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वर्ष-16, अंक-3, जून जुलाई अगस्त 2023

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प्रकाशक-श्रीमती पुष्पा शर्मा, 51/1509, वेद विहार, लोहाखान, अजमेर द्वारा मैसर्स सृजन संस्थान, अजमेर की ओर से प्रकाशित एवं मुद्रक-श्रीमती उषा गर्ग द्वारा मैसर्स आर्य प्रिन्टर्स, केसरगंज, अजमेर से मुद्रित।

Nanomaterial-Based Purification Technologies: A Chemistry Perspective

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1. Introduction

Clean and safe drinking water is a fundamental necessity, yet millions of people worldwide lack access to contaminant-free water. Industrial discharge, agricultural run-off, heavy metals, organic pollutants, pathogens, dyes, and pharmaceutical residues threaten global water quality. Conventional purification methods-such as sand filtration, chlorination, and activated carbon-often fall short in removing emerging contaminants. In recent decades, nanomaterial-based purification technologies have emerged as highly effective alternatives due to their unique surface properties, high reactivity, tunable structure, and enhanced adsorption capacities.

Nanomaterials work at the molecular level, allowing faster, selective, and more efficient removal of pollutants.

2. Chemistry of Nanomaterials in Water Purification

Nanomaterials (1-100 nm) possess a high surface-to-volume ratio, enhanced surface energy, and active functional groups, making them ideal for binding, degrading, or transforming contaminants.

Key chemical properties enabling purification:

Adsorption capability: High surface area allows trapping of metal ions and organic molecules.

Photocatalytic activity: Materials like TiO2 generate reactive oxygen species (ROS) under UV/visible light to degrade pollutants.

Antimicrobial mechanism: Silver nanoparticles (AgNPs) release Ag+ ions that disrupt bacterial enzymes and DNA.

Redox reactivity: Zero-valent iron (nZVI) reduces toxic metals such as Cr(VI) to less toxic Cr(III).

Functionalization chemistry: Surface modification with polymers. ligands, or biomolecules enhances? selectivity.

3. Major Nanomaterials Used in Water Purification

3.1 Metal and Metal-Oxide

Nanoparticles, Silver Nanoparticles (AgNPs) Act as powerful antimicrobial agents.

Mechanism: Ag^+ ions bind to bacterial cell walls and generate ROS ? cell death.

Used in household filters, membranes, and point-of-use technologies.

Titanium Dioxide (TiO_2) Nanoparticles . Excellent photocatalysts.

Under UV/visible light, TiO_2 forms OH and O_2 radicals which degrade:

dyes, pesticides, pharmaceuticals.

Safe, stable, non-toxic, widely used in advanced oxidation processes (AOPs). Iron Nanoparticles (nZVI). Used for heavy metal removal and chlorinated organic pollutant degradation.

Provide reductive transformation of contaminants.

Example: Cr(VI) $\rightarrow$ Cr(III), TCE ethene/ethane.

3.2 Carbon-Based Nanomaterials Carbon Nanotubes (CNTs)

Possess high adsorption ability for metals and hydrophobic organic compounds.

Surface functionalization (-COOH, -OH) improves dispersion and enhances binding capacity. CNT membranes show faster water flux and high strength.

Graphene and Graphene Oxide (GO) sheets are rich in oxygen groups ? excellent adsorption for heavy metals like Pb^{2+}, Cd^{2+}, As^{3+}. Graphene membranes exhibit near-perfect selectivity for desalination and dye removal. High conductivity also enables electrochemical purification.

3.3 Polymer-Based Nanomaterials Nanofibers and Nanocomposites

Produced using electrospinning. Can incorporate AgNPs, TiO2, ZnO, or activated carbon to provide multi-functional purification.

Used in point-of-use portable filters.

3.4 Zeolite and Clay Nanomaterials

Nanostructured zeolites have high cation-exchange capacity. Efficient for removing ammonium, heavy metals, and radionuclides.

Clay nanomaterials offer cost-effectiveness and naturalabundance.

4. Nanotechnology-Based Water Purification Techniques

4.1 Nanofiltration (NF)- A pressure-driven membrane process with pore sizes of 1 nm.

It selectively removes: multivalent ions (Mg2+, Ca2+), dyes, organic molecules.Nanomaterial coatings (CNTs, TiO?) enhance flux and reduce fouling.

4.2 Photocatalytic Water Treatment

TiO_2, ZnO, and doped semiconductor nanoparticles are used.

Mechanism: Light excites electrons (e-) $\rightarrow$ conduction band. Holes (h+) remain in the valence band. e-/h^+ pair reacts with water/oxygen ROS generation.

ROS break pollutant molecules into CO_2, H_2O.

Applications: dye degradation in textile industry wastewater, herbicide/ pesticide treatment,

pharmaceutical residue destruction.

4.3 Adsorption-Based Nanotechnology

GO, CNTs, nZVI, and metal-oxide nanoparticles adsorb contaminants through:

ion exchange, electrostatic attraction, ?-? interactions, surface complexation.

Advantages:

fast kinetics,

high capacity,

selective adsorption.

4.4 Antimicrobial Nanotechnology

AgNPs, ZnO, and CuO nanoparticles are incorporated into membranes and filters to kill bacteria, viruses, and fungi.

Mechanisms include:

membrane disruption,ROS generation, protein/enzyme inactivation,interference with DNA replication.

4.5 Magnetic Nanoparticle Purification

Magnetite nanoparticles (Fe3O4) are functionalized to bind pollutants.After treatment, a magnetic field is used to remove nanoparticles along with adsorbed contaminants.

Useful for: dyes, arsenic,chromium ions.

5. Advantages of Nanomaterial-Based Water Purification

Highly efficient even at low concentrations.

Faster purification rates.

Reduced energy consumption compared to thermal methods.

Tunable chemical properties for selective removal.

Capable of removing emerging contaminants (microplastics, pharmaceutical residues).

6. Environmental and Health Concerns

While extremely effective, nanomaterials raise concerns:

potential toxicity to aquatic organisms,

persistence and bioaccumulation, difficulty in separation from treated water, need for regulation and safe disposal methods.

Green synthesis using plant extracts and biodegradable polymers is being explored to minimize risks.

7. Future Prospects

Development of smart nanomaterials that can detect and degrade contaminants simultaneously.

Solar-driven photocatalytic systems for rural and remote water purification. Low-cost nanocomposite filters for household use.

Integration with IoT sensors for real-time water quality monitoring. Biodegradable and eco-friendly nanomaterials to reduce toxicity concerns.Nanotechnology is expected to play a crucial role in achieving UN Sustainable Development Goal 6 (Clean Water & Sanitation).

8. Conclusion

Nanomaterial-based technologies represent a breakthrough in modern water purification chemistry. Their high reactivity, tunable surface chemistry, and versatility enable removal of a broad spectrum of pollutants that conventional methods fail to treat. While environmental and health implications require careful management, the future of nanotechnology in water purification remains highly promising and essential for sustainable water management.

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