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NANO COMPOSITES AND WATER TREATMENT: REVIEW

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ABSTRACT

Water scarcity and the contamination of aquatic ecosystems by industrial, agricultural, and emerging pollutants present urgent global challenges that conventional water treatment technologies struggle to address effectively. Nanocomposites—multiphase advanced materials formed by embedding functional nanoscale fillers (such as metal oxides, carbon-based nanostructures, metal-organic frameworks, or biopolymers) into macroscopic polymer, ceramic, or metallic matrices—have emerged as a transformative solution. By synergistically combining the high surface area, catalytic reactivity, and targeted affinity of nanomaterials with the structural stability and ease of processing of matrix materials, nanocomposites overcome critical limitations of standalone nanoparticles, including agglomeration and difficult post-treatment recovery. These materials perform multifunctional roles in water purification, encompassing high-capacity heavy metal adsorption, photocatalytic degradation of persistent organic pollutants and pharmaceuticals, antimicrobial disinfection, and enhanced thin-film nanocomposite (TFN) membrane filtration with superior antifouling properties. Despite significant performance advantages, widespread commercial deployment requires overcoming challenges related to scalable synthesis, long-term stability, nano-filler leaching risks, and cost-effectiveness in real-world wastewater conditions. Overall, nanocomposites represent a pivotal milestone toward sustainable, highly efficient, and integrated water treatment paradigms.

Keywords: Nano Composites; Water Treatment; Photocatalytic Degradation; Adsorption

1 INTRODUCTION

Nanocomposites represent one of the most promising classes of advanced materials for solving global water pollution challenges. By combining bulk matrix materials (like polymers, ceramics, or metals) with nanoscale filler particles (1–100 nm), nanocomposites deliver exceptional chemical reactivity, physical strength, and targeted pollutant removal capabilities that traditional water treatment materials cannot match.

A nanocomposite is a multiphase material formed by embedding nanomaterials—such as nanoparticles, carbon nanotubes, or graphene sheets—into a macroscopic matrix material [1,2].

- **The Matrix Phase:** Provides structural support, flexibility, and shape (commonly polymers like polyvinylidene fluoride (PVDF), polysulfone (PSf), or natural biopolymers like chitosan).
- **The Nano-Filler Phase:** Delivers active chemical, optical, or magnetic properties due to its extremely high surface-area-to-volume ratio.

By merging these two phases, nanocomposites overcome the key limitations of pure nanomaterials (such as agglomeration and difficulty in recovery) while vastly outperforming conventional bulk materials [3].

2 PRIMARY MECHANISMS IN WATER TREATMENT

Nanocomposites target a wide spectrum of water contaminants through four primary mechanisms:

2.1 Adsorption

Nanocomposites adsorb heavy metal ions (Pb^{2+}, Cd^{2+}, $As^{3+/5+}$), organic dyes, and fluorine/arsenic species onto functionalized nano-sites.

- **Example:** Magnetic iron oxide (Fe_3O_4) embedded in chitosan allows high-capacity heavy metal binding, followed by rapid magnetic separation from treated water.

2.2 Photocatalytic Degradation

Under sunlight or UV irradiation, semiconductor nano-fillers generate reactive oxygen species (ROS) like hydroxyl radicals ($\cdot OH$) that break down organic pollutants, dyes, and pharmaceutical residues into benign molecules (CO_2 and H_2O) [4,5].

- **Example:** Titanium dioxide (TiO_2) or zinc oxide (ZnO) integrated with graphene oxide or polymer scaffolds to prevent nanoparticle wash-off.

2.3 Membrane Filtration (Thin-Film Nanocomposites - TFN)

Incorporating nanomaterials into reverse osmosis (RO), nanofiltration (NF), or ultrafiltration (UF) polymeric membranes increases water permeability while maintaining high salt/solute rejection.

- **Key benefit:** Reduces membrane fouling (biofouling and organic scaling) and lowers operational energy requirements [6].

2.4 Antimicrobial Disinfection

Silver (Ag), copper (Cu), and zinc oxide (ZnO) nanocomposites kill waterborne bacteria and viruses by disrupting cellular membranes or producing oxidative stress.

3 ADVANTAGES AND CURRENT CHALLENGES

3.1 Major Advantages

- **Ultra-High Efficiency:** High density of active binding/catalytic sites enables trace-level contaminant removal down to parts-per-billion (ppb).
- **Multi-Functional Action:** A single nanocomposite can simultaneously filter, disinfect, and degrade chemical pollutants.
- **Ease of Recovery:** Magnetic nanocomposites allow simple post-treatment retrieval using external magnets, preventing secondary pollution [7].

3.2 Key Industrial Challenges

- **Scalability & Cost:** High synthesis cost of certain nanostructures (e.g., high-purity CNTs or MOFs).
- **Leaching & Toxicity:** Risk of nanoparticle detachment into treated water, raising environmental and toxicological concerns.
- **Fouling in Real Effluents:** Industrial wastewater contains complex mixtures that can block reactive nano-sites over time [8].

Water treatment is one of the most critical pillars of public health, environmental sustainability, and economic stability. While water covers about 71% of Earth's surface, **less than 1% of it is accessible fresh water** fit for human consumption.

3.2.1 Protecting Public Health and Preventing Disease

The single most immediate purpose of water treatment is eliminating pathogens and toxic substances that cause severe illness or death.

- **Eradicating Waterborne Pathogens:** Untreated water carries bacteria, viruses, and parasites (*Cholera, Typhoid, Dysentery, Giardia, E. coli*). According to the World Health Organization (WHO), waterborne diseases cause millions of preventable deaths annually, particularly among young children.
- **Removing Toxic Chemicals:** Modern industrial and agricultural runoff introduces heavy metals (lead, arsenic, mercury), nitrates, pesticides, and synthetic contaminants like PFAS ("forever chemicals") that cause chronic neurological, developmental, and oncological conditions.

3.2.2 Safeguarding the Environment and Ecosystems

Proper wastewater treatment protects natural bodies of water from ecological collapse.

- **Preventing Eutrophication:** Untreated wastewater contains high levels of nitrogen and phosphorus (from detergents, sewage, and fertilizers). When dumped into rivers or lakes, these nutrients trigger massive algal blooms that starve aquatic life of oxygen, creating biological "dead zones."
- **Preserving Aquatic Biodiversity:** Treating industrial discharge neutralizes extreme pH levels, heavy metals, and toxic organic compounds, allowing freshwater and marine ecosystems to thrive [9].

3.2.3 Addressing Global Water Scarcity

Population growth, climate change, and urbanization are rapidly straining natural water supplies.

- **Enabling Water Reuse and Recycling:** Advanced treatment processes—such as membrane filtration, reverse osmosis, and nanocomposite systems—allow municipal wastewater and industrial effluents to be purified back into safe drinking water or industrial process water.
- **Desalination:** Water treatment technologies allow coastal regions to convert seawater into fresh water, providing a reliable lifeline for arid and drought-prone regions.

3.2.4 Supporting Economic Growth and Industry

Water is an indispensable input for virtually every industry across the global economy.

- **Agriculture:** Agriculture accounts for roughly 70% of global freshwater withdrawals. Treated wastewater provides a reliable, nutrient-controlled source for crop irrigation without depleting natural groundwater reserves.
- **Manufacturing & Technology:** Industries like microchip manufacturing, pharmaceuticals, and beverage production require ultra-pure water. Impurities can ruin sensitive manufacturing equipment or contaminate consumer products.
- **Power Generation:** Thermal and nuclear power plants require massive volumes of treated, low-mineral water for steam generation and cooling towers to prevent equipment corrosion and scaling [10].

3.2.5 Infrastructure and Domestic Protection

Treating water before it enters municipal distribution networks prevents infrastructural damage.

- **Corrosion Control:** Hard or acidic water erodes municipal water mains and residential plumbing, causing costly leaks and heavy metal leaching (like lead from old pipes into household tap water).
- **Scale Prevention:** Removing excess minerals (calcium and magnesium) prevents scaling inside industrial boilers, residential water heaters, and household appliances, drastically extending their operational lifespan and energy efficiency.

3.2.6 Key Takeaway

Water treatment transforms raw, hazardous water into a safe resource. By bridging the gap between finite natural freshwater supplies and growing global demands, water treatment protects human health, drives sustainable industry, and preserves natural ecosystems for future generations.

3.2.6.1 Smart Engineering Informatics and Digital Solutions for Efficient Produced Water Treatment with Nanocomposite Membranes

In sectors like oil and gas, where it is necessary to treat water polluted with metals, salts, and hydrocarbons effectively, produced water treatment poses serious environmental problems. This research investigates how smart engineering informatics and nanocomposite membranes can be combined to improve produced water treatment efficiency. While digital techniques, including as real-time monitoring and AI-driven optimization, are applied to lower operational costs and improve treatment sustainability, advanced materials, such as polybenzimidazole (PBI), graphene oxide (GO), and reduced graphene oxide (rGO), are used to improve membrane performance. Comparing the research to standard approaches, it shows enhanced pollutant removal, energy savings, and membrane longevity. The results provide a technique to scale up the application of digitalized nano-composite water treatment technologies [11]

3.2.6.2 A Study on the Hydrophobic Characteristics of Laboratory Prepared Silicone Rubber Insulator Samples with Al2O3 Nano-Filler

Silicone rubber based nano composite insulators are gaining popularity for the use of power transmission and distribution networks. Hence it is important to study the behaviour of these technologically new silicone rubber based composite insulators before use, in terms of the severity of environmental contamination levels. Based on the above facts, this study focuses on the analysis of the surface properties of the silicon rubber insulator prepared with alumina (Al_2O_3) nano-fillers, under different levels of surface contaminations. The analysis is done based on static contact angle measurement. For this purpose, seven different silicone rubber composite insulator samples have been prepared which differ according to the concentration of alumina nano-fillers. The static contact angles have been measured for all the test samples with five different levels of surface contamination, depending on the equivalent salt deposit density (ESDD). Based on these measurements the surface properties of the test samples have been analysed. [12]

3.2.6.3 Water treatment via non-membrane inorganic nanoparticles/cellulose composites

Nanomaterials offer innovations in water purification technology with decreased operational and capital cost, reduced dosage, and improved pollutant selectivity. Inorganic nanoparticles (NPs)/cellulose hybrid nanocomposites have attracted growing interest due to the unique properties of cellulose and high specific surface area of NPs and their pollutant selectivity. The integration with cellulose brings benefits to inorganic NPs for water treatment, including preventing agglomeration, ensuring colloidal stability, and allowing for separation by magnetic nanoparticles after purification. [13]

3.2.6.4 Antibacterial properties of recoverable CuZnO@Fe3O4@GO composites in water treatment

The growth of bacteria will lead to water quality deterioration and equipment damage. Therefore, it is necessary to control the growth and reproduction of microorganisms in water treatment. A new type of magnetic recoverable CuZnO@Fe3O4@GO composites was prepared by ultrasonic method, and the composites were characterized and analyzed by SEM, TEM, XPS, and other methods. The optimum mass ratio of composites was determined by orthogonal experiment, and the antibacterial properties and mechanism of the composite were investigated by gram-positive bacteria Staphylococcus aureus and gram-negative bacteria Escherichia coli. Finally, the antibacterial properties of the composites in the effluent of the secondary sedimentation tank were researched. It was shown that the optimum mass ratio of the composites was GO:Fe3O4:CuZnO =1:2:3. When the dosage of composites was 180 mg L-1 and the action time was 100 min, the antibacterial rate against S. aureus and E. coli reached more than 99.5%. The composites could destroy the cell structure of two kinds of bacteria, increase the content of active oxygen in bacteria cells, and enhance the leakage rate of protein by more than 9 times in 150 min, thereby causing the death of the bacteria. And the antibacterial rate of the composites in effluent of the secondary sedimentation tank could reach 99%, and the magnetic recovery rate could reach more than 98%. After 5 cycles of use, the antibacterial rate could still exceed 90%. [14]

3.2.6.5 Red Mud Cement Colloidal Nano Silica Composites for the Heavy Metal Ion Removal from the Wastewater

Industrial wastewater is a significant threat to aquatic and environmental habitats. The harsh chemicals and heavy metal ions present in industrial wastewater heavily impact the equilibrium of nature. This study uses red mud (RM), an industrial waste byproduct, as a metal adsorbent over thermal processing. A recent study examined the effects of calcined red mud and colloidal nano-silica (CNS) composite on metal extraction efficiency. This study measured the concentration of Cd, Pb, As, and Cu remaining in the wastewater solution after exposure to the ternary blended red mud CNS cement samples over time using atomic absorption spectroscopy. The Red mud cement CNS mortar samples are kept in the wastewater over a period, and the heavy metal ion concentration in the solution before and after the exposure is measured. The results showed that a combination of ternary blended mortar with cement replacement by 1.5% CNS and 15% red mud showed the highest adsorption. Calcination significantly enhanced the metal extraction efficiency of red mud. The metal extraction efficiency order for the proposed composites is in the order of Cr > Cd > Pb > Cu. The X-ray diffraction patterns of heavy metal ions loaded samples revealed changes in silicate crystallinity and an alumina phase transition, which shows the affinity of the proposed ternary blend mortar to the heavy metal ions. Therefore, the red mud CNS nano composites can alter the mineral phases, impacting its functionality as a metal adsorbent. Hence, red mud CNS cement composites can be used as a metal extraction agent for wastewater purification. [15]

3.2.6.6 Nanofiltration membranes prepared from pristine and functionalised multiwall carbon nanotubes/biopolymer composites for water treatment applications

A filtration method was used to prepare buckypaper (BP) membranes for water desalination. The samples are made from a biopolymer (chitosan) containing functionalized multiwall carbon nanotubes (MWCNTs) with –NH2 and −COOH moieties. Comprehensive characteristics of all BP membranes were systematically investigated. This included optimisation of sonication time, electrical and mechanical properties (ranging from 7 ± 1 to 69 ± 1 S/cm and tensile strengths between 17 ± 2 and 60 ± 2 MPa, respectively), contact angle (36 ± 3° to 105°±2°), morphology, surface area (ranging from 12 ± 2 m2/g to 112 ± 4 m2/g), surface charge, water permeability (from 0.5 ± 0.1 to 6.5 ± 0.2 L/m2 h bar), and salt rejection. The results indicate that the properties of the BP membrane have been significantly affected as the top layer by the type of multi-walled carbon nanotubes. With MWCNTs−COOH / chitosan BP membranes, the highest permeability towards water was achieved while the MWCNTs-NH2/chitosan membranes provided the best performance in salt rejection by properly balancing amine groups on the top layer, which could be separate monovalent and multivalent cations from salt solutions. Moreover, for monovalent cations (e.g. Na+) BP membranes (MWCNTs/chitosan and MWCNTs-NH2/chitosan) with sufficiently balanced amine groups on the top layer are shown to be much bigger rejection than for higher-valent cations (e.g. Mg2+). [16]

3.2.6.7 Recent advances and challenges of the green ZnO-based composites biosynthesized using plant extracts for water treatment

Recently, there has been a notable rise in the prevalence of persistent pollutants in the environment, posing a significant hazard due to their toxicity and enduring nature. Conventional wastewater treatment methods employed in treatment plants rarely address these persistent pollutants adequately. Meanwhile, the concept of green synthesis has garnered considerable attention, owing to its environmentally friendly approach that utilizes fewer toxic chemicals and solvents. The utilization of materials derived from sustainable sources presents a promising avenue for solving pressing environmental concerns. Among the various sources of biological agents, plants stand out for their accessibility, eco-friendliness, and rich reserves of phytochemicals suitable for material synthesis. The plant extract-mediated synthesis of zinc oxide nanoparticles (ZnONPs) has emerged as a promising solution for applications in wastewater treatment. Thorough investigations into the factors influencing the properties of these green ZnONPs are essential to establish a detailed and reliable synthesis process. Major weaknesses inherent in ZnONPs can be addressed by changing the optical, magnetic, and interface properties through doping with various semiconductor materials. Consequently, research efforts to mitigate water pollution are being driven by both the prospects and limitations of ZnO-based composites. This review underscores the recent advancements of plant extract-mediated ZnONP composites for water treatment. [17]

3.2.6.8 Green synthesis of Metal-Organic framework based Hybrid Nanocellulose/ Nano silver composites derived from watermelon peel waste for effective removal of heavy metals from textile effluent

Cellulose, a widely available carbon polymer found in various plant, animal, and bacterial sources, constitutes a significant portion of fruit and vegetable waste also. In tune with the current research, cellulose is also being extensively developed as a nano material, i.e. nano cellulose crystals (CNC). CNCs are advanced version of cellulose particles at nanometer scale and have additional properties other than natural and biodegradable attributes like high surface area, nano size effect, non-toxic, high mechanical strength, thermal stability, hydrophilic, possibility of functionalization due to presence of hydroxyl groups on surface. Nano cellulose has been extensively used in the field of food packaging materials, wastewater treatment, and drug delivery and as a catalyst. Nano cellulose and its hybrid nano composites are among the emerging nanomaterials of this century employed for wastewater remediation application specifically to remove heavy metals from industrial effluents. Recently, with the modification of surface properties of CNC with metal or metal oxide nanoparticles via ex-situ simple blending method, metal-organic framework based hybrid nano composites are synthesized for abundant application worldwide. Biodegradable watermelon peel waste derived nano cellulose (CNC)/nano silver (AgNPs) nano composite synthesized herein is applied as an adsorbent for the removal of heavy metals to purify waste water or textile effluent, mitigating problem of water pollution as well as solid fruit peel waste management. During the study, CNCs were prepared by ultrasonication and acid hydrolysis of isolated cellulose. Pure Cellulose is isolated from natural watermelon peel waste through chemical pre-treatment in which all non-cellulosic components were removed subsequently. Silver nanoparticles (AgNPs) were also synthesized by green biological method from leaf extract of Nyctanthus arbour tristis. CNCs were characterized by FTIR, XRD and FESEM to analyze purity of cellulose, crystallinity of CNCs and morphology and size of CNCs respectively. Excellent potential of CNC/ AgNPs hybrid nano composites towards water purification application is successfully explored in this study via AAS adsorption estimates and FESEM and EDX analysis of CNCs/AgNPs adsorbent (before and after adsorption of heavy metal ions). Adsorption of heavy metals such as lead, cadmium and copper from textile effluent by CNCs/AgNPs is estimated with 88.68%, 35.44% and 88.04% removal efficiency. This recent development on low cost, natural waste derived sustainable production of novel metal-organic framework based CNCs/AgNPs adsorbent encourages sustainable waste management practices specially towards circular economy concept (3R's) which suggests waste reduction, recycling, and reuse of waste in the production of eco-friendly materials for cleaner environment. [18]

3.2.6.9 Layered double hydroxide–agarose composites for water treatment: carbonate contamination during the drying process

Layered double hydroxides (LDH) are anion exchangers and have been investigated intensively as adsorbents for removal of hazardous and toxic anionic substances in water treatment. However, LDH, which are usually synthesized in the form of a powder, are often difficult to separate from suspensions in water treatment. Incorporating LDH into composite hydrogels is a strategy to avoid this difficulty: in this study, aqueous suspensions of Cl-containing LDH of high and low crystallinity were mixed with agarose solution while heating, and the mixtures were allowed to cool to form gels. However, in wet conditions, LDH would be susceptible to carbonate contamination from atmospheric CO2. In this context, LDH–agarose composite hydrogels were synthesized, and gels dried in three different ways (air drying, oven drying in air at 110 °C, and vacuum drying) were evaluated as anion adsorbents by using SO42 −. The air-dried gels showed significant reductions in SO42 − adsorption abilities compared to those of the original undried gels: 56% reduction for air-dried gels containing the low-crystallinity LDH and 29% reduction for air-dried gels containing the high-crystallinity LDH. This result shows that carbonate contamination was extremely serious for low-crystallinity LDH in the gel. In contrast, the oven- and vacuum-dried gels retained adsorption abilities that were almost the same as those of the original undried gels, regardless of crystallinity of LDH in the gels. Powdery form of LDH showed similar results about drying. These results show how important the drying methods are and provide fundamental information about carbonate contamination.

3.2.6.10 Photocatalytic degradation of Rhodamine-B dye using composite prepared from drinking water treatment sludge and nano TiO_2.

In this study, composite Sludge adsorbent (ASN)/TiO2 was prepared from the drinking water treatment sludge ASN (activated with nitric acid) and nanoparticle TiO2 by the sol-gel method, followed by using it to remove Rhodamine-B (RB) dye from polluted water. The prepared composite was characterized by transmission electron microscopy, X-ray fluorescence spectrometry, X-ray diffraction, and surface area N2-adsorption/desorption analysis. Photocatalytic degradation of RB dye was investigated by UV and UV/hydrogen peroxide (H2O2) irradiation. Parameters such as composite dosage, initial dye concentration, UV irradiation time, and solution pH were applied to obtain the optimum conditions for high RB dye degradation. The results showed that the highest RB dye degradation (96.7%) was using a 2:1 ratio of ASN/TiO2. High degradation of dye was achieved within 4 h at pH 7, 50 ppm dye concentration, and 0.125 g/50 ml composite dose. The maximum degradation of RB dye using the prepared composite under UV irradiation with H2O2 (99.85%) was higher than that with UV irradiation only (96.85%). The rate of the dye photocatalytic degradation followed the first-order kinetics. [20]

3.2.6.11 Application of polyaniline-manganese nanocomposite for water pollution control

Water resources are currently being contaminated because of the rapid rise of industrialization, urbanization, population growth, and climate change. The biggest risk for many nations is a lack of clean, fresh water. The focus and attention of numerous scientists and governmental organizations have recently turned to water purification techniques. For efficient and effective sanitization of water bodies, academics from all over the world are focusing on water purification technologies centered on nanotechnology. Due to their great surface area, high chemical reactivity, excellent mechanical strength, and low cost, nanoscale composite materials offer a significant potential to cleanse water in a variety of ways. Polymer nano-composites (Polyaniline-Mn) have been selected as an effective and economical solution for wastewater pollution treatment. An effectiveness of polymer nano-composites for water purification is provided in this research [21]

3.2.6.12 Efficient preparation of greener N-doped carbon nanotube composites for water treatment by the microwave polyol method

N-doped carbon nanotubes have unique structures and strong interactions with metal nanoparticles due to the presence of nitrogen. There is actually a need for nanoparticles to treat water, without leaching of toxic metals. Here, we synthesized nanocomposites by deposition of Ag and Fe nanoparticles on N-doped carbon nanotubes with a surface area of 52 m2/g and 2 % N content to form nanocomposites. Transmission electron microscopy (TEM) of the nanocomposites revealed that the best dispersion of the deposited nanoparticles was achieved by the microwave-assisted polyol method. The Ag and Fe nanoparticles were indeed monodispersed and uniformly distributed on the surface of the N-doped carbon nanotubes. Deposition could be achieved in 5 min. The wet impregnation and deposition–precipitation methods gave composites with agglomerated nanoparticles. We observed that leaching of Fe and Ag into water was also influenced by the preparation method. No leaching of nanoparticles was observed when the composites were prepared by the microwave polyol method. This synthesis is therefore efficient with less energy and time. The strong metal/N-doped carbon nanotube interactions render these composites suitable for use in water purification [22].

3.2.6.13 Tensile Property of the Flax/Polyester Composites after Water Treatment

Flax fabric was woven and composites were produced by using the VARI technique with flax fabric as the reinforcement and unsaturated polyester as the matrix. Laminates with two, three and four layers were fabricated respectively. After saturated in the water for different durations of time (7, 14, 21 and 30 days), the tensile strength of the composites was tested. After being soaked in the water for 7, 14 and 21 days, the tensile strength of the two-layer composites was decreased. For the three and four layers specimens, the tensile strength was increased initially with water treatment for 7 and 14 days,and decreased for 21 and 30 days. Scanning electron microscopy (SEM) confirmed that it might be contributed to the thickness of the two-layer composites. The thinner specimen is easier to be damaged by the penetrated moisture owing to the delamination between the fiber and the matrix after water immersion. For the three and four layers specimens, their contradictory tensile strength suggests that the thicker specimen can delay the moisture permeation and is of better water durability [23].

Fabrication and Application of Photocatalytic Composites and Water Treatment Facility Based on 3D Printing Technology . Currently, the degradation of organic pollutants in wastewater by photocatalytic technology has attracted great attention. In this study, a new type of 3D printing material with photocatalytic activity was first prepared to print a water treatment equipment, and then a layer of silver-loaded TiO2 was coated on the equipment to further improve the catalytic degradation performance. The composite filaments with a diameter of 1.75 ± 0.05 mm were prepared by a melt blending method, which contained 10 wt% of modified TiO2 and 90 wt% of PLA. The silver-loaded TiO2 was uniformly coated on the equipment through a UV-curing method. The results showed that those modified particles were uniformly dispersed in the PLA matrix. The stable printing composite filaments could be produced when 10 wt% TiO2 was added to the PLA matrix. Moreover, the photocatalytic degradation performance could be effectively improved after 5 wt% of silver loading was added. This novel facility showed good degradability of organic compounds in wastewater and bactericidal effect, which had potential applications for the drinking water treatment in the future [24].

3.2.6.14 Ultrafine silver(II) oxide particles decorated porous ceramic composites for water treatment

Ultrafine silver(II) oxide particles-decorated porous ceramic composites have been prepared directly by chemical oxidation, with diatomite-based porous ceramics as the carrier. The prepared composites were characterized by mercury intrusion method, XRD, XPS, FT-IR, SEM, AAS and shake-flask method. The results show that silver(II) oxide decorated diatomite-based porous ceramic composites possess crystal structure and are composed of tetragonal cristobalite, monoclinic silver(II) oxide and cubic silver(I) oxide. The silver(II) oxide weight percentage content of the composites prepared is 8.5% and the average pore diameter, median pore diameter, apparent density and porosity of the composites are 3.862 μm, 0.354 μm, 1.794 g mL^{-1} , and 57.985%, respectively. The composite can release silver in water solution, with a release rate of 7.420×10^{-3} mg L^{-1} h^{-1} . The composites show the strong bactericidal activity. When the contact time with Staphylococcus aureus and Escherichia coli exceeds 20 min, the bactericidal rates reach up to 99.9%. [25].

3.2.6.15 Property improvement of natural fiber-reinforced green composites by water treatment

In the present study, natural fibers (jute, kenaf and henequen) reinforced thermoplastic (poly(lactic acid) and polypropylene) and thermosetting (unsaturated polyester) matrix composites were well fabricated by a compression molding technique using all chopped natural fibers of about 10 mm long, respectively. Prior to green composite fabrication, natural fiber bundles were surface-treated with tap water by static soaking and dynamic ultrasonication methods, respectively. The interfacial shear strength, flexural properties, and dynamic mechanical properties of each green composite system were investigated by means of single fiber microbonding test, 3-point flexural test, and dynamic mechanical analysis, respectively. The result indicated that the properties of the polymeric resins were significantly improved by incorporating the natural fibbers into the resin matrix and also the properties of untreated green composites were further improved by the water treatment done to the natural fibbers used [26].

3.2.6.16 Current Advances of Polymer Composites for Water Treatment and Desalination

Over the past five years, a lot of research activities in polymer composites were done to improve environmental sustainability and to present advantages for commercial applications of water treatment and desalination. Polymers offered tunable properties, improved processability, remarkable stability, high surface area for fast decontamination, selectivity to eliminate different pollutants, and cost-cutting of water treatment. Hence, the development of polymeric materials is one of the future directions to meet the environmental water standards and to supply the water requirements of the growing populations. This review highlighted the very recent achievements in fabrication, characterization, and applications of polymeric composites used for water treatment and desalination. The polymeric modifications, the addition of functional groups, and the assemblies of nanomaterials were also discussed in detail. In particular, great attention was paid to the recent advances in polymer/polymer composites, polymer/carbon composites, and polymer/clay composites, presenting their usage in the removal of various types of contaminants, e.g., metal ions, dyes, and other toxic pollutants. The review also summarized the main advantages and disadvantages of the different adsorbent materials. Specific attention was paid to the mechanism of adsorption, including chemisorption and physisorption mechanisms. In addition, the challenges and the future perspectives were identified to reach the optimal performance of the different adsorbents [27].

3.2.6.17 The performance changes and migration behaviour of PLA/nano-silver composite film by high-pressure treatment in food simulation solution

Polylactic acid (PLA) is one of the most promising biodegradable materials, which can reduce the environmental pollution caused by food and material industry. The effect of the addition proportion of nano-silver and different food simulant on the migration and the performance changes of film during migration were evaluated, revealing the association between the performance changes and nano-silver migration. The results showed that nano-silver had the largest migration amount and the fastest migration rate in 4% (v/v) acetic acid solution, followed by 50% (v/v) ethanol solution, and the lowest in isooctane solution. Performance changes were affected by the compatibility of silver nanoparticles and PLA, and the strength of the interaction between the film and acetic acid. Performances of composite film deteriorated during high proportions of nano-silver addition and long soaking. Adding a small amount of nano-silver to the composite was the effective method considering the balance between good performances and migration [28].

3.2.6.18 Prospective life cycle assessment for sustainable synthesis design of organic/inorganic composites for water treatment

Considering a sustainable approach to the production of novel materials used for water treatment processes, this study presents the development and implementation of prospective life cycle assessment (LCA) as an environmental support tool to identify and quantify the potential environmental impacts during the design, synthesis and testing of innovative organic/inorganic composites for heavy metal ions removal. This research explores two layer-by-layer syntheses routes to develop silica//polyethylenimine (PEI) microparticles with similar characteristics but different efficiencies in the sorption of Cu2+ ions from water and it investigates how scenario-based LCA may be used to forecast potential environmental impacts and sustainability hot spots during the design and synthesis phases. Furthermore, the study explores different approaches to critical LCA elements (e.g. functional units, system limits, design scenarios, and uncertainty analysis). The LCA uses a cradle-to-gate approach for the laboratory scale synthesis and testing processes of inorganic/organic composites, for which chemicals and energy production processes were considered in the life cycle inventory (LCI). Life cycle impact assessment (LCIA) was performed with ReCiPe 2016 at midpoint in 3 steps: at first, initial environmental profiles were generated to evaluate the environmental impacts of the two silica/polymer composites syntheses routes; secondly 3 alternative eco-design scenarios were investigated for replacing some of the chemicals and finally, a scenario-based sensitivity analysis was performed to investigate how inventory data impacts the environmental profiles. The environmental profiles of the two syntheses routes have shown that the B synthesis strategy leads to lower environmental impacts, except for the toxicity related categories, where the initial PEI complexation with Cu2+ ions leads to higher environmental impacts. The eco-design scenarios have demonstrated that by changing the silica support particle with inert quartz microparticles would greatly increase impacts, while changing the initial PEI complexation ion from Cu2+ to another metal would decrease the toxicity related impacts. A sensitivity analysis has recorded significant coefficients of variability for 10 out of 18 impact categories, meaning high uncertainty for these impact values and has identified the silica source as the most important variability contributor [29].

3.2.6.19 Exploring the synergistic effect of MXene@ZIF-8 hybrid composites for water treatment

Due to their exceptional physical and chemical properties, MXenes have been the focus of growing research attention for their potential to effectively eliminate a wide range of pollutants from the aquatic environment. However, disadvantages such as limited adsorption capacity due to low specific surface area and undeveloped porosity have led to challenges in using these materials. In this work, we use a well-known MXene, Ti3C2Tx, by decorating zeolitic imidazole frameworks (ZIF-8) between MXene layers (MX@ZIF) to remove methyl orange (MO) and ciprofloxacin (CIP), as well as, the effect of -O and -OH terminal groups on adsorption efficiency of MX@ZIF substrate is investigated. Our findings from molecular dynamics simulations showed that the MXO@ZIF and MXOH@ZIF systems have stronger electrostatic interactions than the MX@ZIF system due to the formation of hydrogen bonds between the –O, –OH terminal groups from the substrates and heteroatoms of pollutant molecules. Moreover, the van der Waals energy values in the MXOH@ZIF-CIP and MXOH@ZIF-MO systems are − 253.454 and − 201.660 kJ/mol, respectively, demonstrating the effective adsorption and removal of contaminants by designed substrates. The MD results show that the van der Waals interaction has a greater contribution than the electrostatic interaction in studied systems. Also, the number of contacts of pollutant molecules with the substrate increases with time, and the highest number of contacts belongs to the MXOH@ZIF-CIP and MXOH@ZIF-MO complexes, demonstrating that this substrate has a greater tendency to adsorb pollutants. Furthermore, the results of AIM calculations confirm the presence of non-covalent interactions between pollutant molecules and studied substrates. This study shows that MXOH/ZIF can be considered a promising high-performance adsorbent for removing organic dyes and antibiotics [30]

3.2.6.20 Adsorption removal of lead ions from water-filtration system filter poly lactic acid coated nano iron oxide

PLA-manufacturing composites for water treatment applications is a recent development made possible by the efficiency of 3D printing. It creates intricate items quickly and affordably, making it preferable to traditional production methods. There has been a significant rise in study utilizing applications of 3D printing for desalination, membrane separation, and water purification using sustainable manufacturing in recent years. In this review research efficiency of lead ions removal from s wastewater by adsorptive filtration (PLA filter coating with nano iron oxide) through batch processes was investigated under conditions of infill filter, diameter filter, adsorbent dose, pH, initial concentration of Pb ions, and contact time. And biodegradable PLA materials were used for manufacturing of 3-D water system filter the CAD software will convert the 3-D model to STL format to print. (α-Fe_2O_3) Nano was synthesized by the co-precipitation technique and coated on the PLA filter system. Many techniques were utilized for α-Fe_2O_3 characterization such as (XRD, EDX, and SEEM). The methods indicate the effective creation of α-Fe_2O_3 with a surface area of 95 m^2/g, consisting of 32.7% iron and 67.3% oxygen. This study will utilize the Langmuir isotherm model, while the kinetic study was accurately described by the pseudo-second- order. The imprinted polymer exhibited a remarkable maximum adsorption capability of 172.413mg/g at pH 6. 98.34% removal at optimum conditions: 300 ppm,1gm dose, 70% infill, 50 cm diameter filter [31]

3.2.6.21 Evaluation of Biological Effects of Nanoneedle Calcium Carbonate Crystals Used for Water Treatment

Aragonite nanoneedles were synthesized for use in purifying drinking water via a mechano-bactericidal effect, and the biological effects of this aragonite and the calcium carbonate compounds produced during its synthesis were evaluated. Three types of cells (intestinal epithelial-derived Caco-2 cells, keratinocyte-derived HaCaT cells, and macrophage-differentiated THP-1 cells) were exposed to four types of calcium carbonate compound suspensions containing aragonite nanoneedles. No effects on cell viability were observed for any of the cells. However, at a high concentration of 1000 mg/mL, cell membrane damage was observed. In particular, cell membrane damage was observed in THP-1 cells. The acicular calcium carbonate samples also significantly induced IL-8 expression in THP-1 cells. In particular, one of the calcium carbonate compounds significantly promoted the expression of IL-8, TNF-α, MCP-1, and IL-1β. In THP-1 cells, an increase in intracellular calcium levels was also observed. These in vitro results suggest that calcium carbonate-containing aragonite nanoneedles have the potential to induce inflammation. To confirm that inflammation is actually induced in the body, in vivo examinations were performed. These acicular calcium carbonate suspensions were administered intraperitoneally to C57BL/6N mice. Serum cytokines were measured 1 and 3 months later. No significant difference in effect was observed among the samples. Pathological observations also showed no induction of inflammation. These results suggest that acicular calcium carbonate has the potential to induce cytokine secretion by macrophages, but that its in vivo effects are limited. At the levels present in drinking water, the effects of acicular calcium carbonate are likely to be small. These findings pave the way for the application of aragonite nanoneedles in water purification, potentially contributing to the resolution of drinking water challenges, particularly in developing countries. [32]

3.2.6.22 Nano-chitosan-Aloe Vera Coating with Tomato Seed Protein Hydrolyzate for Preserving Button Mushroom (Agaricus bisporus) Quality.

Button mushroom (Agaricus bisporus) is a widely consumed edible mushroom, but its quality deteriorates rapidly after harvest. Therefore, the use of edible coatings with natural preservative compounds is essential for delaying microbial growth and maintaining mushroom quality. This study examined the effects of a nano-chitosan (NC) and aloe vera (AV) edible coating combined with tomato seed protein hydrolyzate (TPH) as a natural preservative on the chemical, microbial, and organoleptic properties of button mushrooms. TPH was prepared using the enzyme Alcalase. Five edible films containing NC, NC-AV, and varying concentrations of TPH (0%, 0.5%, 1%, 1.5%) were produced. The relationship between the concentration of TPH and the resulting physicochemical properties was investigated. The shelf lives of coated mushrooms were evaluated during 16 days of refrigerated storage (4 ± 1 °C). Results showed that TPH had high levels of protein (90.16%), hydrophobic amino acids (31.78%), and aromatic amino acids (11.74%). The produced films exhibited significant antioxidant and antimicrobial activities, with improvements observed at higher concentrations of TPH ($P < 0.05$). The interaction between the protein hydrolyzate film and the mushroom's natural proteins may enhance nutrient retention and stability. Compared to uncoated mushrooms, the nanocomposite coatings significantly reduced physicochemical changes, quality degradation, and microbial spoilage. Increased concentrations of TPH further enhanced browning inhibition, free radical scavenging, and reduction of microbial spoilage ($P < 0.05$). Sensory evaluation indicated that the sample containing 1.5% TPH had the highest overall acceptance. The NC-AV composite coating containing TPH effectively extended the shelf life of button mushrooms by approximately 8 days [33].

3.2.6.23 Surfactant-modified coconut coir powder (SMCCP) as a low-cost adsorbent for the treatment of dye-contaminated wastewater: parameters and adsorption mechanism.

The dye-contaminated wastewater discharged from various industries such as dye manufacturing, paint, textile, paper, and cosmetic is a prime source of surface water pollution having serious detrimental effects on both the environment and human beings. These hazardous dyes when exposed to water obstruct the penetration of sunlight into the water and thus restrain aquatic plants from generating photosynthetic compounds. Moreover, some dyes are potential cancer-causing and also negatively impact the human nervous and respiratory systems. In this current study, modification of coconut coir powder (CCP) was carried out through cationic surfactant treatment and was successively utilized as the adsorbent for decoloring anionic dye (acid blue 185 (AB 185)) containing waste stream. Further, a comparative investigation of the dye removal efficiency of raw CCP and surfactant-modified coconut coir powder (SMCCP) as the adsorbent was studied. On surfactant treatment, using a very minimal SMCCP dosage of 8.3 g/L, a very high percentage dye removal of 98.4% is possible, whereas with raw CCP, even after using a higher dosage of 14 g/L, only 70.1% dye removal can be achieved. Characterization of SMCCP adsorbent was done by Fourier transform infrared, thermogravimetric, X-ray, and scanning electron microscope analyses. Furthermore, the optimization of critical operating parameters was investigated for the effective adsorption of AB 185 dye in batch mode. The adsorption of AB 185 onto SMCCP was a thermodynamically spontaneous endothermic process, following the Langmuir isotherm and pseudo-second-order kinetic model. Moreover, regeneration of exhausted SMCCP by 0.1 (M) NaOH was achieved with a satisfactorily high recovery of 97% in the first cycle. Subsequently, SMCCP can be successfully reutilized for five consecutive cycles with a loss of 17.6% in the total adsorption capacity. With all such advantages, the present study delivers a new paradigm to utilize the novel adsorbent SMCCP as a promising eco-friendly adsorbent aided by its advantage of regeneration and reusability for the treatment of dye-contaminated wastewater [34].

3.2.6.24 Microstructure-guided design of biopolymer-supported tri-phasic TiO_2 for sustainable lead and cadmium detoxification

The feasibility of synthesizing tri-phasic TiO2 Nano-particles via the sol-gel method and their immobilization within chitosan biopolymer matrix was investigated. Structural characterization using XRD, HR-TEM, FTIR, and UV-vis DRS confirmed the successful formation of a stable hetero-structure consisting of anatase, rutile, and brookite phases (A34.6R56.8B8.6) with strong interfacial interactions within the biopolymer matrix. Reduced direct and indirect band gaps to 2.97 and 2.58 eV, respectively, demonstrated improved optical characteristics under sunlight. The immobilized tri-phasic TiO2 Nano-particles within chitosan biopolymer matrix exhibited significantly enhanced sorption performance toward Pb2+ and Cd2+ ions, reaching maximum removal efficiencies of 99.86% for Pb2+ and 97.85% for Cd2+ at pH 7, with equilibrium contact times of 90 and 120 min, respectively. According to the Langmuir isotherm model, the maximum removal capacities were 73.67 mg/g for Pb2+ and 68.72 mg/g for Cd2+. These results highlight the potential of the biopolymer-supported tri-phasic TiO2 Nano-composite as a sustainable and effective material for detoxifying heavy metals in water treatment applications [35].

3.2.6.25 Effect of Heat Treatment on the Molecular and Functional Properties of Pea Protein Isolate

This work aimed at understanding the effect of heat treatment on the properties and functionalities of pea protein isolate (PPI). PPI was characterised using thermogravimetric methods coupled with evolved gas analysis, differential scanning calorimetry, and X-Ray powder diffraction. As water is an integral component in determining protein properties, inelastic neutron scattering was further used to study water populations in the PPI powder. Hydration time was identified as key in determining solubility. Heat treatment resulted in partially denatured, more soluble, less thermodynamically stable, and less crystalline PPI compared to the control. Heating, often associated with protein aggregation and particle size increase, was found to reduce PPI particle sizes, which was attributed to the disruption of non-covalent interactions. During emulsification, these features enhanced formation of smaller drops, stable against coalescence. Compared to the control, the heat-treated PPI produced emulsions with increased shear thinning (power law index of 0.6 compared to 0.9) and consistency (≈10 times higher), as it has been previously reported for emulsions with fine, compared to coarse, droplets. Acid-induced gels of the heat-treated PPI were ≈4 times more elastic (G') compared to the control. Overall, this work contributes towards the design of plant-based foods with predictable characteristics by understanding the link between protein physicochemical properties and food functionality [36].

3.2.6.26 Reactive engineered biochar from agricultural wastes and its application for water purification.

The remediation of water contaminated with toxic oxy-anions and persistent antibiotics remains a significant challenge. This study addresses this issue by designing a novel, multifunctional sulfur-iron engineered magnetic biochar (S-Fe-BC) from corn stover for the simultaneous removal of hexavalent chromium (Cr (VI)) and sulfamethoxazole (SMX). The material was synthesized through a sequential process of pyrolysis, magnetite (Fe_3O_4) impregnation, and sulfidation, resulting in a composite with integrated magnetic separability (28.4 emu/g), a reactive FeS shell and a porous carbon matrix. Comprehensive characterization confirmed successful functionalization and revealed key structure-property relationships. Batch experiments demonstrated high Langmuir adsorption capacities of 118.9 mg/g for Cr (VI) and 65.1 mg/g for SMX. Mechanistic investigations using XPS and radical quenching elucidated distinct removal pathways, that are; Cr (VI) was primarily reduced to less toxic Cr (III) by surface Fe^{2+} /S^{2-} species (82% conversion), while SMX was eliminated via adsorption followed by peroxydisulfate-activated catalytic degradation, driven mainly by sulfate radicals. In competitive binary systems, S-Fe-BC showed preferential removal of Cr (VI). The material maintained robust performance in a complex synthetic water matrix and exhibited excellent reusability over five cycles with >78% capacity retention and minimal metal leaching. A preliminary techno-economic analysis suggested viable production costs. This work provides a sustainable, multifunctional adsorbent-catalyst and a detailed mechanistic framework for tackling complex inorganic-organic water pollution [37].

3.2.6.27 Research Progress on Material, Preparation, Properties, and Water Purification Applications of Solar Energy-Driven Hydrogels.

The global water resource crisis is continuing to intensify, and it is urgent to develop low-energy consumption and sustainable water purification technologies. Traditional water purification technologies can address the issue of water shortage. However, these traditional water purification technologies have many limitations, including high energy consumption, secondary pollution, etc. Solar-powered water purification technology has become a current research hotspot due to low cost, high efficiency, and environmental friendliness. Solar-driven hydrogels (SDHs) with high hydrophilicity and porous structure, as the emerging water purification materials, can efficiently convert solar energy into thermal energy through photothermal conversion, thereby enhancing the efficiency of interface evaporation, which provides innovative solutions for seawater desalination and wastewater treatment. This article systematically reviews the advanced substrate materials and photothermal agents utilized in SDHs. Moreover, this review comprehensively introduces the preparation strategies and mechanisms of SDHs. Furthermore, this paper comprehensively explores the design principles for enhancing the efficiency of light-to-heat conversion and the rate of water evaporation, and improving mechanical strength, durability, and salt resistance. Finally, the review discusses the practical applications of SDHs in seawater desalination, heavy metal ion removal, organic dye degradation, etc., while exploring their innovative roles in multi-level solar energy utilization and water resource recovery [38].

3.2.6.28 Enhanced Functionalities of Starch-Based Nanocomposite Films Incorporating Lignin Nanoparticles and Cinnamaldehyde for Sustainable Food Packaging Applications.

The utilization of lignin nanoparticles (LNPs) derived from black liquor, in combination with cinnamaldehyde (CI), shows great potential for the development of high-performance composite films in the food packaging industry. This study presents an approach for preparing LNPs from black liquor and integrating them with CI into starch (ST) films to produce active nanocomposite films with specific functionalities. Binary and ternary ST-based nanocomposites were prepared with varying weight percentages of LNPs (1, 3, and 5 wt%) and CI (3 and 5 wt%). Characterization of the resulting nanocomposites revealed significant improvements in physicochemical, morphological, thermal, mechanical, optical, antioxidant, and antimicrobial properties. The composite films exhibited a low water vapor transmission rate (WVP: 3.97 to 3.06 × 10− 10 g s− 1m− 1Pa− 1), reduced water solubility (WS: 53.00 to 19.76%), and enhanced mechanical strength (tensile strength: 3.66 to 5.15 MPa). The inclusion of LNPs also provided UV-blocking properties while maintaining visible light transmission and improved thermal stability. Morphological studies showed smooth surfaces without cracks or pores. Additionally, the composite films demonstrated antibacterial activity against S. aureus and E. coli, with enhanced efficacy in ternary-based nanocomposites. Overall, the combination of ST film with LNPs and CI shows promise for advanced functionalities in food packaging applications [39].

3.2.6.29 Ball Milling-Ultrasound Modification of Citrus Fiber-Carrageenan Complex for Improving Functional Properties of Salted Egg White

Effect of ball milling (BM) (6 h) combined with ultrasound (U) (200 and 400 W, 10, 20, 30 min) modified citrus fiber-carrageenan (CFC) on functional properties of salted egg white (SEW). Compared with single BM modified CFC, after 200 W-U-treatment for 10 min of CFC, gel strength, gel water-holding capacity (WHC), surface hydrophobicity, emulsifying activity index (EAI), emulsifying stability index (ESI) and FC of CFC-SEW complex increased by 12.10, 2.60, 43.15, 6.59, 6.71 and 42.71%, respectively, whereas its FS decreased by 6.48%. Fourier transform infrared spectroscopy (FTIR) shown that after BM-U treatment of CFC, the hydroxyl content of CFC-SEW complex was increased. Scanning electron microscope (SEM) demonstrated that SEW was tightly embedded with CFC after BM-U treatment. Thus, addition of BM-U treatment of CFC would be an effective approach for improving functional properties of SEW, possibly expanding the application of SEW with high salt contents in food processing fields.Highlights: FG treated by BM-U better improved functional properties of SEW than single BM. Particle size of FG-SEW was reduced after BM-U treatment of FG than single BM. BM-U treatment of FG could promote protein was tightly embedded with it. BM (6h)-U (200W, 10min) treated FG made SEW show the best functional properties [40]

3.2.6.30 Perilla (Perilla Frutescens L.) Seed Protein Isolate: A Current Status on Emerging Extraction Processes, Multilevel Techno-Functional Properties and Industrial Applications

Perilla seed (Perilla frutescens L.), being an important source of plant protein and part of the Lamiaceae family, is well known for its nutritional value, health benefits, and industrial applications with sustainability. It contains ~ 25% protein and essential amino acids. It is widely distributed in southeast Asia and the Indian Highlands; it is used as human food but is still underutilized and under-researched. Therefore, this review article aims to summarize the nutritional importance, potential health benefits, bioactivities, and chemical composition of perilla seed. Moreover, a detailed description of the isolation of protein from perilla seed using different extraction technologies is critically discussed to identify the most efficient protein extraction method. There are numerous ways to separate seed protein isolates using extraction technologies, among which emerging technologies provide better yields with higher efficiency and less wastage than conventional methods. Apart from the extraction technologies, functional parameters, including water holding capacity, solubility, emulsifying, foaming ability, etc. amino acid profile, and structural properties of perilla protein isolates are briefly discussed to investigate the potentiality. As food industries have placed higher priority on the development of healthy food through the incorporation of functional ingredients, perilla can also be another option for these industries as it has diverse functions. Being a rich plant-based protein, it can be further incorporated with food products to fulfil the requirements of daily intake [41].

3.2.7 Carbon Quantum Dots: A Green and Efficient Material for Fruits and Vegetables Preservation.

Fruits and vegetables deteriorate easily in quality due to their high water content and active metabolic processes, leading to significant economic losses. The development of novel, environmentally friendly, and cost-effective preservation technologies is highly required. This paper provides a comprehensive review about one novel promising preservation technology – carbon quantum dots (CQDs), includes their synthesis methods, physicochemical properties, and applications on fruits and vegetables. The synthesis methods of CQDs includes "Top-down" strategies and "Bottom-up" strategies. CQDs illustrate excellent antibacterial, antioxidant, UV-blocking, and potential ethylene-regulating capabilities, making them promising candidates for enhancing the shelf life of fruits and vegetables. Additionally, CQDs may also be used as intelligent indicators for real-time monitoring of the freshness of fruits and vegetables. We also discussed the safety of CQDs and pointing out the future research directions, such as clarifying the ethylene removal mechanism and combining with nanotechnology to extend application effect of CQDs. This review aims to provide a comprehensive understanding of the potential applications of CQDs in extending the shelf life and improving the quality of fruits and vegetables. [42].

4 CONCLUSION

Nanocomposites have emerged as highly promising materials for water treatment due to their unique physical, chemical, and mechanical properties. Their high surface area, enhanced adsorption capacity, and catalytic and antimicrobial activities make them effective in removing a wide range of contaminants, including heavy metals, organic pollutants, dyes, pathogens, and emerging contaminants. Compared with conventional treatment methods, nanocomposite-based technologies often provide higher efficiency, faster treatment rates, and improved reusability. Despite these advantages, challenges such as production cost, large-scale implementation, environmental safety, and the potential release of nanoparticles must be addressed before widespread commercialization. Future research should focus on developing sustainable, cost-effective, and environmentally friendly.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

I am interested in water treatment and removal of heavy metals using environmentally friendly materials also low-cost materials and applied electrochemistry like electropolishing, electroplating, and corrosion

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