

Nanomaterials and Their Applications in Chemical Technology

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Received: 02/12/2025 ; Accepted: 27/07/2026 ; Published: 24/08/2026

Abstract

Nanomaterials possess structural features at the nanoscale that can produce chemical, physical, optical, electrical, and catalytic properties different from those of bulk materials. Their high surface-area-to-volume ratios, tunable electronic structures, surface reactivity, and size-dependent behavior have created important opportunities in chemical technology. Nanomaterials are increasingly used in catalysis, sensing, environmental remediation, energy conversion and storage, coatings, membranes, and advanced manufacturing. This paper examines nine major dimensions of nanomaterials and their applications in chemical technology, including nanoscale properties, synthesis, catalysis, sensors, environmental applications, energy technologies, nanocomposites, safety, and sustainable future development.

Keywords

Nanomaterials; Nanotechnology; Chemical Technology; Nanocatalysts; Nanosensors; Environmental Remediation; Nanocomposites; Energy Storage; Surface Chemistry; Sustainable Nanotechnology

Introduction

Nanomaterials are materials with at least one characteristic dimension in the nanoscale range. At these dimensions, changes in surface area, electronic structure, quantum effects, and interfacial interactions can produce properties that differ substantially from conventional bulk materials.

Chemistry is central to nanomaterial development because the synthesis method, composition, surface functionalization, particle size, morphology, and aggregation state determine many of the resulting properties.

Chemical technologies use nanomaterials to accelerate reactions, detect chemical species, separate substances, remove pollutants, store energy, and create materials with improved mechanical or functional characteristics.

The rapid development of nanotechnology has therefore created opportunities across chemical engineering, analytical chemistry, environmental science, energy research, and industrial materials development.

1. 1. Nanoscale Properties and Surface Chemistry

The properties of nanomaterials are strongly influenced by their large surface-area-to-volume ratios. A greater proportion of atoms are located at or near surfaces, where they

can participate in chemical reactions or interact with surrounding molecules.

Particle size, shape, crystallinity, surface defects, and surface functional groups can influence adsorption, catalytic activity, optical behavior, and chemical stability.

Surface chemistry is therefore a major tool for tailoring nanomaterials for specific chemical applications.

2. 2. Synthesis and Functionalization of Nanomaterials

Nanomaterials can be produced using chemical, physical, and biological approaches. Sol-gel methods, precipitation, hydrothermal synthesis, chemical vapor deposition, reduction reactions, and self-assembly are among the techniques used for different material classes.

Controlling nucleation and growth allows researchers to adjust particle size and morphology. Surface functionalization can then introduce chemical groups that improve stability, selectivity, compatibility, or reactivity.

Reproducible synthesis is essential for translating laboratory nanomaterials into industrial technologies.

3. 3. Nanocatalysts and Chemical Reactions

Nanomaterials can function as catalysts because their high surface areas provide many accessible active sites. Metal nanoparticles, metal oxides, supported nanocatalysts, and other nanoscale structures are used in oxidation, reduction, hydrogenation, photocatalysis, and environmental reactions.

Catalytic performance depends on particle size, surface structure, oxidation state, support interactions, and reaction conditions. Nanostructuring can improve activity and selectivity, although particle aggregation may reduce performance.

Nanocatalysis is therefore an important area where surface chemistry directly supports chemical process improvement.

4. 4. Nanosensors and Analytical Chemistry

Nanomaterials are increasingly used in chemical sensors because their electrical, optical, magnetic, or catalytic properties can respond sensitively to target molecules. Gold nanoparticles, metal oxides, graphene-related materials, and other nanostructures have been investigated for sensing applications.

Functionalization can improve selectivity by providing binding sites for specific analytes. Changes in conductivity, color, fluorescence, or other measurable properties can then be used to detect chemical substances.

Nanotechnology can support compact and sensitive analytical systems for environmental, industrial, and biomedical monitoring.

5. 5. Environmental Remediation and Water Treatment

Nanomaterials can assist in removing or transforming contaminants in water, soil, and air. Adsorptive nanomaterials can capture metals and organic pollutants, while photocatalytic materials can promote the degradation of selected contaminants.

Iron-based nanoparticles, metal oxides, carbon nanomaterials, and engineered composites have been studied for remediation applications. Their high surface areas and tunable surface chemistry can provide strong interactions with pollutants.

Environmental applications require careful evaluation of nanoparticle stability, recovery, transformation, and potential release into ecosystems.

6. 6. Nanomaterials in Energy Conversion and Storage

Nanomaterials are used in batteries, supercapacitors, fuel cells, solar cells, and hydrogen-related technologies. Their high surface areas and short diffusion pathways can improve charge transport and reaction kinetics.

Nanostructured electrodes can provide increased active surface area, while nanoscale catalysts can improve electrochemical reactions. Semiconductor nanomaterials can also be used for light absorption and photocatalytic processes.

Balancing performance with stability, manufacturability, cost, and resource sustainability remains important.

7. 7. Polymer Nanocomposites and Advanced Materials

Nanoparticles can be incorporated into polymers to create nanocomposites with improved mechanical, thermal, electrical, barrier, or optical properties. Nanoclays, carbon nanotubes, graphene-related materials, silica, and metal nanoparticles are examples of fillers used in polymer systems.

The interface between the polymer and nanofiller strongly affects performance. Surface modification can improve dispersion and interfacial bonding.

Such materials have applications in packaging, coatings, transportation, electronics, construction, and specialized industrial products.

8. 8. Safety, Toxicity, and Responsible Nanotechnology

The same nanoscale properties that make nanomaterials useful can also influence their interactions with biological systems and the environment. Particle size, surface

chemistry, solubility, shape, and aggregation can affect exposure and biological responses.

Responsible development therefore requires appropriate characterization, exposure assessment, safe handling, and consideration of environmental release. Recovery and disposal strategies should be considered alongside material performance.

Risk assessment and lifecycle thinking are essential for ensuring that nanotechnology develops in a safe and responsible manner.

9. 9. Future Trends and Sustainable Nanochemical Technology

Future nanomaterials research is likely to emphasize precise synthesis, multifunctional structures, bio-based approaches, recyclable materials, and lower-energy production methods. Advanced characterization and computational modeling can help predict nanoscale behavior and optimize material design. Green nanotechnology aims to reduce hazardous reagents, energy use, waste, and environmental impacts during nanomaterial synthesis and application. Reusable catalysts and recoverable nanoparticles can also support more sustainable chemical processes. The integration of nanomaterials with artificial intelligence, biotechnology, advanced manufacturing, and circular-economy principles may further expand their role in chemical technology.

Diagram

The diagram below summarizes major applications of nanomaterials in chemical technology, including catalysis, chemical sensing, environmental remediation, energy systems, and advanced materials.

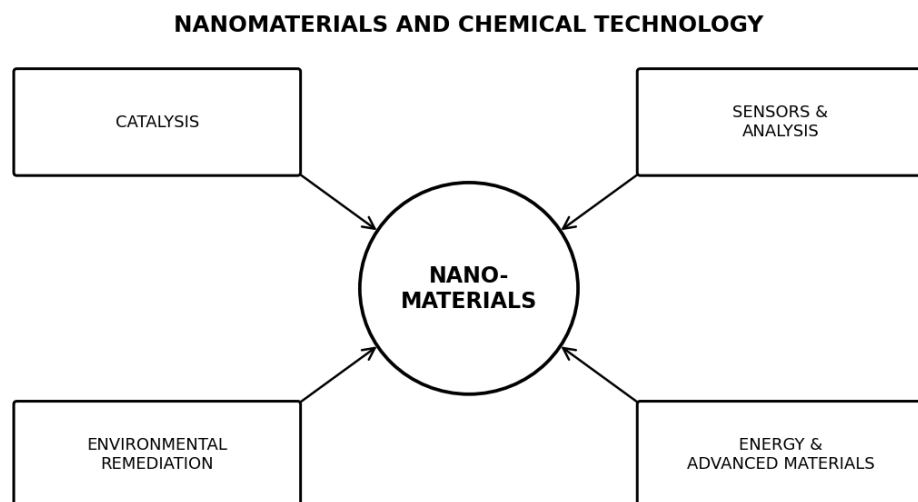


Figure 1. Simplified overview of nanomaterials and their applications in chemical technology.

Conclusion

Nanomaterials provide important opportunities in chemical technology because their nanoscale dimensions produce distinctive surface, electronic, optical, and catalytic properties. These characteristics can be tailored through chemical composition, synthesis conditions, morphology, and surface functionalization.

Applications in catalysis, sensing, environmental remediation, energy storage, and advanced composites demonstrate the broad technological value of nanomaterials. However, practical development must also address stability, cost, scalability, safety, and environmental impacts.

Future progress will depend on combining nanoscale chemical design with green synthesis, lifecycle assessment, responsible risk management, and scalable manufacturing. Such approaches can help realize the benefits of nanotechnology while supporting sustainable chemical development.

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