

## NANOTECHNOLOGY AND ADVANCED MATERIALS FOR ENVIRONMENTAL SUSTAINABILITY ACROSS WATER TREATMENT, AIR QUALITY, AND GREEN ENERGY TECHNOLOGIES

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### Abstract

The accelerating deterioration of environmental quality coupled with escalating global energy demands has created an urgent need for innovative, sustainable technological solutions. Nanotechnology, operating at the atomic and molecular scale, offers unprecedented opportunities to address these intertwined challenges through engineered materials with exceptional physicochemical properties. This comprehensive review critically examines recent advances in nanomaterial and nanotechnology-enabled processes for water treatment, air quality management, and green energy technologies. Nanostructured materials including noble metal nanoparticles (Ag, Au), transition metal oxides (TiO<sub>2</sub>, ZnO, Fe<sub>3</sub>O<sub>4</sub>), carbon-based nanomaterials (carbon nanotubes, graphene, graphene oxide), and their multifunctional nanocomposites demonstrate remarkable efficacy in pollutant removal, contaminant sensing, and energy conversion. In water remediation, these materials function through adsorption, photocatalysis, nanofiltration, and disinfection, achieving complete mineralization of organic pollutants and near-total removal of heavy metals and pathogens. For air quality, nanomaterials enable high-efficiency particulate filtration, catalytic conversion of NO<sub>x</sub>, SO<sub>2</sub>, and VOCs, and real-time monitoring via nano sensors. In the green energy sector, nanotechnology enhances photovoltaic efficiency, improves battery and supercapacitor performance, facilitates photocatalytic hydrogen production, and optimizes biofuel generation. The review also critically addresses nanomaterial toxicity, environmental fate, life

cycle assessment, and the principles of green nanotechnology for sustainable implementation. Despite remarkable progress, challenges persist regarding large-scale production, cost-effectiveness, regulatory frameworks, and long-term ecological impacts. This synthesis provides a foundational resource for researchers, environmental engineers, and policymakers working toward nanotechnology-driven environmental sustainability.

## 1. INTRODUCTION

### 1.1 The Global Environmental Crisis

The twenty-first century is defined by unprecedented environmental challenges that threaten both human well-being and planetary health. Global population growth, rapid industrialization, and intensive agricultural practices have collectively overwhelmed natural ecosystems, leading to severe contamination of water resources, deterioration of air quality, and escalating greenhouse gas emissions[1]. According to the World Health Organization (WHO, 2022)[2], approximately 2.2 billion people lack access to safely managed drinking water services, while ambient air pollution contributes to 4.2 million premature deaths annually. Concurrently, the energy sector accounts for nearly three-quarters of global greenhouse gas emissions, necessitating an urgent transition toward renewable and sustainable energy sources.

Water pollution manifests through multiple contaminant classes: toxic heavy metals (lead, mercury, cadmium, chromium, arsenic), persistent organic pollutants (pesticides, dyes, pharmaceuticals, personal care products), pathogenic microorganisms, and emerging contaminants such as endocrine-disrupting compounds and microplastics[3]. Conventional water treatment technologies including coagulation-flocculation, sedimentation, activated carbon adsorption, and biological treatment often fail to completely remove these contaminants, particularly when present at trace concentrations (parts per billion or lower). Advanced processes such as reverse osmosis and advanced oxidation, while more effective, remain energy-intensive and cost-prohibitive for widespread deployment, especially in developing nations[4].

Air pollution similarly presents a complex challenge. Particulate matter ( $PM_{2.5}$  and  $PM_{10}$ ), nitrogen oxides ( $NO_x$ ), sulfur dioxide ( $SO_2$ ), carbon monoxide (CO), volatile organic compounds (VOCs), and ground-level ozone originate from industrial emissions, vehicular exhaust, power generation, and domestic fuel combustion. Existing control technologies electrostatic precipitators, fabric filters, cyclones, wet scrubbers, and catalytic converters have limitations in removing ultrafine particles (below 100 nm) and achieving complete conversion of gaseous pollutants[5].

### 1.2 Nanotechnology: A Paradigm Shift in Environmental Solutions

Nanotechnology, defined as the manipulation of matter at dimensions of approximately 1–100 nanometers, has emerged as a transformative platform for environmental applications. At this scale, materials exhibit fundamentally altered physicochemical properties compared to their bulk counterparts, including exceptionally high surface-area-to-volume ratios, quantum confinement effects, enhanced chemical reactivity, superior mechanical strength, and tunable optical and electrical characteristics[6]. These unique attributes make nanomaterials particularly attractive for processes where surface interactions, catalytic activity, selective binding, and charge transfer are critical[6].

The convergence of nanotechnology with environmental science often termed "green nanotechnology" or "nano-remediation" encompasses three major domains: (1) water and wastewater treatment, (2) air pollution monitoring and control, and (3) renewable energy technologies[7]. In water treatment, nanomaterials

function as highly efficient adsorbents, photocatalysts, antimicrobial agents, and membrane components[7]. For air quality, they enable advanced filtration media, catalytic converters, and sensitive nano sensors. In the energy sector, nanotechnology enhances photovoltaic conversion efficiency, improves energy storage capacity, facilitates hydrogen production through water splitting, and optimizes biofuel generation processes[7].

### **1.3 Scope and Organization of This Review**

This review aims to provide a comprehensive, critical, and up-to-date analysis of nanotechnology and advanced materials for environmental sustainability. The specific objectives are: (i) to systematically review nanostructured materials employed for water and wastewater treatment, including their synthesis, mechanisms, and performance metrics; (ii) to examine nanomaterial-based technologies for air pollution monitoring, control, and carbon capture; (iii) to explore applications of nanomaterials in solar energy, hydrogen production, energy storage, and biofuels; (iv) to critically assess the environmental and health implications of nanomaterials, including ecotoxicity and life cycle considerations; (v) to discuss the principles of green nanotechnology for sustainable implementation; and (vi) to identify current challenges, knowledge gaps, and future research directions.

The review synthesizes information from peer-reviewed literature published between 2014 and 2026, with emphasis on recent advances, while incorporating supplementary data from authoritative sources including the World Health Organization, International Energy Agency, and United Nations Environment Program.

## **2. Nanomaterials for Water and Wastewater Treatment**

### **2.1 Classification of Water Contaminants and Treatment Limitations**

Water contaminants can be systematically categorized based on their chemical nature and origin. Heavy metals ( $Pb^{2+}$ ,  $Hg^{2+}$ ,  $Cd^{2+}$ ,  $Cr^{6+}$ ,

$As^{3+}/As^{5+}$ ) originate from industrial discharges, mining operations, and electronic waste; they are non-biodegradable and bioaccumulate through food chains, causing neurological, renal, and carcinogenic effects [1]. Organic pollutants include synthetic dyes (approximately 700,000 tons annually discharged into water bodies), pesticides, pharmaceuticals (antibiotics, analgesics, hormones), and personal care products; many are resistant to conventional biodegradation and exhibit endocrine-disrupting activity[8]. Pathogenic microorganisms (bacteria, viruses, protozoa) cause waterborne diseases including cholera, typhoid, hepatitis, and dysentery, responsible for approximately 1.7 million deaths annually[9]. Emerging contaminants such as microplastics, per- and polyfluoroalkyl substances (PFAS), and antibiotic resistance genes present new challenges that conventional treatment plants are ill-equipped to address[10], [11], [12].

Conventional treatment technologies face inherent limitations: activated carbon adsorption transfers pollutants rather than destroying them; chemical coagulation generates hazardous sludge; biological treatment is ineffective for recalcitrant compounds; chlorination produces carcinogenic disinfection byproducts; and membrane processes (reverse osmosis, nanofiltration) suffer from fouling, high energy consumption, and concentrate disposal issues[13], [14].

## **2.2 Metal-Based Nanostructured Materials**

### **2.2.1 Silver Nanoparticles (AgNPs)**

Silver nanoparticles have garnered exceptional interest as both photocatalysts and antimicrobial agents for water treatment. comprehensively reviewed the synthesis and application of AgNPs, noting that nanoparticles synthesized using *Zanthoxylum armatum* leaf extract achieved complete degradation of methyl orange, methylene blue, methyl red, and safranin O within 24 hours, attributed to their high surface area and accelerated electron migration efficiency[1], [15].

The photocatalytic mechanism involves generation of reactive oxygen species (ROS) including hydroxyl radicals (OH) and superoxide anions ( $O_2^-$ ) under light irradiation, which attack and mineralize organic pollutants. AgNPs loaded on  $Ag_2SO_3$  nanocomposites demonstrated 99% removal of rhodamine B within 2 hours under natural sunlight, maintaining structural stability and recyclability for five consecutive cycles[1]. A novel plasmonic Z-scheme photocatalyst coupling HKUST-1 MOF with  $Ag_2CrO_4$ -AgCl/Ag nanoparticles exhibited enhanced photocatalytic mineralization of orange G and amido-black dyes under UV-Vis illumination, combining high MOF adsorption capacity with Ag-based photocatalytic performance[16].

AgNPs synthesized using *Phyllanthus amarus* leaf extract produced flower-like nanostructures that achieved complete degradation of rhodamine B within 20 minutes[17]. The antimicrobial activity of AgNPs involves interaction with thiol (-SH) groups of bacterial proteins, inhibition of respiratory chain enzymes, disruption of cell membrane integrity, and induction of DNA damage. AgNPs smaller than 10 nm exhibit enhanced antibacterial and antiviral activity due to efficient attachment to viral glycoprotein spikes[1].

### 2.2.2 Gold Nanoparticles (AuNPs)

Gold nanoparticles possess unique optical properties (surface plasmon resonance), catalytic activity, and biocompatibility. Green synthesis of AuNPs using *Dalbergia coronand* and *Eliana* roots, achieving complete elimination of methyl orange and Congo red dyes following pseudo-first-order kinetics with rate constants of  $1.7 \times 10^{-3} s^{-1}$  and  $4.5 \times 10^{-3} s^{-1}$ , respectively[18]. AuNPs synthesized using *Sansevieria roxburghiana* leaf extract exhibited degradation efficiencies of 87.98% (4-nitrophenol), 93.09% (Congo red), and 88.16% (phenol red)[19].

A particularly important application of AuNPs is mercury ion ( $Hg^{2+}$ ) removal from water. AuNPs demonstrate strong affinity for  $Hg^{2+}$  through amalgam formation ( $Au_3Hg$ ). AuNPs conjugated with  $NaBH_4$  exhibited sorption capacity of 4.065

mg Hg/mg Au, more than triple that of AuNPs immobilized on  $Al_2O_3$  (0.27 mg Hg/mg Au)[20]. The electrostatic interaction between  $Hg^{2+}$  and citrate-stabilized AuNPs leads to aggregation and subsequent removal by filtration or centrifugation. Importantly, AuNPs show high affinity for organomercury species (phenylmercury, ethyl mercury, methylmercury) as well as inorganic  $Hg^{2+}$ [21].

### 2.2.3 Zinc Oxide Nanoparticles (ZnO NPs)

Zinc oxide nanoparticles are widely employed in photocatalytic water treatment due to their low cost, abundant availability, non-toxicity, high absorption capability, and chemical stability[1]. ZnO nanoparticles for catechol degradation, achieving 69.8% removal under optimized conditions (pH 3.0, catalyst dosage 0.24 g/L, catechol 74 mg/L, UV intensity 40 W, 98 minutes)[22].

Ag-ZnO nanocomposites fabricated via a two-step modified polymer-network gel strategy exhibited markedly enhanced photocatalytic performance compared to pristine ZnO, achieving complete degradation of methyl orange (40 min, rate  $0.120 min^{-1}$ ), methylene blue (25 min, rate  $0.247 min^{-1}$ ), and rhodamine B (30 min, rate  $0.198 min^{-1}$ ) under sunlight at  $30^\circ C$ [23]. The enhanced activity was attributed to huge specific surface area, abundant surface oxygen vacancies, and uniform Ag NP dispersion. The robust contact between ZnO and Ag promotes separation of photo-generated electrons and holes, increasing ROS generation.

Magnetically recoverable flower-shaped  $TiO_2/Fe_2O_3$  nanostructures were successfully fabricated for paracetamol degradation, with 33%  $TiO_2/Fe_2O_3$  exhibiting the highest photocatalytic performance over multiple cycles [24]. Degradation intermediates including 4-acetamidocatechol, 4-acetamidoresorcinol, and hydroquinone were identified by GC/MS.

### 2.2.4 Iron Nanoparticles (Fe NPs and nZVI)

Iron-based magnetic nanomaterials (FeMNP) combine excellent catalytic properties with

superparamagnetic behavior, enabling easy separation and manipulation using external magnetic fields [1]. However, challenges include instability in environmental matrices and agglomeration due to high surface energy.

Engineered  $\text{Fe}_3\text{O}_4$  magnetic nanoparticles with CMC-g-poly(acrylic acid-co-acrylic amide) hydrogel, achieving 98.2% phenol removal and 80.4% COD reduction within 3 hours[25]. The pH-responsive hydrogel provided good dispersibility, hydrophilicity, and permeability, with >55% COD reduction maintained after three cycles[25].

Nano zero-valent iron (nZVI) has emerged as a powerful reductant for environmental contaminants. nZVI particles (10–100 nm) possess core-shell structures with  $\text{Fe}^0$  core and iron oxide shell. They effectively reduce and immobilize heavy metals ( $\text{Cr}^{6+} \rightarrow \text{Cr}^{3+}$ ,  $\text{Pb}^{2+} \rightarrow \text{Pb}^0$ ,  $\text{As}^{3+}/\text{As}^{5+} \rightarrow \text{As}^0$ ), dechlorinate chlorinated organic compounds (trichloroethylene, PCBs), and degrade nitroaromatic compounds[26]. nZVI-Cu bimetallic nanoparticles enhanced nitrate reduction, while hydrotalcite-supported nZVI effectively removed methylene blue dye. The high reactivity of nZVI stems from its large surface area (20–40  $\text{m}^2/\text{g}$ ) and standard reduction potential ( $E^0 = -0.44 \text{ V}$ )[27].

### 2.2.5 Copper Nanoparticles (CuNPs)

Copper nanoparticles offer robust catalytic, antimicrobial, and electrical properties with low cost and eco-friendly synthesis requirements. Duranta erecta fruit extract to synthesize CuNPs, achieving 90.35% Congo red removal within 5 minutes and 96% methyl orange degradation in 4 minutes using  $\text{NaBH}_4$  as reducing agent[28]. CuNPs embedded in chitosan biopolymer (CuNPs-CH) achieved complete transformation of 4-nitroaniline to diaminobenzene in very short exposure time[29]. CuO nanoparticles incorporated on clinoptilolite achieved 59% degradation of 2,6-dimethylphenol after 6 hours, with COD reduction from 166 to 68  $\text{mg O}_2/\text{L}$ , indicating near-complete mineralization[30].

## 2.3 Transition Metal Oxide Nanomaterials

### 2.3.1 Titanium Dioxide ( $\text{TiO}_2$ ) Photocatalysts

Titanium dioxide is widely regarded as the gold standard photocatalyst for water treatment due to its low cost, non-toxicity, chemical stability, and strong oxidizing ability.  $\text{TiO}_2$  exists in three crystalline phases: anatase (bandgap 3.2 eV), rutile (3.0 eV), and brookite (3.1–3.4 eV), with anatase exhibiting the highest photocatalytic activity[26].

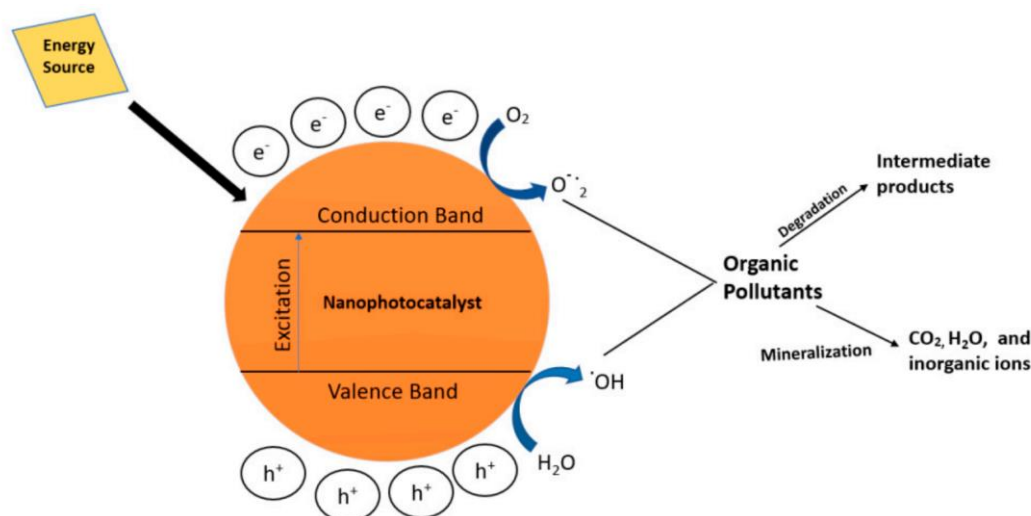


Figure. 1. Photocatalytic degradation mechanism on  $\text{TiO}_2$  nanoparticles[31].

The generated hydroxyl radicals ( $\text{OH}^\bullet$ ,  $E^0 = +2.80$  V) and superoxide radicals ( $\text{O}_2^{\bullet-}$ ) non-selectively attack organic pollutants, leading to complete mineralization to  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and inorganic ions. Visible light-triggered C,N,S-tri-doped mixed-phase  $\text{TiO}_2$  photocatalyst for ibuprofen degradation, achieving complete removal with first-order rate of  $1.779 \text{ mM min}^{-1}$  over 5 hours, representing a 40-fold increase compared to non-doped  $\text{TiO}_2$ [32]. The enhanced activity was attributed to narrowed bandgap, increased visible light absorption, and reduced electron-hole recombination[32].

$\text{TiO}_2$  nanoparticles have also been extensively used for heavy metal photoreduction. Some reported >90% reduction and recovery of  $\text{Cd}^{2+}$  onto  $\text{TiO}_2$  surface under 253.7 nm irradiation[33].  $\text{TiO}_2$ -Au nanocomposites achieved 91% Cr(VI) reduction compared to 87% with  $\text{TiO}_2$  alone, attributed to broader light absorption from Au surface plasmon resonance

and modified electron-hole recombination rates [34]

### 2.3.2 Iron Oxide Nanomaterials ( $\text{Fe}_3\text{O}_4$ , $\gamma\text{-Fe}_2\text{O}_3$ , $\alpha\text{-Fe}_2\text{O}_3$ )

Iron oxide nanomaterials are primarily classified into three categories: magnetite ( $\text{Fe}_3\text{O}_4$ ), maghemite ( $\gamma\text{-Fe}_2\text{O}_3$ ), and hematite ( $\alpha\text{-Fe}_2\text{O}_3$ )[1]. Their magnetic properties enable easy separation from treated water, addressing one of the major challenges in nanoparticle-based treatment.

**Magnetite ( $\text{Fe}_3\text{O}_4$ ):** Polyethyleneimine-functionalized  $\text{Fe}_3\text{O}_4$  nanoparticles demonstrated high adsorption for  $\text{Cd}^{2+}$ ,  $\text{Zn}^{2+}$ , and  $\text{Cu}^{2+}$ . Carboxymethyl- $\beta$ -cyclodextrin grafted to  $\text{Fe}_3\text{O}_4$  effectively removed  $\text{Cu}^{2+}$  from aqueous media[35]. EDTA-modified chitosan/ $\text{SiO}_2/\text{Fe}_3\text{O}_4$  core-shell adsorbents were developed for heavy metal removal [36]. Carbon-based porous magnetic nanoparticles achieved  $\text{Pb}^{2+}$  removal of 99.57% and >90% removal of  $\text{Co}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Cd}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Mn}^{2+}$ , and  $\text{Zn}^{2+}$  using an ultrafast process[37].

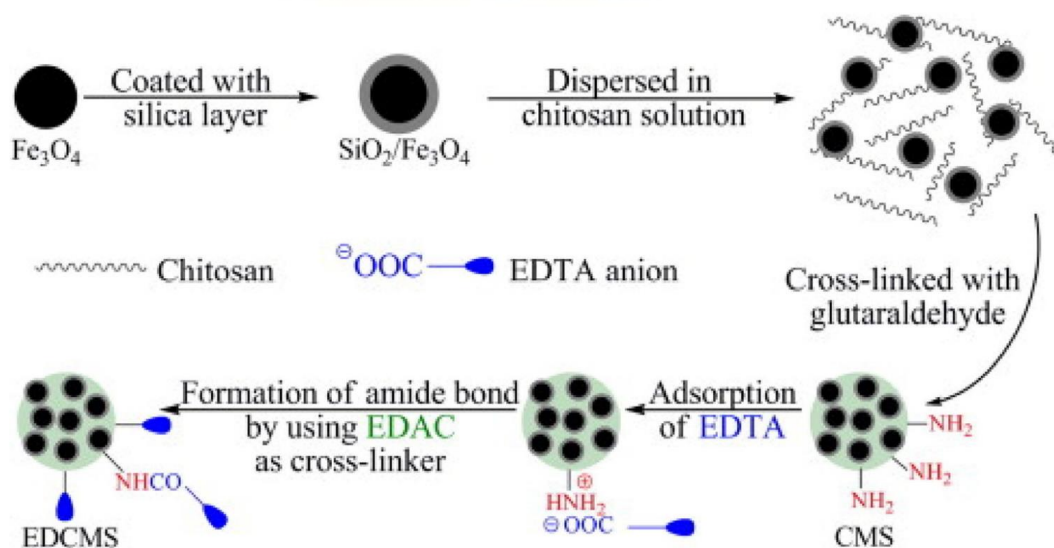


Figure. 2. Procedure for preparation of CMS and EDCMs core-shell adsorbents[1], [36]

**Maghemite ( $\gamma\text{-Fe}_2\text{O}_3$ ):** Polyrhodanine-encapsulated maghemite nanoparticles were prepared for  $\text{Hg}^{2+}$  removal [38]. Poly-L-cysteine-coated  $\gamma\text{-Fe}_2\text{O}_3$  nanoparticles adsorbed  $\text{Zn}^{2+}$ ,  $\text{Cd}^{2+}$ ,  $\text{As}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Pb}^{2+}$ , and  $\text{Cu}^{2+}$  ions [39]. Chitosan-coated  $\gamma\text{-Fe}_2\text{O}_3$  modified with  $\alpha$ -

ketoglutaric acid removed  $\text{Cu}^{2+}$  from aqueous media [40].

**Hematite ( $\alpha\text{-Fe}_2\text{O}_3$ ):** Three-dimensional porous nanostructures of Mn-doped  $\alpha\text{-Fe}_2\text{O}_3$  exhibited excellent removal capacities for  $\text{Pb}^{2+}$ ,  $\text{AsV}$ , and  $\text{CrVI}$  from wastewater [41].  $\text{Fe}_2\text{O}_3\text{-Al}_2\text{O}_3$

nanocomposite fibers were applied for adsorption of  $\text{Hg}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Cu}^{2+}$ , and  $\text{Pb}^{2+}$  ions[42].

### 2.3.3 Other Metal Oxide Nanoparticles

**Alumina ( $\text{Al}_2\text{O}_3$ )** nanoparticles were used for solid-phase extraction and pre-concentration of  $\text{Cd}^{2+}$  and  $\text{Pb}^{2+}$  [43]. **Cerium oxide ( $\text{CeO}_2$ )** nanostructures portrayed improved removal capacity for  $\text{Cr(VI)}$  and  $\text{As(V)}$  ions [44]. **Zirconia ( $\text{ZrO}_2$ )** spheres with large porous structures showed excellent removal capacities for  $\text{As(III)}$  and  $\text{As(IV)}$  [45]. **Fe-Mn oxide** nanoparticles stabilized by polysaccharide were employed for immobilization of  $\text{As(III)}$  from groundwater and soil [46].

## 2.4 Carbon-Based Nanomaterials

### 2.4.1 Carbon Nanotubes (CNTs)

Carbon nanotubes, discovered by Iijima in 1991, are cylindrical graphene sheets rolled into seamless tubes with diameters ranging from 0.4 to 100 nm and lengths up to millimeters. They exist as single-walled (SWCNTs) and multi-walled (MWCNTs) varieties, each offering unique properties for water treatment [1], [47].

CNTs possess exceptional adsorption capacity due to their high specific surface area (150–1500  $\text{m}^2/\text{g}$ ), hydrophobic surfaces, and  $\pi$ - $\pi$  electron interactions with aromatic contaminants. Multiple interaction mechanisms govern pollutant adsorption: hydrophobic interactions,  $\pi$ - $\pi$  stacking, electrostatic attraction, hydrogen bonding, and covalent bonding[47].

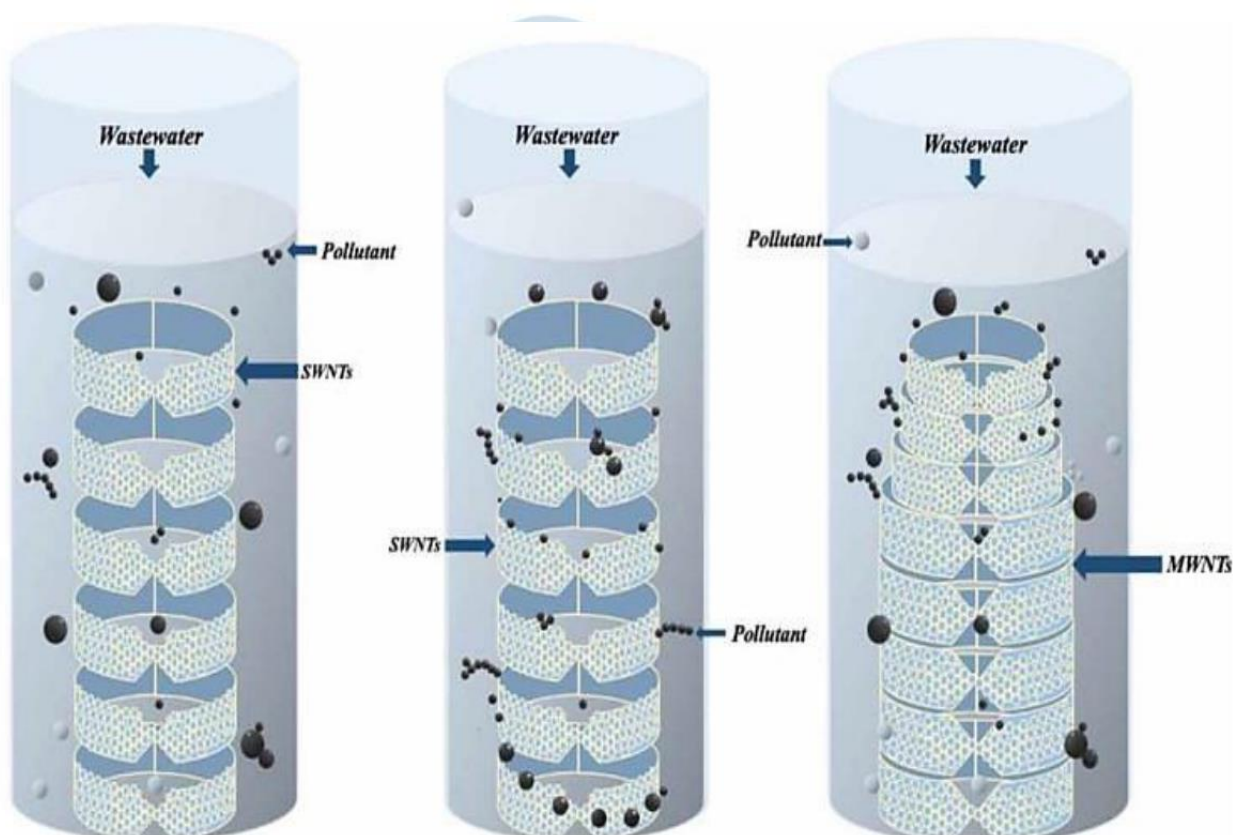


Figure. 3. Schematic showing adsorption capabilities of carbon nanotubes for wastewater purification[47].

CNT-based membranes represent an emerging technology for water filtration. The nanoscale pore

diameters (1–10 nm) allow only water molecules to pass while blocking chemical and biological

contaminants. Water permeation through CNTs is extremely fast 4–5 orders of magnitude faster than theoretically predicted due to smooth hydrophobic walls and slip flow. Freestanding CNT membranes with  $\sim 1$  nm pores, increasing rejection rates for organic dyes by nearly three orders of magnitude compared to commercial membranes [48].

#### 2.4.2 Graphene and Graphene Oxide (GO)

Graphene, a single-atom-thick two-dimensional sheet of  $sp^2$ -hybridized carbon, and its oxidized

derivative graphene oxide (GO) have attracted enormous interest for water treatment due to their exceptional surface area (theoretically  $2630 \text{ m}^2/\text{g}$  for graphene), mechanical strength, and chemical stability [1], [6].

EDTA-functionalized magnetic GO effectively removed  $\text{Cu}^{2+}$ ,  $\text{Pb}^{2+}$ , and  $\text{Hg}^{2+}$  through electrostatic attraction between EDTA chelating groups and metal ions [49]. Graphene/ $\delta\text{-MnO}_2$ -based three-dimensional nanostructures achieved exceptional adsorption capacities:  $\text{Pb}^{2+}$   $643.62 \text{ mg/g}$ ,  $\text{Cu}^{2+}$   $228.46 \text{ mg/g}$ , and  $\text{Cd}^{2+}$   $250.31 \text{ mg/g}$  [50].

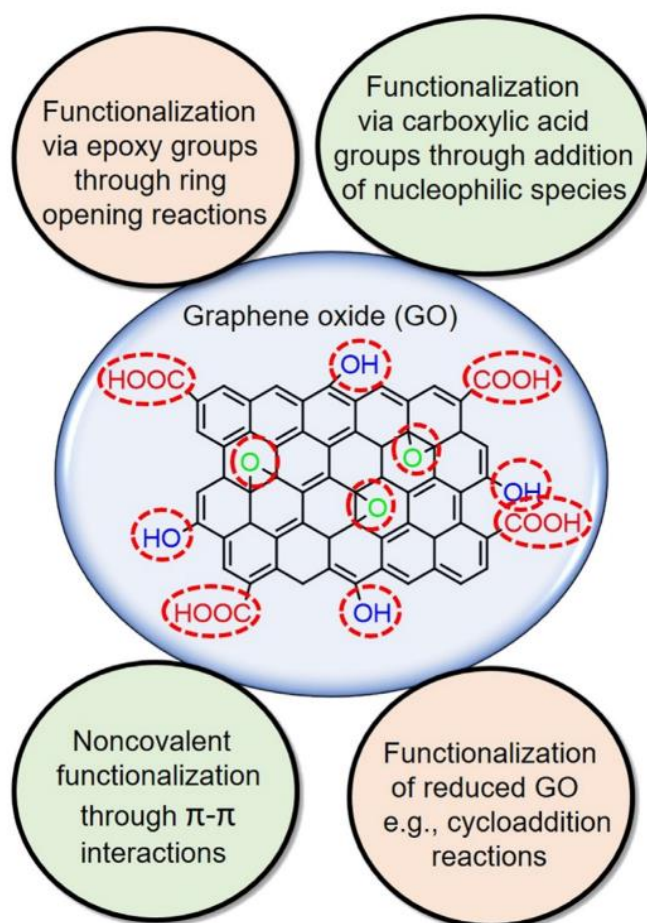


Figure. 4. Different approaches for functionalization of graphene oxide [51].

### 2.5 Nanocomposites and Hybrid Materials

Nanocomposite materials combine the advantages of impregnated nanoparticles with host matrices (polymers, ceramics, carbons), addressing key challenges of nanoparticle agglomeration, difficult separation, and potential environmental release[52].

**Inorganic nanocomposites:** Kaolin/ZnO nanocomposites achieved removal efficiencies of Fe(III): 98%, Cr(VI): 100%, BOD: 94%, COD: 95%, and chloride: 78%[53]. Magnetite-zeolite nanocomposites demonstrated COD removal of 99.88%, BOD 99.96%, and TOC 99.87%[54]. ZnO-decorated halloysite achieved 90–97% methylene blue dye removal[55]

### 2.6 Nanofiltration Membranes

Nanofiltration (NF) is a pressure-driven membrane separation technique with pore sizes of 1–5 nm, offering unique charge-based repulsion properties and high permeation rates at lower pressures (7–30 atm) compared to reverse osmosis (20–100 atm)[56]. NF membranes reject multivalent ions ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{SO}_4^{2-}$ ) while allowing monovalent ions ( $\text{Na}^+$ ,  $\text{Cl}^-$ ) to pass, making them ideal for water softening and selective contaminant removal.

CNT-based NF membranes exhibit high solvent permeability and excellent rejection rates.  $\text{TiO}_2$  nanowire mesh membranes achieved almost 100% humic acid removal and >90% total organic carbon reduction under UV irradiation[57]. ZnO nanoparticle incorporation into poly(phenyl sulfone) membranes enhanced water flux from 76 to 107  $\text{L m}^{-2} \text{ h}^{-1} \text{ bar}^{-1}$  due to increased hydrophilicity[58].

Graphene oxide membranes fabricated showed very high retention for organic dye molecules[59]. Micrometer-thick GO membranes exhibited extremely high impermeability to liquids, vapors, and gases excluding water, enabling selective water permeation[60].

### 2.7 Nanosorbents

Nanosorbents possess high sorption capability due to large surface area, accessible adsorption sites,

short intraparticle diffusion distance, and tunable surface chemistry [31]. Carbon-based Nanosorbents (activated carbon, carbon black, graphite, graphene oxide) are most commonly reported. Granular activated carbon (GAC) exhibits adsorption capacities for benzene of 400–500 mg/g and toluene of ~700 mg/g [61].

Magnetic Nanosorbents coplay a vital role in water treatment, enabling easy separation using magnetic fields.  $\text{Fe}_3\text{O}_4@\text{Ag}$  and  $\text{Fe}_3\text{O}_4@\text{TiO}_2$  nanoparticles were successfully employed against pathogenic bacteria including *E. coli*, *Staphylococcus epidermidis*, and *Bacillus subtilis*[62], [63].

Dendrimers, hyperbranched polymers with well-defined architecture, are functional for eliminating organic pollutants and heavy metals. Copper ions were effectively removed using dendrimer-ultrafiltration systems[64]. Dendrimers can be regenerated by pH adjustment and exhibit biocompatibility and non-toxicity.

## 3. Nanotechnology for Air Quality Management

### 3.1 Air Pollution: Sources, Health Impacts, and Control Challenges

Air pollution is the single largest environmental health risk globally. According to the WHO (2022)[2], ambient air pollution causes 4.2 million deaths annually, with 91% of the world's population living in areas exceeding WHO guideline limits. Major pollutants include:

- **Particulate matter ( $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ ):** Particles <2.5  $\mu\text{m}$  and <10  $\mu\text{m}$  diameter, originating from combustion processes (diesel engines, power plants, biomass burning), industrial emissions, and natural sources.  $\text{PM}_{2.5}$  penetrates deep into alveoli, causing cardiovascular and respiratory diseases.
- **Nitrogen oxides ( $\text{NO}_x$ ):** Produced during high-temperature combustion (vehicles, power plants), contributing to smog, acid rain, and respiratory inflammation.
- **Sulfur dioxide ( $\text{SO}_2$ ):** Emitted from fossil fuel combustion (coal, oil) and industrial processes (metal smelting), causing respiratory irritation and acid rain.

- **Volatile organic compounds (VOCs):** Emitted from solvents, paints, fuels, and industrial processes; many are carcinogenic and contribute to ozone formation.

- **Carbon monoxide (CO):** Produced by incomplete combustion; binds to hemoglobin reducing oxygen transport.

Conventional air pollution control technologies include electrostatic precipitators (ESPs), fabric filters (baghouses), cyclones, and wet scrubbers for particulate removal, and selective catalytic reduction (SCR), flue gas desulfurization (FGD), and catalytic converters for gaseous pollutants. However, these technologies have limitations in removing ultrafine particles (<100 nm) and achieving complete pollutant conversion at ambient temperatures.

### 3.2 Nanomaterials for Particulate Filtration

Nanomaterials offer advanced solutions for particulate matter filtration due to their high surface area, tunable pore structures, and ability to capture nanoparticles through multiple mechanisms: interception, impaction, diffusion, and electrostatic attraction [5].

**CNT-based filters:** Aligned CNT filters demonstrate exceptional capability for capturing fine and ultrafine particulates. The high aspect ratio (length: diameter >1000) of CNTs creates a dense network of nanoscale pores that trap particles while maintaining high air permeability. CNT filters effectively removed bacterial contaminants including *E. coli* and poliovirus from water, with similar principles applicable to air filtration[65].

**Graphene oxide filters:** The layered structure of GO membranes provides controlled interlayer spacing enabling size-selective filtration. GO-based filters exhibit high adsorption capacity for gaseous pollutants and particulate matter[5].

**Nanofibrous filters:** Electro spun nanofibers (diameters 50–500 nm) offer high surface-to-volume ratio, high porosity (>90%), and small pore size, enabling efficient capture of submicron particles. Surface functionalization with

antimicrobial nanoparticles (Ag, CuO, ZnO) provides additional disinfection capability[66].

### 3.3 Catalytic Converters and Nano catalysts

Nano catalysts play a crucial role in converting harmful gases into less toxic substances. The high surface-area-to-volume ratio of nano catalysts enables lower precious metal loading while maintaining or enhancing catalytic efficiency [5].

**Platinum group metal Nano catalysts:** Pt, Pd, and Rh nanoparticles (2–10 nm) supported on high-surface-area oxides ( $\text{Al}_2\text{O}_3$ ,  $\text{CeO}_2$ ,  $\text{ZrO}_2$ ) are used in three-way catalytic converters for simultaneous oxidation of CO and hydrocarbons and reduction of  $\text{NO}_x$ . The unique electronic properties of nanoscale Pt enhance CO oxidation at lower temperatures (light-off temperature <150°C compared to >250°C for bulk Pt).

**Cerium oxide ( $\text{CeO}_2$ ) nanoparticles:**  $\text{CeO}_2$  exhibits oxygen storage capacity due to facile  $\text{Ce}^{4+}/\text{Ce}^{3+}$  redox cycling, buffering oxygen concentration in exhaust streams and enhancing catalytic activity under fuel-rich conditions[5]. Nanostructured  $\text{CeO}_2$  with exposed reactive facets demonstrates enhanced  $\text{NO}_x$  reduction activity.

**$\text{TiO}_2$  photocatalysts for air purification:**  $\text{TiO}_2$  nanoparticles immobilized on surfaces (building facades, road pavements, indoor walls) enable photocatalytic degradation of  $\text{NO}_x$ , VOCs, and  $\text{SO}_2$  under UV or visible light illumination. The process generates hydroxyl radicals that oxidize adsorbed pollutants to harmless products ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ). Visible light-activated doped  $\text{TiO}_2$  (N-doped, C-doped, S-doped) extends utility to indoor environments with limited UV exposure[5].

### 3.4 Nano sensors for Air Quality Monitoring

Nanomaterial-based sensors offer unprecedented sensitivity (detection limits down to parts-per-trillion), selectivity, and real-time response for air pollutant monitoring. These sensors enable distributed sensing networks for urban air quality mapping and personal exposure assessment[5].

**Graphene-based sensors:** The high carrier mobility and large surface area of graphene enable

extremely sensitive gas detection. Functionalized graphene oxide sensors detect NO<sub>2</sub>, CO, and VOCs with rapid response and recovery times (<1 minute).

**Metal oxide semiconductor (MOS) sensors:** Nanostructured SnO<sub>2</sub>, ZnO, WO<sub>3</sub>, and In<sub>2</sub>O<sub>3</sub> exhibit changes in electrical conductivity upon gas adsorption due to surface-mediated redox reactions. Operating temperatures (200–400°C) can be reduced by Nano structuring,

lowering power consumption. Doping with noble metals (Pd, Pt, Au) enhances sensitivity and selectivity.

**Optical nanosensors:** Gold nanoparticles exhibit localized surface plasmon resonance (LSPR) shifts upon binding of pollutant molecules, enabling colorimetric detection. Quantum dots (CdSe, CdTe) exhibit fluorescence quenching or enhancement in the presence of specific gases[5].

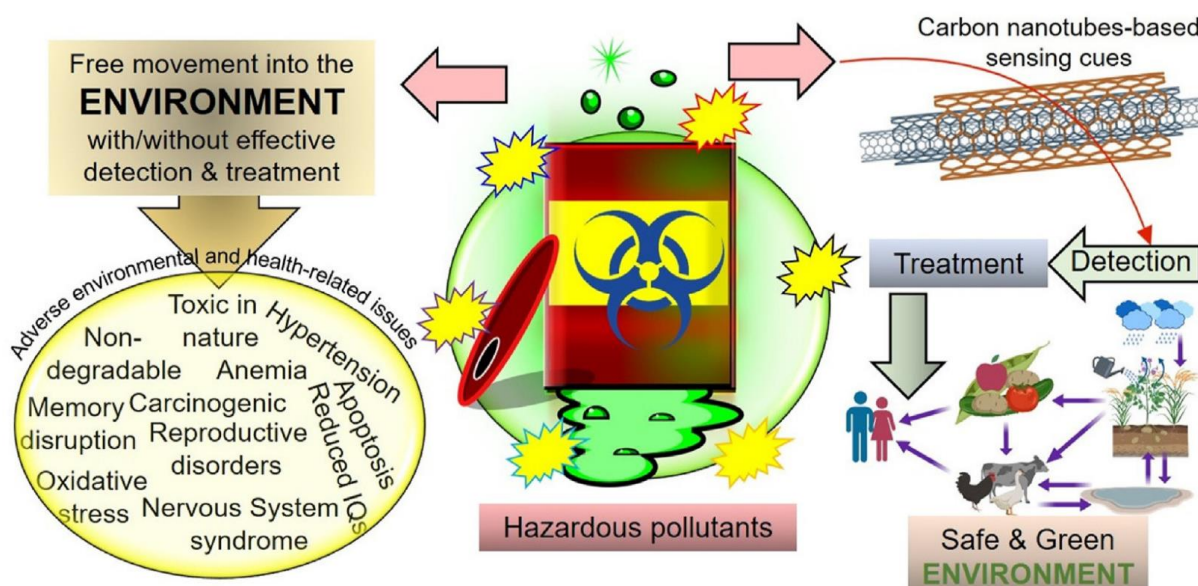


Figure. 5. Carbon nanotube-based sensor array for environmental pollutant detection[67].

### 3.5 Carbon Capture and Sequestration (CCS)

Nanomaterials contribute significantly to carbon capture and sequestration technologies aimed at mitigating CO<sub>2</sub> emissions. Metal-organic frameworks (MOFs), graphene-based materials, and carbon nanotubes demonstrate high CO<sub>2</sub> adsorption capacity due to their large surface area (3000–7000 m<sup>2</sup>/g for MOFs) and tailored pore structures [5].

**MOFs for CO<sub>2</sub> capture:** MOFs are crystalline porous materials composed of metal clusters connected by organic linkers. Their tunable pore sizes and functionalize surfaces enable selective CO<sub>2</sub> capture over N<sub>2</sub> and O<sub>2</sub>. Amine-functionalized MOFs (e.g., Mg-MOF-74, UiO-66-

NH<sub>2</sub>) exhibit high CO<sub>2</sub> capacity (up to 8 mmol/g) through chemisorption, while materials with optimal pore sizes (3–5 Å) achieve physisorption separation.

**Graphene-based CO<sub>2</sub> adsorbents:** Graphene oxide and reduced graphene oxide composites exhibit enhanced CO<sub>2</sub> adsorption through combined physisorption (high surface area) and chemisorption (amine functionalization). N-doped graphene achieves CO<sub>2</sub> capacities of 3–5 mmol/g at ambient conditions.

**Carbon capture from air (direct air capture, DAC):** Nanomaterials enable DAC technologies that remove CO<sub>2</sub> directly from ambient air. Amine-functionalized nanofibers and

nanostructured sorbents achieve CO<sub>2</sub> capture even at 400 ppm concentration, offering a pathway to negative emissions.

### 3.6 Indoor Air Purification

Nanotechnology-enabled air purifiers incorporate multiple nanomaterials for comprehensive indoor air treatment[5]:

- **HEPA filters with nanofiber coating:** Electro spun nanofibers (50–500 nm diameter) achieve >99.97% efficiency for 0.3 μm particles while maintaining low pressure drop.
- **Activated carbon with CNT reinforcement:** Enhanced VOC adsorption capacity through hierarchical pore structure.
- **Photocatalytic filters:** TiO<sub>2</sub>-coated substrates under UV-LED illumination degrade VOCs, formaldehyde, and biological contaminants.
- **Ag nanoparticle-impregnated filters:** Provide antibacterial and antiviral activity, reducing airborne pathogen transmission.
- **Plasma-catalyst hybrid systems:** Non-thermal plasma combined with nano catalysts enhances VOC decomposition efficiency at room temperature.

## 4. Nanomaterials for Green Energy Technologies

### 4.1 Solar Energy Conversion

Nanotechnology has revolutionized photovoltaic (PV) technology through multiple approaches that enhance light absorption, charge carrier transport, and reduce material costs[5].

**Quantum dot solar cells (QDSCs):** Colloidal quantum dots (CdSe, PbS, PbSe, CuInS<sub>2</sub>) exhibit size-tunable bandgaps enabling absorption across the solar spectrum. Multiple exciton generation (MEG) in QDs can theoretically boost power conversion efficiency beyond the Shockley-Queisser limit. Current QDSCs have achieved efficiencies >16% with potential for low-cost solution processing.

**Perovskite solar cells:** Organic-inorganic hybrid perovskites (CH<sub>3</sub>NH<sub>3</sub>PbX<sub>3</sub>) with nanostructured layers have achieved power conversion efficiencies >25% in laboratory cells. Nanoscale control of

grain size, morphology, and interface engineering is critical for performance and stability. TiO<sub>2</sub> and ZnO nanostructures serve as electron transport layers, while NiO and Spiro-OMeTAD serve as hole transport layers.

**Dye-sensitized solar cells (DSSCs):** Nanostructured TiO<sub>2</sub> (mesoporous films, nanotubes, nanowires) provides high surface area for dye loading (up to 1000 m<sup>2</sup>/g), enhancing light harvesting. ZnO nanorods offer higher electron mobility than TiO<sub>2</sub>, reducing recombination losses. Plasmonic nanoparticles (Au, Ag) enhance light absorption through surface plasmon resonance.

**Graphene and CNT electrodes:** Transparent conductive electrodes based on graphene or CNT networks replace indium tin oxide (ITO), reducing cost and improving flexibility. CNT-silicon heterojunction solar cells achieve efficiencies >15% with simple fabrication.

**Nanostructured light trapping:** Nanowire arrays, nanocones, and textured surfaces reduce reflection and increase optical path length, enabling thinner absorber layers and reduced material consumption.

### 4.2 Hydrogen Production via Photocatalytic Water Splitting

Photocatalytic water splitting using semiconductor nanomaterials offers a sustainable pathway for hydrogen production. The process involves absorption of photons with energy ≥ bandgap, generation of electron-hole pairs, and migration of charge carriers to surface active sites where water reduction (H<sup>+</sup> → ½H<sub>2</sub>) and oxidation (H<sub>2</sub>O → ½O<sub>2</sub> + 2H<sup>+</sup> + 2e<sup>-</sup>) occur[6].

**TiO<sub>2</sub>-based photocatalysts:** Anatase TiO<sub>2</sub> (bandgap 3.2 eV) is active only under UV light (4% of solar spectrum). Doping with N, C, S, or transition metals (Fe, V, Cr) extends absorption into visible light. Co-catalyst loading (Pt, Pd, Au, NiO) enhances H<sub>2</sub> evolution by providing active sites and suppressing electron-hole recombination.

**g-C<sub>3</sub>N<sub>4</sub> nanomaterials:** Graphitic carbon nitride (bandgap 2.7 eV) is a metal-free, visible-light-active photocatalyst for H<sub>2</sub> production. Nano structuring

(nanosheets, nanorods, mesoporous structures) increases surface area and exposes more active sites. Heterojunction formation with  $\text{TiO}_2$ ,  $\text{WO}_3$ , or  $\text{BiVO}_4$  enhances charge separation.

**Z-scheme photocatalysts:** Artificial Z-scheme systems mimic natural photosynthesis by coupling two photocatalysts with different bandgaps via a solid-state electron mediator (Au, Ag, RGO). This architecture enables efficient utilization of visible light while maintaining strong redox potentials.

**Photoelectrochemical (PEC) cells:** Nanostructured photoanodes ( $\text{TiO}_2$  nanotubes,  $\text{WO}_3$  nanoplates,  $\text{BiVO}_4$  inverse opals) and photocathodes ( $\text{Cu}_2\text{O}$  nanowires, Si nanowires) enable water splitting with applied bias. The high surface area of nanostructure enhances reaction kinetics, while aligned structures improve charge transport.

#### 4.3 Energy Storage: Batteries and Supercapacitors

Nanomaterials significantly enhance the performance of batteries and supercapacitors by increasing electrode surface area, shortening ion diffusion pathways, accommodating volume changes, and improving electronic conductivity [5].

##### Lithium-ion batteries (LIBs):

- **Anode materials:** Silicon nanoparticles (4200 mAh/g theoretical capacity,  $10\times$  graphite) accommodate volume expansion (300%) through nanoscale design (nanoparticles, nanowires, porous structures). Carbon-coated Si nanoparticles and Si-graphene composites achieve stable cycling >500 cycles.
- **Separators and electrolytes:** Nanofibrous separators (electro spun polyimide, PVDF) improve thermal stability and wettability. Solid-state electrolytes with ceramic nanoparticles (LLZO, LATP) enhance ionic conductivity and safety.

**Sodium-ion batteries (SIBs):** Carbon-based nanomaterials (hard carbon, graphene) and transition metal oxides ( $\text{Na}_3\text{V}_2(\text{PO}_4)_3$ ) offer cost-effective alternatives to lithium systems. Nano

structuring improves  $\text{Na}^+$  intercalation kinetics despite larger ionic radius.

**Supercapacitors:** CNTs, graphene, and metal oxide nanoparticles ( $\text{RuO}_2$ ,  $\text{MnO}_2$ ,  $\text{NiO}$ ) are used as electrode materials. CNT networks provide high electrical conductivity and accessible surface area for electrical double-layer capacitance (EDLC). Graphene achieves specific capacitance up to 550 F/g.  $\text{MnO}_2$  nanoparticles (theoretical 1380 F/g) provide pseudo capacitance through surface redox reactions.

**Lithium-sulfur (Li-S) batteries:** Sulfur has high theoretical capacity (1675 mAh/g) but suffers from polysulfide shuttling. Nanostructured sulfur hosts (mesoporous carbon, CNT networks, MXenes) encapsulate sulfur and trap polysulfides, improving cycle life.

#### 4.4 Fuel Cells

Nanomaterials are critical for improving performance and reducing the cost of fuel cells, particularly proton exchange membrane fuel cells (PEMFCs) [5].

**Electrocatalysts:** Pt nanoparticles (2–5 nm) supported on high-surface-area carbon (Vulcan XC-72, CNTs, graphene) achieve high mass activity (0.2–0.5 A/mg Pt) for oxygen reduction reaction (ORR) and hydrogen oxidation reaction (HOR). Pt-alloy nanoparticles (PtCo, PtNi, PtFe) exhibit enhanced ORR activity due to lattice strain and ligand effects. Pt-free catalysts (Fe-N-C, Co-N-C, transition metal chalcogenides) are under development for cost reduction.

**Membrane materials:** Nanocomposite proton exchange membranes incorporate hydrophilic nanoparticles ( $\text{SiO}_2$ ,  $\text{TiO}_2$ ,  $\text{ZrO}_2$ , graphene oxide) into Nafion or hydrocarbon polymers to enhance water retention at low humidity and reduce fuel crossover.

**Gas diffusion layers (GDLs):** Carbon nanofiber and CNT-based GDLs improve gas transport, water management, and electrical conductivity.

#### 4.5 Bioenergy and Biofuels

Nanomaterials enhance biofuel production through improved enzymatic conversion,

fermentation efficiency, and product separation[5].

**Immobilized enzymes:** Magnetic nanoparticles ( $\text{Fe}_3\text{O}_4$ ) functionalized with cellulase, amylase, or lipase enable enzyme recovery and reuse, reducing biocatalyst costs. Nanostructured supports (mesoporous silica, metal-organic frameworks) provide high enzyme loading and protection against denaturation.

**Algal biofuel production:** Nanoparticles ( $\text{Fe}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{ZnO}$ ) enhance algal growth and lipid accumulation by delivering micronutrients and modulating oxidative stress. Magnetic nanoparticle-based harvesting enables energy-efficient algal biomass recovery.

**Biogas upgrading:** Nanomembrane separation (CNT-polymer mixed matrix membranes) selectively removes  $\text{CO}_2$  and  $\text{H}_2\text{S}$  from biogas, increasing methane purity for grid injection.

## 5. Environmental and Health Implications of Nanomaterials

### 5.1 Ecotoxicity of Nanomaterials

The increasing production and application of engineered nanomaterials raise concerns regarding their potential release into the environment and subsequent ecological impacts. Waste generation during synthesis and application may expose humans and ecosystems through multiple pathways: inhalation, ingestion, dermal contact, and absorption[1].

Physicochemical properties associated with nanomaterial toxicity include: particle size and size distribution, shape (spherical, rod-like, tubular), surface area, surface charge and functionalization, chemical composition, solubility, aggregation/agglomeration state, and crystal structure[1], [31].

**Carbon nanotube toxicity:** CNT toxicity depends on length, surface area, distribution ratio, aggregation degree, and initial concentration. Single-walled CNTs are less toxic than double-walled CNTs[31]. CNTs have been associated with pulmonary inflammation, oxidative stress, granuloma formation, apoptosis, and fibrosis in animal studies.

**Metal oxide nanoparticle toxicity:**  $\text{TiO}_2$  is generally considered non-toxic even at higher concentrations for 24-hour exposure [31]. However,  $\text{Fe}_2\text{O}_3$ -CNT composites showed toxic effects and DNA damage even at lowest concentrations provides a summary of self-toxic effects of common nanomaterials, noting that gold nanorods doped with poly(styrene sulfonate) are non-toxic, while CTAB-doped Au nanorods are highly toxic at certain concentrations[31].

### 5.2 Human Health Effects

Exposure to nanomaterials can occur through occupational (synthesis, handling, manufacturing), consumer (product use), and environmental (release to water, air, soil) pathways. Potential health effects include:

- **Respiratory effects:** Inhalation of nanoparticles (<100 nm) leads to deep lung deposition (alveolar region), causing inflammation, oxidative stress, and fibrosis. CNTs have been compared to asbestos in terms of fiber-like pathogenicity.
- **Cardiovascular effects:** Nanoparticles translocate from lungs to bloodstream, potentially causing endothelial dysfunction, thrombosis, and atherosclerosis.
- **Gastrointestinal effects:** Ingested nanoparticles (from drinking water, food contact materials) may cause intestinal inflammation and alter gut microbiota.
- **Neurological effects:** Nanoparticles can translocate via olfactory nerve or blood-brain barrier, potentially contributing to neurodegenerative diseases.
- **Genotoxicity and carcinogenicity:** Some nanomaterials (CNTs, metal oxide nanoparticles) induce DNA damage, chromosomal aberrations, and oxidative stress, raising carcinogenic potential.

### 5.3 Life Cycle Assessment (LCA) of Nanomaterials

Life cycle assessment is essential for evaluating the overall environmental impacts of nanomaterials from raw material extraction through manufacturing, use, and end-of-life stages. Green

nanotechnology requires incorporation of life cycle thinking to analyze environmental impacts of nanoproducts before commercial release [6].

Key considerations in nanomaterial LCA include:

- **Energy consumption:** Synthesis methods (CVD, sol-gel, hydrothermal, ball milling) vary significantly in energy intensity. Bottom-up synthesis generally consumes more energy but produces less waste.
- **Material efficiency:** The atom economy (fraction of starting materials incorporated into final product) of nanomaterial synthesis is often low (10–50%), generating substantial chemical waste.
- **Solvent usage and recovery:** Organic solvents (toluene, DMF, THF) used in nanoparticle functionalization and purification pose environmental and health hazards.
- **Nanoparticle release during use:** Leaching of nanoparticles from composite materials or membranes during water treatment may lead to environmental release.
- **End-of-life disposal:** Incineration, landfilling, or recycling of nanomaterial-containing products each present unique challenges and environmental impacts.

## 5.4 Regulatory Frameworks and Guidelines

The regulation of nanomaterials for environmental applications requires comprehensive frameworks addressing synthesis, handling, use, and disposal. While the US Environmental Protection Agency (EPA) permits limited production of new nanoscale materials under the Toxic Substances Control Act (TSCA), specific regulations for nanomaterials remain under development in most countries [6].

International organizations developing nanomaterial standards and guidelines include:

- **OECD (Organization for Economic Co-operation and Development):** Working Party on Manufactured Nanomaterials (WPMN) develops test guidelines and safety assessment frameworks.
- **ISO (International Organization for Standardization):** Technical Committee 229

(Nanotechnologies) develops standards for terminology, characterization, and toxicity testing.

- **WHO (World Health Organization):** Guidelines on protecting workers from potential risks of manufactured nanomaterials.
- **EU (European Union):** Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation applies to nanomaterials with specific provisions for nanoforms.

## 6. Challenges, and Future Perspectives

### 6.1 Current Challenges

Despite remarkable advances, several challenges limit widespread implementation of nanotechnology for environmental applications [31]:

1. **Selective recognition and elimination:** Achieving selective removal of target contaminants from complex sample matrices (real wastewater, groundwater) containing multiple competing species remains challenging.
2. **Mechanistic understanding:** The mechanisms associated with specific pollutant removal (adsorption, photocatalysis, reduction) require further elucidation, particularly for emerging contaminants.
3. **Scalable production:** Large-scale synthesis of consistent, high-quality nanomaterials with controlled size, shape, and surface properties remain difficult and costly.
4. **Cost-effectiveness:** Nanomaterial production costs must decrease substantially to compete with conventional treatment technologies.
5. **Post-treatment recovery:** Separation and recycling of nanomaterials after treatment (without secondary contamination) remains a technical and economic challenge.
6. **Agglomeration and stability:** Nanoparticles tend to agglomerate under normal conditions due to high surface energy, reducing effective surface area and activity.
7. **Toxicity and environmental persistence:** The potential long-term ecotoxicity

and environmental persistence of engineered nanomaterials are not fully understood.

8. **Regulatory acceptance:** Lack of standardized testing protocols, risk assessment frameworks, and regulatory guidelines hinders commercial adoption.

9. **Public perception:** Concerns about nanomaterial safety may impede public acceptance of nanotechnology-enabled environmental solutions.

## 6.2 Future Research Directions

**Multifunctional nanomaterial design:** Future research should focus on developing nanomaterials capable of simultaneous removal of multiple pollutant classes (heavy metals, organics, pathogens). Hierarchical nanostructures (nanoflowers, nanorods, nanoflakes, nano cones) with enhanced functional and structural properties offer extensive research opportunities[31].

**Molecularly imprinted polymers (MIPs):** MIP-nanomaterial composites enable selective recognition and removal of specific target contaminants (e.g., individual pharmaceuticals, pesticides) through tailored binding sites.

**Magnetic nanocomposites:** Incorporation of iron oxide nanoparticles with carbon-based materials or polymers enables easy separation and recovery using external magnetic fields, addressing one of the major limitations of nanomaterial applications in water treatment.

**Visible-light-active photocatalysts:** Development of efficient photocatalysts that operate under solar or indoor visible light (rather than UV) is critical for practical applications. Strategies include doping, heterojunction formation, plasmonic enhancement, and defect engineering.

**Continuous flow reactors:** Microfluidic and continuous flow reactor systems offer advantages including large surface-to-volume ratio, improved diffusion effects, high mass transfer coefficients, stable hydrodynamics, and easy scale-up[31].

**Machine learning and high-throughput screening:** Computational approaches can accelerate nanomaterial discovery by predicting

structure-property relationships, optimal synthesis conditions, and pollutant removal performance.

## 7. Conclusions

Nanotechnology and advanced materials offer transformative solutions for environmental sustainability across water treatment, air quality management, and green energy technologies. The unique physicochemical properties of nanomaterials exceptionally high surface-area-to-volume ratios, quantum confinement effects, enhanced chemical reactivity, superior mechanical strength, and tunable optical and electrical properties enable efficient pollutant removal, sensitive environmental monitoring, and improved energy conversion and storage.

**In water treatment:** Metal-based nanoparticles (Ag, Au, Zn, Fe, Cu), transition metal oxides (TiO<sub>2</sub>, ZnO, Fe<sub>3</sub>O<sub>4</sub>, Fe<sub>2</sub>O<sub>3</sub>), carbon-based nanomaterials (CNTs, graphene, GO), and their nanocomposites demonstrate exceptional capabilities for heavy metal removal, organic pollutant degradation, pathogen disinfection, and membrane-based separation. Photocatalytic mechanisms enable complete mineralization of organic pollutants to CO<sub>2</sub>, H<sub>2</sub>O, and inorganic ions, while adsorption processes efficiently remove dissolved contaminants. Nanofiltration membranes offer selective separation with lower energy requirements than reverse osmosis.

**For air quality management:** Nanomaterials enable advanced particulate filtration (CNT filters, nanofibrous media), catalytic conversion of gaseous pollutants (NO<sub>x</sub>, SO<sub>2</sub>, CO, VOCs) using nano catalysts (Pt, Pd, CeO<sub>2</sub>, TiO<sub>2</sub>), and highly sensitive real-time monitoring through nano sensors (Chemi resistive, electrochemical, optical). Carbon capture technologies utilizing MOFs, graphene-based materials, and amine-functionalized nanofibers contribute to climate change mitigation through CO<sub>2</sub> sequestration.

**In the green energy sector:** Nanomaterials enhance solar cell efficiency (quantum dots, perovskites, DSSCs), improve energy storage in batteries (Si nanoparticles, LiFePO<sub>4</sub> nanostructures) and supercapacitors (CNTs,

graphene, MnO<sub>2</sub>), facilitate hydrogen production through photocatalytic water splitting (TiO<sub>2</sub>, g-C<sub>3</sub>N<sub>4</sub>, Z-scheme systems), optimize fuel cell performance (Pt nanoparticles, nanocomposite membranes), and enhance biofuel production (immobilized enzymes, algal harvesting).

**However, the environmental and health implications of nanomaterials require careful consideration.** Ecotoxicity studies have demonstrated potential adverse effects on aquatic organisms (Daphnia, fish, algae), while uncertainties remain regarding long-term environmental fate, chronic toxicity, trophic transfer, and human health effects. Green synthesis approaches utilizing plant extracts, microbial systems, and green chemistry principles offer sustainable production routes while minimizing hazardous byproducts and energy consumption.

**Future research should focus on:** (1) multifunctional nanomaterial design for simultaneous removal of multiple pollutant classes; (2) scalable, cost-effective, and green synthesis methods; (3) integration of nanomaterials with conventional treatment technologies; (4) comprehensive life cycle assessment and ecotoxicity testing; (5) development of standardized regulatory frameworks and risk assessment methodologies; (6) machine learning-accelerated nanomaterial discovery; and (7) demonstration projects at pilot and full scale.

The principles of green chemistry and green engineering must guide nanotechnology development to ensure that environmental solutions do not create new environmental problems. With continued advances in nanomaterial synthesis, characterization, application, and responsible development practices, nanotechnology holds immense promise for addressing global environmental challenges and contributing to the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 11

(Sustainable Cities and Communities), and SDG 13 (Climate Action).

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