere and edible items. They also enter the human body through food chain and are also responsible for their biomagnification. Different toxic heavy metal ions and nanocomposites used as adsorbents are listed in Table 4.

Lim et al. has reviewed the development of economically suitable adsorbents for heavy metals removal from water and wastewater. The different techniques used for metal removal are adsorption, chemical, precipitation, coagulation, flocculation, ion exchange, and membrane filtration. The requirement for these methods is suitable adsorbing materials with flexibility in design and operation to generate high-quality treated effluent. For the reversible nature of adsorption process, the adsorbents should be regenerated for multiple use through suitable desorption method at low maintenance cost, high efficiency, and ease of operation. The interaction between the adsorbent and adsorbate molecules are both physical and chemical.
(ethersulfone) composite membranes showed higher fluxes and enhanced antifouling properties. Other nanocomposite structures like lyotropic liquid crystals exhibited high flux and selective water transportation. For example, zeolite-polyamide based composite membranes offered new ways of designing nano filtration and reverse osmosis membranes with increased water permeability and high salt rejection. Super magnetic sodium alginate supported tetrasodium thiacalixarene tetrasulfonate (TSTC[4]AS-s-SA) nanogel was prepared using sodium alginate nanoparticles and in situ generation of Fe₃O₄. The nanogel was found suitable for adsorptions of Cu(II), Cd(II), Pb(II), Co(II), Ni(II), and Cr(III) ions from aqueous solution at pH 7. The increase in adsorption capacity is due to incorporation of thiacalix[4]arene tetrasulfonate and Fe₃O₄ into sodium alginate nanoparticles and led to the magnetic property. The nanofibers is an important nanostructure due to high specific surface area, uniaxial crystallinity, porosity and complex pore structures. The geometry, morphology, composition, and directional alignment of nanofibers can be easily maneuvered for specific applications. The nano-fiber based mat are reported to be suitable for nano filtration and adsorption with many advantageous features.

Other important metallic pollutants are radioactive waste (RW), which are discharged in huge amount during operations of nuclear plants and reprocessing of nuclear fuel from nuclear plants. The major constituents of RW are cesium, neptunium, americium, titanium, and curium. Cesium radionuclides stand as the most important fission products because of their high fission yield, long half-life, and serious environmental impacts. The contamination caused by cesium is of serious social and environmental concerns. It causes severe risk to human health and environment, because Cs is a strong gamma emitter. Gamma radiation has high solubility and migration properties through groundwater to the biosphere. In this concern, the processing of nuclear waste is important for industrial development and environmental problems. In this regard, solid phase extraction based on polymer nanocomposite ion exchangers has attracted wide interest due to their high selectivity, rapid separation, and high thermal and radiation stabilities. It is reported that magnetic nanocomposite structures are useful for adsorbing different radioactive metal ions. Some polymer nanocomposites used for removal of radioactive metals are potassium zinc hexacyanoferrate loaded polymer nanocomposite for Cs⁺, ammonium molybdenophosphate–polyacrylonitrile (AMP–PAN) for removal of Co(III), Sr(II), and Cs(III). The adsorption takes place due to both physical adsorption, ion exchange and has influence of competitive adsorption and presence of alkali metals. Ma et al. has developed cellulose nano fiber through oxidation of wood pulp employing (2,2,6,6-tetramethylpiperidin-1-yl)oxyl (TEMPO)/NaBr/NaClO process followed by mechanical treatment. The presence of carboxylate groups on the surface of cellulose nanofibers bears negative charges, which is able to adsorb UO₂⁺ in water with adsorption capacity 167 mg/g at least two times better than an adsorbent without carboxyl group.

### Removal of dyes

The tunable surface and catalytic properties of PNCs also find huge potential to remove dyes, one of severe pollutants. Exponential discharge of dyes in water bodies, are creating alarming water problem and water born diseases. Most of the dyes have detrimental effects on atmosphere and aquatic living organism and cause allergy, dermatitis, skin irritation as well as mutations in humans. Various techniques such as adsorption, coagulation, filtration, photo, catalytic and biochemical degradation have been developed for removal of dyes. In this regards, polymer nanocomposites are used by many researchers for efficient removal of dyes. Some important polymer nanocomposites as dye adsorbents are listed in Table 5.

### Table 5 Different types of adsorbents suitable for dyes removal

| Adsorbents                  | Dyes                             | pH | Adsorption model | Kinetic model | Adsorption capacity (mg/gm) | References |
|-----------------------------|----------------------------------|----|------------------|---------------|----------------------------|------------|
| γ-Fe₂O₃/CSCs               | Methyl violet                     | 1.6| Exothermic       | PSEO          | 200 mg dm⁻³                 | 124        |
| L-CAg/Fe₂O₃               | Remazol Red 198                  | 5.0| Exothermic       | PSEO          | 18.2 mg g⁻¹                 | 126        |
| γ-Fe₂O₃/SiO₂/chitosan composite | Basic violet 10                  |    |                  |               | 66.90                       | 125        |
| CNTs/activated carbon fiber | Direct red 28 (Congo red)         |    |                  |               | 18.2 mg g⁻¹                 | 126        |
| Chitosan/Fe₂O₃/MW-CNTs     | Basic blue                       |    |                  |               | 200 mg dm⁻³                 | 127        |
| Banana peel                | Methylene Blue                   |    |                  |               | 378.8 mg g⁻¹                | 128        |
| Bagasse pith               |                                  |    |                  |               |                            |            |
| Hydrolyzed NanoSilica      |                                  |    |                  |               |                            |            |
| incorporated               |                                  |    |                  |               |                            |            |
| Polycrylamide Grafted Xanthan Gum | Methyl Violet |    |                  |               | 908.0 mg/g                 | 129        |
| Methyl Violet onto         | Lagergren Model                  |    |                  |               |                            |            |
| Poly(acrylic acid-co-acrylamide)/Kaolin Hydrogel | Methyl Violet |    |                  |               |                            |            |

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the adsorption process take place into three steps: (a) external mass transfer of impurities across the liquid boundary to exterior surface of the adsorbent surface, this can also be called film diffusion or boundary layer diffusion or outer diffusion (b) transfer of adsorbate from the adsorbent exterior surface to the bulk matrix (pores or capillaries of the adsorbent) or internal structure, which is referred as intra-particle diffusion or inner diffusion (c) the adsorption of adsorbate on top of the active sites in the inner and outer surfaces of the adsorbent. The last step is considered to be very fast, and thus cannot be treated as a rate-limiting step.

The basic requirement of a good adsorbent is porous structure and high surface area. The polymer nanocomposites are suitable for dye removal due to synergism between two compounds with large surface area, high adsorption capacity, suitable pore size, high mechanical strength, easy regeneration, biocompatibility, cost effectiveness, and high selectivity. Some polymeric resins suitable for adsorbents through ion exchange mechanism are sulfonated polystyrene, sulfonated phenolic resin, phenolic resin, polystyrene phosphonate, polystyrene amidoxime, polystyrene-based trimethyl benzyl ammonium, epoxy-polyamine, and aminopolystyrene. These ion exchange resins have efficient dye removal capacity. However, bio-compatibility is an persisting problem during its application. Therefore, a wide spectrum biopolymer-based nanocomposites are explored for dye removal. Chitosan, Alginate, starch based-nanocomposites have been widely used for the removal of different dyes. Particularly chitosan is a polysaccharide-based multifunctional biopolymer with primary and secondary hydroxyl groups, along with reactive amino groups. This makes it useful starting support materials for adsorption purpose. However, its chemical stability need to be optimized. Graphene oxide (GO)-based polymer nanocomposites were fabricated in aq. solution through a hybrid novel strategy. These GO-based polymer nanocomposites were reported efficient absorbents for the removal of organic dyes from the aqueous solution. Furthermore, optimal adsorption time of GO-PDA-PSPSH nanocomposites toward MB was 58 min along with maximum adsorption efficiency at pH 7. Similarly, starch-montmorillonite/polyaniline (St-MMT/PANI) nanocomposite was synthesized by chemical oxidative polymerization of aniline in the presence of starch-montmorillonite. The prepared ternary nanocomposite (St-MMT/PANI) was used for the adsorption of a reactive dye. Results
Some metals like silver, copper, zinc, iron, lead, aluminum, and gold have proved to be an efficient disinfectant. However, some of them are toxic for human, thus the non-toxic metals for mammalian cells are used. The advent of nanotechnology made nanocomposite a potential water decontaminator and replacement to current chemical disinfectants. The metal bound copolymer beads are used efficiently for removing wide spectrum of bacterial strains up to 99.9%. The microscopic structure of Ag coated polyurathane foam used for water purification is shown in Figure 10.

Cellulose acetate fibers embedded with Ag nanoparticles were found to be effective against bacteria. The water filters manufactured by polyurethane's foam coated with Ag nanoparticles have efficient disinfectant properties against bacteria like *Escherichia coli* (*E. coli*). The examples of other materials to prepare low-cost potable water microfilters by incorporating Ag nanoparticles are reported to be used in remote areas in developing countries. The results have indicated that disinfection efficiency of Ag embedded polymer filler decreased over a period of time. The different composites with carbon nano structures such as carbon nanotubes (CNTs), activated carbon fibers (ACFs) are also able to remove pathogenic microorganisms adequately. However, efficiency of DNA molecule of the cell. Some metals like silver, copper, zinc, iron, lead, aluminum, and gold have proved to be an efficient disinfectant. However, some of them are toxic for human, thus the non-toxic metals for mammalian cells are used. The advent of nanotechnology made nanocomposite a potential water decontaminator and replacement to current chemical disinfectants. The metal bound copolymer beads are used efficiently for removing wide spectrum of bacterial strains up to 99.9%. The microscopic structure of Ag coated polyurethane foam used for water purification is shown in Figure 10.

### Removal of other pollutants

The other important water pollutants are microorganism, pesticides, pathogens, and other organic materials. The risks associated with them include the formation of disinfection by-products and multidrug resistant bacterial species and have prompted the exploration of advanced disinfection methods. The nano structured composite kills pathogens by liberating toxic chemicals, conciliating cell membrane integrity on direct contact. In some cases, they also produces reactive oxygen species (ROS). The bactericidal effect of metals are known since ancient times, but advancements in nanotechnology have improved the efficiency and enabled its use as a viable disinfectant. However, the use of metal particles as disinfectant also poses serious health problems. Although, disinfection mechanism is also not completely known but it is proposed that metal atom interacts with base pairs of DNA and disrupts the hydrogen bonding. Thus, it denatures the DNA molecule of the cell.
these composite need to be improved. Gunawan et al.\textsuperscript{161} have investigated the immobilization of AgNP/CNTs coated on the surface of a polyacrylonitrile (PAN) hollow fiber membrane for water purification (Figure 11).

PAN alone and AgNP/CNT/PAN membranes have been used for filtration of \textit{E. Coli} contaminated water. In the continuous filtration mode for \textit{E. coli} feedwater, the relative flux drop over Ag/MWNTs/PAN was 6\%, while over the pristine PAN it was 55\% at 20 h of filtration. The results revealed that AgNP/CNT coating has significantly enhanced antimicrobial activity, as well as antifouling properties of the membranes. The microorganism removal capacity in wastewater filter systems depends on many factors.\textsuperscript{162} These factors are biotic and abiotic in nature like moisture, pH, temperature, species of microorganism. In the context of improving the processes for water treatment containing organic and inorganic solutes, dendrite polymers are used as water-soluble ligands for purification purposes.\textsuperscript{163,164}

The use of nanofibers and composite nanostructure membranes can help in degrading a wide spectrum of organic and inorganic contaminants in real field applications as shown in Figure 12.

The better understanding of the formation of nanocomposite membranes will certainly be a step toward improving the performance of multifunctional nanocomposite membranes. The pattern of nanoparticles within the host matrices of membranes and change in the structures and properties of both nanomaterials and host matrices could be among the

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### Table 6 Different types of sensor based on PNC

| Sensing limit | Sensing materials | Sensed species | Sensing methods | Reference |
|---------------|-------------------|----------------|----------------|---------|
| 0.02 (mg/l)   | Aluminum–morin probe in a PVC membrane | Phosphate | Luminescent | 166      |
| 1 mg/l        | Organotin ionophore, PVC membrane | Phosphate | Potentiometric ion selective electrodes | 167      |
|               | Functionalized superparamagnetic iron oxide PAN/graphene chitosan-carbon nanotubes (Chit-CNT) nanocomposites | Bacteria | MRS sensors | 168      |
|               |                  | Hydrazine |                | 169      |
|               |                  | Organic compound | Electrical | 170      |
| 1.95 × 10^{-3} mol L^{-1} | | trinitrotoluene (TNT) and dinitrotoluene (DNT) | QCM | 171      |
| 0.256, 0.440 and 0.796 ppb respectively | nano-composite carbon paste electrode pyrrole and chitosan composite polypyrrole/cellulose (PPCL) composite screen printed electrodes (SPE) | Cd^{2+}, Pb^{2+}, and Hg^{2+} | Potentiometric | 172      |
| 11.6 nM       | | Hg(ll), Ag(ll), and Cr(lll). | Electrical | 173      |
| 8.1 nM(HQ) and 26 nM(CC) | GO with the DNAzyme Graphene nanosheet–poly(4-vinyl pyridine) composite polyaniline-polyvinyl sulfonic acid composite | Pb^{2+}, hydroquinone (HQ) and catechol (CC) | Optical | 174      |
| 1 × 10^{-3} mM | par-amino phenol | Electrochemical | 175      |
| 1.7 × 10^{-6} mol/L | graphene oxide/\_\_\_ cyclodextrin/Au nanoparticles composites | chrysoidine | Electrical | 176      |
| 1 mM          | Chitosan gold nanocomposite | lead nitrate | Electrical | 177      |
Quality monitoring or aquodiagnosis

Water contains significant concentrations of solids, dissolved and particulate matter, microorganisms, nutrients, heavy metals, and micro-pollutants. The monitoring of pollution levels in water bodies like rivers, lakes, and coastal waters are also very important with the requirement to achieve good ecological and chemical status. Furthermore, constant examination of water pollutants and the ability to estimate the impact of effluent discharges in real-time, would preserve the high quality of water bodies and provide the most reliable and economical environmental protection. Thus, it is a current demand for accurate and reliable quality monitoring of pollutants concentration to allow real-time monitoring of water quality. Attempts have been made to develop different PNCs based electrochemical, photochemical devices for water testing. Some important devices are summarized in Table 6.
concentration (ppb) of Hg²⁺ in aqueous solution by monitoring the decrease in intensity (Figure 13).

The quantitative presence of dibutyl phthalate (DBP) in tap water samples was monitored by fluorescence of molecularly imprinted polymer nanocomposites (SiO₂@QDs@MIPs). In optimized conditions, fluorescence intensity decreased linearly with increasing concentration of DBP in the range of 5–50 mmol L⁻¹, with a correlation coefficient of 0.9974. The PNC has also been used for detection of different explosives with encouraging parameters. Patil et al. has developed a piezoresistive ultra-sensitive polymer nanocomposite for explosive vapor detection. The sensor promises to be used as a rugged portable, hand held device for rapid and sensitive detection of explosive vapors at different places.

**Equilibrium studies**

**Adsorption isotherm models**

An adsorption isotherm is an equation relating equilibrium concentration of a solute on the surface of an adsorbent to the concentration of the solute in the liquid, with which it is in contact at a particular temperature and represented graphically. There are several models for predicting the equilibrium distribution. However, some widely accepted models are Langmuir, Freundlich, Dubinin–Radushkevich, Temkin, Flory–Huggins, Redlich–Peterson, Sips, Khan, BET, FHH, Halse, etc.

**Kinetic equations**

The kinetic studies for water purifications are of utmost importance for speculating the most favorable conditions to perform efficient adsorption of pollutants. The kinetics describe the solute uptake rate, which directly controls residence time of sorbate uptake at the solid–solution interface. The study also provides information about adsorption mechanisms.
and probable rate optimizing steps like mass transport, ionization, and chemical interactions. Several efforts have been made to formulate a general relation to describe the kinetics of pollutant adsorption on the surface of a solid adsorbent for liquid–solid phase sorption systems. The sorption kinetics can be both simple and complex. Number of kinetic models have been proposed in the literature.\textsuperscript{195–205}

**Thermodynamic parameters**

The thermodynamic parameters are required to understand the effect of temperature on the adsorption behavior of a pollutant on an adsorbent.\textsuperscript{206} Some thermodynamic parameters related to adsorption process are changes in standard free energy ($\Delta G^0$), enthalpy ($\Delta H^0$), and entropy ($\Delta S^0$). These parameter can be obtained from experimental observation carried out at various temperatures.\textsuperscript{207} It is reported that negative value of $\Delta G^0$ indicate spontaneity of adsorption and a positive $\Delta H^0$ value show that the process of adsorption is endothermic, however, a positive $\Delta S^0$ value show that randomness is enhanced at solid/liquid interface.\textsuperscript{208}

**Future prospects**

The long-term development of the global water situation is closely connected to the growth of the world population and global climate change. The demand for fresh water is growing dramatically. In recent years, the use of nanomaterials in water remediation has increased considerably. The nanomaterials have unique size-dependent properties and allow the development of novel high-tech materials for efficient water and wastewater treatment processes, namely membranes, adsorption materials, nanocatalysts, functionalized surfaces, coatings, and reagents. Because of agglomeration and instability, nanocomposites particularly polymer nanocomposites are now being preferred over nanomaterials. The potential of nanocomposites in various sectors of research and application is promising and attracting increasing investment from Governments and business in many parts of the world. While there are some niche applications where nanotechnology has penetrated the market, the major impact will be at least a decade away. There are certain magnetic polymer nanocomposites which have special features. Biodegradable polymer-based nanocomposites have a great deal of future promise for potential applications as high-performance biodegradable materials. These are entirely new type of materials based on plant and nature materials (organoclay). Inspite of lot of advantages of polymer nanocomposites in water remediation, there are still several drawbacks that have to be negotiated. Materials functionalized with nanoparticles incorporated or deposited on their surface have risk potential, since nanoparticles might release and emit to the environment where they can accumulate for long periods of time. Available information in the literature has revealed that several nanomaterials may have adverse effects on the environment and human health. Nevertheless, standards for assessing the toxicity of nanomaterials are relatively insufficient at present. Hence, comprehensive evaluation of the toxicity of nanomaterials is in urgent need to ensure their real applications. In order to make polymer nanocomposites an efficient and cost effective for water remediation, lot of work is to be done particularly interaction between polymer nanocomposites and the targeted pollutants or the substrates, choice of nanomaterials and polymers, optimizing conditions for water purification and toxic effect on human health and environment. Although these ideas can pave a way toward a sustainable tomorrow, in reality detailed technical study is required to bridge the gap between laboratory-scale and industrial applications.

**Conclusions**

This review provides up to date account of recent developments in the field of polymer nanocomposites used for water treatment. Methods for the preparation, characterization and properties of polymer nanocomposites have been reviewed. Efficiency of decontamination of metal ions, dyes, and microbes from water by nanocomposites, their regeneration possibility and cost effectiveness have made the nanocomposites as one of the most important material. Adsorption, kinetic, and thermodynamic models for removal of pollutants by adsorption have also been referred. Comparatively little information is available on the use of nanocomposite for removal of protozoa and radionucleides removal techniques. Despite various applications and advantages of polymer nanocomposites in water remediation several issues related to their use still remain to be addressed.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**References**

1. M. A. Shannon, P. W. Bohn, M. Elimelech, J. G. Georgiadis, B. J. Mariñas and A. M. Mayes: ‘Science and technology for water purification in the coming decades,’ Nature, 2008, 452, 301–310.
2. X. Qu, P. J. Alvarez and Q. Li: ‘Applications of nanotechnology in water and wastewater treatment,’ Water Res., 2013, 47, 3931–3946.
3. The United Nations World Water Development Reports: ‘Water for sustainable world,’ 2015, United Nations Educational, Scientific and Cultural Organization, ISBN 978-92-3-100071-3.2. place de Fontenoy, 75352 Paris 07 SP, France.
4. Application of Nanotechnology in Water Research, (ed. A. K. Mishra), Scrivener Publishing, Wiley-Scrivener, 2014, ISBN: 978-1-118-49630-5.
5. P. Malaviya and A. Singh: ‘Physicochemical technologies for remediation of chromium-containing waters and wastewaters,’ Crit. Rev. Environ. Sci. Technol., 2011, 41, 1111–1172.
6. A. Bhatnagar and M. Sillanpää: ‘Applications of chitin- and chitosan-derivatives for the detoxification of water and wastewater — A short review,’ Adv. Colloid Interface Sci., 2009, 152, 26–38.
7. S. Daer, J. Kharraz, A. Giwa and S. W. Hasan: ‘Recent applications of nanomaterials in water desalination: A critical review and future opportunities,’ Desalination, 2015, 367, 37–48.
8. P. Z. Ray and H. J. Shipley: ‘Inorganic nano-adsorbents for the removal of heavy metals and arsenic: a review,’ RSC Adv., 2015, 5, 29865–29907.
9. T. E Twardowski: ‘Introduction to nanocomposite materials: properties, processing, characterization,’ 2007, DEStech Publications. Pennsylvania 17601 USA.
10. J. Jordan, K. I. Jacob, R. Tannenbaum, M. A. Sharaf and I. Jasiuk: ‘Experimental trends in polymer nanocomposites – a review,’ Mater. Sci. Eng. A, 2005, 393, 1–11.
11. G. Lofrano, M. Carotenuto, G. Libralato, R. F. Domingos, A. Markus, L. Dini, R. K. Gautam, D. Baldantoni, M. Rossi, S. K. Sharma, M. C. Chattopadhyaya, M. Giugni and S. Meric: ‘Polymer functionalized nanocomposites for metals removal from water and wastewater: An overview,’ Water Res., 2016, 92, 22–37.
12. Z. Fu, C. He, H. Li, C. Yan, L. Chen, J. Huang and Y.-N. Liu: 'A novel hydrophilic hydrophobic magnetic interpenetrating polymer networks (IPNs) and its adsorption towards salicylic acid from aqueous solution', Chem. Eng. J., 2015, 279, 250–257.
13. R. Surudži, A. Janković, N. Bibić, M. Vukasinović-Sekulić, A. Perić-Gruijić, V. Miljković-Stanković, S. J. Park and K. Y. Rheem: 'Physico–chemical and mechanical properties and antibacterial activity of silver/poly(vinyl alcohol)/graphene nanocomposites obtained by electrochemical method', Compos. Part B, 2015, 86, 102–112.
14. F. Sun, M. Lin, Z. Dong, J. Zhang, C. Wang, S. Wang and F. Song: 'Nanosilica-induced high mechanical strength of nanocomposite hydrogel for killing fluids', Colloid Interface Sci., 2015, 458, 45–52.
15. H. A. Shaker, S. Chakravorty, S. Lin and M. R. Wiesner: 'Synthesis and characterization of a carbon nanotube/polymer nanocomposite membrane for water treatment', Desalination, 2011, 272, 46–50.
16. M. Rahmat and F. Hubert: 'Carbon nanotube–polymer interactions in nanocomposites: A review', Compos. Sci. Technol., 2011, 71, (1), 71–84.
17. B. Arash, H. S. Park and T. Rabczuk: 'Mechanical properties of carbon nanotube reinforced polymer nanocomposites: A coarse-grained model', Compos. Part B, 2015, 80, 92–100.
18. F. Hussain, M. Hojati, M. Okamoto and R. E. Gora: 'Review article: Polymer-matrix nanocomposites, processing, manufacturing, and application: An overview', J. Compos. Mater., 2006, 40, 1511–1575.
19. S. K. Shukla, S. K. Shukla, P. P. Govender and E. S. Agorku: 'A resistive type humidity sensor based on crystalline tin oxide nanoparticles encapsulated in polyaniline matrix', Microchem. Acta, 2016, 183, (2), 573–580.
20. H. Dong, Y. R. Sloborz, J. F. Snyder, J. Steele, T. L. Chantawansiri, J. A. Orlicki, S. D. Walck, R. S. Reiner and A. W. Rudie: 'Highly Transparent and Toughened Poly(methyl methacrylate) nanocomposite films containing networks of cellulose nanofibrils', ACS Appl. Mater. Interfaces, 2015, 7, (45), 25464–25472.
21. G. David, M. Drobona and B. C. Simionescu: 'Preparation approach effect on polyurethane/montmorillonite nanocomposites characteristics', High Perform. Polym., 2015, 27, 555–562.
22. C. Li, H. Bai and G. Shi: 'Conducting polymer nanomaterials: electrochemistry and applications', Chem. Soc. Rev., 2009, 38, 2397–2409.
23. S. K. Shukla, N. B. Singh and R. P. Rastogi: 'Efficient ammonia sensing over zinc oxide/polypyrrole nanocomposite', Ind. J. Eng. Mater. Sci., 2013, 20, 319–324.
24. L. Li, H. Duan, X. Wang and C. Wang: 'Fabrication of novel magnetic nanocomposite with a number of adsorption sites for the removal of dye', Int. J. Biol. Macromol., 2015, 78, 17–22.
25. M. Cantarella, R. Sanz, M. A. Buccheri, L. Romano and V. Privitera: 'PMMA/TiO2 nanotubes composites for photocatalytic removal of organic compounds and bacteria from water', Mater. Sci. Semicond. Process., 2016, 42, 58–61.
26. P. Meneghetti and S. Quirabuddin: 'Synthesis, thermal properties and applications of polymer-clay nanocomposites', Thermochim. Acta, 2006, 442, 74–77.
27. A. Cobut, H. Sehaqui and L. A. Berglund: 'Cellulose nanocomposites by melt compounding of TEMPO-treated wood fibers in thermoplastic starch matrix', Bio. Res., 2014, 9, (2), 3276–3289.
28. Y. Wan, C. Wu, G. Xiong, G. Zuo, J. Jin, K. Ren, Y. Zhu, Z. Wang and H. Lu: 'Enhancing the properties and cytotoxicity of nanolite-like hydroxyapatite/poly(lactide) nanocomposites prepared by intercalation technique', J. Mech. Behav. Biomed. Mater., 2015, 47, 29–37.
29. S. N. Magonov and D. H. Reneker: 'Characterization of polymer solutions with atomic force microscopy', Annu. Rev. Mater. Sci., 1997, 27, 175–222.
30. S. L. Kim, F. Fornasiero, G. Xiong, G. Pellegrino, A. Grino, M. V. Brundo, V. Privitera and G. Impellizzeri: 'Novel synthesis of ZnO/PMMA nanocomposites for photocatalytic applications', Sci. Rep., 2017, 7, 40895.
31. E. Brillais and C. A. Martinez-Huitl: 'Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods. An updated review', Appl. Catal. B Environ., 2015, 166–167, 603–643.
32. C. Han, J. Lalley, N. Devi, K. Cromer and N. N. Mallikarjuna: 'Titanium dioxide-based antibacterial surfaces for water treatment', Curr. Opin. Chem. Eng., 2016, 11, 46–51.
33. M. U. Sankar, S. Aigal, S. Malayekkal, A. Chaudhury, A. Anshup, A. Kumar, K. Chaudhuri and T. Pradeep: 'Biopolymer-reinforced synthetic granular nanocomposites for affordable point-of-use water purification', PNAS, 2013, 110, 8459–8464.
34. J. S. Zhang, X. F. Chen, K. Takehara, K. Maeda, K. Domen, J. D. Epping, X. Z. Fu, M. Antonietti and X. C. Wang: 'Synthesis of a carbon nitride structure for visible-light catalysis by copolymerization', Chem. Int. Ed., 2010, 49, 441–444.
35. Y. Cui, Z. Ding, P. Liu, M. Antonietti, X. Fu and X. Wang: 'Metal-free activation of H2O2 by g-C3N4 under visible light irradiation for the degradation of organic pollutants', Phys. Chem. Chem. Phys., 2012, 14, 1455–1462.
36. Y. L. Tian, B. B. Chang, J. L. Lu, J. Fu, F. N. Xi and X. P. Dong: 'Hydrothermal synthesis of graphitic carbon nitride–Bi2O3 heterojunctions with enhanced visible light photocatalytic activity', ACS Appl. Mater. Interfaces, 2013, 5, 7079–7085.
37. R. Hao, G. Wang, H. Tang, L. Sun, C. Xu and D. Han: 'Template-free preparation of macro/mesoporous g-C3N4/TiO2 heterojunction photocatalysts with enhanced visible light photocatalytic activity', Appl. Catal. B Environ., 2016, 187, 47–58.
38. X. J. Wang, Q. Wang, F. T. Li, W. Y. Yang, Y. Zhao, Y. J. Hao and S. J. Liu: 'Novel BiOCl–C3N4 heterojunction photocatalysts: In situ preparation via an ion-liquid assisted solventthermal route and their visible-light photocatalytic activities', Chem. Eng. J., 2013, 234, 361–371.
39. X. N. Yi, J. F. Cao, L. Q. Jiang, Y. H. Zhang and Z. G. Yi: 'g-C3N4/BiVO4 composites with enhanced and stable visible light photocatalytic activity', J. Alloy. Compd., 2014, 590, 9–14.
40. Y. L. Tian, F. Chong, X. Zhang, F. Yan, B. C. Zhou, Z. Chen, J. Y. Liu, F. N. Xi and X. P. Dong: 'Solvothermal synthesis and enhanced visible light photocatalytic activity of novel graphitic carbon nitride–Bi2O3 heterojunction photocatalysts: In situ preparation via an ion-liquid-assisted solventthermal route and their visible-light photocatalytic activities', Chem. Eng. J., 2015, 234, 90–100.
41. S. C. Xing, Z. D. Wu, D. L. Jiang and M. Chen: 'Hydrothermal synthesis of In5S3/g-C3N4 heterojunctions with enhanced photocatalytic activity', J. Colloid Interface Sci., 2014, 433, 9–15.
42. Y. L. Tian, B. B. Chang, J. F. Chen, J. Fu, F. N. Xi and X. P. Dong: 'Graphitic carbon nitride/Cu2O heterojunctions: Preparation, characterization, and enhanced photocatalytic activity under visible light', J. Solid State Chem., 2014, 212, 1–6.
43. X. Chen, P. F. Tan, B. H. Zhou, H. G. Dong, J. Pan and X. Xiong: 'A green and facile strategy for preparation of novel and stable Cr-doped SrTiO3/g-C3N4 hybrid nanocomposites with enhanced visible light photocatalytic activity', J. Alloy. Compd., 2015, 647, 456–462.
56. L. A. Gu, I. Y. Wang, Z. J. Zou and X. J. Han: ‘Graphitic-CN3-hybridized TiO2 nanosheets with reactive [001] facets to enhance the UV- and visible-light photocatalytic activity’, J. Hazard. Mater., 2014, 268, 216–223.

57. S. J. Makireddi, S. Shivprasad, V. Francis, G. Varghese and R. A. Damodar, S. J. You and H. H. Chou: ‘Study the self cleaning, P. Khare, A. Yadav, J. Ramkumar and N. Verma: ‘Microchannel-

58. T. Sreenivasan, R. Sreenivasan and A. R. Tharunl: ‘Adsorptive removal T. Sreenivasan, R. Sreenivasan and A. R. Tharunl: ‘Adsorptive removal of Cs + and Sr 2+ from aqueous solutions: Kinetic, equilibrium, and thermodynamic studies’, Chem. Eng. J., 2007, 256, 44–54.

59. P. K. Chakraborty, A. Das, S. M. Bagchi and N. Guha: ‘Nanosilica-induced high mechanical strength of nanocomposite nanotube reinforced polymer nanocomposites: A coarse-grained model’, Compos. Part B, 2011, 42, 35–56.

60. A. H. El-Ali, A. S. El-Mekawshi, A. M. El-Wahabi and A. A. Hassanein: ‘Nanosilica-induced high mechanical strength of nanocomposite nanotube reinforced polymer nanocomposites: A coarse-grained model’, Compos. Part B, 2011, 42, 35–56.

61. A. Maji and S. K. Maji: ‘Study of the behaviour of thorium adsorption on PAN/zelite composite adsorbent’, J. Hazard. Mater., 2007, 147, 357–362.

62. B. Baybâr and U. Uluosy: ‘The use of polyacrylamide-alumino silicate composites for thorium adsorption’, Appl. Clay. Sci., 2011, 51, 138–146.

63. E. H. Borer, M. M. E. Breky, M. S. Sayer and M. M. Abo-Nly: ‘Synthesis, characterization and application of titanium oxide nanocomposites for removal of radioactive cesium, cobalt and europium ions’, J. Colloid Interface Sci., 2013, 450, 17–25.

64. A. F. Lu and A. Z. Arts: ‘A review on economically adsorbents on heavy metals removal in water and wastewater’, Rev. Environ. Sci. Biotechnol., 2014, 13, 163–181.

65. S. Dhital, K. M. Bhatia, G. C. K. S. Babu and S. Sinha: ‘An application of low-cost adsorbents for arsenic removal: A review’, J. Environ. Eng. Geotech. Environ., 2012, 4, (5), 91–102.

66. B. H. Chau, B. C. Poly and W. R. Lee: ‘A review on carbon nanotubes and graphene as fillers in reinforced polymer nanocomposites’, J. Ind. Eng. Chem., 2015, 21, 31–45.

67. F. A. K. Kaygun and S. A. Akyel: ‘Study of the behaviour of thorium adsorption on PAN/zelite composite adsorbent’, J. Hazard. Mater., 2007, 147, 357–362.

68. G. J. L. Almeida, M. I. R. H. Chou and A. K. Sengupta: ‘Hybrid anion exchanger from water under dynamic conditions’, Chem. Eng. J., 2016, 293, 44–54.

69. H. Mittal, A. Malty and S. S. Ray: ‘Synthesis of co-polymer-grafted gum karaya and silica hybrid organic–inorganic hydrogel nanocomposite for the highly effective removal of methylene blue’, Chem. Eng. J., 2015, 279, 166–175.

70. H. Baghshian, M. Iravani, M. Moayed and M. Ghaandeh-Maragheh: ‘Preparation of a novel PAN–zeolite nanocomposite for removal of Cs’ and Sr’ from aqueous solutions: Kinetic, equilibrium, and thermodynamic studies’, Chem. Eng. J., 2013, 222, 41–48.

71. R. C. Pan, Q. R. Zhang, W. M. Zhang, B. J. Pan, W. Du, L. Lv, Q. J. Zhang, Z. W. Xu and X. Q. Zhang: ‘Highly effective removal of heavy metals by polymer-based zirconium phosphate: A case study of lead ion’, J. Colloid Interface Sci., 2007, 310, 99–105.

72. B. Arash, Q. Wang and V. Varadan: ‘Mechanical properties of carbon nanotube/polymer composites’, Sci. Rep., 2014, 4, 6479.

73. Z. Sui, Q. Meng, X. Zhang, R. Ma and B. Cao: ‘Green synthesis of carbon nanotube–graphene hybrid aerogels and their use as versatile agents for water purification’, J. Mater. Chem., 2012, 22, 8767–8771.

74. G. Mittal, V. Dhand, K. Y. Rhee, S.-J. Park and W. R. Lee: ‘A review on carbon nanotubes and graphene as fillers in reinforced polymer nanocomposites’, J. Ind. Eng. Chem., 2015, 21, 11–25.

75. S. Makrededi, S. Shivprasad, V. Francis, G. Varghese and K. Balasubramanium: ‘Electro–elastic properties of MWNT/PMMA nanocomposite thin films’, J. Mater. Chem. Sci. Eng., 2015, 2, 24–28.

76. S. B. Patil, S. D. Patil and P. A. Patil: ‘Electro–elastic properties of MWNT/PMMA nanocomposite thin films’, J. Mater. Chem. Sci. Eng., 2015, 2, 24–28.

77. J. Shi, H. Li, H. Lu and X. Zhao: ‘Use of carboxyl functional magnetite nanoparticles as potential sorbents for the removal of heavy metal ions from aqueous solutions’, Sci. Rep., 2014, 4, 6479.
| Author(s) | Title                                                                 | Journal                                                                 | Year | Pages |
|----------|----------------------------------------------------------------------|------------------------------------------------------------------------|------|-------|
| B.-H. Jeong, E. M. V. Hoek, Y. Yan, A. Subramani, X. Huang, G. Hurwitz, A. K. Ghosh and A. Jawor | Interfacial polymerization of thin film nanocomposites: A new concept for reverse osmosis membranes | J. Membr. Sci. | 2007 | 288, 231–238 |
| G. Y. Zhu, R. Jiang, L. Xiao and G. M. Zeng | Preparation, characterization, adsorption kinetics and thermodynamics of novel magnetic chitosan enwrapping nanosized γ-Fe2O3 and multi-walled carbon nanotubes with enhanced adsorption properties for methyl orange | Biotechnol. | 2010 | 101, 5063–5069 |
| A. Lopes and S. Martins | Degradation of a textile dye C. I. Direct red 80 by electrochemical processes | Portugaliae Electrochim Acta | 2004, 22, 279–294 |
| H. Mahmoodian, O. Moradi, B. Shariatzadeh, A. Rad, M. Zrinji, Y. Osada, Z. Ma and Y. M. Chen | Fe₃O₄ anisotropic nanostructures in hydrogels: efficient catalysts for the rapid removal of organic dyes from wastewater | J. Phys. Chem. B | 2017, 111, 1999–2007 |
| J. R. Smith, K. L. Li and X. H. Wang | Adsorptive removal of Pb(II) by activated carbon | Desalination | 2011, 258, 164–170 |
| R. R. Sheha and E. A. El-Shazly | Kinetics and equilibrium modeling of immobilized nano-sized magnetite layer for phosphate removal | J. Coll. Interface Sci. | 2011, 357, 440–446 |
| H. Y. Zhu, R. Jiang, L. Xiao and G. M. Zeng | Preparation, characterization, adsorption kinetics and thermodynamics of novel magnetic chitosan enwrapping nanosized γ-Fe₂O₃ and multi-walled carbon nanotubes with enhanced adsorption properties for methyl orange | Biotechnol. | 2010, 101, 5063–5069 |
| A. Lopes and S. Martins | Degradation of a textile dye C. I. Direct red 80 by electrochemical processes | Portugaliae Electrochim Acta | 2004, 22, 279–294 |
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| J. R. Smith, K. L. Li and X. H. Wang | Adsorptive removal of Pb(II) by activated carbon | Desalination | 2011, 258, 164–170 |

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| Author(s) | Title                                                                 | Journal                                                                 | Year | Pages |
|----------|----------------------------------------------------------------------|------------------------------------------------------------------------|------|-------|
| A. Ahmad, S. H. Mohd-Setapar, C. S. Chuong, A. Khatoon, W. A. Wani, R. Kumar and M. Rafatullah | Recent advances in new generation dye removal technologies: novel search for approaches to reprocess wastewater | RSC Adv. | 2015, 5, 30801–30818 |
| A. Z. Zach-Maor, R. Semiat and H. Shemer | Synthesis, performance, and modeling of immobilized nano-sized magnetite layer for phosphate removal | J. Coll. Interface Sci. | 2011, 357, 440–446 |
| R. R. Sheha | ‘Synthesis and characterization of magnetic hexacyanoferrate (II) polymeric nanocomposite for separation of cesium from radioactive waste solutions’ | J. Coll. Interface Sci. | 2012, 388, 21–30 |
| Y. Park, Y.-C. Lee, W. S. Shin and S.-J. Choi | ‘Removal of cobalt, strontium and cesium from radioactive laundry wastewater by ammonium molybdophosphate–polyacrylonitrile (AMP–PAN)’ | Chem. Eng. J. | 2010, 162, 685–695 |
| H. Ma, B. S. Hsiao and B. Chu | ‘Ultrafine cellulose nanofibers as efficient adsorbents for removal of UO₂⁺ in water’ | ACS Macro Lett. | 2012, 1, (1), 213–216 |
| A. Ahmad, S. H. Mohd-Setapar, C. S. Chuong, A. Khatoon, W. A. Wani, R. Kumar and M. Rafatullah | Recent advances in new generation dye removal technologies: novel search for approaches to reprocess wastewater | RSC Adv. | 2015, 5, 30801–30818 |
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| H. Ma, B. S. Hsiao and B. Chu | ‘Ultrafine cellulose nanofibers as efficient adsorbents for removal of UO₂⁺ in water’ | ACS Macro Lett. | 2012, 1, (1), 213–216 |
| A. Ahmad, S. H. Mohd-Setapar, C. S. Chuong, A. Khatoon, W. A. Wani, R. Kumar and M. Rafatullah | Recent advances in new generation dye removal technologies: novel search for approaches to reprocess wastewater | RSC Adv. | 2015, 5, 30801–30818 |
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| H. Ma, B. S. Hsiao and B. Chu | ‘Ultrafine cellulose nanofibers as efficient adsorbents for removal of UO₂⁺ in water’ | ACS Macro Lett. | 2012, 1, (1), 213–216 |
190. H. Freundlich: ‘Über die adsorption in Lösungen’, Z. Phys. Chem., 1906, 57, 385–470.
191. M. M. Dubinin and L. V. Radushkevich: ‘Equation of the characteristic curve of activated charcoal’, Proc. Acad. Sci. USSR, 1947, 55, 331–333.
192. M. I. Temkin and V. Pyžhev: ‘Kinetics of ammonia synthesis on promoted iron catalyst’, Acta Physicochim, 1940, 12, 327–356.
193. S. Brunauer, P. H. Emmett and E. Teller: ‘Adsorption of gases in multilayered surfaces’, J. Am. Chem. Soc., 1938, 60, 309–319.
194. G. Z. Kyzas and K. A. Matsis: ‘Nanoadsorbents for pollutants removal: A review’, J. Mol. Liq., 2015, 203, 159–168.
195. A. K. Bhattacharya and C. Venkobachar: ‘Removal of cadmium (II) by low cost adsorbents’, J. Environ. Eng. ASCE, 1984, 110, 110–122.
196. K. G. Varshney, A. A. Khan, U. Gupta and S. M. Maheshwari: ‘Kinetics of adsorption of phosphamidon on antimony (V) phosphate cation exchanger: evaluation of the order of reaction and some physical parameters’, Colloids Surf. A, 1996, 113, 19–23.
197. M. Kumari, C. U. Pittman Jr and D. Mohan: ‘Heavy metals (chromium (VI) and lead (II)) removal from water using mesoporous magnetite (Fe3O4) nanospheres’, J. Colloid. Interface Sci., 2015, 442, 120–132.
198. S. Lagergren: ‘About the theory of so-called adsorption of soluble substances’, Handlingar, 1898, 24, 1–39.
199. G. Blanchard, M. Maunaye and G. Martin: ‘Removal of heavy metals from waters by means of natural zeolites’, Water Res., 1984, 18, 1501–1507.
200. C. Ho and S. J. Slater: ‘Conformation of the C1 phorbol-ester-binding domain participates in the activating conformational change of protein kinase C’, Biochem., 1999, 344, 451–460.
201. S. H. Chien and W. R. Clayton: ‘Application of Elovich equation to the kinetics of phosphate release and sorption in soils’, Soil Sci. Soc. Am. J., 1980, 44, 265–268.
202. D. L. Sparks: ‘Kinetics of reaction in pure and mixed systems’ in ‘Soil Physical Chemistry’ (ed. D. L. Sparks), 63–145, 1986, Boca Raton, FL, CRC Press.
203. G. McKay and V. J. P. Poots: ‘Kinetics and diffusion processes in colour removal from effluent using wood as an adsorbent’, J. Chem. Biotechnol., 1980, 30, 279–292.
204. W. J. Weber and J. C. Morris: ‘Kinetics of adsorption on carbon from solution’, J. Sanit. Eng. Div. Am. Soc. Civ. Eng., 1963, 89, 31–59.
205. Y. S. Ho and G. McKay: ‘A comparison of chemisorption kinetic models applied to pollutant removal on various sorbents’, Trans. Icheme, 1998, 76, 332–340.
206. L. Ai, Y. Zhou and J. Jiang: ‘Removal of methylene blue from aqueous solution by montmorillonite/CoFe2O4 composite with magnetic separation performance’, Desalination, 2011, 266, 72–77.
207. B. H. Hameed and A. A. Ahmad: ‘Batch adsorption of methylene blue from aqueous solution by garlic peel, an agricultural waste biomass’, J. Hazard. Mater., 2009, 164, 870–875.
208. S. Arivoli, B. R. Venkatraman, T. Rajachandrasekar and M. Hema: ‘Adsorption of ferrous ion from aqueous solution by low cost activated carbon obtained from natural plant material’, Res. J. Chem. Environ., 2007, 17, 70–78.