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Review Article

Sustainable Nanocomposites for Water Treatment

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Abstract

Nanocomposites are now commonly employed to augment the standard polymeric membrane materials that are used in water treatment processes. In recent years, nanocomposite membranes have greatly attracted the attention of scientists for water treatment applications such as wastewater treatment, water purification, removal of microorganisms, chemical compounds, heavy metals, etc. The incorporation of different nanofillers, such as carbon nanotubes, metal nanocomposites, metal oxide nanocomposites, and some other novel nano-scale materials into polymeric membranes have provided great advances, e.g., enhancing on hydrophilicity, suppressing the accumulation of pollutants and foulants, enhancing rejection efficiencies and improving mechanical properties and thermal stabilities. The use of membrane-based technologies has been applied for water treatment applications; however, the limitations of conventional polymeric membranes have led to the addition of inorganic fillers to enhance their performance. Thereby, the aim of this review is to provide up-to-date information related to those novel nanocomposite membranes and their contribution for water treatment application.

Introduction

Water is one of the most vital bases for the living system and is used in daily life activities. Due to rapid industrial growth, natural water resources are affected by several water pollutants. The World Health Organization (WHO) 2014 report on water supply and sanitation estimated that 748 million people still lack safe drinking water, 2.5 billion peoples without access sanitation and 3900 children die every day due to poor quality water and communicable diseases [1]. These statistics indicated that water pollution by numerous pollutants becomes an alarming issue worldwide. Consequently, competent water treatment technologies have been established to raise the potential of water resources and to decline the challenges and concerns associated with water pollution. In this regard, nanocomposite has to play a significant role in the water purification technology including portable water treatment, wastewater desalination, and treatment in order to deliver the real technology to clean water at a lower price using less energy by decreasing further ecological impacts.

Nanomaterials are materials which have the structural components sized from 1 to 100 nm [2]. They have unique properties when compared with other conventional materials, such as mechanical, electrical, optical, and magnetic properties due to their the small size and higher specific surface area [3-8]. In recent years, nanomaterials have been effectively applied to numerous perspectives as catalysis [9-19], medicine [20], sensing, and biology [21-23]. They have extensive applications to prevent several environmental problems like water and wastewater treatment. Because, nanomaterials have the potential to eliminate different toxins, for instance, heavy metals, organic pollutants, inorganic anions, and pathogens [24]. Zero-valent metal nanoparticles (nZVI), metal oxides nanoparticles, carbon nanotubes (CNTs) and nanocomposites are the most recent appropriate nanomaterials for water and wastewater treatment [25].

Composites have many advantages than other compounds due to their unique characteristics such as high durability, high rigidity, high strength, gas-barrier features, corrosion resistance, low density, and heat resistance. The combination of the matrix (continuous phase) and the reinforced materials (dispersed) is known as composite materials.

Technologies of Water Purifications

Surface water (spring, rivers, and lakes) and unconventional water resources (which are not available for direct use. For example, wastewater, seawater and brackish water) are the major universal water resources potentials [26]. Globally, the upsurge in industrialization and urbanization with a quick population growth and weather change contributes to the pollution of freshwater resources [27, 28]. (Table 1) shows the available conventional water purification technologies such as coagulation and flocculation, air flotation and advanced oxidation processes. These methods are very quiet in removing the contaminants efficiently. However, these methods possess several challenges related to the formation of either secondary pollution or higher energy requirement. Therefore, a massive attention should be given to the improvement/innovation of technologies having ecologically friendly, low energy consumption and economical feasible treatments perspectives applicable to the feasible water sanitization systems. To meet the demand for clean water standards, many authors have been focused on the suitable and economically viable water purification approaches including water remediation, reclamation, and desalination [29].

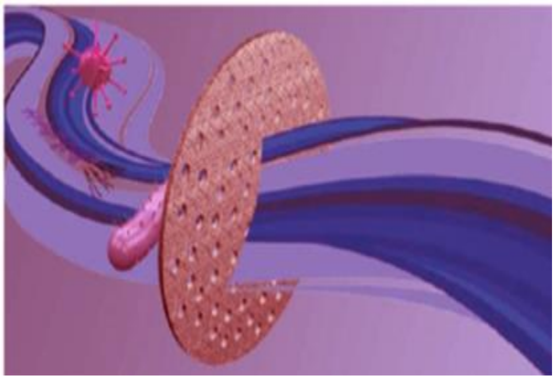
Table (1): Different methods for Water purification [29, 30]

Water purification technologies	Contaminate removed
Coagulation and flocculation	Turbidity, dissolved organic carbon, bacteria and chemical contaminants such as cyanide compounds, phosphorus, fluorides arsenic etc
Boiling	Kill the bacterial cultures
Ultraviolent treatment	Can achieve disinfection of about 99.99%
Distillation	To destroy microbial cells and unwanted chemicals such as calcium
Ozone	It is effective in eradicating tastes, odour, colour, iron, and manganes; and not affected by pH and temperature
Chlorine	Kills several waterborne pathogens
Ultrasound	Damage cellular structures of bacteria
Bioremediation	Eradicating heavy metals, organic toxins, pesticides and dyes by plant extr acts and microbes.
Catalytic process	Applied to breakdown down an extensive diversity of organic materials like organic acids, estrogens, pesticides, dyes, crude oil and microbes

Types of Nanocomposites and its application in purification of water

The use of nanoparticles in water management has associated with some practical problems, such as accumulation, tough separation, drainage into the contact water, possess environmental and human health [31]. One capable approach to improve the application of nano-particulate materials is to develop NC materials that take advantages of both the hosts and impregnated nanoparticles (Figure 1) [32]. NCs have the potential to mitigate the discharge of nanoparticles into the environment, and improves the suitability of nanotechnology with current infrastructures. The NCs are essentially multiphase solid material, including porous media, colloids, gels, and copolymers in a broad sense. The selection of hosts for nanocomposites is of great significance, and even dominates the performance of the resultant nanocomposites. Compared with free nanomaterials, the performance and usability of nanocomposites were significantly improved, in terms of nanoparticle dispersion, stability, and recyclability. Hence, nanocomposite materials could bond the gap between nanoscopic and mesoscopic scale. Till now, nanocomposites were believed to be the most likely way to forward water nanotechnology from laboratory up to the large-scale applications [29].

Figure (1): Application of nanocomposite for water purification [32]



Metal Nanocomposite

Silver-alginate composite beads were effectively prepared using three different methods. Specifically, the adsorption-reduction (AR), hydraulic retention time (HRT) and simultaneous gelation-reduction (SGR) composite beads were talented to succeed a disinfection effectiveness for portable water purifying The synthesized novel NC containing AgNPs and mesoporous alumina have been used for the elimination of dye compounds like methyl orange, bromothymol blue, and reactive yellow from synthetic waste. The results display that the silver/ mesoporous alumina nanocomposite (Ag/OMA NC) was noble adsorbent for the elimination of anionic dyes from aqueous solution, and also this NCs had an antibacterial activity against both Gram-negative and Gram-positive bacteria [33].

Metal Oxide nanocomposite

The Metal oxide nanocomposite (MONC) are often used as adsorbents, photocatalyst,
and devices to challenge environmental pollution problems. MONC are used merging with graphene, silica, other oxides, carbon nanotube (CNT), polymers for the removal of various organic and inorganic of pollutants [34].

Iron oxides (i.e. Fe2O3 and Fe3O4) are unique and talented magnetic constituents which create a new composite with CNTs, and graphene. This is one of the greatest smart magnetic metallic oxides and has established extensive consideration due to its exceptional physical and chemical properties and several benefits such as high reversible capacity, rich abundance, cheap, and environmentally friend [35]. Magnetic nanoparticles are highly advantageous than nonmagnetic nanoparticles.

Since they can simply isolate from water via a magnetic field. Magnetic field separation is a practice also allows simple isolation and recycled the adsorbents. Magnetic nanocomposites can be fabricated using magnetite (Fe_3O_4), maghemite (Fe_2O_3), and jacobsite ($MnFe_2O_4$) nanoparticles as reinforcer filling on a polymer matrix which permits easy separation of the composite from the aqueous solutions after the sorption process [36].

Researchers were investigated series of magnetic alginate polymers prepared and batch trials were shown to examine their capacity to eliminate heavy metal ions such as Co^{2+}, Cr^{6+}, Ni^{4+}, Pb^{2+}, Cu^{2+}, Mn^{2+}, La^{3+} and organic dyes (MB and MO) from aqueous solutions. Different types of iron oxide magnetic composites have been positively useful as an adsorbent for the elimination of various targets of impurities from water and wastewater such as naphthylamine [37], metals [37], phenol [37], and tetracycline [38], As3+, As5+ [39], dyes [40]. Moreover, graphene-based iron oxide NCs have confirmed an exceptional adsorption capacity to fix extra heavy metals and organic dyes such as Cr^{6+}, Pb^{2+}, Co^{2+}, neutral red, MB etc. due to magnetic properties, high surface to volume ratio and rapid diffusion rate [37].

Carbon Nanocomposite

A magnetic multi-wall carbon nanotube (MMWCNT) nanocomposite was used as an adsorbent for removal of cationic dyes from aqueous solutions. The MMWCNT nanocomposite was composed of viable multi-wall CNT and IONPs. The elimination of MB, neutral red and brilliant cresyl blue was deliberate using MMWCNT nanocomposite adsorbent. Investigations were carried out to study adsorption kinetics, the adsorption capacity of the sorbent and the effect of sorption dosage and pH values on the elimination of cationic dyes [41].

Mesoporous carbon with entrenched iron carbide nanoparticles (ICNPs) was effectively synthesized via a facile impregnation-carbonization method. Biomass was used as a carbon basis and an iron pioneer was rooted to create mesopores through a catalytic graphitization reaction. The pore conformation of the NCs structured by the iron pioneer loadings and the immovable ICNPs support as a dynamic component of magnetic isolation next sorption. The newly produced mesopores were established as a critical feature to increase the adsorption capacity of organic dyes while immovable ICNPs are responsible for the careful removal of heavy metal ions (Zn^{2+}, Cu^{2+}, Ni^{2+}, Cr^{6+}, and Pb^{2+}). Composed with the desirable elimination of extra noxious heavy metal species (Cr^{6+} and Pb^{2+}), these mesoporous NCs show favourable applications in impurity removal from water. The facile material preparation permits appropriate scale-up production with economical feasible and lowest ecological impact [42]. Advanced technologies integrating with engineered nanoparticles into biochar fabrication schemes might increase the roles of biochar for numerous uses comprising soil fertility upgrading, carbon sequestration, and wastewater treatment. Inyang et al. [43], investigated that removal ability MB was evaluated in batch sorption using untreated hickory biochars (HC), bagasse biochars (BC) and CNT-biochar composites (HC-CNT and BC-CNT, respectively). The addition of CNTs considerably enriched the physiochemical properties of HC-CNT and BC-CNT such as extreme thermal stabilities, surface areas, and pore volumes. These results recommend that electrostatic magnetism was the principal devices for the removal of MB onto the biochar-nanocomposite. Hybridized CNT-biochar NC can be considered as capable, cheap adsorbent material for eliminating dyes and organic contaminants from water [44].

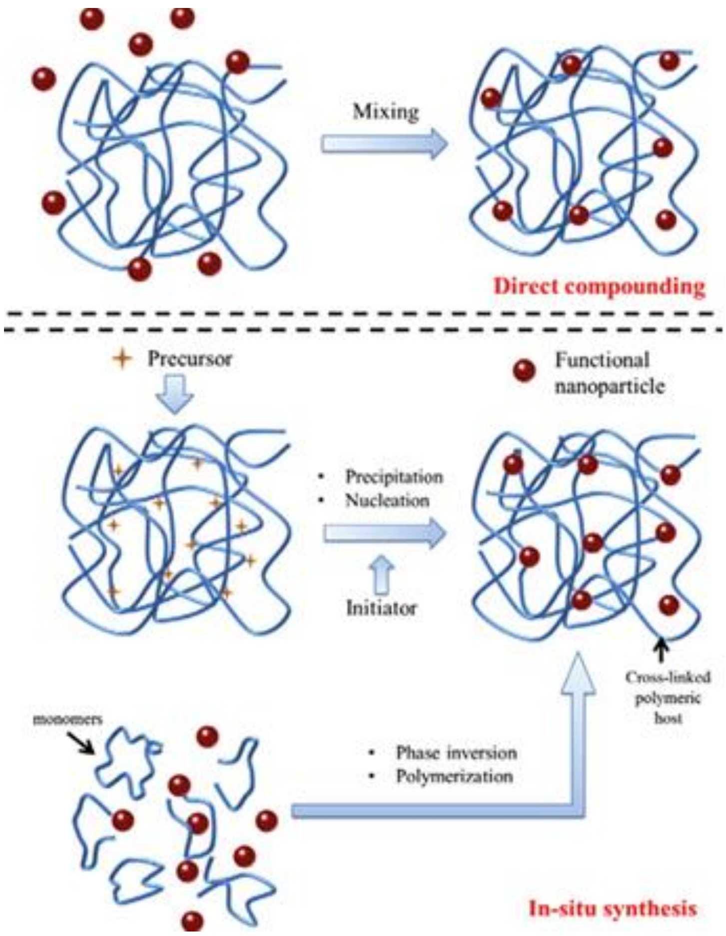
Polymer Nanocomposite

Polymer nanocomposites (PNCs) are a superior type of tools which nanoparticles spread in a polymer matrix resulting in novel materials having unique physical and chemical properties [45]. Polymers are special supports for nanomaterials as they usually possess tunable porous structures, excellent mechanical properties, and chemically bounded functional groups [46]. PNCs are prospecting materials for their sound performance in water and wastewater treatment. Adsorption of contaminant through PNC is among various treatment technologies, which is considered as an advanced tool in water treatment technology. PNCs often integrate the essential advantages of both the nanoparticles and the polymeric matrix [47].

PNCs could be synthesis by either joining nanoparticles into polymer structures or by fixing polymers to nanoparticles. Direct compounding and in situ synthesis are two leading approaches used in the manufacture of several PNCs as shown in (Figure 2) .[29]PNC has of great potential for pollutants removal including heavy metals (Cu, Pb, Cr (III), Ni), As, F, and P. The pollutants were often removed through multiple mechanisms including surface complexation, electrostatic attraction and co-precipitation [48].

New types of polymeric hosts are essentially bio-polymers such as chitosan and cellulose. They are plentiful in nature and eco-friendly. However, they could suffer a serious biodegradation problem in the long-term application. cellulose showed good chemical stability and mechanical strength, due to its densely and systematic aligned, hydrogen-bonded molecules, sound swelling resistance and its characteristics such as hydrophilicity and chirality. Chitosan is the another most naturally rich polysaccharide next to cellulose. Chitosan has exceptional features such as high reactivity, excellent complexation behaviour, and chemical stability. The amino and hydroxyl groups of chitosan aid as energetic sites for water pollutants [48]. Djerahov et al. [49] prepared a steady CS-AgNPs colloid by diffusing the AgNPs sol in chitosan medium and additional recycled it to attain a cast film with high steadiness under packing and good mechanical strength. It showed efficient isolation and extraction of Al(III), Cd(II), Cu(II), Co(II), Fe(III), Ni(II), Pb(II) and Zn(II) [28, 49].

Figure (2): Graphic of fusion methods for PNCs. Adapted with permission [29]



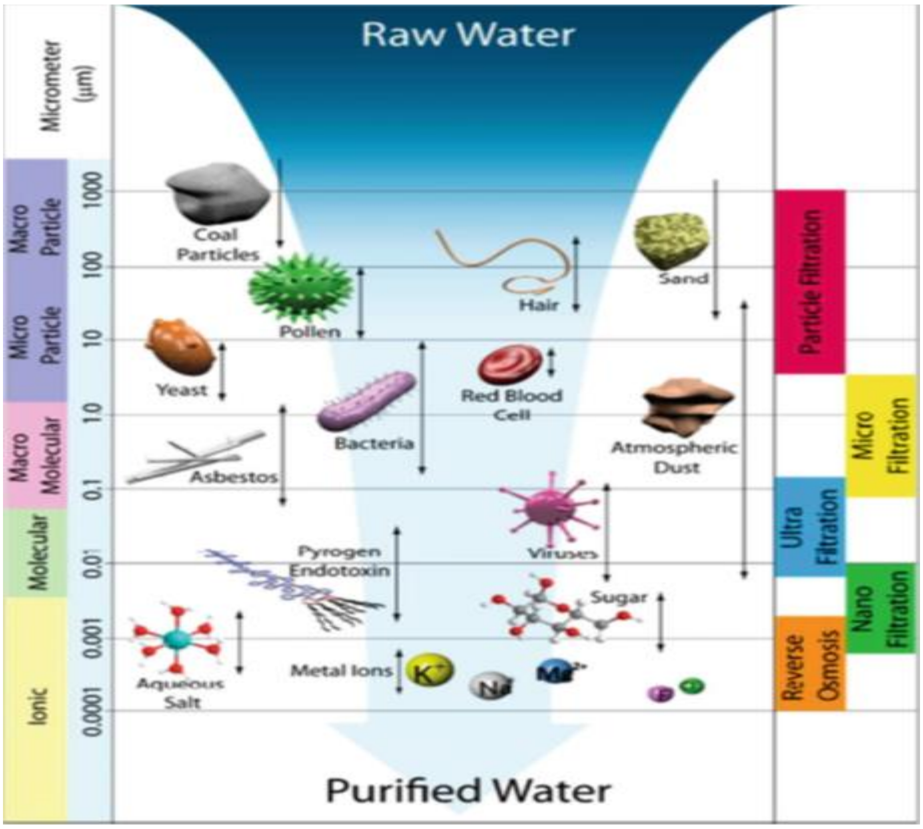
CNTs powerfully sorb varied polar organic compounds attributable to the stuff miscellaneous interfaces together with hydrophobic impact, peppiness

interactions, covalent bonding, valence bonding, and electrical connections. The π-electron wealthy CNT apparent allows energy exchanges with carbon-based molecules with C=C bonds. Organic compounds that have used functional groups like –COOH, – OH, –NH2 might additionally kind a bond with the graphitic CNT exterior that pays electrons. Electricity magnetism enables the surface assimilation of exciting carbon-based chemicals like some antibiotics at appropriate pH range. PNCs are sorbents tailored adsorbents which are talented for eliminating different types of pollutants. Their internal shells can be hydrophobic for sorption of organic compounds while the exterior channels can be tailored (e.g., –OH or $–NH_2$) for sorption of inorganic pollutants like heavy metals.
complexation, electrostatic interactions, hydrophobic effect, and hydrogen bonding are the mechanism established during sorption process [50].

Membranes Nanocomposite

In membrane technology, porous materials are plays capturing role to trap pollutants. Inclusive, numerous forms of membranes with diverse pore sizes engaged in water treatment process including microfiltration, ultrafiltration, reverse osmosis and nanofiltration membranes which depend on their shared materials that would be clean out through each process as shown (Figure 3) [51]. The existing membranes have numerous challenges for water purification, such as the exchange link between permeability, selectivity and low resistance to fouling. Recent progress in nanotechnology has offered the growth of the new generation membrane for water purification [47].

Figure (3): Schematic illustration of membrane filtration [32]

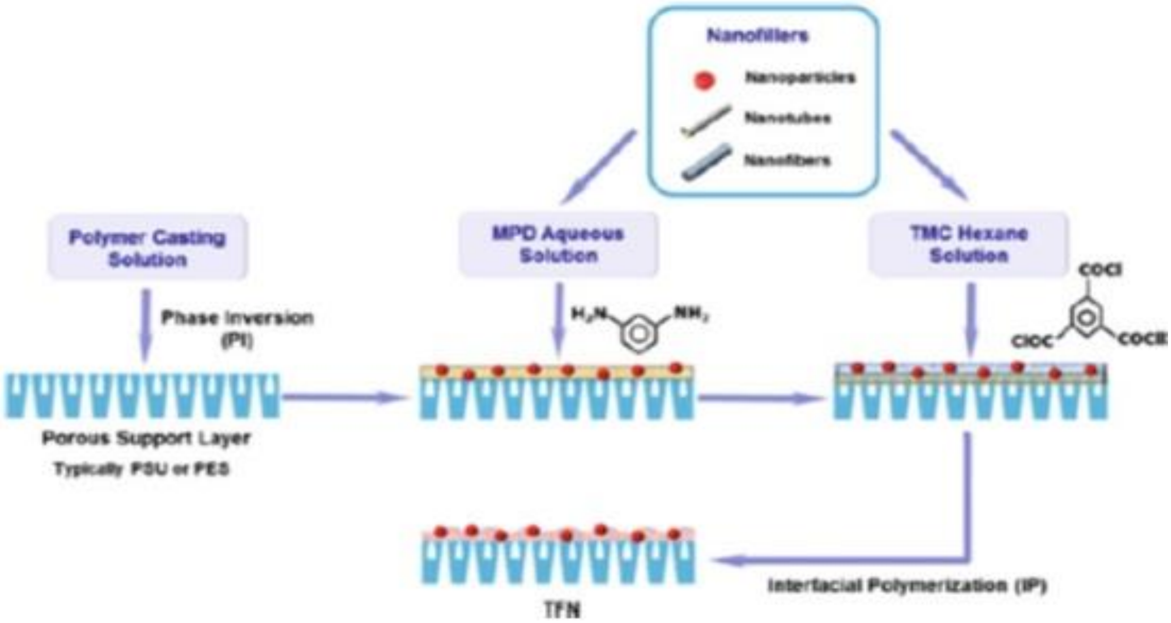


NCM able to reflect as a novel class of filtration tools containing hybrid medium membranes and surface active membranes. Hybrid medium membranes use nanofillers, which are auxiliary to a medium material. In most cases, the nanofillers are inanimate and fixed in a polymeric or inorganic oxide medium. These nanofibers article has larger specific surface area leading to a higher surface-to-mass ratio [52]. NCMs are materials which have no single application of separating pollutants from water. They are also introducing new functionalities such as adsorption [53], photocatalysis [54], antimicrobial activity [55] and surface modification [55] which promoted adsorbing, degrading, and/or deactivating contaminates.

Thin-Film Nanocomposites

Thin film nanocomposites (TFNs) membrane contains an extreme tinny wall sheet above a more permeable assistant material. TFN is interfacially synthesized by reverse osmosis or nano filtration membrane which is extensively applied to remove heavy metals, desalinate seawater/brackish water, hardness causing salts, organic contaminants like pesticides, insecticides and disinfection intermediates. Researchers have been focused to advance water flux, toxin elimination, and antifouling characteristics of TFC l (1) to adapt the auxiliary film thus the linkage among the wall layer and the second layer might be improved, and (2) to enhance the wall layer by changing the IP settings, i.e. exchanging monomers, applying physical layering [56]. Materials like zeolites, CNTs, silica, Ag, and TiO2 used for CNM synthesis have also been discovered to make TFN membranes [57, 58]. In general technologies yield NCs, a novel theory has been projected centred on diffusing nanomaterials into the extremely tinny wall to increase membrane efficiency for water purification [59]. The known production method is done the in situ IP course among aqueous phenylenediamine and trimesoylchloride organic solution as shown in (Figure 4). The nanofiller able to spread either in aqueous or an organic phase.

Figure (4): Production of TFN membranes through the IP method [56]



Conclusion

Growing demand and deficiency of clean water as a result of rapid urbanization, population growth, and climate disruption have become unparalleled urgent global issues. Globally, Water purification is a priority issue for human use, ecosystem management, agriculture, and industry. The water sanitization process using nanoparticles are quite efficient. However, these are linked with some weakness such as aggregation, tough separation, and leakage into the contact water, environmental impact and human health. Therefore, to improve water treatment process system, researchers have been paid to develop eco-friendly, energy efficient and low price for sustainable water purification. The nanocomposites are basically multiphase solid materials, including porous media, colloids, gels, and copolymers in a broad sense. The selection of hosts for nanocomposites has a great consequence, and even controls the performance of nanocomposites in water purification. Compared with free nanomaterials, the efficiency and usability of nanocomposites were significantly improved, in terms of nanoparticle dispersion, stability, and recyclability. Polymers are special supports for nanomaterials as they usually possess tunable porous structures, excellent mechanical properties, and chemically bounded functional groups. Polymer-based nanocomposites (PNCs) are prospecting materials for their sound performance in water and wastewater treatment. Nanocomposite membrane has a great role in water purification and reuses for various sources of water such as drinking water, brackish, seawater, and wastewater treatment.

Abbreviations

WHO World Health Organization
CNTs Carbon Nanotubes
NCs Nanocomposites
AR Adsorption-Reduction
HRT Hydraulic Retention Time
MONC Metal Oxide Nanocomposite
MB Methylene Blue
MO Methylene Orange

MMWCNT Magnetic Multi-Wall Carbon Nanotube
ICNPs Iron Carbide Nanoparticles
HC Hickory Biochars
BC Bagasse Biochars
PNCs Polyme Nanocomposites
NCMs Nanocomposites Membrabes
CNMs Conventional Nanocomposite Membranes
TFC Thin Film Nanocomposites

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