

Chapter-36

Nanotechnology in Sustainable Chemistry: Materials, Processes, and Applications

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Abstract

Nanotechnology has become a pivotal component of sustainable chemistry by offering innovative pathways to design materials and chemical processes that are efficient, environmentally benign, and resource-conserving. By manipulating matter at the nanoscale, chemists can exploit unique size-dependent physicochemical properties such as high surface area, tunable electronic structure, and enhanced catalytic activity. This chapter presents a comprehensive overview of nanotechnology from a chemistry-centered sustainability perspective, focusing on the synthesis, functionalization, and application of nanomaterials in green chemical processes. Emphasis is placed on nanocatalysis, photocatalysis, and electrochemical applications that enable energy-efficient reactions, reduced waste generation, and improved selectivity. The role of nanomaterials in renewable energy conversion, energy storage, environmental remediation, and water purification is critically discussed with mechanistic insights and relevant chemical reactions. Additionally, green synthesis strategies, life-cycle assessment, nanotoxicology, and safe-by-design approaches are addressed to highlight the importance of responsible nanotechnology development. By integrating principles of green chemistry with nanoscience, this chapter demonstrates how nanotechnology can significantly contribute to sustainable chemical innovation while minimizing environmental and health risks.

Keywords: Nanotechnology, Sustainable chemistry, Nanomaterials, Green chemistry, Nanocatalysis, Photocatalysis, Energy conversion, Environmental remediation, Green synthesis, Safe-by-design nanotechnology

1. Introduction

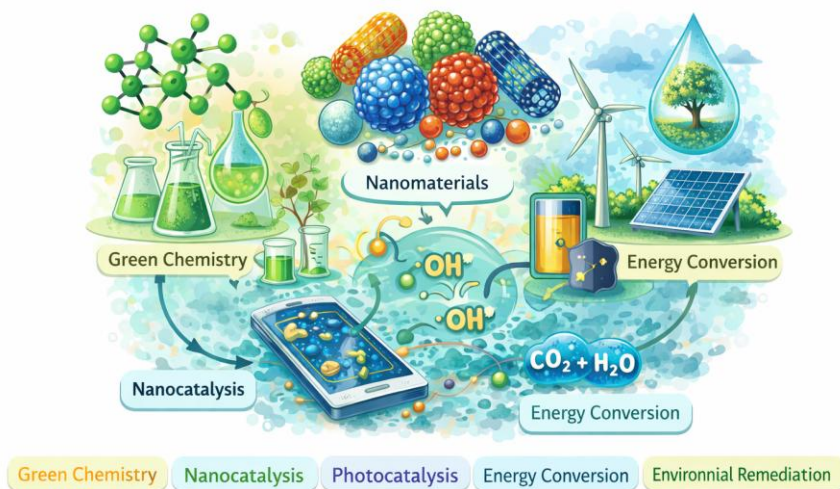
Nanotechnology has emerged as a transformative domain within chemical sciences, enabling precise manipulation of matter at the atomic and molecular scale. Defined by materials with at least one dimension between 1 and 100 nanometers, nanotechnology occupies a unique position between molecular chemistry and bulk materials science. At this scale, matter exhibits distinct physicochemical properties that are fundamentally different from those observed in macroscopic systems. These properties arise due to quantum confinement effects, increased surface area, and altered electronic structure, making nanomaterials highly attractive for sustainable chemical applications. Sustainable chemistry seeks to design chemical products and processes that reduce environmental impact, minimize hazardous substances, conserve energy, and utilize renewable resources. Traditional chemical manufacturing often relies on high temperatures, extreme pressures, toxic solvents, and non-renewable feedstock. These

approaches, although effective, are increasingly incompatible with global sustainability goals. Nanotechnology provides a chemistry-driven solution by enabling highly efficient reactions under mild conditions, reducing waste generation and energy consumption.

The integration of nanotechnology into sustainable chemistry has enabled breakthroughs in catalysis, energy conversion, environmental remediation, and green material design. Nanomaterials act as catalysts, adsorbents, photo catalysts, and functional surfaces, offering superior performance compared to bulk materials. Their effectiveness stems from the dominance of surface chemistry and interfacial phenomena, which are central to chemical reactivity. From a chemical perspective, nanotechnology is not merely a tool but a design philosophy. By controlling size, shape, surface functionality, and composition at the nanoscale, chemists can tailor reactivity and selectivity with unprecedented precision. This capability aligns directly with the principles of green chemistry, particularly those emphasizing atom economy, energy efficiency, and design for degradation.

However, the widespread application of nanotechnology raises critical questions regarding environmental safety, toxicity, and life-cycle impact. Sustainable nanochemistry must therefore balance performance with responsibility, ensuring that nanomaterials contribute positively to environmental and human health.

Nanotechnology in Sustainable Chemistry: Materials, Processes, and Applications



2. Chemical Fundamentals of Nanotechnology

2.1 Surface Area and Reactivity

One of the defining chemical characteristics of nanomaterials is their exceptionally high surface-to-volume ratio. As particle size decreases, the proportion of surface atoms increases dramatically. For example, in a 5 nm nanoparticle, more than 50% of atoms may reside on the surface, compared to less than 1% in bulk materials. Surface atoms possess unsatisfied coordination, leading to higher surface energy and

enhanced chemical reactivity. This property is critical in catalytic reactions, adsorption processes, and redox chemistry.

Example: Catalytic oxidation on metal nanoparticles



Gold, which is chemically inert in bulk form, becomes catalytically active when reduced to nanoscale dimensions due to altered electronic density and surface atom availability.

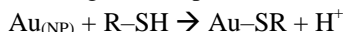
2.2 Quantum Size Effects

At the nanoscale, electrons experience spatial confinement, resulting in discrete energy levels rather than continuous bands. This phenomenon is known as quantum confinement and is particularly significant in semiconductor nanoparticles (quantum dots). The band gap energy (E_g) increases as particle size decreases: $E_g \propto 1/r^2$. This size-dependent tunability allows chemists to control optical absorption and emission, a feature exploited in: Photo catalysis, Solar cells, Chemical sensing.

2.3 Surface Functionalization Chemistry

Nanoparticles tend to aggregate due to van der Waals forces and high surface energy. To stabilize them, surface functionalization is employed using ligands that bind chemically to the surface.

Example: Thiol functionalization of gold nanoparticles



This chemisorption process forms a strong Au-S bond, stabilizing nanoparticles and enabling further chemical modification. Surface functionalization also determines: Hydrophilicity/hydrophobicity, Charge, and Selective binding to pollutants or reactants.

3. Green Synthesis of Nanomaterials

3.1 Chemical Reduction Method (Green Route)

Metal nanoparticles are commonly synthesized by reducing metal ions in solution.

Example: Green synthesis of silver nanoparticles



Here, ascorbic acid acts as a green reducing agent.

Mechanism :

1. Ascorbic acid donates electrons.
2. Ag^+ ions are reduced to Ag^0 atoms.
3. Nucleation occurs when supersaturation is reached.
4. Growth proceeds via atom addition.
5. Capping molecules prevent aggregation.

3.2 Biological (Plant-Mediated) Synthesis

Plant extracts contain polyphenols and flavonoids that act as reducing and stabilizing agents.

General reduction reaction:



This method:

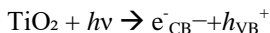
Avoids toxic chemicals

Operates at room temperature

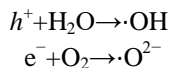
Produces biocompatible nanoparticles

4. Photocatalytic Mechanism (TiO₂ Example)

When TiO₂ nanoparticles absorb UV light:



Subsequent reactions:



These reactive oxygen species degrade pollutants:



4. Nanocatalysis in Sustainable Chemistry

Catalysis lies at the heart of chemical sustainability, as it enables reactions to proceed with higher efficiency, selectivity, and reduced energy consumption. Nanocatalysis represents a significant advancement over conventional catalysis by exploiting the unique physicochemical properties of nanomaterials. At the nanoscale, catalysts exhibit enhanced surface area, altered electronic structure, and increased density of active sites, which collectively contribute to superior catalytic performance. From a chemistry perspective, nanocatalysts function primarily as heterogeneous catalysts, although their behavior often resembles that of homogeneous catalysts due to their high surface reactivity. This dual nature allows nanocatalysts to combine the advantages of both catalytic systems: high activity and selectivity from homogeneous catalysis, and easy separation and recyclability from heterogeneous catalysis.

4.1 Chemical Basis of Nanocatalytic Activity

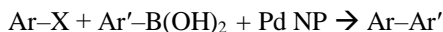
The enhanced activity of nanocatalysts arises from several chemical factors. First, the increased proportion of low-coordination surface atoms creates active sites with unsaturated valency, which readily interact with reactant molecules. Second, quantum size effects alter the electronic density of states, facilitating electron transfer during redox reactions. Third, strong metal–support interactions (SMSI) between nanoparticles and their supports influence adsorption energies and reaction pathways. For example, palladium nanoparticles supported on carbon or metal oxides exhibit significantly enhanced catalytic activity in carbon–carbon coupling reactions due to improved oxidative addition and reductive elimination steps.

4.2 Palladium Nanoparticles in Sustainable Organic Synthesis

Palladium nanocatalysts are extensively used in sustainable organic transformations, particularly in cross-coupling reactions such as Suzuki–Miyaura, Heck, and Sonogashira reactions. These reactions are essential for synthesizing pharmaceuticals, agrochemicals, and fine chemicals.

4.2.1 Suzuki–Miyaura Coupling Reaction

The general reaction is:

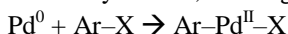


where Ar–X is an aryl halide.

Nanocatalytic Mechanism (Textual Explanation)

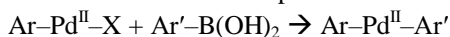
1. Oxidative Addition

Palladium(0) nanoparticles adsorb the aryl halide, forming a Pd(II)–aryl complex:



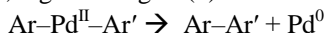
2. Transmetalation

The aryl group from the boronic acid transfers to palladium:



3. Reductive Elimination

The biaryl product is released, regenerating Pd(0):

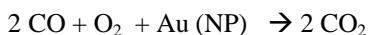


Nanoparticles accelerate these steps by stabilizing Pd(0) species and facilitating rapid electron transfer. Their recyclability reduces metal waste, aligning with green chemistry principles.

4.3 Gold Nanoparticles in Green Oxidation Reactions

Bulk gold is chemically inert; however, gold nanoparticles exhibit remarkable catalytic activity, particularly in oxidation reactions under mild conditions. This unusual behavior arises from charge transfer between gold nanoparticles and their support, often metal oxides such as TiO₂ or Fe₂O₃.

Example: Oxidation of Carbon Monoxide



Mechanistic Insight

1. CO adsorbs onto low-coordination gold atoms.
2. O₂ is activated at the metal-support interface.
3. Electron transfer weakens the O-O bond.
4. CO reacts with activated oxygen to form CO₂.

This reaction occurs at near-ambient temperature, making gold nanocatalysts ideal for air purification and pollution control.

4.4 Iron Oxide Nanoparticles as Green Catalysts

Iron oxide nanoparticles are particularly attractive from a sustainability perspective due to iron's abundance, low toxicity, and magnetic properties. These nanoparticles are widely used in oxidation reactions, Fenton-like processes, and environmental remediation.

Fenton-Like Catalytic Reaction



The hydroxyl radical generated is a powerful oxidant capable of degrading organic pollutants.

Nanocatalytic Advantage

Increased surface Fe²⁺ sites

Faster redox cycling between Fe²⁺ and Fe³⁺

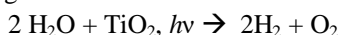
Magnetic recovery reduces secondary pollution

5. Nanotechnology in Sustainable Chemical Processes

5.1 Photocatalysis for Green Chemical Transformations

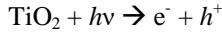
Photocatalysis harnesses light energy to drive chemical reactions, reducing dependence on thermal energy. Semiconductor nanoparticles such as TiO₂, ZnO, and CdS are widely used due to their suitable band gaps and chemical stability.

Photocatalytic Water Splitting

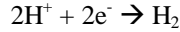


Mechanism

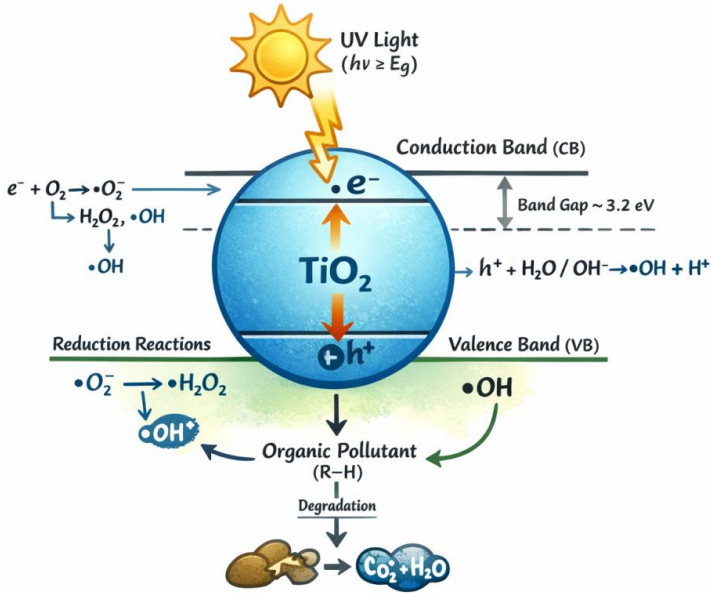
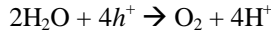
1. Photon absorption excites electrons:



2. Reduction at conduction band:



3. Oxidation at valence band:

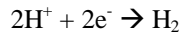


Nanostructuring enhances charge separation and reduces recombination losses.

5.2 Electrocatalysis and Sustainable Redox Chemistry

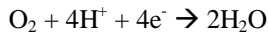
Nanomaterials significantly improve electrocatalytic reactions by lowering overpotentials and enhancing electron transfer kinetics.

Hydrogen Evolution Reaction (HER)



Platinum nanoparticles exhibit near-zero overpotential due to optimal hydrogen adsorption energy.

Oxygen Reduction Reaction (ORR)



Carbon-supported metal nanoparticles improve fuel cell efficiency.

5.3 Nanotechnology in Green Chemical Manufacturing

Nanoreactors and nanostructured catalysts enable: Continuous-flow chemistry, Reduced solvent use, Higher selectivity. For example, nanoporous silica catalysts facilitate acid-catalyzed reactions without corrosive liquid acids, minimizing waste and equipment degradation.

6. Nanotechnology in Sustainable Energy Systems

The global transition toward sustainable energy systems necessitates the development of efficient technologies for energy conversion, storage, and utilization. From a chemistry perspective, these challenges are fundamentally governed by redox reactions, charge transport, catalytic activity, and thermodynamic efficiency. Nanotechnology provides unprecedented control over these chemical processes by tailoring material properties at the atomic and molecular levels. Nanomaterials enhance reaction kinetics, improve electron and ion transport, and enable novel energy pathways that are otherwise inaccessible in bulk systems.

6.1 Nanotechnology in Solar Energy Conversion

Solar energy conversion relies on the absorption of photons and subsequent charge separation and transport. Nanomaterials improve these processes by increasing surface area, tuning band gaps, and facilitating rapid electron transfer.

6.1.1 Semiconductor Nanoparticles in Photovoltaics

In semiconductor nanomaterials, quantum confinement effects lead to size-dependent band gaps. This property is particularly useful in solar cells, where matching the band gap to the solar spectrum is critical for maximizing efficiency.

For a semiconductor nanoparticle:

$$E_g(r) = E_g(\text{bulk}) + \frac{h^2 \pi^2}{2r^2} \left(\frac{1}{m_e^*} + \frac{1}{m_h^*} \right)$$

where r is particle radius and m_e^* , m_h^* are effective masses of electrons and holes.

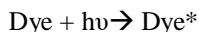
Quantum dots such as CdSe, PbS, and perovskite nanocrystals are employed to enhance light absorption and charge carrier generation.

6.1.2 Dye-Sensitized Solar Cells (DSSCs)

Nanostructured titanium dioxide plays a central role in DSSCs due to its high surface area and suitable conduction band energy.

Key reactions:

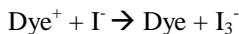
1. Dye excitation:



2. Electron injection:



3. Regeneration of dye:



The nanoscale morphology of TiO_2 ensures efficient electron percolation and minimizes recombination losses.

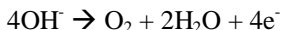
6.2 Nanotechnology in Hydrogen Energy Systems

Hydrogen is a clean energy carrier, producing only water upon combustion or electrochemical oxidation. However, its sustainable production and utilization depend heavily on advanced catalytic materials.

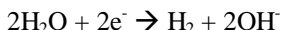
6.2.1 Nanocatalysts for Water Electrolysis

Water electrolysis involves two half-reactions:

Anode (Oxygen Evolution Reaction, OER):



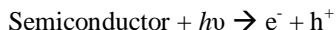
Cathode (Hydrogen Evolution Reaction, HER):



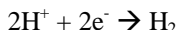
Nanostructured catalysts such as Ni–Fe layered double hydroxides enhance OER kinetics by facilitating proton-coupled electron transfer. Platinum nanoparticles optimize HER by providing near-ideal hydrogen adsorption energy.

6.2.2 Photocatalytic Hydrogen Production

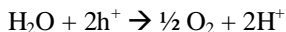
Semiconductor nanoparticles absorb photons to generate electron–hole pairs that drive redox reactions.



Reduction reaction:



Oxidation reaction:



Nano structuring improves charge separation and surface reaction rates.

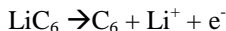
6.3 Nanotechnology in Energy Storage Systems

Energy storage is essential for balancing intermittent renewable energy sources. Nanomaterials enhance storage capacity, cycle life, and power density by optimizing electrochemical interfaces.

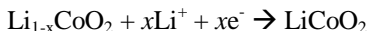
6.3.1 Nanomaterials in Lithium-Ion Batteries

Lithium-ion batteries operate via reversible intercalation reactions.

Anode reaction (graphite):



Cathode reaction (LiCoO_2):



Nanostructured electrodes reduce diffusion lengths for Li^+ ions, improving rate capability and cycling stability.

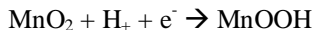
6.3.2 Supercapacitors and Pseudocapacitance

Supercapacitors store energy through electrostatic and faradaic processes.

Electrical double-layer capacitance:

$$C = \epsilon A/d$$

Pseudocapacitive reaction (MnO_2):



Nanostructured carbon materials and metal oxides enhance capacitance by increasing surface area and facilitating rapid redox reactions.

7. Nanotechnology in Environmental Applications

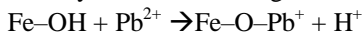
Nanotechnology plays a crucial role in environmental remediation by enabling efficient removal and degradation of pollutants through chemical interactions at the nanoscale.

7.1 Water Purification and Treatment

Nanomaterials remove contaminants via adsorption, catalysis, and antimicrobial action.

7.1.1 Adsorption of Heavy Metals

Iron oxide nanoparticles bind heavy metal ions through surface complexation.



Magnetic properties allow easy separation, reducing secondary pollution.

7.1.2 Photocatalytic Degradation of Organic Pollutants

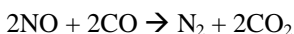


Reactive oxygen species generated by TiO₂ nanoparticles oxidize dyes, pesticides, and pharmaceuticals.

7.2 Air Pollution Control

Nanocatalysts facilitate oxidation and reduction of atmospheric pollutants.

NO_x reduction:



Nanostructured catalysts lower activation energy and improve selectivity.

7.3 Antimicrobial Nanomaterials

Silver nanoparticles release Ag⁺ ions that disrupt microbial cell membranes.

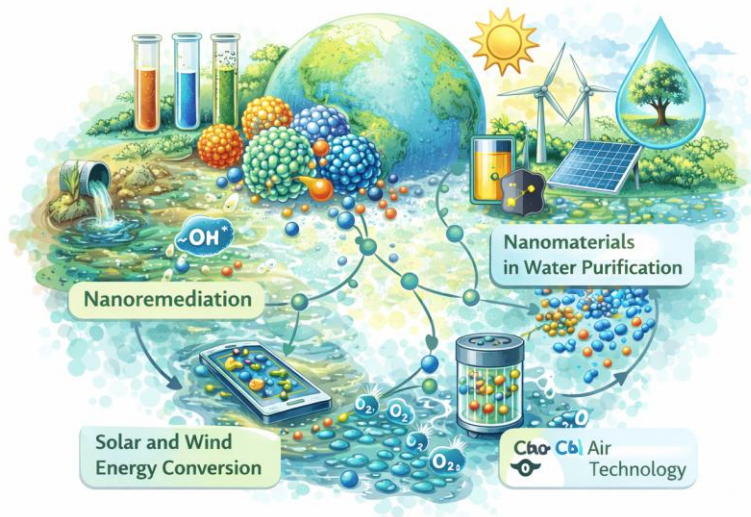


These ions interact with thiol groups in proteins, inhibiting enzymatic activity.

8. Nanotoxicology: Chemical Basis of Environmental and Biological Interactions

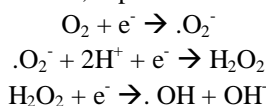
While nanotechnology offers significant advantages for sustainable chemistry, its widespread application necessitates a rigorous evaluation of potential environmental and health risks. Nanotoxicology is the branch of science that examines the adverse effects of nanomaterials on living organisms and ecosystems, with particular emphasis on chemical composition, size, surface chemistry, and reactivity. From a chemistry perspective, toxicity is not an inherent property of nanomaterials but a consequence of their physicochemical characteristics and interactions at the molecular level. One of the primary concerns associated with nanomaterials is their ability to penetrate biological membranes due to their small size. Nanoparticles can enter cells through endocytosis or diffusion and interact directly with intracellular components such as proteins, nucleic acids, and organelles. The chemical reactivity of nanoparticles, particularly those with high surface energy, can lead to the generation of reactive oxygen species (ROS), resulting in oxidative stress.

Nanotechnology in Environmental Applications



8.1 Reactive Oxygen Species Generation

Certain metal and metal oxide nanoparticles catalyze redox reactions that produce ROS such as hydroxyl radicals, superoxide anions, and hydrogen peroxide.



These reactive species can damage cellular components by oxidizing lipids, proteins, and DNA. The extent of ROS generation depends strongly on surface chemistry, crystallinity, and the presence of defects in nanomaterials.

8.2 Influence of Size, Shape, and Surface Chemistry

Particle size plays a critical role in nanotoxicity. Smaller nanoparticles have higher surface area and reactivity, increasing their likelihood of interacting with biological molecules. Shape also influences toxicity; for example, fibrous nanomaterials such as carbon nanotubes may exhibit asbestos-like behavior due to their high aspect ratio. Surface charge and functional groups determine how nanomaterials interact with biological membranes. Positively charged nanoparticles tend to interact strongly with negatively charged cell membranes, increasing cellular uptake. Chemical surface modification using biocompatible polymers such as polyethylene glycol (PEG) can significantly reduce toxicity by minimizing nonspecific interactions.

9. Environmental Fate and Transformation of Nanomaterials

Understanding the environmental behavior of nanomaterials is essential for assessing their long-term sustainability. Once released into the environment, nanomaterials undergo various physicochemical transformations, including aggregation, dissolution, oxidation, and surface modification.

9.1 Aggregation and Sedimentation

Nanoparticles tend to aggregate due to van der Waals forces, reducing their mobility and reactivity. Aggregation is influenced by pH, ionic strength, and the presence of natural organic matter.



Aggregation may reduce toxicity but can also complicate removal from environmental systems.

9.2 Dissolution and Chemical Transformation

Metal-based nanoparticles may undergo dissolution, releasing metal ions into the environment.



Released ions often exhibit higher toxicity than the nanoparticle itself. Surface oxidation and sulfidation reactions also alter nanoparticle reactivity and bioavailability.

10. Life-Cycle Assessment (LCA) in Nanotechnology

Life-cycle assessment is a critical tool in sustainable chemistry, enabling evaluation of environmental impact from raw material extraction to end-of-life disposal. For nanomaterials, LCA considers energy consumption, reagent toxicity, waste generation, and recyclability.

10.1 Chemical Stages in Nanomaterial Life Cycle

1. Synthesis: Energy input, solvent use, precursor toxicity 2. Processing: Surface modification, composite formation 3. Application: Functional performance, release potential 4. Disposal/Recycling: Degradation, recovery, environmental persistence. Green synthesis routes significantly improve LCA outcomes by reducing energy demand and eliminating hazardous chemicals.

11. Safe-by-Design Nanotechnology

Safe-by-design is a proactive strategy that integrates safety considerations into the chemical design of nanomaterials. Rather than evaluating risk after development, this approach emphasizes chemical modification, controlled reactivity, and biodegradability from the outset. Chemical Strategies for Safe Design: Surface passivation to reduce ROS generation, Use of biodegradable polymer coatings, Selection of non-toxic metal oxides, Controlled dissolution rates. For example, coating silver nanoparticles with polysaccharides reduces ion release and toxicity while maintaining antimicrobial activity.

12. Regulatory and Ethical Considerations

Sustainable nanotechnology requires robust regulatory frameworks grounded in chemical risk assessment. International agencies emphasize standardized characterization, toxicity testing, and environmental monitoring. Chemists play a critical role in providing accurate molecular-level data to inform regulations. Ethical considerations include equitable access to nanotechnology benefits, responsible innovation, and transparency in environmental impact reporting.

13. Future Perspectives in Nanotechnology for Sustainable Chemistry

The future of nanotechnology in sustainable chemistry lies in the development of multifunctional, adaptive, and environmentally benign nanomaterials. Advances in computational chemistry, machine learning, and in situ characterization techniques will

enable predictive design of nanomaterials with optimized performance and minimal risk. Emerging areas include: Nano-enabled carbon capture and utilization. Artificial photosynthesis. Self-healing and stimuli-responsive nanomaterials, Fully biodegradable nanocomposites. Interdisciplinary collaboration between chemists, material scientists, and environmental researchers will be essential for translating laboratory-scale innovations into real-world solutions.

14. Conclusion

Nanotechnology represents a powerful extension of chemistry, enabling precise control over matter at the nanoscale to achieve sustainable outcomes. By integrating principles of green chemistry, surface science, catalysis, and materials chemistry, nanotechnology offers transformative solutions for energy conversion, environmental remediation, and sustainable manufacturing. However, the benefits of nanotechnology must be balanced with careful consideration of environmental and health impacts. Through green synthesis, safe-by-design strategies, and life-cycle assessment, chemists can ensure that nanotechnology contributes positively to sustainable development. In conclusion, nanotechnology in sustainable chemistry is not merely a technological advancement but a paradigm shift toward responsible molecular engineering, where efficiency, safety, and environmental stewardship are equally prioritized.

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