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NANOTECHNOLOGY AND SMART MATERIALS FOR THE FUTURE

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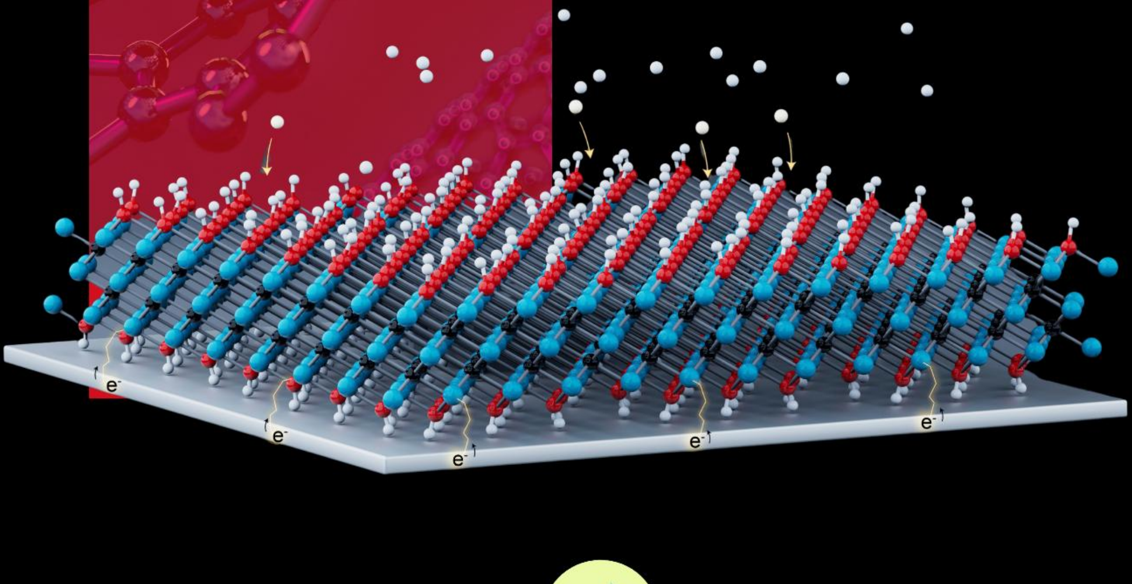

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Nanotechnology and Smart Materials for the Future

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PREFACE

Nanotechnology and smart materials are at the forefront of scientific innovation, offering transformative solutions to some of the most pressing global challenges. The book *Nanotechnology and Smart Materials for the Future* present a comprehensive overview of recent advancements, emerging trends, and interdisciplinary applications that are shaping the next generation of materials science.

Nanotechnology, with its ability to manipulate matter at the atomic and molecular scale, has revolutionized fields such as medicine, electronics, energy, and environmental science. Smart materials, on the other hand, possess the unique ability to respond dynamically to external stimuli such as temperature, pressure, light, and chemical environments. Together, these domains are enabling the development of highly efficient, adaptive, and sustainable technologies.

This volume brings together contributions from researchers, academicians, and industry experts who explore diverse aspects of nanomaterials and smart systems. The chapters highlight innovations in nanocomposites, biomedical applications, drug delivery systems, sensors, energy storage devices, and environmentally responsive materials. Special emphasis is placed on the role of these technologies in promoting sustainability, improving healthcare outcomes, and advancing industrial processes.

In addition to technical advancements, the book also addresses key challenges, including scalability, safety concerns, ethical considerations, and regulatory frameworks. Understanding these issues is essential for ensuring the responsible development and application of nanotechnology and smart materials.

This book aims to serve as a valuable resource for students, researchers, and professionals seeking to understand the evolving landscape of advanced materials. By integrating theoretical insights with practical applications, it aspires to inspire innovation and encourage further research in this rapidly growing field.

We hope that this volume will contribute to the dissemination of knowledge and foster collaborative efforts toward building a smarter, more sustainable future.

- Editors

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NANOTECHNOLOGY-ENABLED SMART GAS SENSORS FOR ENVIRONMENTAL MONITORING AND MULTIDISCIPLINARY APPLICATIONS

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Abstract

Nanotechnology has significantly transformed gas sensing technologies by enabling ultra-sensitive, selective, and low-power detection systems. Nanostructured materials such as metal oxides, graphene, and hybrid nanocomposites exhibit exceptional physicochemical properties, including high surface-to-volume ratios and tunable electronic characteristics, which enhance sensing performance. This review paper critically examines recent advances in nanotechnology-enabled gas sensors, focusing on sensing mechanisms, fabrication techniques, and environmental applications. Furthermore, multidisciplinary applications in healthcare, agriculture, industrial safety, and smart cities are discussed. Finally, key challenges and future research directions involving AI, IoT, and self-powered sensing systems are highlighted [1].

Keywords: Nanotechnology, Gas Sensor, Environment, Multidisciplinary Applications.

1. Introduction

Environmental pollution and toxic gas emissions have become global concerns due to rapid industrialization and urbanization. Accurate detection of gases such as CO, NO_2, SO_2, NH_3, and VOCs is crucial for environmental protection and public health. Traditional gas sensors suffer from limitations such as low sensitivity, high power consumption, and poor selectivity. Nanotechnology provides innovative solutions by enabling miniaturized sensors with improved sensitivity and rapid response times [2].

2. Nanomaterials for Gas Sensing

2.1 Metal Oxide Nanostructures

Metal oxide semiconductors (MOS) such as vanadium pentoxide (V_2O_5), tin dioxide (SnO_2), and titanium dioxide (TiO_2) are among the most widely studied materials for gas sensing applications due to their excellent chemical stability, high sensitivity, and relatively low cost. These materials exhibit semiconducting behavior, where changes in surface chemistry upon exposure to target gases result in measurable variations in electrical properties, particularly resistance. Their robustness under harsh environmental conditions, including high temperatures and reactive atmospheres, makes them highly suitable for environmental monitoring and industrial safety applications [3].

The sensing mechanism of these metal oxides is primarily based on surface adsorption and desorption processes. When exposed to air, oxygen molecules are adsorbed onto the surface of the metal oxide and capture free electrons from the conduction band, forming oxygen ions (O^-, O_2^-). This creates a depletion layer near the surface, increasing the resistance of the material. Upon exposure to reducing or oxidizing gases, reactions occur between the gas molecules and the adsorbed oxygen species, leading to a release or capture of electrons, which in turn alters the resistance. This change is detected and correlated to the gas concentration.

Despite their advantages, pristine metal oxide sensors often suffer from limitations such as poor selectivity and high operating temperatures. To address these challenges, recent research has focused on doping and the formation of heterostructures. Doping involves the intentional introduction of foreign elements (such as noble metals like Pt, Pd, or Au, or transition metals) into the metal oxide lattice. This process enhances catalytic activity, modifies electronic properties, and improves sensitivity and selectivity toward specific gases. For example, Pd-doped SnO_2 shows enhanced response to hydrogen gas due to improved catalytic dissociation.

Heterostructure engineering, on the other hand, involves combining two or more different materials to form junctions (such as p–n or n–n interfaces). These interfaces facilitate charge transfer and create potential barriers that significantly enhance sensing performance [4]. For instance, TiO_2/SnO_2 heterostructures exhibit improved selectivity and faster response times due to synergistic effects between the materials.

2.2 Carbon-Based Nanomaterials

Graphene and carbon nanotubes (CNTs) have emerged as highly promising materials for next-generation gas sensors due to their exceptional electrical, structural, and surface properties. As carbon-based nanomaterials, both graphene and CNTs exhibit remarkably high electrical conductivity, which plays a crucial role in enhancing sensor performance. Their conductivity arises from the delocalized π-electron system, enabling efficient charge transfer across the material. This property allows even small interactions between gas molecules and the sensor surface to produce significant and detectable changes in electrical signals [5].

One of the key advantages of graphene and CNTs is their ability to support fast electron transport. In graphene, electrons behave as massless charge carriers and can move with minimal scattering, resulting in extremely high carrier mobility. Similarly, CNTs, which can be visualized as rolled-up sheets of graphene, provide one-dimensional pathways for electron movement, ensuring rapid signal transduction. This fast electron transport contributes to quick response and recovery times in gas sensing applications, making these materials highly suitable for real-time monitoring systems.

Another critical feature of graphene and CNTs is their excellent adsorption properties. Due to their high surface-to-volume ratio and abundant active sites, these materials can effectively interact with a wide range of gas molecules, including toxic and volatile compounds. The adsorption process can occur through physisorption or chemisorption, depending on the nature of the and the surface functionalization of the material. Additionally, defects, edges, and functional groups on graphene and CNTs further enhance their gas adsorption capacity, leading to improved sensitivity [6].

A significant advantage of graphene and CNT-based sensors is their ability to operate at low or even room temperatures. Unlike traditional metal oxide sensors that require high operating temperatures (200–400°C), carbon-based nanomaterials can function efficiently at ambient conditions. This reduces power consumption and enhances device safety and portability, making them ideal for wearable sensors and portable environmental monitoring systems.

2.3 Hybrid Nanocomposites

Hybrid nanostructures in gas sensing involve the integration of two or more materials—such as metal oxides, carbon-based nanomaterials, polymers, or noble metals—to achieve enhanced sensing performance. These combinations leverage the synergistic properties of each component, resulting in improved selectivity, sensitivity, and long-term stability. For instance, incorporating noble metals like Pt or Pd into metal oxides enhances catalytic activity, enabling more efficient gas adsorption and reaction.

Similarly, combining metal oxides with graphene or carbon nanotubes improves electrical conductivity and facilitates faster electron transfer, leading to quicker response and recovery times. Hybrid structures also help overcome limitations such as poor selectivity by introducing specific binding sites or tuning surface chemistry for target gases. Additionally, they enhance structural stability and reduce sensor degradation over time [7]. Overall, hybrid nanostructures represent a powerful strategy for designing high-performance, reliable gas sensors for advanced environmental and industrial applications.

3. Gas Sensing Mechanisms

3.1 Chemiresistive Sensors

Chemiresistive gas sensors operate on the principle of change in electrical resistance when gas molecules interact with the sensor surface. Typically based on semiconducting materials such as metal oxides, these sensors detect gases through adsorption and desorption processes. When target gas molecules react with adsorbed oxygen species on the surface, charge transfer occurs, leading to a measurable variation in resistance [8]. This simple working mechanism, along with high sensitivity and low cost, makes chemiresistive sensors widely used in environmental monitoring and industrial applications.

3.2 Electrochemical Sensors

Electrochemical gas sensors function through oxidation–reduction (redox) reactions occurring at the surface of an electrode. When a target gas interacts with the sensing electrode, it either gains or loses electrons, generating a current proportional to the gas concentration. These sensors typically consist of a working electrode, counter electrode, and electrolyte. They are known for their high selectivity, low detection limits, and accuracy, making them suitable for detecting toxic gases in environmental and biomedical applications [9].

3.3 Optical Sensors

Optical gas sensors rely on the interaction between light and gas molecules to detect changes in optical properties such as absorption, fluorescence, or refractive index. When a gas is present, it alters the intensity, wavelength, or phase of the transmitted or emitted light. These sensors offer advantages such as high sensitivity, immunity to electromagnetic interference, and the ability to perform remote sensing. They are widely used in atmospheric monitoring and hazardous environment detection [10].

3.4 Photoactivated Sensing

Photoactivated gas sensing involves the use of light energy, typically ultraviolet or visible light, to enhance sensor performance. Illumination generates electron–hole pairs in the sensing material, increasing its reactivity toward gas molecules. This approach enables gas detection at lower operating temperatures compared to conventional methods, reducing energy consumption and improving sensor efficiency [11].

3.5 Piezoelectric Sensing

Piezoelectric gas sensors operate based on changes in the resonant frequency of a piezoelectric material when gas molecules are adsorbed onto its surface. The added mass from gas adsorption alters the vibration characteristics of the material, which can be precisely measured. These sensors are highly sensitive and are often used for detecting trace amounts of gases and volatile compounds [12].

3.6 Plasmonic Sensing

Plasmonic gas sensors utilize the phenomenon of surface plasmon resonance (SPR), where conduction electrons on a metal surface oscillate in response to incident light. The presence of gas molecules near the sensor surface changes the local refractive index, leading to a shift in the resonance condition. This shift can be detected optically and correlated with gas concentration. Plasmonic sensors offer ultra-high sensitivity and fast response times, making them promising for advanced environmental and biomedical sensing applications. [13]

4. Fabrication Techniques

Chemical vapor deposition (CVD), sol-gel synthesis, and lithography-based MEMS fabrication are widely used techniques for developing advanced nanosensors. CVD involves the deposition of thin films through chemical reactions of gaseous precursors, enabling precise control over material composition and thickness. Sol-gel synthesis is a versatile method that transforms liquid precursors into solid nanostructured materials, offering advantages such as low processing temperatures and uniformity. Lithography-based MEMS fabrication uses photolithographic patterning and micromachining to create highly and structured sensor components. These methods collectively support the integration of nanoscale materials into microelectromechanical systems (MEMS). MEMS-based nanosensors are particularly valuable due to their compact size, high sensitivity, and low power consumption [14-15]. Their miniaturized design allows for portability and integration into various applications, including environmental monitoring, biomedical diagnostics, and industrial process control, making them highly efficient and cost-effective sensing solutions.

5. Environmental Monitoring Applications

Nanogas sensors play a crucial role in environmental and multidisciplinary applications due to their high sensitivity and rapid response. In air quality monitoring, they detect pollutants at ppm and ppb levels, enabling real-time tracking of harmful gases. For water and soil monitoring, these sensors identify dissolved gases and contaminants, supporting effective environmental remediation strategies. In climate monitoring, their integration with wireless systems facilitates large-scale data collection and analysis [16-17]. Beyond environmental uses, nanosensors are widely applied in healthcare for breath analysis and non-invasive biomarker detection, allowing early disease diagnosis. In industrial safety, they help detect hazardous gas leaks and ensure workplace safety. In agriculture and food safety, nanosensors monitor gases like ammonia and methane and detect food spoilage, improving quality control. Furthermore, in smart cities, integration with IoT systems enables continuous monitoring, automation, and data-driven decision-making, enhancing overall efficiency and sustainability [18-19].

7. Emerging Trends

Emerging trends in nanosensor technology are focused on enhancing performance, portability, and intelligence. AI-integrated gas sensing systems combine advanced algorithms with sensor data to enable accurate detection, pattern recognition, and predictive analysis of gases. Self-powered nanogenerator-based sensors utilize energy harvesting mechanisms, such as piezoelectric or triboelectric effects, eliminating the need for external power sources and improving sustainability [20-21]. Flexible and wearable sensors are designed using stretchable materials, allowing seamless integration with the human body for continuous health and environmental monitoring. Additionally, 2D material-based nanosensors, using materials like graphene and transition metal dichalcogenides, offer exceptional surface area, electrical properties, and sensitivity, making them highly efficient for detecting trace-level gases. These innovations are driving the development of next-generation nanosensors with improved functionality, adaptability, and real-time monitoring capabilities across various applications [22-23].

8. Challenges

Despite significant advancements, nanosensors face several challenges that limit their widespread adoption. One major issue is poor selectivity in mixed gas environments, where sensors may struggle to distinguish between different gases with similar properties, leading to inaccurate readings [24-25]. Long-term stability is another concern, as sensor performance can degrade over time due to environmental exposure, material aging, or contamination. High fabrication costs also pose a barrier, especially when advanced materials and precise manufacturing techniques are required. Additionally, scalability remains a challenge, as it is often difficult to transition nanosensor production from laboratory-scale processes to large-scale manufacturing while maintaining consistency and performance. Addressing these limitations is essential for improving the reliability, affordability, and commercial viability of nanosensor technologies across diverse applications [26-27].

9. Future Perspectives

Future research in nanosensor technology should focus on advancing performance, efficiency, and real-world applicability. AI-assisted sensing and data analytics can significantly improve the accuracy and reliability of gas detection by enabling intelligent pattern recognition and predictive decision-making [28]. The development of ultra-low power sensors is essential for extending device lifespan, especially in remote and wearable applications where energy efficiency is critical. Exploration of hybrid nanomaterials, which combine the unique properties of multiple materials, can enhance sensitivity, selectivity, and stability of sensors. Additionally, integrating nanosensors with smart infrastructure, such as connected systems and automated networks, can enable real-time monitoring, data sharing, and responsive control in environments like smart cities, healthcare systems, and industrial setups [29]. These research directions will contribute to the development of more robust, scalable, and sustainable nanosensor technologies.

Conclusion

Nanotechnology-enabled gas sensors represent a significant advancement in environmental monitoring and a wide range of multidisciplinary applications. Their ability to detect gases at very low concentrations with high sensitivity and rapid response makes them essential for modern sensing needs. Continuous progress in materials science, particularly the development of nanostructured and hybrid materials, is enhancing sensor performance in terms of selectivity, stability, and efficiency. At the same time, improvements in system integration, including the incorporation of artificial intelligence and wireless technologies, are enabling smarter and more autonomous sensing platforms. These innovations support real-time data analysis, remote monitoring, and adaptive decision-making. As research continues, the focus on scalability, cost-effectiveness, and energy efficiency will further drive their practical deployment [30]. Overall, nanotechnology-enabled gas sensors are poised to play a vital role in building intelligent, efficient, and sustainable sensing systems for future smart environments.

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ECO-FRIENDLY SYNTHESIS METHODS OF ADVANCED MATERIALS: SOL-GEL, HYDROTHERMAL AND BIOMIMETIC APPROACHES

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Abstract

The synthesis of advanced materials is paramount for fostering economic and technical advancement, promoting environmentally sustainable synthesis and developing chemical synthesis methodologies, which collectively offer diverse avenues for effective and sustainable production. Chemical synthesis techniques such as sol-gel, hydrothermal and chemical vapor deposition afford substantial control over the characteristics of materials, including crystallinity, morphology and particle size. These methodologies employ established chemical reactions to yield high-purity materials, encompassing ceramics, composites and nanomaterials, which are particularly suited for applications in energy storage, electronics and catalysis. However, traditional chemical synthesis often necessitates the utilization of hazardous chemicals, which entail significant energy consumption and generate detrimental by-products that adversely affect ecological systems and human health. In contrast, green synthesis prioritizes sustainability by harnessing renewable resources, environmentally benign precursors and energy-efficient methodologies. Green synthesis minimizes waste generation, energy utilization and carbon emissions while maintaining material functionality, thereby aligning with the foundational principles of green chemistry. Recent advancements indicate that in domains such as health, environmental science and energy, materials synthesized through green methods—such as metal nanoparticles and biocompatible polymers—exhibit performance comparable to their conventionally synthesized equivalents. There exists considerable potential for the development of next-generation materials that achieve an equilibrium among cost, performance and environmental impact by integrating the sustainability of green methodologies with the precision afforded by chemical processes.

Keywords: Chemical Synthesis, Green Synthesis, Eco-Friendly, Sol-Gel, Hydrothermal, Biomimetic.

1. Introduction

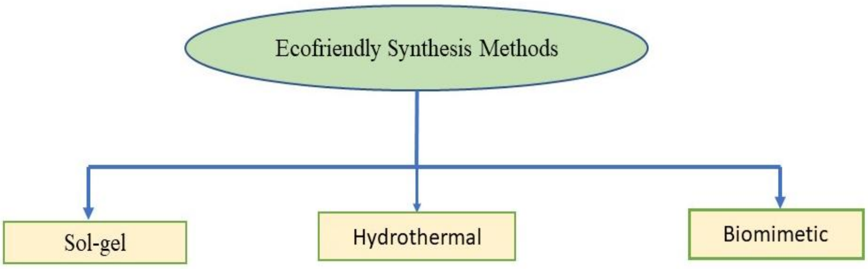
The recent advancements in the fields of chemistry and materials science are predicated upon the synthesis of novel materials, thereby facilitating the creation of sophisticated compounds and structures endowed with specialized properties suitable for diverse applications. Historically, conventional chemical synthesis methodologies have been employed to fabricate materials with precision and efficacy. These methodologies are grounded in traditional practices that often necessitate high-energy procedures, hazardous chemicals and substantial waste production.

In response to the increasing demand for sustainable methodologies, green synthesis techniques that prioritize energy efficiency, environmental stewardship and the utilization of non-toxic renewable materials have been developed. The term "chemical synthesis" encompasses a broad spectrum of technologies that employ various reactions, including sol-gel, hydrothermal and chemical vapor deposition, to generate organic, inorganic and hybrid materials. Conversely, green synthesis employs methodologies such as solvent-free reactions, bio-based precursorsand energy-efficient procedures inspired by natural systems to mitigate its detrimental impacts on the environment.

It is imperative to comprehend the interplay between conventional and green synthesis processes as industrial stakeholders and researchers endeavor to achieve a harmonious equilibrium between performance optimization and environmental sustainability. The objective of environmentally benign nanomaterial synthesis is to produce nanoparticles (1–100 nm) characterized by low toxicity, energy efficiency and sustainability, with applications in energy, medicine and environmental remediation.

2. Eco-Friendly Synthesis Methods of Materials

Sustainable synthesis methodologies utilized in materials chemistry endeavour to fabricate high-performance materials while mitigating environmental impact in accordance with the tenets of green chemistry. These innovative technologies rectify the limitations associated with traditional synthesis, which include the use of toxic reagents, excessive energy utilization and the generation of hazardous waste, by incorporating renewable precursors, environmentally benign solvents and energy-efficient protocols. The three principal sustainable synthesis methodologies are sol-gel, hydrothermal and biomimetic synthesis, each elucidating their respective processes, green adaptations, applications, advantages, challenges and recent advancements.



2.1 Sol-Gel Method

Sol-gel method is a versatile chemical synthesis method which frequently utilized to create advanced substances like glasses, ceramics, thin films and nanomaterials. It has uses in electronics, biomedical engineering and environmental remediation because of its molecular-level control over material properties. However, hazardous precursors, organic solvents and energy-intensive conditions are frequently used in conventional sol-gel processes, which present environmental problems. Green chemistry's principles were addressed by the move toward environmentally friendly sol-gel synthesis, which includes sustainable methods. Key steps include:

- **Hydrolysis**: Metal alkoxides (e.g., tetraethyl orthosilicate TEOS) react with water to form hydroxylated species.
- **Condensation**: Hydroxylated species link to form a three-dimensional network which creates a gel.
- **Aging and Drying**: The gel mature and solvent is removed to form a porous solid.
- **Thermal Treatment**: The material is calcined or sintered to achieve desired crystallinity and properties.

The traditional sol-gel synthesis process is associated with environmental deterioration and elevated energy consumption, primarily due to the recurrent application of volatile organic solvents (including ethanol and methanol) and methodologies that require high-temperature conditions.

2.1.1 Eco-Friendly Modifications to Sol-Gel Synthesis

Eco-friendly sol-gel synthesis combines sustainable precursors, solvents and energy-efficient procedures to lessen its negative effects on the environment. Key green adaptations include:

a. Use of Eco-Friendly Precursors

- **Bio-Based Precursors**: By exchanging bio-derived precursors, such sodium silicate from rice husk ash or plant-derived silicates for harmful metal alkoxides, the need for dangerous chemicals is decreased. Silica nanoparticles made from rice husks and other agricultural waste for instance are sustainable and affordable.
- **Non-Toxic Metal Salts**: In instead of organometallic compounds, water-soluble, non-toxic metal salts (such as nitrates or chlorides) reduce health hazards and streamline trash disposal.

b. Green Solvents

- **Water-Based Systems**: Water-Based Systems: In sol-gel operations, water can replace organic solvents like ethanol or acetone due to its versatility and non-toxicity. Aqueous sol-gel methods have been used successfully to manufacture nanomaterials of silica, titanium and zirconium.

- **Supercritical CO_2**: Supercritical CO_2 is an eco-friendly drying medium that creates porous aerogels without using organic solvents, minimizing environmental impact.
- **Ionic Liquids**: Low-toxicity, recyclable solvents offer a sustainable alternative to sol-gel processes, particularly for hybrid organic-inorganic compounds.

c. Energy-Efficient Processing

- **Ambient or Low-Temperature Synthesis**: Energy usage is decreased when hydrolysis and condensation are carried out at room temperature or at low temperatures. For example, mild conditions can be used for bio-inspired sol-gel processes that use enzymes or biomimetic catalysts.
- **Microwave-Assisted Sol-Gel**: Microwave-Assisted Sol-Gel minimizes energy usage by speeding up gelation and drying, unlike standard thermal treatments.
- **Ultrasound-Assisted Synthesis**: Ultrasonic waves improve precursor mixing and reaction rates, resulting in quicker synthesis with lower energy input.

d. Waste Minimization

- **Recyclable By-products**: Sol-gel processes may be designed to decrease waste by producing recyclable or biodegradable by-products, including alcohols from hydrolysis. Ethanol generated during TEOS hydrolysis, for instance, may be collected and utilized again.
- **Closed-Loop Systems**: Using closed-loop solvent recovery systems guarantees that solvents are reused, which reduces waste and expenses.

2.1.2 Advantages of Eco-Friendly Sol-Gel Synthesis

Eco-friendly sol-gel synthesis offers several benefits, making it a cornerstone of sustainable materials science:

- **Environmental Sustainability**: Green sol-gel technologies lower pollution, greenhouse gas emissions and hazardous waste by employing water-based solvents, non-toxic precursors and low-energy procedures.
- **Cost-Effectiveness**: While energy-efficient methods cut operating costs, the use of agricultural waste or bio-derived precursors lowers the cost of raw materials.
- **Versatility**: Nanoparticles, thin films and porous scaffolds are just a few of the materials that may be produced using green sol-gel techniques and are appropriate for a variety of uses.
- **Biocompatibility**: Eco-friendly materials, such silica nanoparticles made from plant extracts are frequently biocompatible and hence perfect for biomedical uses like tissue engineering and medication administration.

2.1.3 Applications of Eco-Friendly Sol-Gel Materials

Eco-friendly sol-gel synthesis has enabled the development of sustainable materials for various applications:

- **Environmental Remediation**: Green-synthesized silica and Titania nanoparticles serve as photocatalysts for water purification degrading organic pollutants under sunlight.
- **Energy Storage and Conversion**: Eco-friendly sol-gel methods produce porous electrodes and electrolytes for batteries and supercapacitors using bio-derived precursors to enhance sustainability.
- **Biomedical Applications**: Green sol-gel methods are used to produce biocompatible silica hydrogels and nanoparticles for application in tissue engineering, biological sensingand drug delivery.
- **Coatings and Films**: Eco-friendly sol-gel coatings, such as anti-corrosive or self-cleaning films, are applied to surfaces utilizing water-based or supercritical CO_2 techniques.

2.1.4 Challenges and Limitations

Despite its promise, eco-friendly sol-gel synthesis faces several challenges:

- **Performance Trade-Offs**: Green-synthesized materials may exhibit lower purity or less precise control over properties compared to traditional methods limiting their use in high-performance applications.
- **Scalability Issues**: Some green techniques like plant-mediated synthesis struggle to produce on a big scale and maintain consistent quality but others are scalable.
- **Limited Precursor Availability**: Bio-derived precursors may not be universally available or may require additional processing increasing costs.
- **Process Optimization**: Green sol-gel processes often require optimization to match the efficiency and reproducibility of conventional methods, necessitating further research.

2.1.5 Future Directions

The future of eco-friendly sol-gel synthesis lies in integrating advanced technologies and interdisciplinary approaches:

- **Hybrid Green-Chemical Methods**: Green principles combined with the accuracy of classical sol-gel synthesis can produce sustainable high-performing materials. Efficiency might be improved for instance by combining microwave-assisted processing with bio-derived precursors.
- **Advanced Catalysts**: Developing bio-inspired catalysts such as enzyme mimics can further reduce the need for harsh chemicals and high temperatures.
- **Circular Economy Integration**: Designing sol-gel processes within a circular economy framework where all by-products are reused or recycled can maximize sustainability.

- **Machine Learning Optimization**: Green sol-gel techniques may be made more efficient and scalable by using machine learning to optimize reaction conditions and precursor selection.

2.2 Hydrothermal Method

The hydrothermal method is an effective and versatile technique for creating advanced materials in aqueous conditions with high temperatures and high pressures such as metal-organic frameworks (MOFs), zeolites, ceramics and nanomaterials. Its ability to produce highly crystalline materials with controlled size and form makes it ideal for applications in biomedicine, environmental clean-up, energy storage and catalysis. Toxic chemicals, energy-intensive conditions and non-renewable resources are routinely employed in traditional hydrothermal synthesis, raising environmental concerns. Using sustainable precursors, green solvents and energy-efficient processes, eco-friendly hydrothermal synthesis addresses these difficulties while adhering to green chemistry principles. The hydrothermal method's processes, environmentally friendly modifications, benefits, drawbacks and prospects are examined in this article.

2.2.1 Fundamentals of Hydrothermal Method

Hydrothermal synthesis is the process of chemical reactions and crystallization in an aqueous media at elevated temperatures (usually 100-300°C) and pressures (1-100 MPa), which is commonly carried out in a sealed autoclave. The key steps include:

- **Precursor Dissolution**: Metal salts, oxides, or organometallic compounds dissolve in water or other solvents to create a homogenous solution.
- **Nucleation and Growth**: Controlled heating and pressure induce nucleation and crystal growth forming materials with desired structures and properties.
- **Washing and Drying**: The solid is washed to eliminate impurities before drying to produce the finished product.
- **Optional Post-Treatment**: Calcination or annealing may enhance crystallinity or phase purity.

Classical hydrothermal synthesis frequently uses large energy inputs and dangerous chemicals (such as strong acids or bases) which increases environmental impact and produces toxic waste.

2.2.2 Eco-Friendly Modifications to Hydrothermal Synthesis

Eco-friendly hydrothermal synthesis utilizes sustainable resources and procedures to minimize environmental damage. Key green adaptations include:

a. Use of Eco-Friendly Precursors

- **Bio-Derived Precursors**: Biomass-derived products such plant extracts or agricultural waste (like cellulose, lignin, or rice husk ash) are sustainable supplies of organic ligands or metal ions. Hydrothermal carbonization (HTC) can create carbon-based compounds for instance using chitosan or glucose as carbon sources.

- **Non-Toxic Metal Salts**: Health and environmental hazards are reduced when hazardous precursors like heavy metal chlorides are swapped out for safe substitutes like nitrates or acetates.

b. Green Solvents

- **Water as the Primary Solvent**: Water is inherently eco-friendly non-toxic and abundant making it ideal for hydrothermal processes. Optimizing reaction conditions to use water exclusively eliminates the need for organic solvents.
- **Supercritical Water**: Supercritical water (over 374°C and 22.1 MPa) possesses unique characteristics such as low viscosity and high diffusivity allowing for efficient synthesis with minimal waste. It acts as both a solvent and a reactant, avoiding the need for additional chemicals.
- **Ionic Liquids**: These recyclable low-toxicity solvents can be used to substitute volatile organic chemicals in hydrothermal synthesis especially for MOFs and hybrid materials.

c. Energy-Efficient Processing

- **Microwave-Assisted Hydrothermal Synthesis**: Compared to traditional autoclave heating, microwave heating speeds up reaction kinetics cutting down on synthesis time and energy usage. For example, TiO_2 nanoparticles may be synthesized by microwave-hydrothermal synthesis in minutes as opposed to hours.
- **Ultrasound-Assisted Hydrothermal Synthesis**: By enhancing mixing and nucleation and reducing the necessary temperature and pressure ultrasonic waves save energy.
- **Low-Temperature Hydrothermal Routes**: Using catalysts or bio-inspired additives to conduct reactions at lower temperatures (e.g., 100–150°C) lowers energy requirements without sacrificing product quality.

d. Waste Minimization and Recycling

- **Closed-Loop Systems**: Waste in hydrothermal operations is reduced by recycling water and byproducts (such as unreacted precursors). For instance, reusable aqueous effluents are produced when biomass is hydrothermally carbonized.
- **Biodegradable Byproducts**: Reactions that are designed to produce non-toxic or biodegradable byproducts have a smaller environmental effect. For example, the HTC of biomass produces organic acids that are safe to decompose or reuse.

2.2.3 Applications of Eco-Friendly Hydrothermal Materials

Eco-friendly hydrothermal synthesis has enabled sustainable materials for various applications:

- **Environmental Remediation**: TiO_2 or ZnO nanoparticles that have been hydrothermally produced using plant extracts operate as photocatalysts to break down organic pollutants in air and water.

- **Energy Storage and Conversion**: Green hydrothermal synthesis produces carbon-based materials (e.g., hydrothermal carbon) and metal oxides for batteries, supercapacitors and fuel cells using biomass-derived precursors.
- **Biomedical Applications**: Biocompatible nanoparticles and hydrogels synthesized via green hydrothermal routes are used for drug delivery biosensing and tissue engineering.
- **Catalysis**: Zeolites and MOFs synthesized with eco-friendly precursors and solvents are used as catalysts in green chemical processes such as biofuel production.

2.2.4 Challenges and Limitations

Despite its advantages, eco-friendly hydrothermal synthesis faces several challenges:

- **Scalability**: Bio-derived precursors and low-temperature processes may lack consistency or scalability compared to conventional methods limiting industrial adoption.
- **Performance Trade-Offs**: Green-synthesized materials may have lower purity or less precise control over properties affecting performance in high-tech applications.
- **Precursor Availability**: Biomass-derived precursors depend on regional availability and may require pre-processing increasing costs.
- **Process Optimization**: Green hydrothermal methods require optimization to match the efficiency and reproducibility of traditional approaches necessitating further research.

2.2.5 Future Directions

The future of eco-friendly hydrothermal synthesis lies in integrating advanced technologies and interdisciplinary strategies:

- **Hybrid Green-Traditional Methods**: Combining the precision of conventional hydrothermal synthesis with green principles (e.g., bio-derived precursors with microwave heating) can enhance performance and sustainability.
- **Bio-Inspired Catalysts**: Developing enzyme mimics or bio-inspired catalysts can further reduce reliance on harsh chemicals and high-energy conditions.
- **Circular Economy Integration**: Designing hydrothermal processes within a circular economy framework where all byproducts are reused or recycled maximizes sustainability.
- **Machine Learning Optimization**: Using machine learning to optimize reaction parameters, precursor selection and energy use can improve efficiency and scalability.
- **Integration with Other Green Methods**: Combining hydrothermal synthesis with other eco-friendly techniques such as sol-gel or green chemical vapor deposition can expand the range of sustainable materials.

2.3 Biomimetic Approach to Materials Synthesis

Biomimetic materials synthesis employs nature's processes, structures, and functions to produce enhanced materials with superior properties and sustainability. Biomimetic approaches enable the creation of materials with exceptional strength, self-assembly, and environmental adaption by duplicating biological systems such as bone, nacre, and spider silk. Unlike traditional synthesis methods, which commonly utilize harsh chemicals and energy-intensive settings, biomimetic synthesis promotes environmentally friendly procedures, biodegradable precursors and benign reaction conditions that adhere to green chemistry principles.

2.3.1 Principles of Biomimetic Materials Synthesis

Biomimetic synthesis mimics natural processes by using biological molecules, self-organization and hierarchical architecture to create materials. Key principles include:

- **Self-Assembly**: Biomimetic synthesis exploits molecular interactions (e.g., hydrogen bonding, van der Waals forces) to build ordered materials such as nanoparticles or composites, mimicking how proteins or lipids naturally self-organize into complex structures.
- **Hierarchical Organization**: Materials having structures optimized at several scales are produced by nature (e.g., the layered structure of nacre). In order to create materials with particular mechanical, optical or thermal properties, biomimetic approaches mimic this.
- **Bio-Templating**: Using biological molecules (e.g., proteins, polysaccharides) or structures (e.g., diatom frustules) as templates to guide material formation.
- **Mild Reaction Conditions**: Biological systems operate at ambient temperatures and neutral pH inspiring synthesis methods that avoid high energy inputs or toxic reagents.
- **Functional Mimicry**: Materials for specific uses are designed by replicating nature's functional qualities such as self-healing superhydrophilicity or biocompatibility.

2.3.2 Mechanisms of Biomimetic Synthesis

Biomimetic synthesis employs biological or bio-inspired components to control material formation. Common mechanisms include:

- **Enzyme-Catalysed Reactions**: Enzymes such as silicatein (found in sponges) promote silica production under moderate circumstances encouraging the use of enzyme mimics in the synthesis of silica or metal oxide nanoparticles.
- **Biomineralization**: Controlling crystal development and shape by mimicking mineral deposition (for example, calcium carbonate in shells) with organic templates such as proteins or polysaccharides.
- **Phytochemical-Mediated Synthesis**: Plant-derived compounds, such as polyphenols and flavonoids, can act as reducing, stabilizing, or chelating agents during nanoparticle or composite formation.
- **Peptide-Directed Assembly**: Nanomaterials may be assembled using precise peptide sequences, similar to how proteins govern biomineralization naturally.

2.3.3 Eco-Friendly Adaptations in Biomimetic Synthesis

Biomimetic approaches inherently align with sustainability but specific adaptations enhance their eco-friendliness:

a. Bio-Derived Precursors

- **Plant Extracts**: Extracts from plants like green tea, aloe Vera, or citrus peels provide phytochemicals that reduce metal ions (e.g., Au^{3+}, Ag^{+}) to form nanoparticles replacing toxic reducing agents like sodium borohydride.
- **Biomass Waste**: Agricultural by-products (such as rice husk and sugarcane bagasse) provide renewable supplies of silica, carbon and organic ligands, minimizing the need for manufactured compounds.
- **Biopolymers**: Natural polymers like chitosan, cellulose or alginate act as templates or stabilizers, offering biodegradable alternatives to synthetic polymers.

b. Green Solvents

- **Aqueous Systems**: Water, nature's primary solvent is used in biomimetic synthesis to eliminate volatile organic solvents, reducing environmental impact.
- **Supercritical CO_2**: This environmentally friendly solvent mimics nature's capacity to act under precise conditions, allowing for the production of porous materials with minimum waste.
- **Ionic Liquids**: Ionic liquids are eco-friendly and recyclable, making them ideal for biomimetic processes and hybrid materials.

c. Energy-Efficient Processes

- **Ambient Conditions**: Biomimetic synthesis, which mimics biological systems and uses less energy, frequently takes place at ambient temperature and neutral pH.
- **Microwave or Ultrasound Assistance**: These methods reduce energy needs while preserving bio-inspired principles by speeding up biomimetic processes.
- **Solar-Driven Synthesis**: Using sunlight to fuel photochemical processes inspired by photosynthesis increases energy efficiency.

d. Waste Minimization

- **Biodegradable By-products**: Biomimetic processes produce non-toxic byproducts (e.g., organic acids) that degrade naturally or can be reused.
- **Closed-Loop Systems**: Recycling water, enzymes, or bio-templates in synthesis processes minimizes waste, mimicking nature's resource efficiency.

e. Bio-Inspired Catalysts

- **Enzyme Mimics**: By simulating enzymes like urease or silicatein, synthetic catalysts allow for effective reactions in moderate environments, negating the need for harsh chemicals.

- **Peptide Catalysts**: Short peptides or protein fragments catalyse material formation, offering biodegradable alternatives to metal-based catalysts.

2.3.4 Advantages of Biomimetic Synthesis

Biomimetic synthesis offers significant benefits for sustainable materials development:

- **Environmental Sustainability**: Using bio-derived precursors, water-based systems and mild conditions reduces pollution, hazardous waste and carbon emissions.
- **Biocompatibility**: Materials like silica nanoparticles or biopolymer composites are often biocompatible, ideal for biomedical applications.
- **Functional Superiority**: Biomimetic materials improve performance in a variety of applications thanks to their special qualities (such as self-healing and hierarchical organization) that are modelled after nature.
- **Cost-Effectiveness**: Biomass-derived precursors and ambient conditions lower raw material and energy costs.
- **Versatility**: Biomimetic techniques can generate nanoparticles, ceramics, polymers, and composites for a variety of industries.

2.3.5 Applications of Biomimetic Materials

Biomimetic synthesis has enabled sustainable materials for numerous applications:

- **Biomedical Applications**: Drug delivery, tissue engineering and biological sensing all make use of biocompatible silica nanoparticles, hydroxyapatite, or hydrogels that are made using plant extracts or bio-templating. For instance, peptide-directed silica nanoparticles replicate bone mineralization in scaffolds for bone regeneration.
- **Environmental Remediation**: Biomimetic TiO_2 or ZnO nanoparticles, synthesized with plant extracts, serve as photocatalysts for degrading pollutants in water and air, mimicking natural enzymatic processes.
- **Energy Storage and Conversion**: Batteries, supercapacitors and fuel cells employ bio-inspired carbon materials made from hydrothermal carbonization of biomass, which mimic the effective energy storage systems found in nature.
- **Functional Coatings**: Biomimetic designs are used to create superhydrophobic coatings for use in architecture and textiles that are modelled after lotus leaves or self-cleaning surfaces that resemble shark skin.
- **Catalysis**: Biomimetic zeolites or MOFs, synthesized with bio-derived ligands, are used as catalysts in green chemical processes, such as biofuel production.

2.3.6 Challenges and Limitations

Despite its promise, biomimetic synthesis faces several challenges:

- **Scalability**: Bio-derived precursors and complex bio-templating processes may lack consistency or scalability for industrial production.

- **Performance Trade-Offs**: Biomimetic materials may not be as pure or precise as traditional approaches, limiting their use in high-performance applications.
- **Precursor Variability**: The composition of natural precursors, such as plant extracts, varies by source, influencing repeatability.
- **Complexity of Bio-Inspiration**: Advanced knowledge and control are necessary to replicate the intricate hierarchical structures or processes seen in nature, which can be technically difficult.
- **Cost of Bio-Templates**: While biomass is cost-effective, specialized bio-templates (e.g., peptides, enzymes) may be expensive to produce or purify.

2.3.7 Future Directions

The future of biomimetic materials synthesis lies in overcoming current limitations and integrating advanced technologies:

- **Hybrid Biomimetic-Traditional Methods:** Combining traditional methods (such as sol-gel and hydrothermal) with biomimetic concepts can improve accuracy while preserving sustainability.
- **Synthetic Biology**: Engineering microorganisms or enzymes to produce tailored bio-templates or catalysts can improve scalability and reproducibility.
- **Machine Learning Optimization**: Using machine learning to predict optimal reaction conditions, bio-template designs, or precursor combinations can streamline biomimetic synthesis.
- **Circular Economy Integration**: Designing biomimetic processes to recycle all components (e.g., water, bio-templates) aligns with nature’s resource efficiency.
- **Bio-Inspired Multifunctionality**: Developing materials with multiple nature-inspired properties (e.g., self-healing and super hydrophobicity) can expand applications.

Conclusion

In material science, eco-friendly sol-gel, hydrothermal and biomimetic synthesis processes create a ground-breaking trinity that collectively address the growing demand for high-performance, sustainable materials. These solutions combine bio-derived precursors, green solvents, and energy-efficient procedures to reduce the environmental impact of standard synthesis methods while maintaining flexibility and usefulness. Eco-friendly sol-gel synthesis lowers waste and energy consumption by creating compounds for energy, environmental and therapeutic applications utilizing bio-based precursors and green solvents.

Similarly, water-based systems and biomimetic catalysts are employed in eco-friendly hydrothermal synthesis to make highly crystalline materials with minimal environmental effect. Biomimetic synthesis, inspired by nature's exquisite patterns, mixes mild conditions with bio-inspired templates to create materials with distinct features such as biocompatibility and self-healing. Despite scalability, reproducibility and performance challenges, constant developments in biomimetic methods, microwave-assisted processing and waste recycling are driving their acceptability. These methods can collaborate to develop next-generation materials that combine performance with environmental responsibility by utilizing hybrid processes and shared sustainability concepts. Eco-friendly sol-gel, hydrothermal and biomimetic synthesis will be critical in creating a kinder, more sustainable future as the global need for sustainable solutions develops. They will develop cutting-edge materials for energy storage, environmental remediation, biomedical applications and other uses, all while adhering to nature's design principals of sustainability and power.

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NANOTECHNOLOGY-DRIVEN SMART MATERIALS FOR SUSTAINABLE FUTURE

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1. Introduction

Imagine a world where materials can heal themselves, buildings adjust to weather conditions automatically, and medicines target only diseased cells without harming the rest of the body. This is not science fiction—it is the promise of nanotechnology and smart materials (Bhushan, 2017).

The rapid advancement of science and technology in the 21st century has led humanity into an era where the manipulation of matter at the smallest possible scale is no longer just a theoretical concept but a practical reality (Cao *et al.,* 2018). Nanotechnology deals with structures that are extremely small, typically between 1 to 100 nanometers (Agarwal *et al.,* 2017). At this scale, materials behave very differently compared to their bulk counterparts (Wang *et al.,* 2016). These factors contribute to changes in optical, electrical, mechanical, and chemical properties (Chen *et al.,* 2018). For instance, materials may become stronger, more reactive, or exhibit entirely new colors. These novel characteristics open up countless possibilities for innovation across various scientific and engineering fields.

Parallel to the development of nanotechnology is the emergence of smart materials—materials that possess the ability to respond dynamically to external stimuli such as temperature, pressure, light, electric or magnetic fields, and chemical environments (Arora *et al.,* 2018). Unlike traditional materials, which remain passive under changing conditions, smart materials actively adapt their properties in response to their surroundings (Iyer *et al.,* 2019). This adaptability gives them a form of "functional intelligence," enabling them to perform tasks without direct human intervention (Rogers *et al.,* 2016). When combined with nanotechnology, they become even more powerful and efficient (Gupta *et al.,* 2019). Basically, nanotechnology and smart materials represent a significant shift in the way we understand and interact with the material world. They are not merely tools for technological advancement but are fundamental to addressing some of the most pressing challenges facing humanity today (Sharma *et al.,* 2022). As research continues and technologies evolve, these fields will play a crucial role in shaping a smarter, more efficient, and sustainable future.

At the nanoscale, the behavior of materials is governed by three fundamental phenomena: increased surface area, quantum effects, and significant changes in intrinsic material properties (Liu *et al.,* 2019). One of the most important features of nanomaterials is their exceptionally high surface area-to-volume ratio, where a large proportion of atoms are present on the surface rather than inside the bulk, leading to enhanced reactivity and efficiency in applications such as catalysis, drug delivery, and chemical sensing; for example, nanoparticles used as catalysts can accelerate reactions due to the availability of more active surface sites (Zhang *et al.,* 2020). Another defining aspect is the dominance of quantum effects, where classical physics is replaced by quantum mechanics, resulting in unique optical, electrical, and magnetic properties; this is evident in phenomena like quantum confinement, where materials exhibit size-dependent characteristics, such as gold nanoparticles appearing red, purple, or blue instead of their usual metallic yellow, a property widely used in biomedical imaging and diagnostics (Lee *et al.,* 2017). Additionally, nanomaterials exhibit remarkable mechanical and electrical enhancements, becoming stronger, lighter, and more flexible; carbon-based nanostructures like graphene and carbon nanotubes are prime examples, with nanotubes being extremely strong yet lightweight and highly conductive, making them suitable for applications in aerospace, construction, and advanced electronics (De Volder *et al.,* 2013). The electrical properties of nanomaterials also enable innovations such as nanowires and quantum dots, which support the development of smaller, faster, and energy-efficient devices, including nanoscale transistors and high-resolution displays (Reddy *et al.,* 2018). Various types of nanomaterials form the foundation of this field, including nanoparticles used in medicine and cosmetics for targeted drug delivery and UV protection, carbon nanotubes known for their exceptional strength and conductivity, quantum dots with tunable optical properties for imaging and display technologies, and nanowires widely used in electronics and sensing due to their high sensitivity and conductivity (Jain *et al.,* 2020). Furthermore, nanotechnology is highly interdisciplinary, combining concepts from physics, chemistry, biology, and engineering to create innovative solutions, with fabrication techniques such as bottom-up approaches, where materials are built atom by atom, and top-down methods, where bulk materials are reduced to nanoscale dimensions, playing a crucial role in advancing this field; overall, nanotechnology represents a revolutionary approach to material science, enabling the design of highly efficient, multifunctional, and advanced systems (Tripathi *et al.,* 2020; Das *et al.,* 2020).

2. What Are Smart Materials?

Smart materials are materials that can sense and respond to environmental changes (Arora *et al.,* 2018). These materials act like they have “intelligence,” adjusting themselves without human intervention (Bhushan, 2017).

Smart materials represent one of the most fascinating and rapidly developing areas of modern material science. Unlike conventional materials, which remain passive and unchanged under external conditions, smart materials possess the remarkable ability to sense, respond, and adapt to changes in their environment. These changes may include variations in temperature, pressure, stress, light, electric or magnetic fields, and even chemical surroundings (Iyer *et al.,* 2019). Because of this responsive behavior, smart materials are often described as “intelligent” materials, although their functionality is based on well-defined physical and chemical principles rather than actual intelligence (Nair *et al.,* 2021).

Types of Smart Materials

Smart materials can be classified into several categories based on the type of stimulus they respond to and the nature of their response. Some of the most important types are discussed below:

1. Shape Memory Alloys (SMAs)

Shape Memory Alloys are metallic materials that have the unique ability to return to their original shape after being deformed, when exposed to an appropriate temperature (Lagoudas, 2011). This property is known as the shape memory effect. The most commonly used SMA is an alloy of nickel and titanium, often referred to as Nitinol. SMAs are widely used in applications such as medical devices (e.g., stents, orthodontic wires), actuators and sensors, aerospace components, robotics and automation systems (Kumar *et al.,* 2020). Their ability to produce motion without traditional mechanical parts makes them extremely valuable in modern engineering.

2. Piezoelectric Materials

Piezoelectric materials have the ability to generate electrical energy when subjected to mechanical stress (Safari & Akdoğan, 2014). Conversely, they can also deform when an electric field is applied. This dual property makes them highly versatile for both sensing and actuation purposes. The piezoelectric effect occurs due to the displacement of electric charges within the material’s crystal structure when it is compressed or stretched (Lee *et al.,* 2017). Common piezoelectric materials include quartz, certain ceramics, and polymers. Applications of piezoelectric materials include, sensors (pressure, vibration, and sound detection), energy harvesting devices, ultrasound imaging in medical diagnostics, actuators in precision engineering. For example, piezoelectric sensors are used in microphones and speakers, where mechanical vibrations are converted into electrical signals and vice versa.

3. Thermochromic Materials

Thermochromic materials are those that change color in response to temperature variations (Saxena *et al.,* 2018). This change occurs due to alterations in the material's molecular structure, which affects how it absorbs and reflects light. These materials are commonly found in everyday products such as mood rings, temperature-sensitive mugs, smart windows, thermal indicators (Seeboth & Lötzsch, 2014). In advanced applications, thermochromic materials are used in energy-efficient buildings, where windows can adjust their color or transparency based on temperature, helping to regulate indoor conditions and reduce energy consumption.

4. Magnetostrictive Materials

Magnetostrictive materials exhibit the ability to change their shape or dimensions when exposed to a magnetic field (Engdahl, 2015). This property is due to the alignment of magnetic domains within the material, which causes it to expand or contract. These materials are highly sensitive and can produce precise movements, making them suitable for applications such as actuators and transducers, sonar systems, vibration control devices, precision positioning systems (Reddy *et al.,* 2018). Magnetostrictive materials are especially important in industrial and defense applications, where accurate and reliable performance is critical.

Intelligent Behavior of Smart Materials

What makes smart materials particularly exciting is their ability to mimic certain aspects of biological systems (Rogers *et al.,* 2016). Just as living organisms respond to environmental stimuli, smart materials can adjust their properties in real time. For example, just as human skin reacts to temperature changes, thermochromic materials change color; similarly, muscles contract and expand, much like shape memory alloys. This ability to respond without external intervention gives smart materials a form of functional intelligence. However, it is important to note that this "intelligence" is not cognitive but is based on the inherent physical properties of the material. The responses are pre-programmed through material design and composition.

Table 1: Types of Smart Materials and Their Applications

Type of Smart Material	Stimulus	Response	Applications
Shape Memory Alloys	Temperature	Returns to original shape	Medical stents, robotics, aerospace
Piezoelectric Materials	Mechanical stress	Generates electricity	Sensors, actuators, ultrasound devices
Thermochromic Materials	Temperature	Changes color	Smart windows, mugs, thermal indicators
Magnetostrictive Materials	Magnetic field	Changes shape/size	Sonar systems, actuators, precision devices

3. The Synergy: Nano + Smart = Future Materials

When nanotechnology is integrated with smart materials, the result is highly advanced systems with improved sensitivity, faster response, and enhanced durability (Cao *et al.,* 2018). The convergence of nanotechnology and smart materials represents one of the most powerful and transformative developments in modern science and engineering. Individually, both fields have demonstrated immense potential in revolutionizing industries and improving human life. However, when combined, they create highly advanced material systems that are not only responsive but also exceptionally sensitive, efficient, and precise (Bhushan, 2017). This integration leads to the development of what can be called next-generation functional materials, capable of performing complex tasks autonomously and with remarkable accuracy.

Why This Combination Matters

The integration of nanotechnology with smart materials offers several significant advantages that are shaping the future of advanced materials and technologies:

1. Faster Response to Stimuli

One of the most notable benefits of combining nanotechnology with smart materials is the rapid response time (Zhang *et al.,* 2020). At the nanoscale, interactions between materials and their environment occur much more quickly due to the reduced size and increased surface activity. This allows smart materials to react almost immediately when exposed to external stimuli such as heat, pressure, light, or chemical changes. For instance, in biomedical applications, nanoscale smart materials can detect changes in the human body and release drugs instantly when required. Similarly, in structural applications, materials can respond to stress or damage in real time, preventing further deterioration.

2. Greater Efficiency

Nanotechnology enhances the efficiency of smart materials by improving their functional performance while minimizing energy consumption. Because nanoscale components require less energy to operate, the overall system becomes more energy-efficient. Additionally, the high reactivity and sensitivity of nanomaterials ensure that only minimal input is required to trigger a response (Liu *et al.,* 2019). This efficiency is particularly important in applications such as energy systems, where smart nanomaterials are used to optimize energy generation, storage, and utilization. For example, smart coatings embedded with nanomaterials can regulate heat transfer in buildings, reducing the need for external heating or cooling systems.

3. Reduced Material Usage

Another important advantage is the reduction in material usage. Nanotechnology allows materials to achieve superior performance with a significantly smaller quantity of raw material. Since nanomaterials are highly effective even in small amounts, they help reduce waste and lower production costs (Gupta *et al.,* 2019). This aspect is especially beneficial in industries such as construction and manufacturing, where minimizing material consumption without compromising strength or durability is a major goal. Lightweight nanocomposites, for example, can replace heavier traditional materials while offering equal or better performance.

4. Enhanced Precision

The nanoscale precision offered by nanotechnology enables smart materials to perform highly accurate and controlled actions. This level of precision is essential in applications where even minor deviations can have significant consequences, such as in medical treatments, microelectronics, and aerospace engineering (Singh *et al.,* 2021). For example, in targeted drug delivery, nanotechnology allows smart materials to deliver medication directly to specific cells or tissues with high accuracy, avoiding damage to healthy cells. Similarly, in electronics, nanoscale components enable the fabrication of highly precise and compact devices with improved functionality.

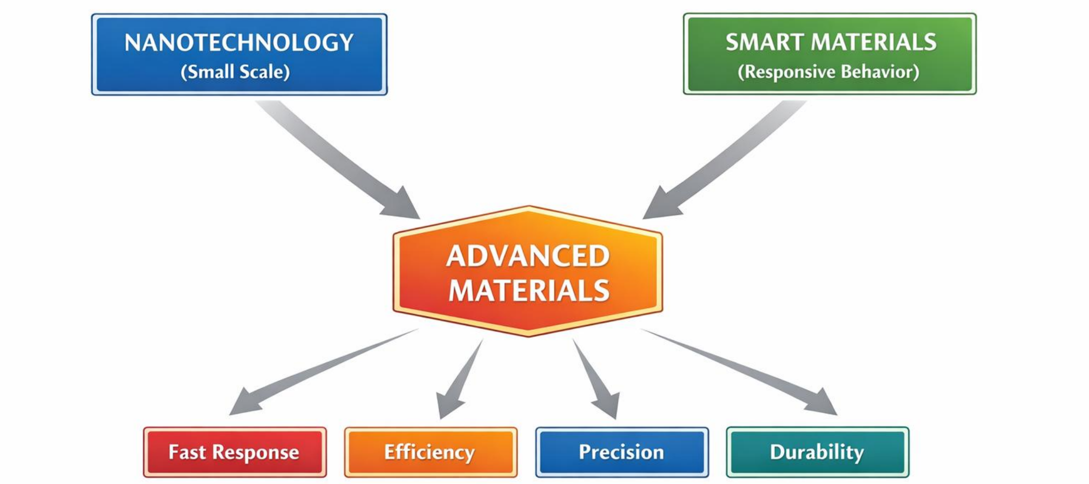

Figure 1: Synergy of Nanotechnology and Smart Materials

4. Applications in Modern Life

Nanotechnology and smart materials have become integral to modern life, driving innovation across a wide range of sectors by enabling systems that are more efficient, adaptive, and intelligent (Bhushan, 2017). In medicine and healthcare, these technologies are revolutionizing the way diseases are diagnosed and treated, with nanoparticles enabling highly targeted drug delivery that ensures medicines act only on affected cells, such as cancerous tissues, thereby minimizing side effects and improving treatment outcomes, while smart materials allow controlled and stimuli-responsive drug release based on internal body conditions like pH, temperature, or biochemical signals, making therapies more precise and personalized (Singh *et al.,* 2021); additionally, nanosensors support early disease detection by identifying minute biological changes at initial stages (Chaudhary *et al.,* 2022). In the energy and environmental sector, nanotechnology enhances the performance of renewable energy systems by improving the efficiency of solar cells through better light absorption and energy conversion, while smart materials optimize energy storage in batteries and supercapacitors by adapting to varying operational conditions, increasing their lifespan and reliability; furthermore, nanofilters play a crucial role in purifying water and air by removing pollutants, microorganisms, and toxic substances, and smart materials contribute to environmental monitoring by detecting contaminants and responding in real time, thus supporting sustainable development (Chen *et al.,* 2018). In construction and infrastructure, these advanced materials significantly improve durability and functionality, with innovations like self-healing concrete that automatically repairs cracks using embedded nanoparticles or microcapsules, reducing maintenance costs and extending structural life, as well as smart windows that regulate indoor temperature by controlling light and heat transmission, thereby conserving energy; adaptive materials also respond to environmental stress such as pressure, humidity, and temperature changes, enhancing the resilience and safety of buildings and infrastructure (Kumar *et al.,* 2020). In electronics and computing, nanotechnology forms the backbone of modern devices by enabling miniaturization, allowing the production of smaller, faster, and more energy-efficient components used in smartphones, computers, and other digital systems, while smart materials facilitate the development of flexible and wearable electronics that can bend, stretch, and conform to different shapes without losing functionality (Jain *et al.,* 2020); nanosensors embedded in these devices enable real-time monitoring of parameters such as motion, temperature, and chemical composition, which is particularly useful in health tracking and smart wearable technology (Kumar *et al.,* 2020). In the defense and aerospace sectors, nanotechnology contributes to the development of lightweight yet extremely strong nanocomposites that enhance fuel efficiency and performance, while smart coatings provide protection against corrosion, wear, and extreme environmental conditions, and are also used in stealth technology to reduce radar detection (De Volder *et al.,* 2013); moreover, adaptive materials capable of withstanding high temperatures, pressure variations, and mechanical stress are essential for spacecraft and advanced aircraft, where they can adjust properties during operation to improve aerodynamics, stability, and safety. Overall, the integration of nanotechnology and smart materials is revolutionizing modern applications by enabling highly efficient, multifunctional, and sustainable systems, and as these technologies continue to advance, their role in shaping a smarter, safer, and more connected world will only become more significant (Mehta *et al.,* 2022).

Conclusion

In conclusion, nanotechnology and smart materials represent a transformative advancement in science and engineering, enabling the development of highly efficient, adaptive, and intelligent systems that are revolutionizing fields such as healthcare, energy, electronics, and infrastructure. Their key advantages include enhanced performance due to unique nanoscale properties, reduced energy consumption through optimized and responsive behavior, and the ability to create innovative, precise, and multifunctional applications that improve quality of life and support sustainable development. However, alongside these benefits, several challenges must be carefully addressed, including high production and implementation costs, potential health and environmental risks associated with the interaction of nanoparticles with biological systems, and ethical as well as regulatory concerns related to safety, privacy, and responsible use. Therefore, while these technologies hold immense promise for the future, it is essential to maintain a balanced approach that promotes innovation while ensuring safety, sustainability, and proper regulation, so that their full potential can be realized for the benefit of society.

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DESIGN AND DEVELOPMENT OF SMART NANOMATERIALS FOR ADVANCED APPLICATIONS

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Abstract

Smart nanomaterials have emerged as a transformative class of materials that integrate the unique properties of nanotechnology with the adaptive and responsive characteristics of smart materials. These materials exhibit the ability to sense, respond, and adapt to external environmental stimuli such as temperature, pH, light, electric and magnetic fields, and biological signals. Their multifunctional nature and tunable properties make them highly valuable in a wide range of advanced applications including healthcare, energy systems, electronics, environmental remediation, and aerospace technologies. This chapter provides a comprehensive discussion on the design principles, synthesis strategies, classification, functional properties, and applications of smart nanomaterials, along with the challenges and future prospects associated with their development.

1. Introduction

Nanotechnology has revolutionized the field of material science by enabling the manipulation and control of matter at the nanoscale, typically in the range of 1 to 100 nanometers. At this scale, materials exhibit distinct physical, chemical, and biological properties that differ significantly from their bulk counterparts due to quantum confinement effects, increased surface-to-volume ratio, and enhanced reactivity. These unique characteristics have paved the way for the development of advanced materials with unprecedented functionalities. In parallel, the concept of smart materials has gained considerable attention due to their ability to respond dynamically to environmental changes in a predictable and controllable manner. Smart materials can alter their properties such as shape, color, stiffness, or chemical activity in response to external stimuli.

The convergence of nanotechnology and smart materials has led to the development of smart nanomaterials, which combine nanoscale advantages with intelligent responsiveness. These materials are designed to mimic biological systems that exhibit self-regulation and adaptability. For instance, similar to how living organisms respond to environmental cues, smart nanomaterials can detect specific stimuli and trigger appropriate responses, making them highly suitable for applications that require precision, adaptability, and efficiency. This interdisciplinary field integrates principles from chemistry, physics, biology, and engineering, making it a cornerstone of modern scientific innovation.

2. Fundamentals of Smart Nanomaterials

Smart nanomaterials are characterized by their ability to undergo controlled and reversible changes in their physical or chemical properties in response to external stimuli. These stimuli can be broadly categorized into physical, chemical, and biological triggers. Physical stimuli include temperature variations, light irradiation, pressure, and magnetic or electric fields, while chemical stimuli involve changes in pH, ionic strength, or redox conditions. Biological stimuli include enzymes, proteins, and other biomolecules that can induce specific responses in the material.

One of the fundamental aspects of smart nanomaterials is their high surface area-to-volume ratio, which enhances their interaction with surrounding environments. This property enables faster response times and improved sensitivity to stimuli. Additionally, quantum effects at the nanoscale lead to unique optical, electronic, and magnetic properties, which can be precisely tuned during material design. The incorporation of functional groups on the surface of nanomaterials further enhances their responsiveness and selectivity, allowing for targeted applications such as drug delivery and biosensing.

Another important feature of smart nanomaterials is their multifunctionality, which allows a single material to perform multiple tasks simultaneously. For example, a nanomaterial used in biomedical applications may possess both diagnostic and therapeutic capabilities, enabling real-time monitoring and treatment of diseases. This multifunctional behavior significantly enhances the efficiency and effectiveness of these materials in complex applications.

3. Design Strategies for Smart Nanomaterials

The design and development of smart nanomaterials require a systematic approach that involves careful selection of materials, structural engineering, and functionalization. The choice of material plays a critical role in determining the properties and performance of the final nanomaterial. Common materials used in the synthesis of smart nanomaterials include carbon-based materials such as graphene and carbon nanotubes, metal nanoparticles such as gold and silver, polymeric nanomaterials, and hybrid nanocomposites that combine multiple components to achieve synergistic effects.

Surface functionalization is a key strategy in the design of smart nanomaterials, as it allows for the modification of surface properties to enhance compatibility, stability, and responsiveness. Functional groups, ligands, or biomolecules can be attached to the surface of nanomaterials to enable specific interactions with target molecules or environments. This is particularly important in biomedical applications, where biocompatibility and targeted delivery are essential.Structural engineering involves the design of nanomaterials with specific and architectures such as nanoparticles, nanorods, nanotubes, nanofibers, and core-shell structures. These structures influence the physical and chemical properties of the materials, including their mechanical strength, optical behavior, and responsiveness to stimuli. The integration of stimuli-responsive components into the material structure further enhances their functionality, enabling them to perform complex tasks such as controlled drug release or environmental sensing.

4. Synthesis Methods

The synthesis of smart nanomaterials can be broadly categorized into top-down and bottom-up approaches. Top-down methods involve the breakdown of bulk materials into nanoscale structures using techniques such as lithography, milling, and etching. These methods are typically used in the fabrication of nanodevices and electronic components, where precise control over and dimensions is required.

In contrast, bottom-up approaches involve the assembly of nanomaterials from atomic or molecular building blocks. Techniques such as sol-gel synthesis, chemical vapor deposition, and self-assembly are commonly used in this approach. Bottom-up methods offer better control over material composition and structure, making them suitable for the synthesis of complex and multifunctional nanomaterials.

In recent years, there has been a growing emphasis on green synthesis methods that utilize environmentally friendly and sustainable processes. These methods often involve the use of plant extracts, microorganisms, or other biological agents to synthesize nanomaterials without the use of toxic chemicals. Green synthesis not only reduces environmental impact but also enhances the biocompatibility of the resulting materials, making them suitable for biomedical applications.

5. Applications of Smart Nanomaterials

Smart nanomaterials have found widespread applications across various fields due to their unique properties and adaptability. In the field of medicine, these materials are used for targeted drug delivery, where they can transport therapeutic agents directly to diseased cells and release them in response to specific stimuli such as pH or enzyme activity. This targeted approach minimizes side effects and improves treatment efficiency. Additionally, smart nanomaterials are used in diagnostic applications such as biosensors and imaging, enabling early detection and monitoring of diseases.

Environmental applications of smart nanomaterials include water purification, air filtration, and pollution monitoring. These materials can effectively remove contaminants from water and air due to their high reactivity and adsorption capacity. In addition, smart nanomaterials are used in smart textiles that exhibit properties such as self-cleaning, antimicrobial activity, and temperature regulation, making them suitable for use in healthcare, military, and sports industries.

6. Challenges and Limitations

Despite their numerous advantages, the development and application of smart nanomaterials face several challenges. One of the major concerns is the potential toxicity and environmental impact of nanomaterials, which can pose risks to human health and ecosystems. The high cost of production and difficulties in large-scale manufacturing also limit their widespread adoption. Additionally, issues related to stability, reproducibility, and long-term performance need to be addressed to ensure reliable applications.

7. Future Perspectives

The future of smart nanomaterials is highly promising, with ongoing research focused on overcoming existing challenges and expanding their applications. The integration of artificial intelligence and machine learning with nanotechnology is expected to accelerate the design and optimization of smart materials. Advances in nano-robotics may lead to the development of autonomous systems capable of performing complex tasks at the nanoscale. Furthermore, the emphasis on sustainability and green chemistry will drive the development of eco-friendly nanomaterials that minimize environmental impact.

Conclusion

In conclusion, smart nanomaterials represent a significant advancement in material science, offering a unique combination of nanoscale properties and intelligent responsiveness. Their ability to adapt to changing environments and perform multiple functions makes them highly valuable in a wide range of advanced applications. Continued research and innovation in this field will undoubtedly lead to the development of next-generation materials that will play a crucial role in shaping the future of science and technology.

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NANO-FERTILIZERS AND NANO-PESTICIDES IN SUSTAINABLE TEA (*CAMELLIA SINENSIS*) CULTIVATION

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Abstract

Nanotechnology offers new tools to increase nutrient use efficiency and to develop targeted pest-management strategies in perennial crops such as tea (*Camellia sinensis*). Nano-fertilizers and nano pesticides can improve foliar and root uptake, reduce losses to leaching and volatilization, and enable slow/controlled release. For tea a high-value, single-leaf harvested perennial crop these technologies promise yield and quality benefits while potentially lowering environmental impacts. This chapter reviews mechanisms of action, recent experimental evidence in tea, nanoparticle-based delivery systems for fertilizers and pesticides, biosynthesis/green synthesis methods, environmental and human-safety considerations, regulatory and socio-economic factors, and future research priorities for sustainable deployment.

1.Introduction, why Nanotechnology for Tea?

Tea is a perennial, high-value crop grown in large monoculture plantations where fertilizer and pesticide inputs strongly influence yield, leaf quality (polyphenols, amino acids), and residue safety. Conventional fertilizers especially nitrogen are often applied in quantities that lead to inefficiencies (volatilization, leaching) and influence tea quality parameters. Similarly, conventional pesticides can persist as residues on harvested leaves and harm non-target organisms. Nanotechnology offers tailored delivery systems and novel active nanomaterials that can increase input efficiency, target release, and reduce off-target losses aligning with sustainability goals for tea cultivation. Recent reviews and experimental studies demonstrate both promise and the need for caution in field implementation.

2. Nano Fertilizers: Definitions, Types, and Mechanisms

2.1 What are Nano Fertilizers?

Nano fertilizers are formulations where nutrients are presented as nanoparticles, nanoscale coatings, or are encapsulated within nanocarriers (e.g., polymeric nanoparticles, nano emulsions, nano clay, liposomes). They differ from conventional granules by their small size (1–1000 nm range for functional nanoparticles) and large specific surface area, which can alter solubility, mobility, and plant uptake dynamics.

2.2 Principal Types Relevant to Tea

- **Nano-Nitrogen** (e.g., foliar nano-urea formulations, urea encapsulated in polymeric nanocarriers).
- **Metal/metal-oxide NPs** supplying micronutrients (e.g., Zn O-NPs for zinc).
- **Nano-encapsulated NPK** for controlled release (biodegradable polymer coatings, clay nanocomposites).
- **Bio-fabricated nanomaterials** (leaf-extract mediated metal NPs used as micronutrient supplements).

2.3 Mechanisms of Improved Efficiency

- **Enhanced foliar penetration:** nanoparticles can improve cuticular penetration and translocation when sprayed, enabling lower doses.
- **Controlled release:** encapsulation gives gradual nutrient release matching plant demand.
- **Targeted delivery:** functionalized carriers can interact with root exudates or leaf surfaces to release nutrients at the site of demand.
- **Improved solubility and bioavailability:** nanoparticulate forms of micronutrients can be more bioavailable than bulky mineral forms.

3. Evidence from Tea: Growth, Yield, and Quality Effects

Several recent experimental studies have evaluated nano fertilizers in tea:

- **Nano-urea foliar sprays:** Field trials and experimental studies on tea clones show that repeated foliar applications of nano-urea (lower concentration sprays) can increase bud-break, plucking point density, and green leaf yield compared to control, often while reducing total conventional N use. Some experiments also report changes in leaf biochemical parameters (caffeine, polyphenol content) following nano-urea application.
- **Zinc oxide nanoparticles (Zn O-NPs):** Controlled experiments demonstrated that foliar or soil application of Zn O-NPs enhanced growth, antioxidant status, and some quality-related biochemical traits in tea plants. Zn as a micronutrient is important for enzyme systems and hormonal balance in plants, and nano-Zn formulations can improve uptake efficiency.

Summary of practical implications for growers: early field evidence indicates that properly formulated nano-fertilizers can increase efficiency (yield per unit N), accelerate bud development, and may influence key quality metrics but responses vary with formulation, dose, tea cultivar, and application timing; therefore, local validation is essential.

4. Nano Pesticides and Nano-Delivery Systems for Tea Pest Management

4.1 Rationale and Types

Nano pesticides include active ingredients formulated at the nanoscale (e.g., nano-sized active biopesticide particles) and nano-enabled delivery systems (polymeric nanocarriers, nanogels, nano emulsions) that enhance target specificity, control release, and protect labile biopesticides from degradation.

4.2 Benefits for Tea IPM (Integrated Pest Management)

- **Improved efficacy at lower active doses** by increasing persistence on leaf surfaces or improving uptake by pests (where appropriate).
- **Reduced non-target exposure** via targeted release or encapsulation that prevents rapid drift and wash-off.
- **Compatibility with biocontrol agents**: some nanocarriers can protect biologicals (microbial pesticides) from UV and environmental degradation.

4.3 Findings Relevant to Tea Pests

Review studies focused on tea underscore nano pesticide potential for major tea pests and fungal pathogens, discussing polymeric carriers and inorganic nanoparticle-based actives. However, much of the research remains at laboratory, greenhouse, or early field trial stages; large-scale, long-term field data in tea plantations are limited.

5. Green Synthesis and Biocompatible Approaches

Concerns about synthesis routes have driven interest in green (biological) fabrication of nanoparticles using plant extracts, microbes, or waste materials. These routes can yield biocompatible NPs and reduce hazardous reagents in production. For tea systems, using tea-derived extracts to cap or synthesize NPs has been explored in other applications (e.g., biomedical), indicating feasibility for low-toxicity nanomaterials for agronomy. Green synthesis may be attractive for smallholder and eco-sensitive tea landscapes but requires standardization for reproducibility and safety.

6. Environmental Fate, Toxicity, and Safety Concerns

6.1 Potential Environmental Risks

- **Persistence and accumulation:** some inorganic NPs (e.g., certain metal oxides) may persist in soil, potentially affecting microbial communities or earthworms.
- **Non-target toxicity:** nano pesticides might affect beneficial insects, soil fauna, or aquatic life if they move off-site.
- **Food safety and residues:** because the tea product is a leaf consumed as infusion, any persistent residues or bioaccumulated nanoparticles raise food-safety questions. Recent literature on pesticide residues in tea emphasizes the importance of mitigating residues; nano pesticide formulations must be evaluated similarly for residue fate.

6.2 Regulatory and Analytical Challenges

Regulators currently treat engineered nanomaterials under existing pesticide and fertilizer laws in many jurisdictions, but specific guidance on nanoforms, testing endpoints (e.g., nanoparticle size, aggregation behaviour, dissolution), and acceptable residue metrics is still evolving.

Analytical detection and quantification of nanoparticles in complex matrices (tea leaf, brewed tea, soil) remain technically demanding.

7. Socio-Economic and Deployment Considerations for Tea Plantations

- **Cost vs benefit:** while nano-formulations may reduce input volumes, their manufacturing costs and upfront price may be higher; economic studies must quantify net returns for smallholders and plantation operators.
- **Adoption drivers:** clear agronomic benefits, residue safety assurances, easy application protocols (compatible with existing sprayers), and regulatory approvals are key to adoption.
- **Capacity building:** extension, demonstration plots, and risk communication are essential when introducing nanotechnologies in traditional tea growing regions.

8. Case Studies and Selected Experimental Outcomes

- **Nano-urea foliar sprays in Assam tea clones (field trials):** reported increases in bud break, pluckable shoots/m² and green leaf yield following repeat foliar sprays of nano-urea combined with basal P and K; some trials reported changes in caffeine and polyphenol content. These indicate real potential but also show responses vary with dose and timing.
- **ZnO nanoparticles in controlled experiments:** ZnO-NP foliar application improved antioxidant enzyme activities and some growth attributes, supporting micronutrient nano-delivery as a practical avenue in tea nutrition management.
- **Reviews on nano pesticides for tea:** systematic reviews summarize nano pesticide types, polymeric carriers, and potential applications for major tea pests, but call for careful ecotoxicological and field evaluation.

9. Research Gaps and Priorities

- **Long-term field trials:** multi-season, multi-site trials across major tea-growing regions to quantify yield, quality, residue dynamics, and environmental impact.
- **Standardized formulations and dosing guidelines** adapted to tea phenology (flush cycles).
- **Analytical methods for residues and nano-speciation** in fresh leaf and brewed tea.
- **Risk assessment frameworks and regulatory guidance** specific to nanoforms in agro inputs.
- **Farmer economics and lifecycle analyses** to evaluate net sustainability benefits.

Conclusions

Nano fertilizers and nano pesticides offer promising routes to increase nutrient use efficiency and improve pest control precision in tea cultivation, with potential benefits for yield, product quality, and environmental footprint. Early experimental and review literature including work on nano-urea and ZnO-NPs and systematic reviews of nano pesticides for tea supports this potential, but also highlights significant knowledge gaps in long-term effects, residue safety, and socio-economic feasibility. Responsible deployment requires robust field validation, standardized safety testing, transparent regulation, and extension to ensure technologies serve both plantation sustainability and consumer safety.

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NANOSCIENCE INNOVATIONS DRIVING TECHNOLOGICAL PROGRESS

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Abstract

Nanoscience has become a revolutionary field that operates at the atomic and molecular scale, offering a new level of control over material properties and functions. The chapter discusses how nanoscience innovations have contributed to technological advancement across fields such as medicine, electronics, energy, and environmental sustainability. It examines the basic concepts of nanoscience and recent innovations in nanomaterials and their various applications. Another aspect of the chapter worth noting is the combination of nanotechnology with emerging areas of artificial intelligence and biotechnology. It underscores the potential of nanoscience to solve global problems by reviewing current research and technological advances. The discussion also covers the risks and ethical and regulatory issues related to nanotechnology. The chapter concludes with an overview of future research and innovation in this rapidly developing area.

Keywords: Nanoscience, Quantum Effects, Nanoelectronics, Nanomedicine, Smart Materials, Sustainability, Technological Innovation.

Introduction

Nanoscience is the study of materials and phenomena at the nanoscale, typically ranging from 1 to 100 nano meters, where unique physical, chemical, and biological properties emerge. At this scale, quantum effects and surface interactions dominate, leading to behaviours that differ significantly from those observed in bulk materials. Over the past few decades, nanoscience has evolved into a multidisciplinary field, integrating physics, chemistry, biology, and engineering. Its rapid development has led to groundbreaking innovations that are transforming industries and reshaping modern technology.

The growing demand for efficient, sustainable, and high-performance technologies has accelerated research in nanoscience. From targeted drug delivery systems in medicine to high-speed transistors in electronics, nanotechnology has enabled solutions that were previously unimaginable. As global challenges such as climate change, energy scarcity, and healthcare demands intensify, nanoscience offers promising pathways for innovation and sustainable development.

Objectives

This chapter aims to explore the fundamental concepts of nanoscience and examine its role in technological advancement. It seeks to analyse recent innovations in nanomaterials and their applications across various sectors. Additionally, the chapter aims to evaluate the benefits, challenges, and future potential of nanoscience in driving sustainable technological progress.

Methodology

The chapter is based on a comprehensive review of recent scientific literature published between 2020 and 2025, including peer-reviewed journal articles, books, and research reports. A qualitative approach was adopted to synthesize information on nanoscience innovations and their applications. Key themes such as nanomaterials, nanoelectronics, nanomedicine, and environmental applications were identified and analysed. Comparative analysis of different technologies was conducted to evaluate their effectiveness and scalability. The methodology also involved examining case studies to understand real-world applications and challenges associated with nanotechnology.

Fundamentals of Nanoscience

Nanoscience is grounded in the understanding of how matter behaves at extremely small scales. At the nanoscale, materials exhibit unique properties due to increased surface area and quantum effects. These properties include enhanced strength, electrical conductivity, chemical reactivity, and optical behaviour. Nanomaterials can be classified into various types, including nanoparticles, nanotubes, nanowires, and thin films. The synthesis and characterization of these materials involve advanced techniques such as electron microscopy, atomic force microscopy, and spectroscopy.

The ability to manipulate matter at the atomic level has opened new possibilities for designing materials with specific properties. This has led to the development of smart materials that can respond to external stimuli such as temperature, light, and pressure. These materials are increasingly used in applications ranging from sensors to biomedical devices.

Innovations in Nanomaterials

Recent advancements in nanomaterials have significantly contributed to technological progress. Carbon-based nanomaterials, such as graphene and carbon nanotubes, have revolutionized the field of electronics due to their exceptional electrical and mechanical properties. Metal and metal oxide nanoparticles are widely used in catalysis, environmental remediation, and medical applications. Additionally, polymer-based nanomaterials have found applications in drug delivery and tissue engineering.

The development of multifunctional nanomaterials has enabled the integration of multiple properties into a single system. For example, nanoparticles can be engineered to simultaneously deliver drugs, monitor biological processes, and respond to environmental changes. Such innovations have expanded the scope of nanotechnology in various fields.

Applications of Nanoscience

Nanomedicine

Nanoscience has transformed the field of medicine by enabling targeted drug delivery, early disease detection, and advanced diagnostic techniques. Nanoparticles can be designed to deliver drugs directly to specific cells, reducing side effects and improving treatment efficiency. Nanotechnology is also used in imaging techniques, allowing for the detection of diseases at early stages.

Nanoelectronics

The miniaturization of electronic devices has been driven by nanoscience innovations. Nanoelectronics involves the use of nanoscale materials to develop faster, smaller, and more energy-efficient devices. Transistors, memory devices, and sensors have all benefited from advancements in nanotechnology, contributing to the development of modern computing systems.

Energy Applications

Nanoscience plays a critical role in addressing energy challenges by improving the efficiency of energy generation, storage, and consumption. Nanomaterials are used in solar cells, batteries, and fuel cells to enhance performance and reduce costs. For example, nanostructured materials improve the efficiency of photovoltaic cells by increasing light absorption.

Environmental Applications

Nanotechnology offers innovative solutions for environmental protection and sustainability. Nanomaterials are used in water purification, air filtration, and pollution control. Their high reactivity and surface area make them effective in removing contaminants and improving environmental quality.

Discussion

Nanoscience innovations have significantly contributed to technological progress across multiple sectors. The interdisciplinary nature of nanoscience allows for the integration of knowledge from different fields, leading to the development of advanced technologies. However, the widespread adoption of nanotechnology requires addressing challenges related to scalability, cost, and safety. The potential risks associated with nanomaterials, including toxicity and environmental impact, must be carefully evaluated. Regulatory frameworks and ethical considerations are essential for ensuring the safe and responsible use of nanotechnology.

Challenges and Limitations

Despite its potential, nanoscience faces several challenges. The high cost of research and development, limited scalability of production processes, and lack of standardized regulations hinder the commercialization of nanotechnology. Additionally, the potential health and environmental risks associated with nanomaterials require further investigation. Public awareness and acceptance also play a crucial role in the adoption of nanotechnology.

Future Prospects

The future of nanoscience is promising, with ongoing research focused on developing advanced materials and technologies. The integration of nanotechnology with artificial intelligence, biotechnology, and quantum computing is expected to drive further innovation. Emerging areas such as nanorobotics, quantum dots, and nano sensors hold great potential for revolutionizing various industries. Continued investment in research and collaboration among scientists, industries, and policymakers will be essential for realizing the full potential of nanoscience.

Conclusion

Nanoscience innovations are driving technological progress by enabling the development of advanced materials and systems with unique properties. From healthcare to energy and environmental sustainability, nanotechnology offers solutions to some of the most pressing global challenges. However, addressing the associated risks and challenges is essential for ensuring its sustainable development. By fostering interdisciplinary research, promoting responsible innovation, and strengthening regulatory frameworks, nanoscience can continue to play a pivotal role in shaping the future of technology.

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RECENT TRENDS IN ORGANIC DYE REMOVAL BY USING GREEN SYNTHESIS OF TERNARY-NANOCOMPOSITES AND ITS APPLICATIONS

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Abstract

The rapid growth of industrialization, particularly in textile, leather, and dye manufacturing sectors, has led to the discharge of large volumes of toxic organic dyes into aquatic ecosystems, posing serious environmental and health risks. In recent years, advanced nanotechnology approaches alternatives, with particular emphasis on ternary nanocomposites synthesized via green routes utilizing plant extracts, biomolecules, and eco-friendly reducing agents, have gained considerable attention due to their sustainability, cost-effectiveness, and minimal environmental impact compared to traditional chemical and physical synthesis techniques. Ternary nanocomposites metal oxide components enhanced surface area, improved charge separation efficiency, and extended light absorption capability and adsorptive performance in degrading organic dyes under visible or solar irradiation. Recent studies have demonstrated that green-synthesized ternary systems such as metal oxide heterojunctions exhibit superior degradation efficiencies, often exceeding 90% under optimized conditions. Current trends in this field focus on the development of multifunctional nanocomposites that combine photocatalysis, adsorption, and separation properties. Additionally, the integration of carbon-based materials such as graphene oxide into ternary systems has been shown to improve electron mobility and reduce recombination losses, thereby enhancing overall efficiency. The use of sunlight-driven photocatalysis, magnetic recovery systems, the potential of these materials for real-world wastewater treatment applications. Despite these advancements, challenges remain in terms of large-scale production, long-term stability, and understanding the mechanisms of dye degradation pathways. Future research is expected to address these limitations by optimizing material design, exploring hybrid nanostructures, and advancing green chemistry principles. Overall, green-synthesized ternary nanocomposites represent a highly sustainable solution for efficient organic dye removal, contributing significantly to environmental remediation and water purification technologies.

Keywords: Green Synthesis, Ternary Nanocomposites, Organic Dye Removal, Photocatalysis, Wastewater Treatment.

Introduction

The textile industry, paper industry, plastics and pharmaceutical industries release a lot of wastewater containing dyes, which estimates indicating that a significant portion of dyes that are used in their processing is not contained and it enters aquatic systems. In addition to the colour that these dyes give to water bodies, which leads to a decrease in light penetration and consequently aquatic organisms, these dyes are toxic and carcinogenic to living organisms as well as mutagenic[1]. Traditional methods of wastewater treatment such as coagulation, flocculation, adsorption and biological degradation have demonstrated a weak ability to eliminate complex dye molecules. It is mainly because the aromatic structures are stable and the dyes are man-made, and they are not degraded by the microbes [2]. As a result, AOPs, in particular, heterogeneous photocatalysis have become the subject of serious attention as efficient and sustainable alternatives. Photocatalysis is the production of reactive oxygen species including hydroxyl radicals (•OH) and superoxide radicals ($O_2•^-$) that are capable of reducing organic pollutants to end products that are harmless to the environment like CO_2 and H_2O [3]. The nanomaterials have transformed photocatalysis because of their distinct physicochemical characteristics such as high surface to volume ratio, adjustable band gap and increased reactivity. Metal oxide nanoparticles including TiO_2, ZnO, and CuO have been the most widely researched among them. Nevertheless, single component nanomaterials are usually limited by a high recombination rate of photogenerated electron-hole pairs, poor visible light absorption and low adsorption capacity [4].To address these shortcomings, scientists have come up with binary and more recently, ternary nanocomposites which combine various materials in an effort to realize synergistic effects. These materials are designed to maximize the photocatalytic performance, through charge separation, light absorption and expansion of active surface sites deep in the visible wavelengths [5]. An example is the addition of CuO into TiO_2 based systems which has been demonstrated to serve as an electron trap and lower the recombination rates and increase the photocatalytic activity. In the same way, introduction of carbon source enhances electron movement and a high surface area to dye adsorption, leading to a high degradation performance, which is against the concept of green chemistry [6]. Green synthesis has also become an alternative, which is environmentally friendly and uses plant extracts, microorganisms, and biopolymers as reducing and stabilizing agents [7]. The recent developments in green synthesis have allowed the production of ternary nanocomposites with high efficiency, morphology, size, and composition. As an illustration, photocatalytic efficiency of metal oxide heterojunctions synthesized via plant mediation has shown superiority under the solar irradiation and has been able to degrade dyes reactive orange dyes. Moreover, the green-synthesized nanocomposites have better stability and reusability, and therefore can be used repeatedly in the treatment of the wastewater. The other important trend in this area is the creation of sunlight-powered photocatalytic systems, that involve the use of renewable solar energy to energize nanocomposites [8]. Not only this method saves the costs of operation but also improves the sustainability as the synthesis process is scaled up to be utilized in industrial applications, which guarantees that the synthesis of the nanocomposites remains stable over time, and the precise mechanisms of photocatalytic.

Ternary Nanocomposites

In this regard, the research intends to fabricate and prepare ternary nanocomposites on green synthesis methods that do not require the use of dangerous chemicals hence the highest catalytic activity is expected. Biological reducing and stabilizing agents that include plant extracts, polysaccharides, and microbial metabolites are to be incorporated to increase the environmental friendliness of the synthesis process. The study aims to obtain high photocatalytic and adsorption efficiency in degradation of persistent organic dyes including methyl orange in either the visible light or the solar light irradiation. The other objective is to assess the photocatalytic activity of the produced nanocomposites on different operational conditions such as pH, dosage of catalyst, initial concentration of dye, and light intensity [9]. This will aid in the determination of the kinetics and mechanisms of dye degradation including the involvement of reactive oxygen species like hydroxyl radicals and superoxide ions. Another objective of the study is to determine the reusability, stability, and durability of the nanocomposites in terms of various catalytic cycles, which is essential in the practical use of the nanocomposites in wastewater treatment [10]. Lastly, the research will also be useful in the creation of scalable and sustainable nanotechnology-based remediation of the environment. Applicable in the actual wastewater treatment systems by overcoming the existing constraints, including electron-hole recombination, the limited visible light absorption, and the problem of catalyst recovery treatment technologies.

Recent Advances

Recent studies on the removal of organic dyes have been keen on the creation of novel nanocomposite materials, especially ternary systems that are produced using the green chemistry methods. Therefore nanotechnology-based photocatalysis and adsorption methods have become the possible alternative. Stable, non- toxic and highly reactive nanomaterials can be synthesized in plant- green route of nanomaterials shows e environmentally good attributes, economical characters, makes use of the renewable resources. Research has demonstrated that mediated synthesis can be used in environmental applications. An outstanding case was the $PbO_2/NiO_2/ZnO_2$ synthesized in green pathways biogenic silver nanoparticles produced with plant extracts showed degradation efficiencies of up to ~96% of mixed dye systems under sunlight reach about 91.6 percent degradation of methylene blue under sunlight in 120 minutes with high efficiency and stability in photocatalysis[11]. The improvement of the performance of such systems has been explained by the separation of electrons and holes and the creation of reactive oxygen species that degrade dyes. Likewise, promising results have been demonstrated in clay supports or mineral supports. As an example, a CuO -TiO_2-saponite nanocomposite was found to have a dye removal efficiency of approximately 83 percent, with the clay matrix playing a dual role as a structural support and also increasing adsorption capacity and catalytic activity. Cellulose-derived ternary systems of $CuFe_2O_4$ zeolite have been employed to study ultra-high adsorption capacity of dyes such as brilliant green and it has been observed that porous structures and functionalized surfaces play a crucial role in ternary systems [12]. Ibrahem M. A. Hasan *et al.* green-synthesized NiO_2/MnO_2 nanocomposites of plant extracts and agricultural waste have demonstrated good adsorption and reusability, recent literature also indicates the introduction of noble metals and semiconductor modifications in ternary systems to further improve photocatalytic activity. An example is the ternary nanocomposites of $CuFe_{12}O_{19}$ at ZnO/Au that were synthesized by eco-friendly methods possessing a high degradation efficiency almost 89.61% and antibacterial activity, which demonstrated multifunctional properties. Complex wastewater is being treated using these multifunctional materials with dyes, pathogen, and emerging contaminants [13]. Further, polymer and hybrid nanocomposites have also been of interest owing to their very high adsorption capacities. Recent surveys suggest that high-order nanocomposites may reach adsorption capacities of over 900 mg of some azo dyes though the majority of experiments remain in laboratory scale [14]. This shows the necessity of more studies concerning the actual wastewater use and scalability. The formation of multiphase heterojunctions is determined by structural characterization by X-ray diffraction (XRD) and demonstrates the existence of separate phases of metals or metal oxides in a single composite structure. The efficiency of the green synthesis pathways in stabilizing nanoparticles and inhibiting agglomeration is demonstrated by the presence of bio-organic functional groups as determined by Fourier-transform infrared spectroscopy (FTIR). Morphological studies (scanning electron microscopy-SEM and transmission electron microscopy-TEM) indicate that ternary nanocomposites synthesized green have irregular, porous, and heterogeneous surface structures. Adding more and more catalyst usually enhances efficiency of degradation up to a certain level, after which, light scattering and aggregation could limit the performance. Correspondingly, an increased concentration of initial dyes is likely to reduce the efficiency of degradation because of insufficient active sites and lower penetration of light. Kinetic investigations show that the majority of photocatalytic degradation reactions obey pseudo-first-order reaction kinetics, so the degradation rate is sensitive to the dye concentration. The ternary constants of rate were determined.

On the whole, the literature shows that there is a definite shift to green, sustainable, and multifunctional ternary nanocomposites to remove dyes and be environmental-friendly.

Nevertheless, issues of mass production, cost efficiency, and sustainability in the environmental profile are among the major topics that need to be explored in the future.

Classification of dyes

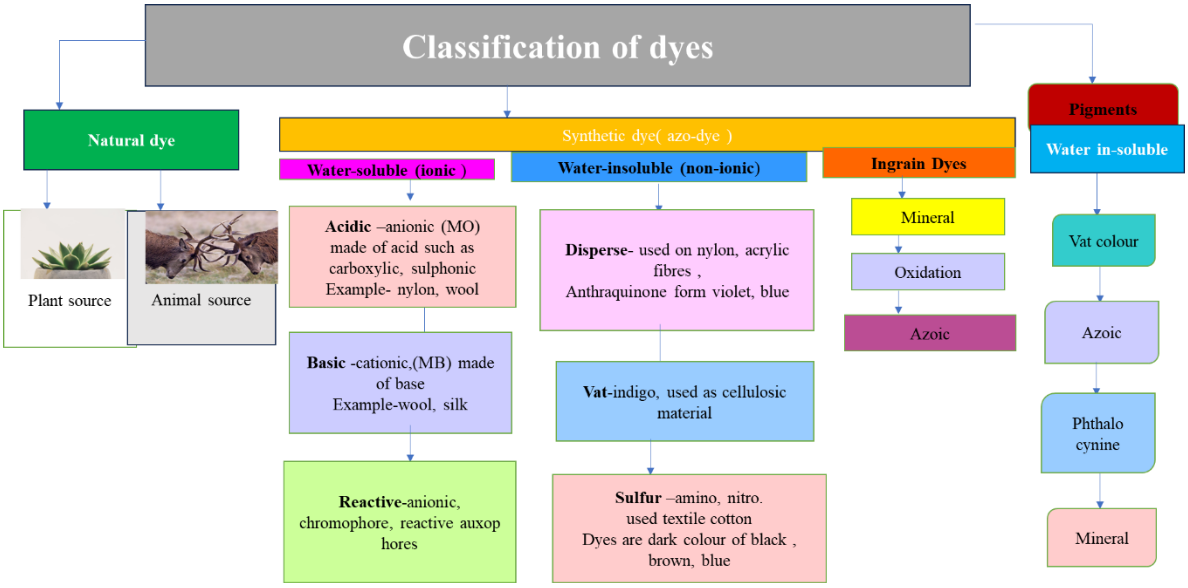

Figure 1: Classification of dyes

Green Synthesis Methods

This research method will be by systematic method of green synthesis. The initial measure entails preparation of plant extracts that can replace the use of traditional chemical reagents that are environmental pollutants. In most cases, aqueous extraction is done on plant materials, including leaves, peels or roots, which have been washed and dried. The extract derived will be bioactive compounds in flavonoids, phenolics, alkaloids, and proteins which are decisive in the reduction of metal ions and stabilization of the obtained nanoparticles. Ternary nanocomposites are synthesized through the combination of salts of zinc, titanium, copper, iron or silver desired metals or metal oxides. The conditions of temperature, pH and stirring are controlled in the process of plant extract. The metal ions reduction and nanoparticles formation is facilitated by the bioactive molecules in the extract, which also serve as capping agents to avoid agglomeration [15]. The mixture of the reaction is usually treated by the bottom-up method so that the crystallinity of the product is increased and uniform particles are produced. Centrifugation is then used to collect the resulting nanocomposite, wash thoroughly to get rid of impurities, and dried to analyse it further [16]. The synthesized ternary nanocomposites are characterized by applying a variety of analytical methods to establish their structural, morphological, and optical characteristics. Photocatalytic activity of the produced nanocomposites is determined by dye degradation experiments using the model organic dyes like methylene orange. A certain quantity of catalyst is added, and the known concentration of dye solution is prepared under continuous stirring. The mixture is then subjected to a light source and this could be a UV light, visible light or even the natural sunlight. At fixed time intervals, the aliquots of the solution are taken, centrifuged to eliminate the particles of catalysts, and the reduction in the concentration of the dye is measured by UV-visible spectroscopy [17]. The rate of degradation is measured as the variation in the absorbance of the dye solution with time and kinetic analysis is conducted to obtain the rate of the reaction. In general, this methodology combines the concepts of green chemistry and the high-tech nanomaterials synthesis and assessment methods to create efficient and sustainable solution to organic dyes removal. The strategy focuses on reproducibility, environmental protection. The catalyst durability is tested by comparing the efficiency of the dye removal.

Applications and Challenges

Green-synthesized ternary nanocomposites have a wide application potential in the environmental and energy-related sector, and not only in dye degradation. The key application lies in the treatment of wastewater, and in this case, these nanocomposites find use to eliminate a broad spectrum of organic contaminants, such as dyes, drugs, or pesticides [18]. This is because of their capacity to produce reactive oxygen species when they are irradiated by light, which is subsequently used to fully mineralize pollutants to non-toxic substances like carbon dioxide and water. These nanocomposites find application especially in the textile industry in treating dye-contaminated effluents. They are also cost-effective and sustainable because they are highly efficient when used to treat wastewater with large amounts of water in the sun. Green synthesis also increases the applicability of them because it lowers the impact on environment and production cost. The other significant usage is in antimicrobial and antibacterial therapy. Numerous ternary nanocomposites are highly antimicrobial to microorganisms like Escherichia coli and Staphylococcus aureus. This feature renders them applicable to the use in water disinfection, medical coating, and sanitation systems [19]. Due to its example, some ternary composites have been shown to possess not only the ability to remove dye, but also to act as antibacterial agents, meaning that they are multifunctional. They are also exploring these nanocomposites in removing heavy metal in wastewater. This is because of their large surface area and functional groups that allow them to adsorb toxic metal ions like lead, chromium and cadmium efficiently. Photocatalytic reduction of metal ions has also been demonstrated in certain instances and this has further improved their remediation properties [20]. Ternary nanocomposites find application in photocatalytic hydrogen generation and solar energy collection in the energy conversion and storage field. They are capable of absorbing visible light and producing charge carriers, which makes them viable in their use in solar fuel production and photocatalytic water splitting. Also, they find applications in supercapacitors and batteries because they have a high conductivity and are electrochemically stable. The other developing usage is in environmental sensing. Highly sensitive sensors which detect pollutants, gases and biomolecules can be developed using ternary nanocomposites. Their increased capability of electron transfer and surface reactivity allow them to sense contaminants fast and with precision, and this makes them useful in environmental monitoring systems. Moreover, these nanocomposites are in the process of being explored to be used in catalytic and photocatalytic degradation of new contaminants like antibiotics, as well as endocrine-disrupting chemicals. They are multifunctional and hence they can be used to solve complex environmental problems [21].

To conclude, green-synthesized ternary nanometal composites have a diverse application such as wastewater treatment, antimicrobial activity, removal of heavy metals, energy conversion, sensing, and environmental remediation. They are promising in the future of technological development in the field of environmental and material science because they are highly efficient, sustainable and versatile.

Future Prospectives

The use of green synthesized ternary nano composites in the removal of organic dyes has shown enormous advances in the past few years. Although major steps towards photocatalytic efficiency, charge separation and environmentally-friendly synthesis methods have been made, there are still a number of challenges and opportunities in the translation of laboratory performance to real-world wastewater treatment systems. The following studies should be directed to material design enhancement and reaction mechanisms comprehension and environmental sustainability. The development of green synthesis strategies is one of the major directions of the future. Although plant-mediated synthesis has proven to be effective, there is still a need to standardize synthesis protocols to ensure reproducibility and scalability. The inconsistency of nanocomposite properties may be caused by variations in the composition of the plant extracts, seasonal variations and the conditions used in extracting the extracts. Thus, the goal of work in the future is to find certain active biomolecules that lead to reduction and stabilization, which will make it possible to synthesize them with controlled morphology and behaviour. Also, alternative biological sources like algae, fungi, and bacteria are promising alternatives to developing more sustainable and varied nanomaterials. The other significant part is the architecture of sophisticated ternary nanocomposites. In future studies, the rational design of heterostructures, including Z-schemes and S-schemes, that can greatly improve charge separation and redox potential, should be highlighted. Light absorption and electron mobility can be enhanced even further by the introduction of new inorganic metal doped materials such as two, three-dimensional nanostructures (e.g., graphene derivatives, carbon nano tubes, layered double hydroxide). Engineering hierarchical and porous structures will also increase surface area and active sites, leading to improved adsorption and degradation efficiency. The optimization of bandgap energies to optimize the use of visible light is an important goal in realizing solar-driven photocatalysis. Another key area of future development is the use of solar energy. Most of the existing research uses artificial UV or visible light source, which restricts the use of this technique at large scale because of the energy costs. The creation of photocatalysts that are capable of effectively utilizing natural sunlight will make the dye degradation processes much more economically viable and sustainable. This demands a fine bandgap tuning and optimization of ternary systems in light-harvesting. As far as application is concerned, there is an urgent need to cease to dwell on the model dye systems and direct attention to actual industrial wastewater treatment. Single dyes like methylene blue or rhodamine B are commonly used in laboratory studies under controlled conditions, which are not a similarity to the real wastewater. Future studies are needed to cover multi-component pollutant systems, such as dye-pharmaceutical and heavy metal mixtures. Also, continuous-flow reactors and pilot-scale research will have to be developed to assess the feasibility of these nanocomposites in practice. There is also a need to know more about the mechanistic pathways that are involved in the degradation of dyes. The reactive species and the intermediate products should be identified by using advanced characterization methods, including electron spin resonance spectroscopy, in situ spectroscopic analysis, and time-resolved photoluminescence studies. Moreover, computational techniques like density functional theory (DFT) can be used to give important insights into the nature of charge transfer and interfacial interactions in ternary systems. This chapter will be useful in the development of more effective and specific photocatalysts. Nanocomposites stability, recyclability and environmental safety should also be taken into consideration. Even though a significant number of ternary systems exhibit good reusability when in the laboratory, it is not clear whether they would continue to be stable in the long run when exposed to actual environmental conditions. It is also necessary to assess the possible toxicity and environmental effect of nanomaterials post-use. Future directions ought to be to either create catalysts that are readily recoverable to include magnetically separable systems and to guarantee that the degradation byproducts are non-toxic. The importance of life cycle assessment studies will be to determine the total environmental footprint of these materials. Academia, industry and environmental agencies will have to collaborate to ensure that the gap between research and implementation is bridged. To sum up, ternary nanometal composites synthesized greenly have enormous prospects in sustainable dye removal processes. Nevertheless, to realize their potentials, interdisciplinary research should be done concerning material innovation, mechanistic insight, environmental safety, and process engineering. As the technology further develops, these materials may serve as a major component of overcoming the global water pollution problem and promoting environmentally-friendly wastewater treatment technologies.

Conclusion

Finally, green-synthesized ternary nanometal composites have also become a very promising technology when it comes to the effective decontamination of wastewater organic dyes. Combining the concepts of green chemistry with high-level nanotechnology has facilitated the creation of cost-efficient, sustainable, and eco-friendly materials that have a high photocatalytic and adsorption capacity. These ternary systems have been found to have pronounced strengths compared to the traditional and single-component materials which are characterized by high surface area, increased charge separation, prolonged light absorption and efficiency in degradation. The literature has revealed that the application of plant extracts and biological resources in synthesis does not only decrease environmental impact, but also adds functional groups to improve catalytic performance and stability. The synergistic effects of the constituents in ternary nanocomposites are very relevant in enhancement of the efficiency of dye degradation which in the best circumstances can reach a high of 85-95 percent. Besides that, the inclusion of support material, carbon based structures and magnetic constituents have also enhanced the feasibility of such systems by increasing the adsorption capacity, the electron transfer, and the recovery of the catalysts. Regardless of these developments, there are a number of issues that lie between laboratory-scale achievement and practical application. There are issues like mass-scale synthesis, cost-efficiency, long-term stability, and possible environmental hazards related to nanomaterials that should be taken care of. Additionally, majority of the studies have been carried out with synthetic dye solutions, which portrays the necessity of conducting more studies with real industrial wastewater systems. The further studies ought to concentrate on the creation of scalable synthesis processes, investigating new material combinations, and studying the mechanisms of degradation better. Further possibilities are also exciting with the integration of multitask properties, e.g., antimicrobial activity, and the removal of heavy metals to develop comprehensive wastewater treatment solutions. All in all, the green-synthesized ternary nanocomposites are a high breakthrough in technologies of environmental cleaning. These materials are capable of becoming very important in the realization of sustainable water purification and combating the challenges of global water pollution with the continued research and development of the materials.

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NANOMATERIALS:
THE FUTURE OF SMART ENERGY STORAGE DEVICES

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Abstract

The fast growth of global energy consumption, as well as the transition to renewable energy sources, have raised the demand for high-performance energy storage technology. Nanomaterials have evolved as "smart materials" due to their unique physicochemical properties such as increased surface area, versatile electronic structure, and enhanced electrochemical performance. This research investigates the function of nanomaterials as smart materials in modern energy storage devices such lithium-ion batteries, supercapacitors, and hybrid systems. The most recent developments are examined, with an emphasis on new materials, charge storage systems, and enhanced performance. There is also discussion of important issues including scalability, cost, and environmental concerns. The study emphasizes nanoparticles' transformational potential for next-generation energy storage systems.

Keywords: Nanomaterials, Energy Storage, Supercapacitors, Lithium-ion Batteries, Smart Materials, Electrochemical Systems, Sustainable Energy.

Introduction

The global shift to renewable energy sources, such as solar and wind power, has generated a significant demand for efficient and reliable energy storage systems. The energy density, power output, and long-term stability of conventional energy storage methods are frequently restricted. Researchers are increasingly concentrating on new materials with improved performance characteristics to overcome these issues.

Materials with at least one dimension in the nanometer scale (1–100 nm) are referred to as nanomaterials. They have distinct chemical and physical properties that set them apart from bulk materials. They are great options for energy storage applications because of these properties, which include a higher surface-to-volume ratio, greater electrical conductivity, and increased electrochemical reactivity.

In recent years, nanoparticles have been extensively studied as "smart materials" capable of adjusting to dynamic operating conditions in energy storage systems. They are at the center of modern energy research because of their capacity to improve electrode stability, accelerate increase ion movement, and increase charge storage capacity.

The goal of this work is to present a thorough overview of nanomaterials in energy storage devices, including their types, methods, uses, difficulties, and objectives for the future.

Classification of Nanomaterials in Energy Storage

Nanomaterials used in energy storage systems are broadly classified into carbon-based nanomaterials, metal oxide nanomaterials, conducting polymer nanomaterials, and nanocomposites, each offering distinct electrochemical advantages due to their nanoscale dimensions and unique physicochemical properties. Carbon-based nanomaterials, such as graphene, carbon nanotubes (CNTs), and activated carbon, are widely used due to their high electrical conductivity, large specific surface area, and superior mechanical strength, which allows rapid electron transport and efficient charge accumulation in devices such as supercapacitors and lithium-ion batteries. Metal oxide nanomaterials like manganese oxide (MnO_2), titanium dioxide (TiO_2), and nickel oxide (NiO) have high theoretical capacitance and are commonly used in pseudocapacitive applications.

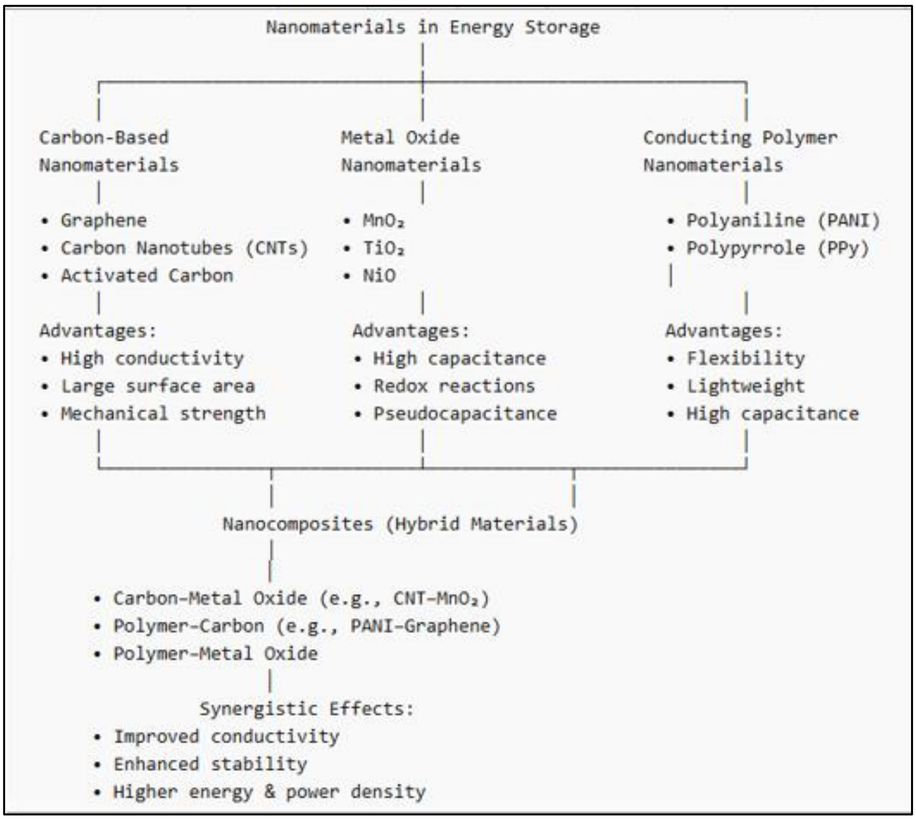

Figure 1: Classification of Nanomaterials in Energy Storage

They store energy through fast and reversible redox reactions at or near the electrode surface. Conducting polymer nanoparticles, such as polyaniline (PANI) and polypyrrole (PPy), offer additional benefits such as flexibility, lightweight construction, and high pseudocapacitance, but their long-term stability in cycles may be limited. To address these constraints, nanocomposites have been created by combining various types of nanomaterials, such as carbon-metal oxide or polymer-carbon hybrids, which result in synergistic develops in electrical conductivity, structural stability, and overall energy storage capacity. These classifications is the important part that nanomaterial design performs in optimizing next-generation smart energy storage systems [1-4].

Working Mechanism of Nanomaterials in Energy Storage

Nanomaterials work in energy storage systems through a number of electrochemical reactions which take place at the electrode-electrolyte interfaces. Nanomaterials improve energy storage performance by using use of their wide surface area, short ion diffusion paths, and unique electronic structures. Whether the system uses battery-type faradaic storage, electrical double-layer capacitance (EDLC), or pseudocapacitance determines in which they work, but in all situations, nanoscale properties greatly enhance the efficiency and kinetics of charge storage.

Core Mechanisms

1) Electrical Double-Layer Formation (EDLC)

Electrical double-layer capacitance (EDLC) is a non-faradaic charge storage mechanism found mostly in carbon-based nanomaterials including graphene, carbon nanotubes (CNTs), and activated carbon. Without any charge transfer or chemical reaction, energy is stored in this process via the electrostatic formation of electrolyte ions at the electrode–electrolyte interaction. When a potential is applied, oppositely charged ions from the electrolyte migrate toward the electrode surface, forming a dense layer known as the Helmholtz double layer. Nanomaterials' porous shape and very high specific surface area allow for the absorption of larger ions, which increases capacitance. These materials' high electrical conductivity also promotes quick electron transit, leading to an increase in faster charge-discharge cycles as well as high power density. The absence of faradaic reactions also leads to improved cycling stability and operating life, making EDLC-based systems ideal for applications requiring high power delivery and long-term performance. [2, 5-6]

2) Faradaic Redox Reactions (Pseudocapacitance)

Pseudocapacitance is caused by quick and reversible faradaic redox reactions at the surface of electroactive materials such transition metal oxides (e.g., MnO_2, RuO_2, NiO) and conducting polymers (e.g., polyaniline (PANI), polypyrrole (PPy). In contrast to electrical double-layer capacitance, this method results in a larger specific capacitance by transferring charge between the electrode and electrolyte. Ions from the electrolyte interact with the electrode surface through redox reactions when a potential is applied, leading to electron exchange and transient changes in oxidation states. These materials have many active sites and short ion diffusion routes because of their nanoscale size, which enable quick kinetics and high-rate capabilities. Moreover, partial bulk participation and surface-controlled processes improve energy storage efficiency. [2, 6-7]

3) Ion Intercalation/Deintercalation (Battery-Type Storage)

Ion intercalation and deintercalation activities in the electrode's bulk structure mostly regulate the charge storage mechanism in battery-type nanomaterials. Under the influence of an electric field, electrolyte ions (such as Li^+, Na^+, or K^+) migrate toward the electrode–electrolyte interface when an external potential is applied. These ions are then introduced (intercalated) into the nanostructured electrode material's crystal lattice without seriously breaking the structure. For the purpose to maintain charge neutrality, this operation is accompanied by a matching flow of electrons across the external circuit. The diffusion path length for ions is greatly reduced due to the nanoscale size, which improves ion transport kinetics and allows high charge/discharge rates. Ions are removed (deintercalated) and returned to the electrolyte during discharging, whereas they occupy interstitial sites in the host material during charging, frequently producing intermediate phases. Nanomaterials' large surface area and structural adaptability enhance ion accessibility and allow for volume variations during cycling, increasing capacity and cycling stability. The intercalation/deintercalation process is essential to improved rechargeable batteries because it generally offers a higher energy density than surface-based storage methods. [8 -12]

4) Synergistic Effects in Nanocomposites

In energy storage systems, nanocomposites are created by combining two or more functional nanomaterials, usually conducting polymers, metal oxides, and/or materials based on carbon. The main goal of this hybridization is to use faradaic (pseudocapacitive or battery-type) and electrical double-layer capacitance (EDLC) charge storage methods in in concert within a single electrode system. In these materials, the carbonaceous component (e.g., graphene or carbon nanotubes) forms a highly conductive network that allows for rapid electron transit and enhances electrical conductivity, while simultaneously contributing to EDLC via ion adsorption at the wide surface area interface. Furthermore, a faradaic redox activity is introduced by conducting polymers or metal oxides, greatly increasing specific capacitance by reversible charge transfer reactions. These components' close interfacial contact shortens ion diffusion ways and reduces internal resistance, which improves reaction kinetics. Additionally, the flexible carbon matrix improves structural stability and extends cycling life by buffering the volumetric fluctuations of redox-active materials after multiple charge-discharge cycles. Because of this, nanocomposites show better energy density, power density, and long-term electrochemical stability than their individual components, which makes them extremely attractive for hybrid energy storage devices and next-generation supercapacitors. [2]

Applications of Nanomaterials in Energy Storage Systems

Nanomaterials have emerged as key components in advanced energy storage systems due to their distinct physicochemical features, which include large surface area, adjustable shape, increased electrical conductivity, and shorter ion transport paths. They are used in lithium-ion batteries, sodium-ion batteries, supercapacitors, and hybrid energy storage devices. Nanomaterials, with their nanoscale architecture, initially allow rapid ion transport from the electrolyte to the electrode surface in a typical operational sequence. Charge storage then takes place by one or more processes, such as ion intercalation in battery-type materials, faradaic redox reactions in metal oxides and conducting polymers, or electrical double-layer creation in carbon-based nanomaterials. In order to maintain charge neutrality all over the charging process, electrons are simultaneously moved through highly conductive nanostructured networks. High power delivery is made possible by the effective release of the accumulated ions and electrons upon discharge. In practical applications, transition metal oxides are utilized in high-energy devices because of their superior capacitance, while carbon-based nanomaterials like graphene and carbon nanotubes are frequently used in high-power supercapacitors for fast energy transfer. For wearable electronics, conducting polymer nanostructures offer lightweight and versatile energy storage options, while nanocomposites combine several functions to obtain high energy and power density. Nanomaterials are essential for next-generation portable electronics, electric cars, and grid-scale energy storage systems because they greatly improve electrochemical performance when electrode materials are engineered at the nanoscale.[2, 16-17]

Application Mechanism Diagram

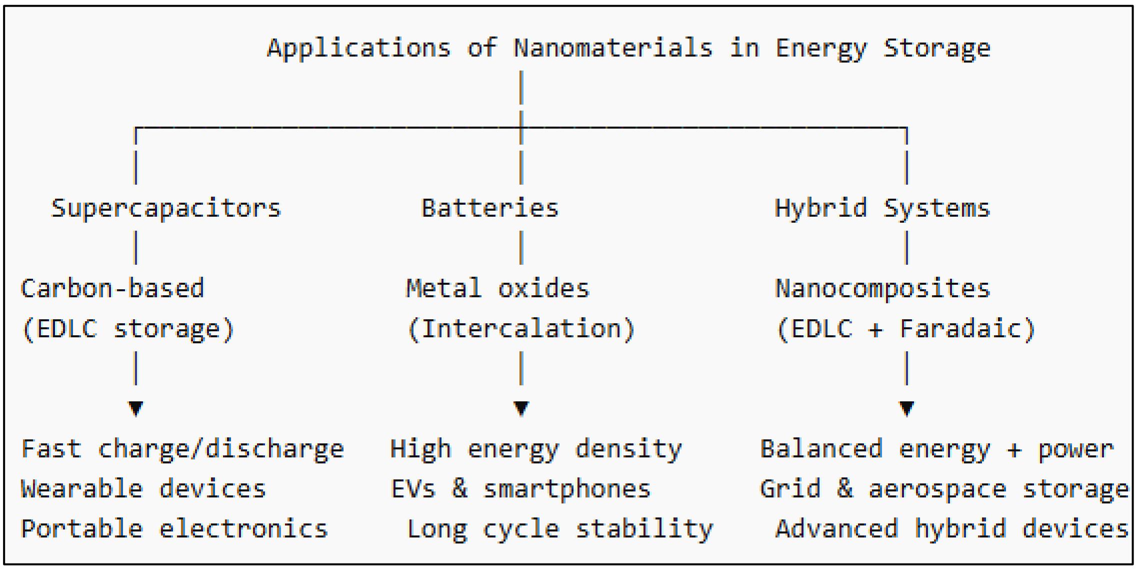

Figure 2: Application of Nanomaterials in Energy Storage

Future Scope

Nanomaterials for smart energy storage devices are a fast-developing topic with many prospects for further study and technical development. The development of next-generation nanostructured materials with increased energy density, higher charge-discharge rates, and longer cycle lives is anticipated to advance significantly in the next few years. In order to overcome the present constraints of lithium-ion batteries, supercapacitors, and hybrid energy storage systems, advanced hybrid nanomaterials incorporating metals, metal oxides, carbon-based structures, and polymers are probably going to be essential.

Future research could also focus on generating eco-friendly and sustainable nanomaterials to lessen reliance on rare or harmful ingredients. For large-scale commercial applications, scalable and economical synthesis techniques—like bio-inspired manufacturing methods and green chemistry techniques—are expected to become more significant.

Furthermore, integrating nanomaterials with cutting-edge technologies like smart grids, flexible/wearable electronics, and solid-state batteries will produce new opportunities for intelligent energy storage systems. By anticipating high-performance structures and characteristics, artificial intelligence and machine learning could expedite the discovery and optimization of nanomaterials.

Overall, nanomaterials have the potential to convert energy storage technology; however, future research must address difficulties like as commercialization, safety, recyclability, and environmental effect to assure long-term progress.

Conclusion

Nanomaterials have emerged as a transformative option for next-generation energy storage systems due to their unique physicochemical qualities such as high surface-area-to-volume ratio, increased electrical conductivity, and programmable electrochemical behavior. Through processes like electrical double-layer formation, pseudocapacitance, ion intercalation /deintercalation, and synergistic effects in nanocomposites, this study emphasizes their critical role in enhancing the performance of lithium-ion batteries, supercapacitors, and hybrid energy storage devices.

The combination of carbon-based nanomaterials, metal oxides, conducting polymers, and their composites has greatly increased energy density, power density, charge-discharge rates, and cycling stability. These developments show that overcoming the drawbacks of traditional energy storage technologies and satisfying the expanding demand for effective and sustainable energy systems everywhere depend significantly on nanoscale technology.

However, despite these positive improvements, issues like as large-scale production, cost-effectiveness, environmental impact, and long-term stability must be addressed. It is anticipated that future developments in advanced hybrid materials, green synthesis techniques, and AI-assisted material design will speed up commercialization and expand application areas.

In summary, nanomaterials play an important part in future renewable energy infrastructure, portable electronics, electric vehicles, and grid-scale storage systems by enabling smart, high-performance, and sustainable energy storage devices.

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GIBBS BARRIER OF AQUEOUS L-ALANINE MORPHS' INTERCONVERSIONS AT HUMAN BODY TEMPERATURE BY DFT-D3 METHOD

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Abstract

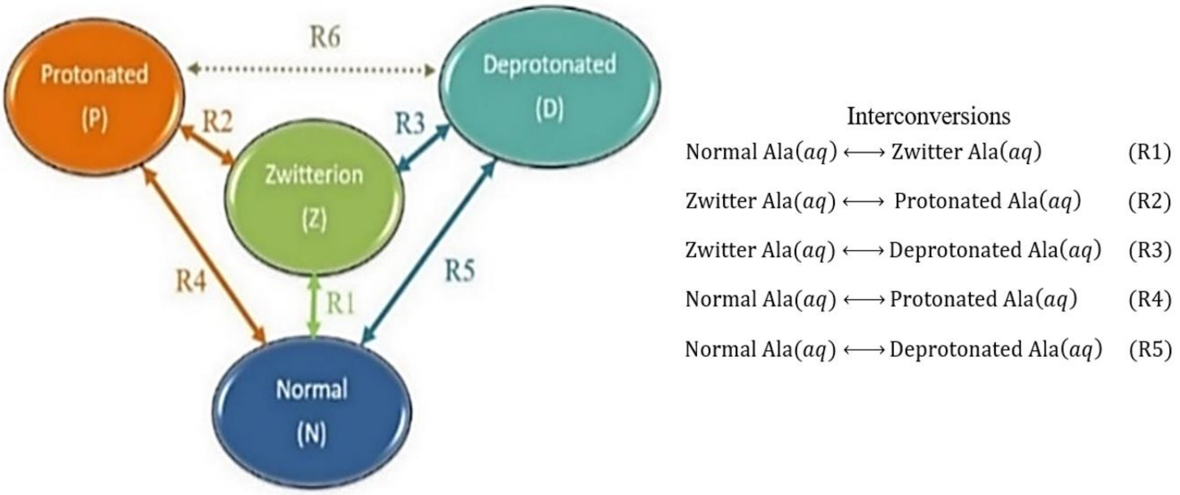
L-Alanine (L-Ala) found in four morphs or molecular forms state viz., Zwitterionic, deprotonated, protonated and normal. Their spontaneous formation of equilibrium state is subjected to solvation and its pH; in human body it's usually zwitterionic form. The possibilities of the stimulated interconversions were predicted and examined in this study through the Gibbs barrier concept. In the present study, this Gibbs barriers were investigated for the effect of variation of body temperature from healthy 96 F to ill 104 F. As well as some thermochemistry features are compared for this. This has been conducted first time using DFT-D3 method in this work. For the human body temperature range, the Gibbs barrier revealed insignificant variations. The other four possible interconversions were also computationally examined in the range of body temperature.

Keywords: Gibbs Barrier, DFT-D3, Human Body Temperature, L-Alanine, Ultrasonic Evidence.

Introduction

Alanine (Ala), an amino acid, is found in a human body and well known as non-essential and the L-Alanine (L-Ala) naturally occurred in abundant compared to the d-Alanine (d-Ala) form. L-Ala is a zwitterionic polar form in an aquatic fluid in human body at body temperature with usual pH. Zwitterion is a polar form of L-Ala. L-Alanine exhibits structural changes and became protonated in acidic solvation and de-protonated in basic solvation of water. Already reported works evident the ranges of temperatures: 36.32 - 37.76 °C for rectal, 35.76 - 37.52 °C for tympanic, 35.6 - 37.61°C for urine, 35.73-37.41 °C for oral, and 35.01-36.93 °C for axillary in their study of 7636 subjects; minimum to maximum range in Fahrenheit scale is 95 F (axillary) to 99.96 F (rectal) [1]. Human body temperature for healthy to non-healthy (cold or fevered) case is rises above 97 F and can elevated up to 104 F [2-6]. These temperature helps body to performed different physiological activities: eg. Glycolysis and Gluconeogenesis, protein synthesis, energy fuelling, Heme-synthesis etc. [7-10]. The changes in amino acid with respective to various parameter like pH, temperature etc. cannot be avoidable [11-12]. At normal human body temperature 97 F to 98.5 F body functioning healthy activity [5, 6]. The study of variations from the normal temperature to the 99 - 104 F from healthy to fevered cases respectively was not yet reported in literature for the L-Ala and their interconversions with other morphs. In a previously reported work, the interconversion of zwitterions (Z) to normal (N) form $(Z \rightarrow N)$was shown: i) spontaneous route due to naturally occur and ii) stimulated route due to ultrasonic exposer with their physiological importance [13-16]. The Gibbs energy barrier between Zwitterion and non-Zwitterion is well known in L-Ala and their structures are extensively studied. But the Zwitterion-L-Ala interconversion with other forms/morphs in water solvation (considering within the body) is not reported for the range of human body temperature and did not study within the framework of DFT yet. The natural conversion of zwitterion to normal L-Ala (N) is impossible in water abandoned human body.

Therefore, this work is primarily focused on Zwitterion in water and on how does the thermo-chemical properties get affected as a function of temperature sustained by the body. In the present work, only single Zwitterion molecule in water solvation is evaluated by DFT for obtaining the properties to trace the directions/routes. The present study has investigated spontaneous reaction cases firstly and then predicted the barrier from the stimulated approach. For this, the four morphs of L-Ala (Normal L-Ala, Zwitterion, protonated and de-protonated) were optimized for the expected reactions or routes. Five routes of reactions have been selected; the morphs' interconversions in these reactions are shown in Fig.1. In the present article, details of the methodology used in study has been presented in second section and the computational and experimental outcomes have been described in the third section.



Interconversions

Normal Ala$(aq) \longleftrightarrow$ Zwitter Ala(aq) (R1)

Zwitter Ala$(aq) \longleftrightarrow$ Protonated Ala(aq) (R2)

Zwitter Ala$(aq) \longleftrightarrow$ Deprotonated Ala(aq) (R3)

Normal Ala$(aq) \longleftrightarrow$ Protonated Ala(aq) (R4)

Normal Ala$(aq) \longleftrightarrow$ Deprotonated Ala(aq) (R5)

Figure 1: Alanine different morphs interconversion scenario for the possible reactions

Computational part and Methodology

All codes were implemented in ORCA software within DFT-D3 framework [17-19]. Computation done with PBE and B3LYP functional but only PBE based results were chosen to report here due to close agreement with experimental value. The PBE/def2-SVP with coulombs fitting and the CPCM model for water solvation were framed to optimize the geometries and frequencies as per the guideline provided in source literature [20-22]. Tight convergence has been implemented. Frequency optimization calculations done for all selected temperatures to obtain the thermochemistry at relaxing state. Temperature ranges from 96 to 104 F (in Centigrade scale, range of 36 to 40 °C) of 0.5 F steps were selected for inside body temperature. This way, the optimization of the four morphs of L-Ala (Zwitterion, protonated and de-protonated) conducted along with H_2O. H_3O^+, OH^- and H_2 for the reactions or routes. There are five routes of reactions were selected. How does the Alanine morphs interconverted in these reactions are (shown in Fig.1) identified by the routes R1, R2, R3, R4 and R5 for the N↔Z, Z↔P, Z↔D, N↔P and N↔D interconversions respectively. Present work is not interested in R6 mentioned in Fig.1 due to i) the previously reported observation and ii) the zwitterion is a relax and stable morph in water solvation; previously Zwitterion to Normal conversions was predicted under ultrasonic exposer. Thus, inter-conversion between Protonated and deprotonated are not considered in this study. The spontaneous direction is subjected to DFT result to choose and it is investigated in the sections. Entropy, Enthalpy and Gibb's free energy have been calculated within DFT framework. The outcomes were used to calculate the product and the reactant and their difference in the form of change in Gibbs energy of reaction.

Results and Discussion

Thermochemistry and Spontaneous Route of Reaction

Results for the thermochemistry associated with Infra-red (IR) spectra from DFT-D3 computation are summarised in the Fig.2 and Fig.3. Absorption frequencies in IR transmittance spectra for protonated, deprotonated, zwitterion and normal forms are resembled on their structures and showing the different functional characteristics. Absorption near 2500 cm^{-1} in zwitterion form (which is highest absorption peak in zwitterion L-Ala indicated by * marker) is not observed in IR spectra of other forms. Peaks were characterized by first three higher intensity peaks which are below the 2000 cm^{-1} and shown by mark of 1, 2 and 3 in Fig.2(a) for all forms. Their corresponding thermochemistry are investigating to calculate Gibbs Barrier. The information reflected distinguish characteristics of all different forms and we referred those as the IR Marker. These IR markers are successfully reproduced on same machine for the optimization and confirmed the same corresponding thermochemistry.

Plot in Fig.2(b) elucidated the Zwitterionic and Basic (De-protonated) L-Ala has significantly larger entropy than Acidic (Protonated) and Normal forms of L-Ala which indicated the Zwitterion and Basic L-Ala are more disordered in comparison with other. This indicated that within temperature range of human body naturally formation of zwitterionic form of L-Ala and basic or deprotonated form of L-Ala are more probable, and this is in accordance with 2nd law of thermodynamics. Also, their trend is linear, constantly increasing (positive slope with the same rate) and constant separation (~0.725 KJ/molK). It is well known that negative change in Gibbs free energy decides the direction of the spontaneous process used during the chemical reaction [23].

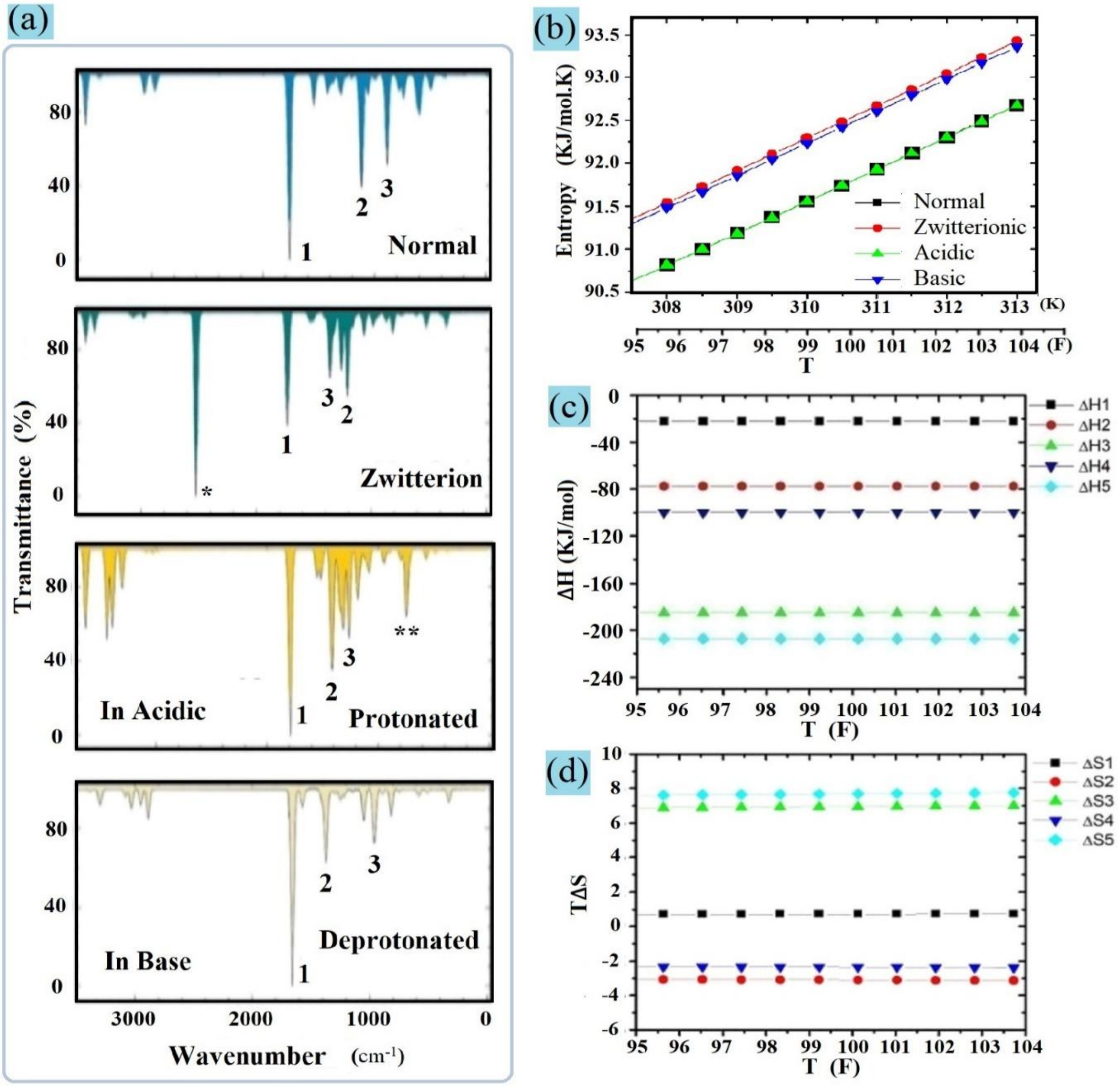


Figure 2: (a) Computed IR transmittance spectra of Normal, Zwitterion, Protonated and De-protonated forms of L-Ala from DFT. (Normal-L-Alanine in Blue filled, Zwitterion in Green filled, protonated in dark yellow filled and de-protonated by muddy yellow filled). (b) Plot illustrates entropy in different forms as a temperature in the range of body temperature. The (c) and (d) plots illustrate the analysis of two thermodynamic parameters as a function of the body temperature variation. These parameters are, i) Enthalpy Change in the reaction (c) and ii) Entropy change factor in the reaction (d).

After examination, the directions were found negative and routes can be represented as R1:N→Z, R2:Z→P, R3:Z→D, R4:N→Pand R5:N→D. Resemble on this direction, the change in enthalpy (ΔH) and the change in work done ((TΔS); since, T is constant, the ΔS is examined) associated with those were decided as shown in graph of Fig 2(b) and (c) respectively. Enthalpies are negative and linear for the range of body temperature and seem to be constant, but the slope is not zero. ΔH1 is least negative, ΔH5 is most negative and other are in between these values. However, the change in entropy of the reaction is not negative for all; it is negative only for ΔS2(R2:Z→P) and ΔS4(R4:N→P), and positive for the rest: ΔS1(R1:N→Z), ΔS3(R3:Z→D) and ΔS5(R5:N→D). This again implies that the occurrence of zwitterion L-Ala and deprotonated L-Ala is more probable within the temperature range of human body and its usual pH. Finally, the change in Gibbs Energy (ΔG) was determined and observed in a similar order of change as observed in the case of ΔH. Since study is focused on the barrier, the order of their absolute value is considered for the height of the barrier, and it is obtained as |ΔG1| < |ΔG2| < |ΔG4| < |ΔG3| < |ΔG5| as illustrated in Fig.3 (a). Here Absolute term is used to understand that the direction of reaction is altered to natural route of reaction (i.e., spontaneous).

The directions for the spontaneous reactions are finalized from the negative value of change in Gibb's free energy barrier and represented by arrow direction as:

For Normal to Zwitterion case ($R1: N \rightarrow Z$)

$$C_2H_4NH_2COOH(aq) + \ H_2O \xrightarrow{-\Delta G1} C_2H_4NH_3^+COO^-(aq) + H_2O$$

R1 is already reported in [12-14] by predicting the overcoming of the barrier by the ultrasonic excitation in non-acidic and non-basic water solvation. The reaction is spontaneous from Normal to Zwitterion form and occurred due to ΔG1 around -22 KJ/mol for body temperature by DFT. Similar spontaneous reactions can be writable for the other cases with the corresponding DFT calculated approximated ΔG shown in Fig.3 (a). In the case of Zwitterion Ala as a reactant, R2 and R3 found spontaneous for protonated L-Ala and deprotonated L-Ala respectively as the end products and it can be written as:

For Protonated case ($R2: Z \rightarrow P$)

$$C_2H_4NH_3^+COO^-(aq) + H_3O^+ \xrightarrow{-\Delta G2} C_2H_4NH_3^+COOH\ (aq) + H_2O$$

For De-protonated case ($R3$): $Z \rightarrow D$

$$C_2H_4NH_3^+COO^-(aq) + OH^- \xrightarrow{-\Delta G3} C_2H_4NH_2COO^-(aq) + \ H_2O$$

In the case of Normal L-Ala as a reactant, R4 and R5 found spontaneous for protonated L-Ala and deprotonated L-Ala respectively as the end products as:

For Protonated case ($R4: N \rightarrow P$)

$$C_2H_4NH_2COOH(aq) + \ H_3O^+ \xrightarrow{-\Delta G4} C_2H_4NH_3^+COOH\ (aq) + H_2O$$

For De-protonated case ($R5: N \rightarrow D$)

$$C_2H_4NH_2COOH(aq) + OH^- \xrightarrow{-\Delta G5} C_2H_4NH_2COO^-(aq) + H_2O$$

All ‘R’s in the spontaneous reactions are found to be true within a human body temperature range, and the corresponding change in thermochemical parameters are illustrated in Fig.2(b-d) and Fig.3. As well as these are true for the body temperature tending to 0 °C and to 40 °C (*Fig.2*). This thermochemistry is not new until the perspective became altering (i.e., stimulated reaction), which is not normal. Here, another thing is that the change in Gibbs free energy for the different body temperature (Fig.3(a)) is examining by DFT for first time. A close observation of resolving the y-axis data of each Gibbs energy change in Fig.3(a) shows the slope is not zero in Fig.3(b). The negative value of Gibbs energy change is (ΔG is negative) showing the natural trend of this change (spontaneous reaction) in term of slope (see Fig.3(b)). This slope found decreasing for the $-\Delta G1$:N→Z, $-\Delta G3$:Z→D and $-\Delta G5$:N→D and found increasing for the $-\Delta G2$:Z→P and $-\Delta G4$:N→P; these all are observed with the relatively very small slope corresponding to the trend. All $-\Delta G$ showed spontaneous reaction and its direction (reactant to product) to relax state for the stable formation.

For the spontaneous reactions, the Zero Point Energy (ZPE) and the Total Electronic Energy (E_{ele}) of the systems remain same for variation in temperature. It is also observed in calculations. Hence, the change in ZPE and E_{ele} for the reaction is remained constant for all computed temperature including for body temperature. Predicted value of ΔZPE and Electronic Energy ΔE_{ele} of all four forms from DFT is provided in Table 1. It is elucidated that the ΔZPE of de-protonated L-Ala in the basic medium has shifted to lower value, whereas the ΔZPE of protonated L-Ala in the acidic medium shifted to higher (increased). Zwit to Ala has shown lower side positive value of 1.992. Up to this point the Gibbs free energy change study made the clues for what should be the barrier. It is easy to hypothesize but need some experimental proof to prove it. Previous studies done it; and observed with different concentration of L-Ala. In present case, it was done for different four temperature ranging for the human body for only first case R1, in the next section. Further sections have rendered the barrier perspective for all route cases.

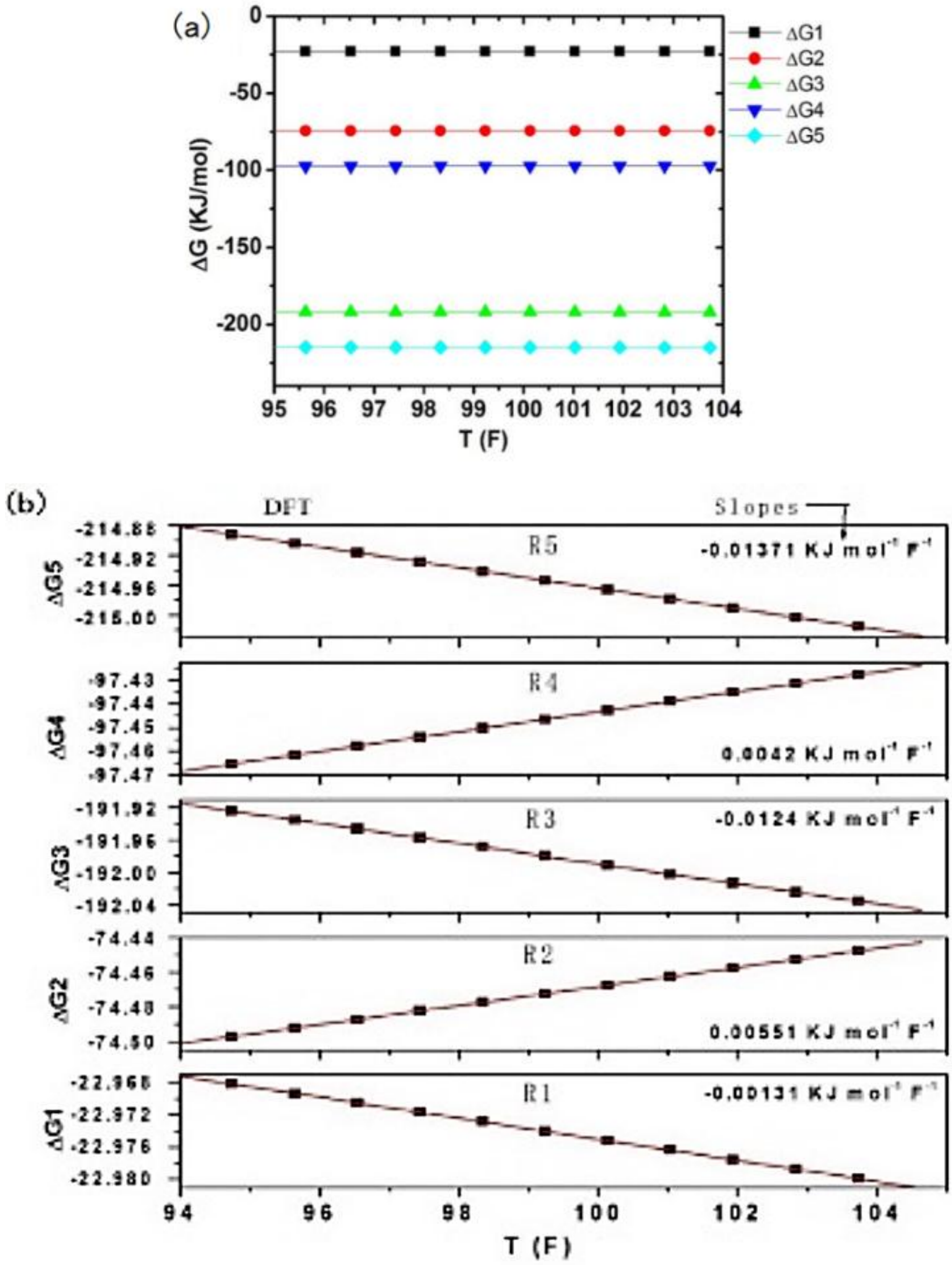


Figure 3: (a) Comparative analysis of the Gibb's Free Energy of the reaction as a function of temperature in F unit. (b) Change of Gibb's energy (in KJ/mol) with respective to body temperature in F represented as a characteristic in term of slope.
(The red lines represent linear fitting to the data points.
Slopes are also provided with fitting.).

Table 1: Change in ZPE and Electronic Energy for the route of reactions.

Reaction	ΔE_{ele} (KJ/mol) 2	ΔZPE (KJ/mol)
1. R1: N → Z	-24.68	1.99
2. R2: Z → P/A	-78.72	37.25
3. R3: Z → D/B	-185.87	-33.40
4. R4: N → P/A (direct)	-103.39	39.24
5. R5: N → D/B (direct)	-210.54	-31.41

(Note: (1) Forms are denoted by letter indicating that N-Normal, Z-Zwitterion, P-Protonated A-Acidic, D-Deprotonated, B-Basic; (2) E_{ele} is electronic energy and ZPE is Zero-point energy.)

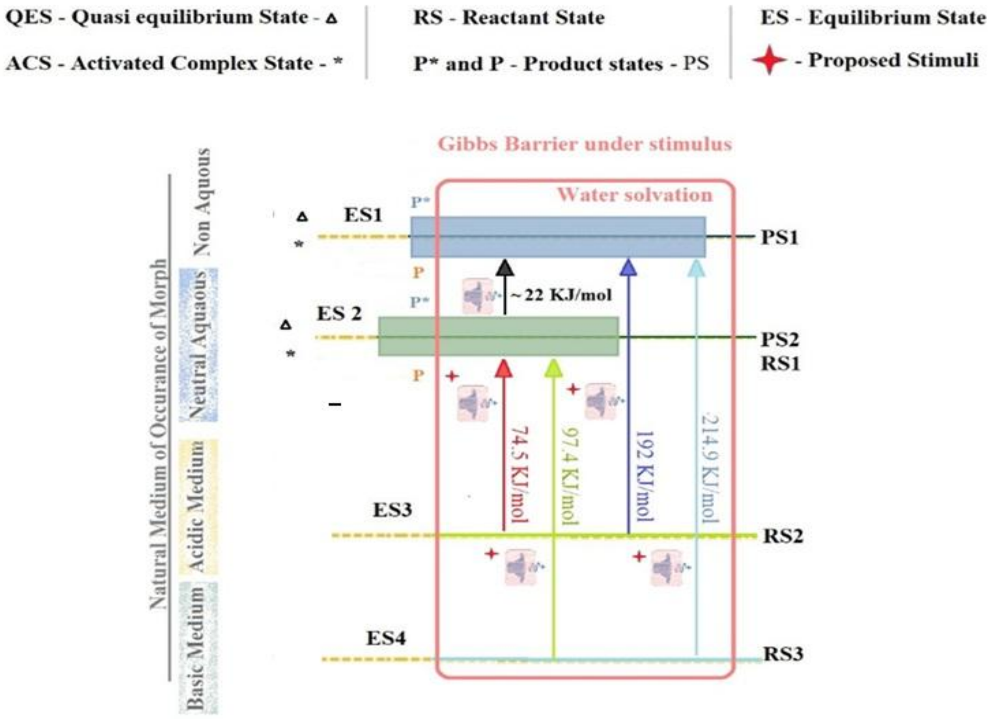


Figure 4: Illustrated the Gibbs barrier scenario for present five routes cases by using DFT. The colours of the transition arrows (inside pink box) showing crossing a Gibbs barrier) are same for the routes used in previous Fig.2(b-d) and 3

Gibbs Barrier and Importance

Barrier mechanism at a glance for four morphs of L-Ala is tried to be depicted in a Fig.4 for the idea drawn from the DFT prediction. Overall, the Gibbs Barrier is particularly important in concerned to zwitterion amino acids (here it is L-Ala) in concern with health hazards. here would be other alternate reactions rather than the above five, more can be possible. Present research is at its infant stage and a bit ahead of the concept. There is indirect evidence to DFT for R1 case. Others evidence is yet to unfold; our understanding suggested direct methods should be employed instead of indirect ultrasonic method reported in literature [13-16]; the work is in progress. With compared to a previous work by Tayade *et al.,* the basic thoughts being rigorously discussing in connection with ultrasonic study are, (1) whether the stimulated R1 to R5 cases really disturbs the routine processes in human body or not, and if it disturbs then (2) what is its cause, is it stimulation (especially ultrasonic)? This paper, with the experimental results from [13, 16], shows affirmation to these thoughts to some extent. The opinion drawn from the study are: (i) R1 stimulated case has predicted the loss of zwitterion-ness [16] or ionic-nature of the L-Alanine; and perhaps it stops making covalent bonds needed for peptization which affected synthesis of bigger molecular species like proteins in human body. (ii) In R3 stimulated case, L-Ala stops protonation from the acidic solvation and in R5 stimulated case, L-Ala stops deprotonation; these affects human body to controlling its pH via L-alanine. (iii) In stimulated R2 and R3 cases, the formation of zwitterion in lower pH (acidic) and higher pH (basic) parts respectively in a human body, but it again stops to neutralise the pH from L-Ala; this probably be a source of pH imbalance originated health issues. (iv) For all temperatures in body temperature range, no significant change would be seen for above possibilities to take place, because DFT did not showed significant change in Gibbs barrier.

Conclusion

Present work conducted the DFT-D3 calculations for four L-ala morphs at the human body temperature range for different R routes. Thermochemistry has been examined from parameters entropy, electronic energy, enthalpy, Gibb's free energy. DFT study confirms that most stable product to form under the aqueous solvation is only zwitterion for the human body temperature. Also, any kind of excitation to overcome Gibb's barrier can be able to alter the zwitterion to normal morph (R1: stimulated reaction). This happened to R2, R3, R4 and R5 in analogous way. It can be occurred in one way direct or two-way indirect reactions; five reactions are expected in this sense which are discussed successfully as well. However, for the range of human body temperature, the Gibbs barrier was not significantly varied for all five routes discussed in this paper.

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INTERDISCIPLINARY ADVANCES IN CHEMICAL SCIENCES: GREEN CHEMISTRY, NANOTECHNOLOGY, AND DRUG DESIGN

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Introduction

The field of chemical sciences is experiencing profound evolution, propelled by pressing worldwide issues such as climate change, limited resources, and public health emergencies. This chapter offers an interdisciplinary perspective on rising research directions, focusing on the integration of green chemistry, nanotechnology, and drug design. These domains connect with areas like biology, materials engineering, and environmental science to promote eco-friendly advancements, evident in AI-enhanced reactions and biologically derived nanoparticle production [1]. Green chemistry principles reducing waste, using safer solvents, and maximizing atom economy align seamlessly with nanotechnology's precision at the atomic scale. In drug design, this convergence enables targeted therapies with minimal side effects. Global research, from COVID-19 vaccine production to renewable energy nanomaterials, exemplifies interdisciplinary collaboration accelerating breakthroughs.

Objectives of the Study

This chapter seeks to clarify the ways green chemistry, nanotechnology, and drug design converge across fields to deliver enduring solutions. It spotlights major patterns, approaches, and uses, while tackling obstacles such as potential toxicity and expansion challenges. Through a compilation of worldwide studies, it provides readers with valuable perspectives for pioneering developments in chemical sciences.

Methodology

The chapter utilizes a structured review of existing literature, sourced from scholarly journals, academic conferences, and industry reports up to 2026. Materials were chosen using targeted keyword explorations on databases including Google Scholar, PubMed, and Scopus, prioritizing works from 2020 to 2026 emphasizing cross-disciplinary impacts.

The design follows a thematic analysis framework:

- **Step 1: Identifying Trends**: Documented progress in eco-friendly synthesis, nanomaterials, and computer-aided drug simulation.
- **Step 2: Cross-Disciplinary Mapping**: Explored intersections (e.g., AI applications in sustainable reactions, nanoparticle drug vectors) via bibliometric methods to measure joint efforts.

- **Step 3: Assessing Case Studies**: Examined real-world applications like aqueous-phase nanocatalysis and plant-derived nanoparticles.
- **Step 4: Evaluating Risks and Benefits**: Incorporated lifecycle analyses for sustainability metrics.

This qualitative synthesis prioritizes high-impact studies, ensuring a global perspective with examples from Asia, Europe, and North America [3].

Discussion

Trends in Green Chemistry

Green chemistry is pivotal in redefining industrial processes, with AI emerging as a key enabler. AI models now predict reaction sustainability by evaluating metrics like energy use, waste, and toxicity, suggesting optimal conditions such as water-based solvents over toxic organics. For instance, pharmaceutical pipelines increasingly adopt aqueous reactions, integrated with flow chemistry for continuous manufacturing, reducing costs and environmental footprints [1].

Cross-disciplinary ties amplify impact: collaborations with microbiology yield bio-based catalysts, mirroring COVID-19 responses where chemical industries supplied vaccine stabilizers. Recent 2026 trends include AI-driven solvent selection, expanding to polymers and materials [2].

Synergies in Nanotechnology

Nanotechnology links chemistry to physics and life sciences, providing sustainable production methods via plants, microorganisms, and biological molecules. Plant-mediated nanoparticles reduce energy demands and pollution compared to chemical methods, producing cost-effective materials for catalysis and remediation [5].

Global research highlights nanostructured materials for renewable energy storage, sensors, and cleaner reactions. In environmental remediation, nano-adsorbents capture pollutants efficiently, while lifecycle assessments mitigate risks like nanomaterial persistence. Cross-disciplinary applications span electronics (nano-conductors) and agriculture (nano-fertilizers), with 2025 studies emphasizing regulatory frameworks for safe innovation [6].

Application Area	Green Nano Contribution	Cross-Disciplinary Link	Example Impact [3]
Catalysis	Plant-based nanocatalysts	Chemistry and Biology	50% waste reduction
Energy Storage	Bio-synthesized electrodes	Materials Science and Engineering	Enhanced battery life
Remediation	Nano-adsorbents	Environmental Science and Physics	Pollutant removal >90%
Sensors	Biomolecule-functionalized NPs	Chemistry and Electronics	Real-time monitoring

Applications in Drug Design

Drug development harnesses the blend of nano-green chemistry for targeted delivery, as illustrated by eco-produced nanoparticles that enclose active agents. These systems improve bioavailability, reduce dosages, and minimize side effects, with plant extracts enabling biocompatible carriers [5]. Intersections with computational chemistry accelerate design: AI optimizes nano-drug interactions, as in cancer therapies using gold nanoparticles for precise release. COVID-era innovations underscore this, blending chemical synthesis with biotech for mRNA stabilizers. Emerging trends include stimuli-responsive nanocarriers (pH/light-activated), fostering personalized medicine [3].

Challenges persist: ensuring nanomaterial safety requires toxicology studies, yet benefits in diagnostics and therapy position this triad as a sustainability cornerstone

Worldwide Interdisciplinary Perspective

Worldwide, chemical research thrives on collaboration. Europe's Horizon programs fund nano-green projects; Asia leads in ferrite nanomaterials; the US excels in AI-drug modeling. Transdisciplinary efforts, like UN net-zero initiatives, integrate chemistry with policy for pollution solutions. This holistic approach addresses grand challenges, from biofuels to pandemic preparedness [7].

Conclusion

Integrating green chemistry, nanotechnology, and drug design signals a new sustainable phase in chemical sciences, propelled by interdisciplinary innovation. Key advancements like AI-directed reactions, biological nanomaterials, and targeted therapies offer financial and ecological advantages, as long as hazards are controlled via rigorous assessments. Future research must prioritize scalable, equitable implementations to realize global impact.

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NANOTECHNOLOGY AND SMART MATERIALS: A VISION FOR THE FUTURE

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Abstract

The convergence of nanotechnology and smart materials represents a transformative frontier in contemporary materials science, enabling a shift from conventional passive systems to dynamic and intelligent functional materials. This chapter examines the synergistic interplay between nanoscale material engineering and the development of stimuli-responsive systems capable of adapting to external environmental conditions. Central to this discussion is the distinctive behavior of materials within the nanoscale regime (1–100 nm), where enhanced surface-to-volume ratios and quantum confinement effects provide exceptional control over mechanical, electrical, optical, and thermal properties. The chapter systematically explores major classes of smart materials, including shape memory alloys, piezoelectric materials, electroactive polymers, and self-healing systems, emphasizing how nanostructuring significantly improves their responsiveness, efficiency, and multifunctionality. In addition, the chapter presents a forward-looking perspective on emerging applications across key domains. These include targeted drug delivery and nanoscale biosensors in healthcare, advanced energy harvesting and storage systems, and the development of self-repairing and adaptive materials for aerospace and structural engineering. Despite these advancements, critical challenges such as scalability, cost-effectiveness, long-term stability, and potential environmental and health risks associated with nanomaterials are also discussed. Overall, this chapter provides a comprehensive framework and future outlook for the design and implementation of next-generation smart materials, highlighting their potential to redefine innovation across engineering, biomedical sciences, and sustainable technologies.

Keywords: Nanotechnology, Smart Materials, Nanoelectronics, Stimuli-Responsive, Self-healing, Nanocomposites, Future Technology.

1. Introduction

Nanotechnology has emerged as one of the most transformative and interdisciplinary fields of modern science, fundamentally reshaping the way materials are designed, synthesized, and applied. Defined as the manipulation and control of matter at the nanoscale (typically 1-100 nm), nanotechnology enables the tailoring of material properties at atomic and molecular levels, resulting in unprecedented physical, chemical, and biological functionalities. At this scale, materials exhibit unique characteristics such as enhanced surface area, quantum confinement effects, high reactivity, and tunable optical and electronic properties, which are significantly different from their bulk counterparts. Parallel to the evolution of nanotechnology, the development of smart materials also known as responsive or intelligent materials has opened new frontiers in advanced material science [1-3]. Smart materials are capable of sensing environmental stimuli (such as temperature, pressure, light, pH, magnetic or electric fields) and responding in a predictable and useful manner. These responses may include changes in shape, color, mechanical strength, electrical conductivity, or chemical activity. The integration of nanotechnology with smart materials has further amplified their capabilities, leading to the creation of highly efficient, adaptive, and multifunctional systems [4,5].

The convergence of nanotechnology and smart materials is driving innovation across a wide range of sectors, including healthcare, energy, environmental remediation, electronics, and aerospace engineering. In the biomedical field, nanomaterials such as nanoparticles, nanotubes, and nanocomposites are being engineered for targeted drug delivery, cancer therapy, biosensing, and tissue engineering. Smart biomaterials can respond to physiological conditions, enabling controlled drug release and real-time monitoring of biological processes. For instance, stimuli-responsive polymeric nanoparticles can release therapeutic agents selectively at disease sites, minimizing side effects and improving treatment efficiency. In the energy sector, nanotechnology-enabled smart materials are playing a crucial role in the development of next-generation energy storage and conversion systems. Nanostructured materials are being utilized in high-performance batteries, supercapacitors, solar cells, and fuel cells due to their enhanced charge transport, increased surface area, and improved catalytic activity [6]. Smart materials that can adapt to environmental conditions contribute to energy efficiency and sustainability, such as thermochromic windows that regulate heat transmission or piezoelectric materials that convert mechanical energy into electrical energy. Environmental applications of nanotechnology and smart materials are equally significant [7].

Advanced nanomaterials are being developed for water purification, air filtration, and pollutant degradation. For example, metal oxide nanoparticles and nanocomposites exhibit excellent photocatalytic properties, enabling the degradation of toxic organic pollutants under light irradiation. Smart sensing materials can detect environmental contaminants at ultra-low concentrations, facilitating real-time monitoring and early warning systems [8]. In electronics and information technology, the miniaturization enabled by nanotechnology has led to the development of faster, smaller, and more efficient devices. Smart materials such as shape memory alloys, electrochromic materials, and conductive polymers are being incorporated into flexible electronics, wearable devices, and intelligent systems. These materials enable self-healing, adaptability, and enhanced performance, which are essential for the advancement of next-generation technologies such as the Internet of Things (IoT) and artificial intelligence (AI)-driven systems [9].

Despite the remarkable progress, several challenges remain in the widespread implementation of nanotechnology and smart materials. Issues related to scalability, cost-effectiveness, long-term stability, and environmental and health impacts need to be carefully addressed. The potential toxicity of certain nanomaterials and their ecological implications require comprehensive risk assessment and the development of sustainable and green synthesis approaches. Regulatory frameworks and standardization are also critical to ensure safe and responsible deployment. Looking ahead, the future of nanotechnology and smart materials is exceptionally promising. Advances in computational modeling, machine learning, and artificial intelligence are accelerating the discovery and design of novel materials with tailored properties [10]. The concept of “smart systems” is evolving toward fully autonomous, self-regulating, and adaptive technologies capable of interacting seamlessly with their environment. The integration of nanotechnology with emerging fields such as biotechnology, quantum computing, and advanced manufacturing is expected to revolutionize industries and improve the quality of human life. In conclusion, nanotechnology and smart materials represent a synergistic and dynamic area of research with vast potential to address global challenges in healthcare, energy, environment, and technology. As research continues to advance, the development of innovative, sustainable, and intelligent material systems will play a pivotal role in shaping a smarter and more efficient future [11].

2. Historical Development of Nanotechnology

Nanotechnology, the manipulation of matter at 1–100 nanometers, originated with Richard Feynman’s 1959 talk "There's Plenty of Room at the Bottom". Norio Taniguchi coined the term in 1974, and the 1981 invention of the scanning tunneling microscope (STM) enabled atomic manipulation, driving advancements in electronics, medicine, and materials science.

Key Historical Developments

- **1959 - Conceptual Birth**: Physicist Richard Feynman delivered his famous lecture at Caltech, suggesting the ability to manipulate individual atoms and molecules.
- **1974 - Terminology**:
- Japanese scientist Norio Taniguchi coined the term "nanotechnology" to describe precision manufacturing of materials at the atomic level.
- **1981 - Enabling Tool**: Gerd Binnig and Heinrich Rohrer invented the Scanning Tunneling Microscope (STM) at IBM, allowing scientists to "see" and map individual atoms for the first time.

- **1985/1991 - Molecular Structures**: Discovery of fullerenes (buckyballs) in 1985 and carbon nanotubes in 1991 introduced new, highly durable materials.
- **2000s - Commercialization**: The launch of the U.S. National Nanotechnology Initiative in 2000 spurred global research, leading to, among other advancements, cancer treatment nanoparticles (Abraxane) in 2005 and widespread consumer product integration.

3. Principles of Nanotechnology

- **Size-Dependent Properties**: As materials are reduced to the nanoscale, their physical, chemical, and optical properties (e.g., color, melting point, conductivity) change significantly compared to their bulk counterparts.
- **High Surface Area-to-Volume Ratio**: A massive percentage of atoms are on the surface, drastically increasing reactivity, catalysis, and interaction with surroundings.
- **Quantum Mechanics**: At this scale, electron behavior is dictated by quantum effects rather than classical physics, altering electrical, magnetic, and optical behaviors.
- **Self -Assembly:** Some nanomaterials spontaneously organized into ordered structured mimicking biological processes like DNA formation,which is critical for scalable manufacturing (Whitesides & Grzybowski,2002).
- **Interdisciplinary Integration:** Nanotechnology bridges multiple disciplines, requiring collaboration to design functional systems.

4. Differences between nanomaterials and bulk materials

Nanomaterials (1–100 nm) differ from bulk materials (>100 nm) primarily due to their extremely high surface-area-to-volume ratio and quantum effects, leading to unique physical, chemical, and optical properties. These materials often exhibit higher reactivity, different colors, lower melting points, and improved strength compared to their bulk counterparts, making them highly efficient in applications [12-15].

4.1. Key differences between nanomaterials and bulk materials

Size and Visibility: Nanomaterials are defined by having at least one dimension less than 100 nm, making them invisible to the naked eye, whereas bulk materials are larger and typically visible.

- **Surface-Area-to-Volume Ratio:** Nanomaterials have a much higher surface area compared to bulk materials, which increases their reactivity and allows for higher chemical activity.
- **Quantum Confinement Effects:** At the nano-scale, electrons are confined, which changes optical, magnetic, and electronic properties (e.g., gold nanoparticles appearing red or purple, while bulk gold is yellow).

- **Mechanical and Physical Properties:** Nanomaterials often show significantly improved hardness, ductility, and higher strength compared to the same material in bulk form.
- **Lower Melting Points:** Nanomaterials tend to have lower melting points compared to their bulk counterparts due to the increased surface energy.
- **Colour:** Colour of nanomaterials changes with size (e.g Gold can be red or purple) whereas colour of bulk materials is always constant (e.g., Gold is always gold).
- **Electronic and Quantum Effects:** Bulk Material follows the laws of Classical Physics. Electrons move freely in what we call energy bands, and electrical conductivity is predictable whereas nanomaterial follows Quantum Mechanics. Because the space is so small, electrons become "confined" (Quantum Confinement).
- **Example:** Gold in bulk is yellow, non-reactive, and has a high melting point, but at the nanoscale, it becomes red/purple, highly reactive, and has a lower melting point.

4.2. Top-Down Approach (Descending)

This approach involves starting with a larger, macroscopic piece of material and "carving" or breaking it down until you reach the desired nanoscale dimensions [16]. It is often compared to a sculptor carving a statue from a block of marble (Fig.1.).

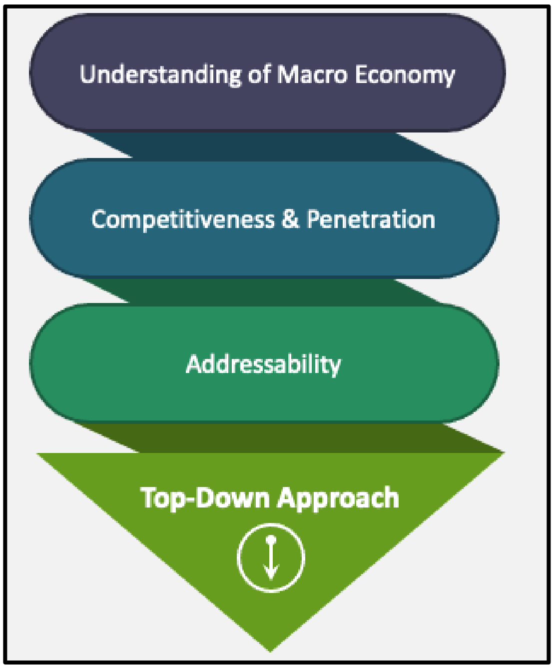

Figure 1: Top-Down Method

Mechanism: Bulk material is systematically reduced in size through physical or chemical means.

Common Techniques:

- **Lithography:** Patterning a surface by exposing it to light, ions, or electrons.
- **Etching:** Chemically or physically removing material to leave behind a nano-sized pattern.

- **Mechanical Milling:** Using high-energy balls to grind bulk powder into smaller particles.

Pros/Cons: It is a well-established industrial standard, especially in the semiconductor industry for making microprocessors. However, it can be costly, time-consuming, and often results in surface imperfections or contamination.

4.3. Bottom-Up Approach (Ascending)

This approach builds nanostructures from the "bottom" by arranging individual atoms or molecules into more complex structures [17]. This mimics how nature builds biological systems (Fig.2.).

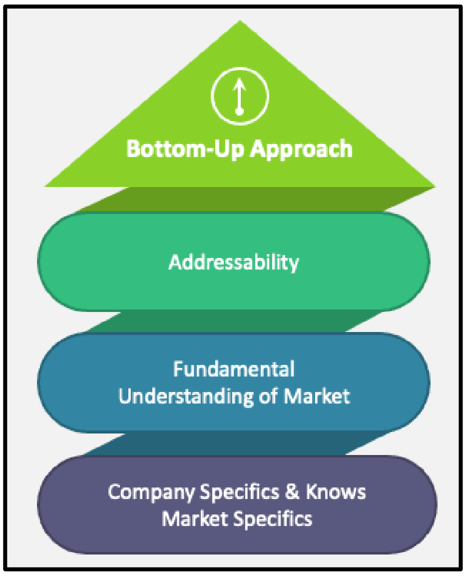

Figure 2: Bottom-Up Method

Mechanism: Individual building blocks (atoms or molecules) are assembled through chemical reactions or physical forces.

Common Techniques:

- **Self-Assembly:** Molecules spontaneously organize themselves into ordered structures based on their chemical properties.
- **Chemical Vapor Deposition (CVD):** Using gas-phase reactions to deposit a solid material onto a surface.
- **Sol-Gel Method:** A chemical process used to produce solid materials (like ceramics) from small molecules in a solution.

Pros/Cons: It typically produces structures with fewer defects and a more homogeneous composition. It is often less expensive than top-down methods. However, it can be difficult to manage as the complexity of the desired structure increases.

5.1 Foundational Concepts: The Nano-Smart Interface

To envision the future, one must first understand the synergy. Nanotechnology provides the *mechanism*; smart materials provide the *function* [18].

- **Nanoscale Sensing:** At the nanoscale, surface-area-to-volume ratios become astronomical. A nanoparticle can be functionalized with thousands of receptor molecules, making it an exquisitely sensitive sensor. For instance, *quantum dots* (semiconductor nanocrystals) can be tuned to fluoresce at specific wavelengths when they bind to a target molecule, forming the basis of smart diagnostics.
- **Nanoscale Actuation:** Shape-memory alloys (SMAs), a classic smart material, recover their shape when heated. Nanotechnology refines this by embedding *carbon nanotubes (CNTs)* or *graphene* into polymer matrices. When an electric field (detected by a nanosensor) induces a localized temperature change, the nanoscopic reinforcement triggers a macroscopically observable shape change at lower power and faster speeds.
- **Programmable Matter:** The holy grail is *claytronics* ensembles of nanoscale robots ("catoms") that can adhere to one another, compute, and reconfigure into arbitrary three-dimensional shapes. While currently prototypical at millimeter scales, the trajectory points toward microscopic catoms. A smartphone made of such material could dynamically morph into a steering wheel, a medical cast, or a drinking cup.

The operational principle of future nano-smart systems will follow a closed-loop: **Stimulus → Nanosensor → Nanocomputer → Nanoactuator → Response**. The "smartness" arises not from a central processor but from the distributed, emergent behavior of billions of nanoscale agents.

5.2 Sector-by-Sector Vision: The Next Fifty Years

5.2.1 Biomedical and Regenerative Medicine

Imagine a future free from chronic disease. This is the promise of *smart nanomedicine* [19].

- **The "Physician-on-a-Chip":** A programmable nanocarrier, resembling a virus-sized capsule, is injected intravenously. Its outer surface is coated with *aptamers* (nanoscale DNA/RNA strands) that bind only to cancer cell surface markers. Inside, it carries a cargo of siRNA (gene-silencing molecules) and a chemotherapeutic agent. Upon binding, a *nanovalve*, constructed from mechanically interlocked molecules (rotaxanes), opens only in the reducing environment of the cancerous cell.
- **Responsive Drug Release:** Future implants, such as an artificial pancreas, will not just passively release insulin. Embedded with *glucose-responsive nanopores* (e.g., phenylboronic acid-functionalized gold nanoparticles), the membrane expands in the presence of high glucose, opening pores to release insulin and contracting when glucose normalizes.
- **Regenerative Scaffolds:** A broken spinal cord or a damaged heart is repaired using a *shape-memory nanofiber scaffold*. This sponge-like material is injected as a liquid suspension of nanofibers. At body temperature, the nanofibers self-assemble into a three-

dimensional matrix whose topography includes nanoscale grooves that guide the direction of axonal or cardiomyocyte growth. The scaffold is "smart" because it releases differentiation factors (e.g., NGF, BDNF) at a rate dictated by the local metabolic need, sensed via pH or oxygen concentration.

5.2.3. Architecture, Construction, and Infrastructure

The static concrete jungle will give way to dynamic, living buildings [20].

- **Self-Healing Concrete:** Today's concrete cracks, leading to catastrophic failure. Tomorrow's concrete contains a dormant slurry of *bacterial endospores* (e.g., *Bacillus pasteurii*) and calcium lactate nanoparticles. When a crack propagates, water and air ingress activate the spores. The bacteria metabolize the lactate, precipitating calcite (limestone) that bonds the crack. Embedded *carbon nanotube networks* sense the crack's location (via a resistance change) and prioritize healing by focusing a small electric current to the area, accelerating bacterial activity.
- **Climate-Responsive Facades:** An office building's skin is a *metamaterial* composed of tunable photonic crystals. These are nanolayered structures (e.g., vanadium dioxide) that undergo a phase transition at a programmed temperature. Below 25°C, the surface is transparent to infrared radiation, allowing passive solar heating. Above 25°C, the lattice constant shifts, reflecting IR and turning the window into a mirror. No external power is required—the window *is* the thermostat.
- **Smart Aggregate:** The concrete itself contains *piezoelectric zinc oxide nanowires*. The floor of a smart bridge senses not just the weight of a passing truck but the exact distribution of stress across each nanofiber, predicting fatigue failures weeks in advance. Vibration energy from traffic is harvested and used to power embedded wireless stress sensors, creating a perpetual, self-powered structural monitoring system.

5.2.4. Energy and Environment

The energy crisis will be solved not by a single breakthrough but by a suite of nano-smart systems [21].

- **The Artificial Leaf 3.0:** A robust, thin-film device that mimics photosynthesis. Its nanoscale surface is a *heterostructure* of molybdenum disulfide (MoS_2) and tungsten selenide (WSe_2) quantum dots, catalyzing water splitting into hydrogen and oxygen. The "smart" feature: when hydrogen pressure builds, a *nanoporous polymer membrane* changes conformation to release the gas, preventing overpressure. When sunlight wanes, the same membrane closes to prevent back-reaction.
- **Energy-Absorbing Smart Glass:** Electrochromic windows are old news. Future windows are *thermoradically adaptive*. They consist of a thin film of nanocrystal-in-glass composite (e.g., lanthanum strontium manganite) that can dynamically switch between

three states: transparent (visible and IR pass), "cool" (IR reflected, visible passes), and "dark" (both reflected). Controlled by a simple low-voltage signal derived from a building-integrated photovoltaic film, these windows reduce HVAC load by over 60%.

- **Smart Filters:** Water purification is revolutionized by *magnetic shape-memory nanoporous membranes*. The pores are lined with *polymer brushes* (e.g., poly(N-isopropylacrylamide)) that change their conformation from expanded (open) to collapsed (closed) based on pH or specific toxin binding. By applying a rotating magnetic field to the embedded ferromagnetic nanoparticles, the membrane can be made to "wiggle" at a nanoscale, shaking off accumulated biofilms and continuously self-cleaning.

5.2.5. Consumer Electronics and Human-Machine Interface

The rigid rectangle of the smartphone will become an archaeological curiosity [22].

- **Morphing Devices:** A handheld device is a solid block of *electroactive polymer (EAP) aerogel* infused with a network of *single-walled carbon nanotubes (SWCNTs)* for conductivity and strength. By applying specific voltage patterns to the SWCNT network, the aerogel can soften, harden, and change its shape on demand. Your "phone" becomes a bracelet on your wrist, a flat tablet in your bag, and a gaming controller with tactile buttons that emerge and disappear as needed (haptic morphing).
- **Electronic Skin (E-Skin):** Prosthetics and robots are covered in a flexible, self-powered *triboelectric nanogenerator* (TENG) skin. This film, with nanopatterned surfaces (e.g., arrays of polymer nanorods), generates a small electric charge when touched. Beyond sensing pressure, the e-skin’s *graphene field-effect transistors* can sense chemical signatures—sweat pH, glucose, or specific proteins—offering a true sense of "touch" that includes chemical composition. The skin heals itself: when cut, microcapsules of conductive polymer monomer break, capillary action draws them into the tear, and a small built-in current triggers polymerization, sealing the circuit.
- **Augmented Reality Contact Lenses:** Not Google Glass, but a soft contact lens containing a *nanoscale Fresnel lens array* embedded directly into the hydrogel. A *semiconductor quantum dot display* (less than a micron thick) projects data directly onto the retina, while a *nanoplasmonic biosensor* measures tear fluid glucose and lactate, alerting the wearer to metabolic shifts via a color-change in the lens’s periphery.

5.2.6 The Enabling Technologies: Deep Dive into Mechanisms

For the above visions to materialize, several key nanotechnologies must mature beyond the laboratory.

- **DNA Origami and Molecular Assembly:** The future is not top-down lithography but bottom-up self-assembly. Using DNA as a scaffold, we can program the precise 3D placement of nanoparticles (gold, quantum dots, proteins) with sub-2-nanometer precision. This allows the construction of nanorobots with active hinges, locks, and rotors, all powered by hybridization energy or external fields.

- **Metamaterials and Topological Photonics:** Smart materials need to sense without losing energy. *Topological insulators* at the nanoscale allow the lossless guiding of light and electrons around corners and defects. This will lead to smart coatings that can route optical information—a window that senses motion not because it has a camera, but because the pattern of scattered light is computed topologically.
- **2D Materials Beyond Graphene:** Transition metal dichalcogenides (TMDCs: MoS_2, WS_2, WSe_2) and MXenes offer a playground for excitonic and phononic computing. A single layer of MoS_2 can act as a transistor, a light emitter, and a piezoelectric actuator simultaneously. Future smart materials will be stacked van der Waals heterostructures where each layer performs a different function (sensing, computing, acting) in a single atomic plane.

5.2.7 Challenges and Critical Risks: The Shadow of Progress

A responsible vision must acknowledge the obstacles. The path is fraught with technical and existential risks [23].

- **Manufacturing at Scale:** We can make a perfect nanoscale gear in a cleanroom. Can we make a trillion of them for a dollar? The gap between laboratory synthesis (e.g., chemical vapor deposition of CNTs) and industrial roll-to-roll manufacturing remains vast. The future requires "self-limiting" and "error-correcting" assembly lines based on molecular recognition.
- **Environmental and Health Toxicity:** The same surface reactivity that makes a nanoparticle a good catalyst also makes it a potential toxin. The long-term fate of nanoscale debris—from broken self-healing concrete, discarded e-skin, or degraded artificial leaves—is unknown. We need *biodegradable nanomaterial* frameworks (e.g., using silk fibroin or polylactic acid as sacrificial templates) and "design-for-degradation" protocols.
- **The Gray Goo Problem (Revisited):** While replicating nanobots are likely impossible with current physics (energy constraints, the Second Law), *programmable* matter that can be reconfigured by external fields poses a security risk. A terrorist could, in theory, reconfigure a building's smart concrete into a weapon. Thus, future nano-smart materials must have *cryptographic authentication* at the nanoscale each particle has a unique quantum ID that must be presented to a central "coordinator" field before responding.
- **Energy Autonomy:** All these smart functions require energy. While harvesting (vibration, light, heat) will be ubiquitous, high-demand functions (reconfiguration, computation) may outstrip supply. The vision depends on the parallel development of

ultra-low-energy computing (e.g., neuromorphic, stochastic resonance) that operates close to the thermodynamic limits.

6. Ethical and Societal Implications: Who Gets the Future?

Nanotechnology and smart materials are not ethically neutral. Their distribution will create new classes of "augmented" humans and "obsolete" infrastructure [24-27].

- **The Augmentation Divide:** When smart contact lenses offer perfect vision and real-time health data, and morphing devices become ubiquitous, those who cannot afford them become functionally disadvantaged in workplaces and education. This could stratify society into "nano-haves" and "nano-have-nots."
- **Privacy and the Smart Environment:** A room with smart structural materials that senses pressure, temperature, EM fields, and chemical composition is a panopticon. Your own house could report your movements, conversations (via vibration of window glass), and even stress levels (via sweat traces on a chair) to a corporate or state server without a single "bug." Future building codes must mandate *data sovereignty* layers smart materials that compute locally and only transmit aggregated, anonymized data.
- **Post-Human Bodies:** As implantable smart materials blur the line between therapy (a smart scaffold for a broken bone) and enhancement (a smart exoskeletal mesh that doubles muscular strength), we face the *yuck factor* and the definition of humanity. Regulatory frameworks must distinguish between restoration of typical function and enhancement beyond the human norm, although that line will inevitably shift.

Conclusions

The vision presented here is neither a utopian promise nor a dystopian warning it is a trajectory. The convergence of nanotechnology and smart materials will yield materials that are alive in function if not in composition. We will wear our environment, and our environment will become aware of us. The buildings of the future will heal their own wounds, the cars will be the roads, and the medicines will be intelligent hunters. However, this future requires a new kind of engineer: an *aporetic engineer*-one who is as comfortable with uncertainty, ethics, and ecology as with quantum mechanics and polymer chemistry. The question is not *if* we can build this future, but *which* version we choose to build. The atomic precision of nanotechnology, coupled with the responsive nature of smart materials, gives us the most powerful toolkit humans have ever held. Whether we use it to create a world of adaptive, resilient, and equitable prosperity, or a world of brittle, surveillance-laden, and stratified control, will be determined not in the laboratory, but in the public square. The future is not written in atoms; it is written in choices. And for the first time, those choices can be made at the scale of a single molecule.

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NANOTECHNOLOGY IN INTEGRATED PEST MANAGEMENT: SYNTHESIS, FORMULATIONS, AND PHYSIOLOGICAL MODES OF ACTION

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Introduction

Recently, there has been a lot of interest in the use of nanoparticles produced by different synthesis methods as new insecticides. Their toxic potential against a variety of arthropod pests and vectors has been tested in an astounding number of research, with a primary focus on mosquitoes and ticks. However, specific details regarding the methods of action. The notable exception of silica, alumina, silver, and graphene oxide nanoparticles on insects, there are few nanoparticles that are effective against both insects and mites; information on mites is lacking. Insect antioxidant and detoxifying enzymes are significantly impacted by both silver and graphene oxide nanoparticles, which can result in oxidative stress and cell death. While polystyrene nanoparticles inhibited CYP450 isoenzymes, Ag nanoparticles also decreased acetylcholinesterase activity. Au nanoparticles can interfere with growth and reproduction by acting as trypsin inhibitors. Proteins' S and nucleic acids' P can be bound by metal nanoparticles, respectively, resulting in a reduction in membrane permeability, which leads to denaturation of organelles and enzymes and ultimately cell death. Key insect genes are both upregulated and downregulated by nanoparticles, which lowers protein synthesis and gonadotrophin release and causes developmental defects and reproductive failure. $SiO2$ and $Al2O3$ nanoparticles are harmful because they attach to insect cuticles and then physico-sorb lipids and waxes, which causes insects to become dehydrated.

Nanopesticide Formulations

The application of technology like encapsulation and controlled release techniques for pesticide use is highly in demand. Numerous studies have emphasized the potential for using NPs and nanocapsules on plants for agricultural purposes.

Many companies provide formulations containing NPs with sizes ranging from 100 to 250 nm. A few use suspensions of nanoscale particles (nanoemulsions), which can be water or oil-based and include uniform suspensions of pesticidal NPs ranging from 200 to 400 nm. The emulsions are easily mixed into gels, creams, and liquids, and they have a wide range of applications for harvest product prevention, treatment, and preservation.

The usage of silica-based compounds has recently become a common method for controlled pesticide release. Porous hollow silica nanoparticles (PHSN) as pesticide carriers to investigate the controlled release of avermectin insecticide. The PHSN carriers significantly delayed the release of the pesticide, and they concluded that PHSNs may be used in controlled pesticide delivery applications. Because of their huge surface areas, NPs can quickly absorb and bond with other compounds, circulate more freely in lepidopteran systems, and potentially be used for pesticide production.

Formulations combining some plant extracts with nanosilica significantly increased insecticidal action and extract shelf life. Combining α-pinene and linalool with nanosilica improves the bioactivity and stability of the formulation, resulting in higher zeta potential, controlled release of botanical compounds, and extended shelf life for isolated botanicals.

A new pesticide delivery system in the form of nanoformulation, which incorporates *A. arborescens* essential oil into solid lipid NPs (SLN) using the high-pressure homogenization technique with Compritol 888 ATO as lipid and Poloxamer 188 or Miranol Ultra C32 as surfactants, has gained popularity. The average diameter of *A. arborescens* essential oil-loaded SLN remained constant during storage but rose somewhat after spraying the SLN dispersions. Interestingly, the quick evaporation of the essential oil was slowed by SLN, indicating that SLN formulations are appropriate carriers in agriculture. Potential advantages indicated include the solubilization of hydrophobic pesticides/herbicides, which eliminates the need for hazardous organic solvents.

Nanoparticles to Improve Pesticide Formulations

Nanoparticles (NPs) are a subclass of ultrafine particles with dimensions ranging from 1 to 100 nm that exhibit features distinct from non-nanoscale particles of the same chemical makeup (Auffan *et al.* 2009). The 100-nm limit is based on the notion that particles gain distinct features that distinguish them from the bulk material at a crucial size of less than 100 nm. Developed new formulations based on micro- and nanoemulsions capable of producing NPs ranging in size from 20 to 100 nm.

There are several microemulsion formulations available on the market for broad-spectrum disease control in various types of target plants, including plant growth regulators and systemic fungicides. Microemulsions are more stable than nanoemulsions, which require a lot of energy and may be difficult to scale up for commercial agrochemical production, or may not be practical for on-site preparation by handlers (for example, high-shear stirring, high-pressure homogenizers, or ultrasound generators).

Microemulsions offer numerous benefits, including improved tank mix compatibility, improved stability, reduced low flammability, reduced handler toxicity (due to low solvent content), and, most importantly, increased efficacy due to improved penetration or uptake due to surfactant's high solubilizing power (Green and Beestman 2007). The disadvantages of these substrates include low active ingredient content (<30%), high surfactant concentration (~20%), and a limited number of acceptable surfactant systems. These constraints can be partially alleviated by another formulation approach based on nanodispersion or nanosuspension, in which active ingredients of nanocrystals, or crystalline or amorphous NPs of 50 nm (made by particular process), create nanodispersions with similar properties to solutions.

The majority of pesticides used today are weakly water soluble compounds, and their formulations are based on emulsifiable concentrates (ECs), oil-in-water (O/W) emulsions, or variations on the above. ECs are often made up of organic solvents that are expensive, volatile, and poisonous, or a combination of surfactant emulsifiers to assure spontaneous emulsification into water in the spray tank. O/W emulsions do not have these shortcomings because they are based on the removal of the solvent and the introduction of a mixture of a non-ionic surfactant, block polymers, and polymeric surfactants; however, one of the major drawbacks in their use is that emulsification requires a high-energy input.

Pesticide Delivery System using Nanoparticles as Nanocarriers

Learning on drug delivery principles presented in medicine, where NPs have been effectively employed for delivering pharmaceuticals for medical therapy, a similar concept was developed for pest management, termed as "pesticide delivery system" (PDS).

Controlled administration is especially crucial for ensuring the optimal release of pesticides over time in order to achieve maximal biological efficacy while minimizing potential negative effects. The advantage of using NPs as nanocarriers is their ability to have high effective loading due to their higher surface area, facile attachment of single and multiple pesticide molecules, and a relatively fast mass transfer to the target, i.e., insect body. Pesticides that are encapsulated are likely to have a more steady release over time, requiring less frequent application as opposed to very highly concentrated and potentially hazardous first treatments followed by repeated applications. At the same time, NPs help to delay the loss of efficacy caused by degradation.

Adsorption, covalent attachment mediated by different ligands, encapsulation, and entrapment inside NPs are some of the several concepts for loading active pesticide molecules on NPs. The degrading qualities of the nanocarrier (e.g., polymer), the bonding of the ingredients to the material, and the environmental conditions all contribute to the controlled and delayed release of active chemicals. Polymers (soft NPs), synthetic silica, titania, alumina, Ag, Cu, and natural minerals/clays with nanoscale dimensions (inorganic or solid NPs) are the most appealing pesticide carriers.

Nanoporous materials, in particular, have structured pore distributions and larger surface areas, which boost sorbent capacity and allow for the inclusion of functionality. This characteristic improves selectivity and yield in catalyst-based synthesis, as well as the sensitivity of detection methods. Among the numerous NPs available, silica-based NPs have sparked interest as pesticide delivery agents in plants. This is mostly due to their structural flexibility in creating NPs of different sizes and shapes, as well as their capacity to construct pores for loading biomolecules.

NPs are key gene carriers in a variety of plants and can be used to efficiently overcome transgenic silencing by modulating DNA copies and function. Furthermore, NPs can facilitate multigene transformation without using the typical complex carrier construction strategy. Demonstrated the effective transport of DNA and drugs via silica NPs internalized in plant cells using no specialist equipment. A 3-nm mesoporous silicon nanoparticle (MSN) was effectively used to transfer DNA and drugs to isolated plant cells. This approach was successfully used to transfer DNA into tobacco and corn plants (Torney *et al.* 2007).

Nanoparticles as Novel Insecticides and Acaricides

Recently, new approaches to controlling vector and pest populations have been made possible by a promising interface between nanotechnology and arthropod control research (Sharon *et al.,* 2010). One of the main challenges facing modern entomology and parasitology is the widespread application of effective management methods against arthropod pests and vectors (Benelli and Mehlhorn 2016; Benelli and Beier 2017; Benelli and Duggan 2018).

However, the widespread usage of chemical pesticides had detrimental effects on both human health and the environment, as well as causing targeted arthropods to rapidly evolve resistance As evidenced by the recent Zika virus epidemics in the Americas and the Pacific, the failure of control programs and the rapid expansion of highly invasive arthropod vectors have significantly impacted public health. More than half of them relied on nanomaterials made using the so-called "green synthesis method", which successfully reduced and stabilized nanoparticles in aqueous suspensions using extracts from bacteria, fungi and even dead insects. When compared to traditional physical and chemical synthesis methods, the green fabrication process has a number of advantages because it doesn't require the use of highly hazardous chemicals or significant energy inputs (Teimouri *et al.,* 2018).

The entire procedure is inexpensive, simple, and produces a variety of nanoparticles, including gold. These nanoparticles have been successfully tested against a variety of noxious arthropods, including agricultural pests and vectors relevant to livestock science and public health. Although there have been some remarkable studies on lice and mites, the most majority of the latter have concentrated on mosquito vectors and ticks (Kirthi *et al.,* 2011). With LC50 values ranging from less than 1 to 35 μg/ml, the nanoparticles produced as previously mentioned shown extremely promising toxicity against both mosquitoes and ticks.

Inorganic Nanoparticles as Nanocarriers

Solid inorganic NPs have been extensively studied for pharmaceutical formulation over the last two decades, as they combine the benefits of nanoemulsions, liposomes, and polymer NPs while avoiding their drawbacks by providing better stability, more controllable release, higher loading, and simpler production, resulting in lower costs. As a result, it produces enhanced pesticide delivery methods.

Silica NPs are among the most appealing inorganic NPs being investigated as nanocarriers for pesticide delivery, including insecticides, growth promoters, fungicides, biopesticides, and pheromones. Silicon has long been known to improve plant tolerance to a variety of abiotic and biotic stimuli, and silica nanoparticles have thus been proposed as prospective candidates for enhancing pest control.

New formulations based on silica nanoparticles have recently been developed for the gradual release of chlorfenapyr and growth stimulants, with promising results.

Using Nanoparticles Alone as Pesticides

Insecticidal nanoparticles can be employed as both nanocarriers and active pesticide agents or biopesticides. The most promising examples are based on amorphous nanosilica obtained from various natural sources such as the shell wall of phytoplankton, epidermis of vegetables, burnt pretreated rice hulls, straw at thermoelectric plants, and volcanic soil. Some of these materials have particle sizes that exceed 1 μm, but have minute pores that are considerably smaller than 100 nm. The silica NPs were physio-sorbed by the cuticular lipids, shattering the protective barrier and so causing the death of insects purely by physical means, with a mode of action similar to that reported for diatom particles employed to safeguard stored grain.

Silica nanoparticles eradicated all adults of the rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae). Furthermore, surface charged modified hydrophobic silica NPs (3-5 nm) have been successfully employed to control a variety of agricultural insect pests and animal ectoparasites with veterinary value. It was successfully used as a thin layer on seeds to inhibit fungus growth and promote grain germination. As a result, nanosilica particles have prospective uses in the control of stored grain and domestic pests, animal parasites, fungus, and worms.

Mechanisms of Action of Nanoparticles

The practical application of nanoparticles in terrestrial and aquatic environments raises a number of difficulties, despite their extremely promising potential as insecticides and acaricides. It is difficult to forecast their fate in the environment and the consequences for human health given our poor understanding of them from an ecotoxicology approach. This information is essential for forecasting the toxicological effects of using nanoparticles as insecticides in the actual world. Since the size, shape, and charge of silver nanoparticles have a significant impact on their toxicity in biological models, the processes causing cytotoxicity and genotoxicity have mostly been investigated for these particles (Foldbjerg *et al.,* 2015).

Additionally, only a small number of studies have examined potential mechanisms of action against insects and mites; the majority of this research has been conducted on bacterial models or in vitro cytotoxicity experiments. Many types of nanoparticles are thought to cause toxicity by inducing oxidative stress in the tissues of arthropods (Foldbjerg *et al.,* 2015). Furthermore, the penetration of nanoparticles through the exoskeleton may possibly be the cause of their toxicity. The nanoscale substance then quickly denaturates organelles and enzymes in the intracellular space by binding to phosphorus from DNA or sulfur from proteins. Consequently, loss of cellular function and cell death may result from the disruption of proton motive force and decrease in membrane permeability.

Ag Nanoparticles

The effects of exposure to green-synthesized nanoparticles in mosquito young instars have been clarified by recent research (Kalimuthu *et al.,* 2017) shown that exposing *Aedes aegypti* (L.). The impact of commercial silver nanoparticles (0.2, 0.5, and 1 mg/l) on the expression of glutathione S-transferase (GST) genes, which are associated with oxidative stress, in the aquatic midge *Chironomus riparius* (Meigen). Based on the tested concentration and length of exposure to the contaminant, the scientists found that all of the GST genes examined in C. riparius exhibited up- or down-regulation to varied degrees. The GST classes with the highest mRNA expression were Delta3, Sigma4, and Epsilon1. These results demonstrated the critical involvement of GST genes in preventing oxidative stress after nanosilver exposure (Nair and Choi, 2011).

Fruit fly development was negatively impacted and *D. melanogaster* died as a result of consuming silver nanoparticles. Ag nanoparticles cause reactive oxygen species (ROS) to build up in fly tissues when tested at sub-lethal concentrations, which results in ROS-mediated apoptosis, DNA damage, and autophagy. Furthermore, the scientists reported that the Nrf2-dependent antioxidant pathway was activated (Mao *et al.,* 2018). The stress-responsive transcription of antioxidant and detoxifying genes is impacted when *C. riparius* is exposed for 24 hours to three distinct concentrations (i.e., 0.2, 0.5, and 1 mg/l) of commercial silver nanoparticles and free ionic silver. Following exposure to Ag+ ions and silver nanoparticles, respectively, the scientists demonstrated the overexpression of Cu and Mn superoxide dismutase.

The impact of nanosilver on two lepidopteran species, the castor semilooper, *Achaea janata* (L.), and the Asian armyworm, *Spodoptera litura* (Fabricius), demonstrating nano-induced oxidative stress in moth larval intestines, as demonstrated by the increased levels of antioxidant enzymes. However, it should be mentioned that the tested values in this study were relatively high (500–4000 mg/l). Subsequently, Ag nanoparticles made from *Punica granatum* L. peel extract (LC50 = 19.21 μg/larva) on S. litura larvae in their third instar, finding a decrease in the activities of lipase, invertase, amylase, and protease. Weight, pH, and the overall number of heterotrophic bacteria all declined, as did gut microbiota and the synthesis of extracellular enzymes (Bharani and Namasivayam 2017).

Au Nanoparticles

Au nanoparticles' mode of action against insects is less numerous when compared to the information presented above for silver nanomaterials. Small *et al.* (2016) found that gold nanoparticles impaired reproduction and development in German cockroaches, *Blattella germanica* (L.). Patil *et al.* (2016) found that Au nanoparticles derived from Jatropha curcas L. latex inhibited trypsin in the serum of numerous insect species, including Ae. aegypti mosquitoes, beetles, and mealybug pests.

A. aegypti larvae (third and fourth instar) exposed to 400 ppm Au nanoparticles made from *Artemisia vulgaris* L. leaf extract experienced damage to the midgut, epithelial cells, and cortex, as well as Au accumulation. Nanoparticles in the midgut. Furthermore, exposure of Ae. aegypti third instar larvae to zein-capped Au nanoparticles. Exposure to LC50 = 6.81 mg/l for 24 hours caused damage to the epithelium layer, midgut, and caeca, as well as hair loss in the head and caudal regions.

Carbon Nanoparticles

Carbon nanostructures were identified in the tissues of *D. melanogaster.* Exposing fruit fly adults to dry carbon black and multiwalled nanotubes resulted in substantial adherence to their body parts, impairing motor function and causing insect mortality. Injecting graphene oxide nanoparticles (0.1 µl/100 mg of insect body weight) into the hemolymph of *Acheta domesticus* (L.) crickets was found to be harmful. Graphene oxide nanoparticles caused oxidative stress in crickets, resulting in enhanced catalase and glutathione peroxidase activity, as well as elevated HSP 70 and antioxidant capacity levels (Dziewięcka *et al.,* 2016).

The carbon-dotsilver nanohybrid, made from potatoes (*Solanum tuberosum* L.), was tested against mosquitos *Anopheles stephensi* Liston and *Culex quinquefasciatus*. Say was very toxic to both species' larvae and pupae (LC50 values of 0.609 and 0.766 ppm for larvae and 0.300 and 0.329 ppm for pupae). The nanohybrid caused deformation of larval bodies, as seen by SEM. Electro diffraction X-ray examination revealed the presence of Ag (2.93%) in the tissues of treated mosquitoes, indicating nano Ag toxicity at the cellular level. Furthermore, HR-TEM demonstrated cuticle and cellular organization damages.

Polystyrene Nanoparticles

Polystyrene nanoparticles interact with drug-metabolizing cytochrome P450 isoenzymes CYP3A4, CYP2D6, CYP2C9, and CYP2A1 produced in insect cells (Baculosomes®) and decrease their activity.

Silica and Alumina Nanoparticles

Insects are physio-sorbed by cuticular lipids, causing significant injury and mortality. This mechanism is similar to that of diatom earths used to control food pests (Kavallieratos *et al.* 2018). A recent study found that silica nanoparticles treated larvae of *Plutella xylostella* (L.) showed 85% mortality after 72 hours. Light microscopy and SEM revealed that the larvae died due to desiccation, body wall abrasion, and spiracle blockage. Nanoparticles did not affect genes in the insect trachea. According to WHO, amorphous silica is a safe nanopesticide to use on humans.

In testing silica nanoparticles against Chironomidae, found that exposure to porous SiO2 particles increased mortality in C. riparius larvae, despite no significant changes in growth indicators, The unpredictability of the above-cited data and only examined one concentration (1 mg/l) make it impossible to draw valid inferences from these findings. Studies examined the effects of silica nanoparticles on insect morphology and histology. Found that exposure to Ludox TMA silica nanoparticles caused severe midgut epithelial damage in bumblebees (*Bombus terrestris* L.) with intoxicated workers (≥ 34 mg/l).

Titania Nanoparticles

Studies on the mechanisms of action of titania nanoparticles against insects are limited. On the other hand, the recent findings seem interesting. Titania nanoparticles administered to silkworms, Bombyx mori L., have been shown to stimulate 20-hydroxyecdysone biosynthesis, shorten development, and reduce molting duration (Li *et al.,* 2014). This suggests potential benefits for sericulture. Incorporating titania and silver nanoparticles (at concentrations ranging from 0.005 to 0.05%) into D. melanogaster diets resulted in considerable offspring loss and decreased developmental progress.

Zinc Oxide Nanoparticles

Zinc oxide nanoparticles made from Lobelia leschenaultiana (C. Presl) Skottsb. leaf extract caused morphological and histological abnormalities in *A. Aegypti* third instar larvae exposed to an LC50 of 1.57 mg/l for 24 hours showed abdominal shrinkage, thorax shape alterations, midgut injury, loss of lateral hairs, anal gills and brushes, and accumulation of ZnO nanoparticles in the thorax and abdomen. The LC50 of ZnO nanoparticles coated with *Ulva lactuca* L. aqueous extract and *Bacillus licheniformis* Dahb1 exopolysaccharide on Ae yielded similar findings. aegypti and An. stephensi Liston fourth-instar larvae, respectively. There is a lack of detailed investigations on how ZnO exposure affects insect physiology and genetics.

Future Perspectives and Research Challenges

The analysis found a significant gap between reports on the toxicity of nanoparticles against agricultural, medical, and veterinary arthropods and studies on the mechanism of action responsible for observed toxicity rates. Green nanoparticles have shown promising efficacy in managing arthropod pests and vectors, sparking interest among research organizations worldwide. Although some researchers have attempted to understand the harmful effects of silica, alumina, silver, gold, titania, and graphene nanoparticles on arthropods, there is currently limited knowledge in this subject. Green fabrication processes using specific compounds like β-caryophyllene, stearic acid, and zein are preferred due to their insecticidal and acaricidal effects. NPs have a promising future in generating safer and more effective chemical pesticide formulations for pest control, which could lead to revolutionary advances in this industry. However, due to potential toxicity concerns about nanomaterials, which are not yet standardized, well understood, or explored, this development will likely face intense scrutiny from international and national safety regulators, with requests for additional research on the environmental and human impacts of these materials. Nonetheless, despite substantial study on plant-mediated synthesis of NPs for arthropod control, there is a gap between theory and practical use, particularly on a large scale.

Conclusion

The process of nanomaterial synthesis is also important, and changes in the method of synthesis may result in changes in dimensions and shape, as well as in the risks associated with the use of such materials. Risk assessment studies are required before the use of such materials, because there are no specific guidelines for using these formulations on nanomaterials, so the toxic nature of these compounds to plants and insects must be investigated. There is still a lot of work to be done on nanopesticide formulations before they become more common in pest management by integrating analytical techniques that can identify, describe, and quantify the active ingredient and adjuvants radiating from them. Nanotechnology will make agriculture more environmentally benign and profitable by lowering the use of crop protection.

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ADVANCED NANOMATERIALS IN AGRICULTURE: CHARACTERIZATION, PROPERTIES AND CONTROLLED RELEASE

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Abstract

Growing food demand, limited arable land, climate change, and environmental concerns have increased the need for sustainable agricultural technologies. Advanced nanomaterials offer promising solutions for improving the delivery and efficiency of fertilizers, herbicides, insecticides, and fungicides. Their high surface area, tunable pore structure, nanoscale size, and modifiable surface chemistry enable enhanced loading capacity, targeted delivery, and controlled-release behavior. These properties help reduce nutrient loss, pesticide leaching, volatilization, repeated applications, and environmental contamination while improving crop productivity. This chapter discusses major synthesis methods of agricultural nanomaterials, including chemical, physical, and green approaches, along with their advantages and limitations. It also highlights key characterization techniques such as SEM, TEM, XRD, FTIR, and XPS for evaluating morphology, crystallinity, pore structure, and surface chemistry. The influence of these properties on release kinetics, stability, and environmental interactions is examined. Controlled-release applications of mesoporous silica nanoparticles, polymeric carriers, layered double hydroxides, lignin nanoparticles, hydrogels, and smart stimuli-responsive systems are reviewed. Although challenges related to cost, safety, regulation, and field-scale adoption remain, future advances in biodegradable and intelligent nanocarriers are expected to support precision agriculture and sustainable crop production.

Keywords: Nanomaterials, Controlled Release, Agrochemical Delivery, Precision Agriculture, Sustainable Agriculture.

1. Introduction

The rising global consumption of food, reduction of cultivable land, climatic changes, pest tolerance, and environmental pollution have intensified the development of efficient input systems in agriculture. The conventional agrochemicals, such as fertilizers, herbicides, fungicides, and insecticides, exhibit poor application efficiency because of the processes of volatilization, photo-decomposition, leaching, runoff, and microbial decomposition, leading to economic wastage and pollution of the environment (Kah *et al.,* 2018; Usman *et al.,* 2020). Large amounts of applied pesticides do not reach their target destinations but disperse in the soil, aquatic ecosystems, and non-target species, posing risks to both ecological and human health (Fraceto *et al.,* 2016).

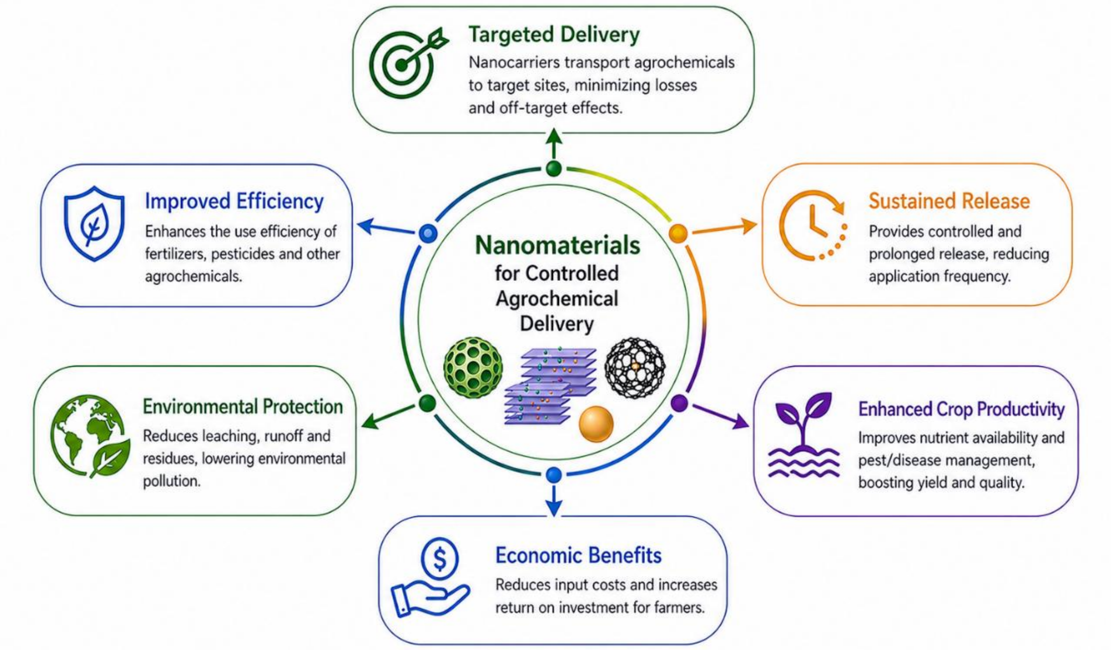

Figure 1: Overview of Advanced Nanomaterials in Agriculture for Efficient and Sustainable Agrochemical Delivery

Nanotechnology can provide a suitable means through the use of nano-delivery vehicles for agrochemicals, which will ensure efficient loading, protection of the agrochemicals, and control/triggered release of the substances. Nanodelivery vehicles, including mesoporous silica nanoparticles, polymeric nanoparticles, layered double hydroxides, lignin nanoparticles, nano-clays, and lipids, have tunable sizes, porosities, and functionalities for targeted delivery into the plants or soils (Khot *et al.,* 2012; Kah *et al.,* 2018). Nanocarrier technologies can provide better adhesion, retention, bioavailability of agrochemicals, and reduced number of applications. Studies have shown that there are prolonged actions, reduction of burst release, minimized leaching, and improved agricultural yield using controlled release of agrochemicals via nanotechnologies. In addition, polymer and lignin carriers are found to promote sustained release of the herbicides, and mesoporous silica nanoparticles are useful in providing high loading efficiency and triggered delivery of agrochemicals (Grillo *et al.,* 2021; Yearla & Padmasree, 2016). However, large-scale adoption requires a deeper understanding of physicochemical properties, synthesis reproducibility, environmental fate, toxicity, and regulation. Factors such as morphology, crystallinity, pore structure, surface chemistry, colloidal stability, and biodegradability strongly affect loading, release kinetics, transport, and plant interactions (Kah *et al.,* 2018; Shang *et al.,* 2019). Therefore, advanced characterization is essential for designing safe and effective nano-enabled agrochemical systems. This chapter discusses advanced nanomaterials in agriculture, focusing on their structural properties, physicochemical behavior, and controlled-release applications for fertilizers and agrochemicals. It highlights key characterization techniques and recent nanocarrier systems that improve efficiency, reduce losses, and support sustainable agriculture.

2. Characterization and Physicochemical Properties

2.1 Morphological and Structural Analysis (SEM, TEM, XRD)

Morphological and structural characterization is essential for understanding nanomaterial-based agrochemical delivery systems, as particle architecture directly governs loading capacity, release kinetics, transport behavior, and environmental interactions.

2.1.1 Scanning Electron Microscopy (SEM):

Morphology and Surface Features: Scanning Electron Microscopy (SEM) provides detailed information on particle size, shape, surface roughness, aggregation, and porosity, all of which influence loading efficiency, soil adhesion, and burst release (Aouada & de Moura, 2015). Mesoporous silica nanoparticles (MSNs) typically appear uniform, spherical, and monodisperse, ensuring reproducible loading and predictable release behavior. Polymer-coated MSNs exhibit smoother surfaces, indicating successful functionalization and reduced burst release of pesticides (Cao *et al.,* 2016a). Lignin-based carriers, in contrast, display irregular and compact morphologies, which restrict water penetration and slow diffusion, helping reduce leaching losses (Yearla & Padmasree, 2016). SEM also distinguishes plate-like aggregation and porous networks in layered and hybrid nanocomposites, which influence release rates based on pore connectivity and particle packing (Fookes *et al.,* 2022).

2.1.2 Transmission Electron Microscopy (TEM):

Internal Architecture and Encapsulation: Transmission Electron Microscopy (TEM) complements SEM by providing high-resolution visualization of internal nanostructures such as pore ordering, shell thickness, interlayer spacing, and encapsulation uniformity, which govern diffusion and sustained release (Aouada & de Moura, 2015). TEM confirms that MSNs have highly ordered mesoporous channels (~2–5 nm) that serve as defined pathways for agrochemicals. In chitosan-capped MSNs, the mesoporous framework remains intact after coating, explaining the biphasic release pattern observed with pyraclostrobin: an initial burst followed by prolonged diffusion-controlled release (Cao *et al.,* 2016a). Lignin-based nanoparticles show homogeneous herbicide dispersion within dense, amorphous matrices, resulting in restricted diffusion and extended activity (Yearla & Padmasree, 2016). In layered double hydroxides (LDHs) and graphene-based systems, TEM reveals interlayer expansion of approximately 0.7–0.9 nm after pesticide intercalation, which correlates with increased loading capacity and slow, controlled release (Liu *et al.,* 2017).

2.1.3 X-ray Diffraction (XRD):

Crystallinity and Structural Order: X-ray Diffraction (XRD) provides complementary insight into crystallinity, phase composition, interlayer spacing, and structural order, which are key to understanding loading mechanisms and release kinetics (Aouada & de Moura, 2015). MSNs display characteristic low-angle reflections, and peak broadening after agrochemical loading indicates pore filling without structural collapse. Chitosan-coated MSNs maintain mesostructural order, supporting sustained release following an initial burst (Cao *et al.,* 2016a). LDH carriers show basal plane shifts (e.g., 003 planes), with interlayer expansion from ~0.70 to ~0.87 nm in graphene oxide–ZnAl LDH systems, explaining prolonged chlorpyrifos release and reduced burst effects (Liu *et al.,* 2017). Lignin-based carriers show broad amorphous halos and disappearance of crystalline pesticide peaks, reflecting molecular-level dispersion and slow, biphasic release with lower environmental mobility (Yearla & Padmasree, 2016). In polymeric–inorganic hybrids, the distinction between intercalated and exfoliated structures is critical, as exfoliation generates tortuous diffusion pathways that further retard agrochemical migration.

2.2 Surface Chemistry and Functional Group Identification (FTIR, XPS)

Surface chemistry critically influences nanomaterial performance in agrochemical delivery, as the type, density, and chemical state of surface functional groups govern agrochemical adsorption, binding strength, environmental interactions, and release kinetics (Aouada & de Moura, 2015).

2.2.1 Fourier Transform Infrared Spectroscopy (FTIR) identifies surface functional groups through characteristic vibrational bands, confirming surface modification, polymer grafting, and successful agrochemical encapsulation (Baraton, 2000). In mesoporous silica nanocarriers, detection of $–NH_2$, –SH, and $–SO_3H$ groups demonstrates effective functionalization, enhancing hydrogen bonding and electrostatic interactions with agrochemicals, which improves loading efficiency and enables sustained release (Alswieleh, 2020). Shifts or attenuation of agrochemical absorption bands after encapsulation indicate strong molecular interactions or confinement within nanopores, correlating with reduced burst release and enhanced formulation stability (Yearla & Padmasree, 2016).

2.2.2 X-ray Photoelectron Spectroscopy (XPS) provides complementary, surface-sensitive data on elemental composition, oxidation states, and chemical bonding within the outermost nanometers of the nanocarrier surface (Lopinski *et al.,* 2025). High-resolution spectra (e.g., C 1s, O 1s, N 1s, Si 2p) differentiate physically adsorbed species from chemically bound functional groups, clarifying mechanisms of agrochemical retention and controlled release. In polymeric and lignin-based carriers, XPS reveals enrichment of oxygen-containing groups (–OH, –COOH), which increase surface polarity and intermolecular interactions with herbicides, explaining the diffusion-controlled and biphasic release patterns observed in controlled-release nanoformulations (Yearla & Padmasree, 2016).

Table 1: Characterization Techniques and Physicochemical Properties of Nanocarriers Used in Controlled Agrochemical Delivery

Technique	Properties analyzed	Key Findings	References
Scanning Electron Microscopy (SEM)	Particle size, shape, surface roughness, porosity, aggregation	MSNs spherical and uniform; polymer coating smoothens surface; lignin carriers compact and irregular	Aouada & de Moura (2015); Cao *et al.* (2016a); Yearla & Padmasree (2016); Fookes *et al.* (2022)
Transmission Electron Microscopy (TEM)	Internal pores, shell thickness, interlayer spacing, encapsulation	MSNs show ordered 2–5 nm pores; LDHs show layer expansion after pesticide loading	Aouada & de Moura (2015); Cao *et al.* (2016a); Liu *et al.* (2017)
X-ray Diffraction (XRD)	Crystallinity, phase structure, pore ordering, interlayer spacing	Peak broadening confirms loading in MSNs; LDH basal spacing increases; lignin appears amorphous	Aouada & de Moura (2015); Cao *et al.* (2016a); Liu *et al.* (2017); Yearla & Padmasree (2016)
Fourier Transform Infrared Spectroscopy (FTIR)	Surface functional groups, bonding interactions, encapsulation	$–NH_2$, –SH, $–SO_3H$ groups confirm functionalization; peak shifts indicate strong agrochemical binding	Baraton (2000); Alswieleh (2020); Yearla & Padmasree (2016)
X-ray Photoelectron Spectroscopy (XPS)	Surface elemental composition, oxidation state, chemical bonding	C 1s, O 1s, N 1s, Si 2p spectra identify surface chemistry; –OH and –COOH enhance herbicide interactions	Lopinski *et al.* (2025); Yearla & Padmasree (2016)

3. Controlled Release Applications

Controlled-release nanomaterials improve agrochemical efficiency by encapsulating active ingredients within nanoscale carriers and releasing them gradually through diffusion, carrier degradation, ion exchange, swelling, or external stimuli. Release behavior depends on particle size, pore structure, surface functional groups, crystallinity, and environmental conditions such as pH, moisture, temperature, and microbial activity (Kah *et al.,* 2018; Usman *et al.,* 2020).

3.1 Controlled Release of Fertilizers

Nanoparticles used for fertilizer delivery include mesoporous silica nanoparticles (MSNs), hydroxyapatite nanoparticles, nano-clays, zeolites, chitosan nanoparticles, alginate beads, and lignin carriers. Nutrients such as N, P, K, Zn, and Fe are loaded into pores or bound to surface groups. Release occurs by water penetration, followed by diffusion of nutrients through pores or gradual matrix biodegradation. In clay and zeolite systems, ion exchange also contributes to nutrient release. These mechanisms reduce nutrient loss and prolong soil availability (Shang *et al.,* 2019).

3.2 Controlled Release of Herbicides

Common nanocarriers studied for herbicides include lignin nanoparticles, chitosan nanoparticles, starch nanocarriers, polymer nanocapsules, mesoporous silica, and nano-clays. Herbicides such as diuron and atrazine are entrapped within polymer matrices or adsorbed onto porous surfaces. Water slowly diffuses into the carrier, dissolves the herbicide, and releases it in a sustained manner. In lignin carriers, dense hydrophobic matrices slow diffusion and reduce leaching (Yearla & Padmasree, 2016; Fookes *et al.,* 2022).

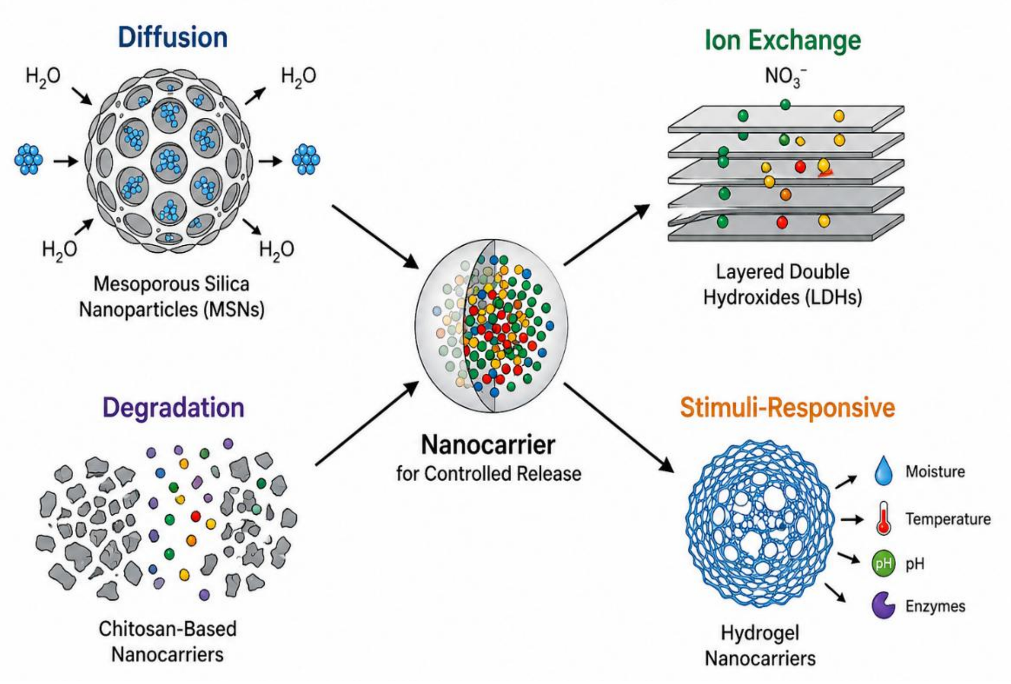

Figure 2: Major Controlled-Release Mechanisms of Nanocarriers for Agrochemical Delivery

3.3 Controlled Release of Insecticides

Particles investigated for insecticide delivery include layered double hydroxides (LDHs), graphene oxide composites, mesoporous silica nanoparticles, lipid nanoparticles, and polymeric nanocapsules. In LDHs, insecticides such as chlorpyrifos are intercalated between layers and released gradually through ion exchange and diffusion. In silica particles, insecticides are stored in mesopores and diffuse outward over time. Lipid carriers release actives through slow erosion or melting of the lipid matrix (Liu *et al.,* 2017).

3.4 Controlled Release of Fungicides

Fungicide delivery systems commonly use chitosan-coated mesoporous silica nanoparticles, polymer nanoparticles, nanoemulsions, and lipid nanocarriers. Pyraclostrobin-loaded MSNs are a widely studied example. The fungicide is first released rapidly from the particle surface (burst phase), followed by slower diffusion from internal pores. Chitosan coatings further retard release by acting as a semi-permeable barrier (Cao *et al.,* 2016a).

3.5 Stimuli-Responsive Release Systems

Advanced carriers include pH-responsive polymers, moisture-sensitive hydrogels, enzyme-degradable biopolymers, magnetic nanoparticles, and light-responsive nanocomposites. These systems remain stable under normal conditions but release cargo when triggered. For example, hydrogels swell in moist soil, pH-sensitive coatings dissolve near root exudates, and enzyme-degradable carriers break down in the rhizosphere.

4. Challenges and Future Prospects

Despite the agricultural potential of nanomaterial-based controlled-release technology, there are several barriers hindering its widespread implementation. The prohibitive costs associated with synthesizing, characterizing, and scaling up advanced nanocarriers, such as mesoporous silica, functionalized polymers, and nanocomposites, represent one of the main obstacles. Additionally, the development of scalable manufacturing processes capable of producing particles with consistent sizes, high loading efficiencies, and enhanced stability is crucial. The environmental fate and safety of nanoparticles post-application represent another challenge. Upon entering agricultural soils and water, nanomaterials may undergo interactions with soil and aquatic microbial communities and non-target organisms, leaving a knowledge gap concerning their environmental persistence, degradation, toxicity, and bioaccumulation in plants (Kah *et al.,* 2018; Shang *et al.,* 2019). Additional limitataions to large-scale adoption include regulatory issues, the absence of established safety guidelines, farmers' knowledge, and public awareness. Future efforts need to be directed toward developing smart stimuli-responsive delivery systems activated by moisture, pH, enzymes, or pest-related factors. The incorporation of nanosensors and AI-powered precision agriculture technologies might improve efficiency and sustainability.

Conclusion

Advanced nanomaterials have emerged as promising platforms for controlled-release delivery of fertilizers, herbicides, insecticides, and fungicides. Their tunable structural properties, surface chemistry, and nanoscale architecture enable improved loading efficiency, sustained release, reduced losses, and enhanced crop productivity compared with conventional formulations. Characterization techniques such as SEM, TEM, XRD, FTIR, and XPS play a vital role in understanding morphology, crystallinity, pore structure, and surface functionality that govern release behavior. Despite challenges related to cost, safety, and regulation, continued progress in biodegradable and smart nanocarriers is expected to accelerate their practical use. Nanotechnology offers a valuable pathway toward efficient, environmentally safer, and sustainable agriculture.

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NANOBIOSENSORS FOR PHYTOPATHOGEN DETECTION AND DISEASE DIAGNOSIS

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Abstract

Plant diseases are major constraint to global agricultural productivity causing significant yield losses and threatening food security worldwide. Traditional diagnostic methods although reliable are often time-consuming, costly and unsuitable for rapid field-based applications. In this context, nanobiosensors have emerged as innovative tools that integrate nanotechnology with biosensing systems to enable fast, sensitive and precise detection of plant pathogens. These devices utilize nanomaterials such as metal nanoparticles, carbon-based nanostructures and quantum dots to enhance signal amplification and improve detection efficiency. Nanobiosensors can identify a wide range of plant pathogens including fungi, bacteria, viruses and nematodes through electrochemical, optical, thermal and other sensing mechanisms. Despite their advantages, several challenges limit their widespread adoption in phytopathology. Moreover, regulatory gaps and limited commercialization further restrict their practical implementation. Future advancements are expected to focus on integrating nanobiosensors with smart farming technologies, artificial intelligence and IoT systems for real-time crop monitoring and precision agriculture. Nanobiosensors hold strong potential to revolutionize plant disease management and support sustainable agricultural practices.

Introduction

Plant diseases pose critical challenge to global food security, causing annual crop yield losses of approximately 20–40% (Savary *et al.* 2019). The situation is further exacerbated by nearly 140 types of pathogens and pests which can reduce the production of staple crops by up to 41% (Farooq *et al.* 2021). Among these, plant viruses are particularly threatening accounting for nearly 50% of known crop diseases and resulting in annual economic losses exceeding $30 billion worldwide. Early detection and effective management of plant pathogens is essential for reducing these losses. Diagnostic and control strategies typically account for less than 3% of total production costs, underscoring their economic viability (Leake *et al.* 2002). However, traditional disease control approaches are increasingly constrained by the emergence of pesticide-resistant strains, environmental contamination, and unintended effects on beneficial organisms (Chhipa 2019; Kah *et al.* 2013).

Conventional diagnostic methods, including polymerase chain reaction (PCR), enzyme-linked immunosorbent assay (ELISA), fluorescence in situ hybridization (FISH) and colony-counting techniques remain widely used due to their high sensitivity and specificity (de la Rica and Stevens 2012; Hijri 2008). Nevertheless, these methods are often labor-intensive, time-consuming, and reliant on costly reagents with limited shelf life, which restricts their applicability in field conditions.

In recent years, biosensors have emerged as promising tools for rapid, sensitive, and cost-effective pathogen detection. These systems enable precise identification of disease biomarkers and facilitate real-time, on-site diagnostics. Their development relies on the identification of highly specific biomarkers, minimally invasive detection techniques and the ability to distinguish complex molecular interactions. Nanotechnology involves the manipulation of materials at the nanoscale (1–100 nm) and has significantly advanced biosensor technology. Nanomaterials such as metal oxides, carbon-based nanostructures, and organic nanoparticles exhibit unique physicochemical properties that enhance sensitivity, selectivity, and signal amplification (Kulkarni *et al.* 2022). A typical nanobiosensor comprises a bioreceptor, a transducer, and a signal processing system, where a bioreceptor is the component of a biosensor that specifically detects a target substance. The integration of nanomaterials such as gold nanoparticles, quantum dots and nanofilms improves detection efficiency and analytical performance of nanobiosensor (La Spada and Vegni 2018).

Types of Nanobiosensors

Nanobiosensors can be broadly categorized based on their detection mechanisms into electrochemical, optical, thermal, mass-sensitive and piezoelectric systems. Each type offers distinct advantages depending on the application; for instance, optical biosensors provide high sensitivity whereas electrochemical biosensors are valued for their rapid response and operational simplicity. Metal oxide nanomaterials can be synthesized through various approaches, including sol–gel processing, chemical vapor deposition (CVD), hydrothermal synthesis and environmentally friendly green synthesis methods (Feng *et al.* 2023). The integration of nanobiosensors into plant health systems provides a transformative approach to disease management and effective risk mitigation in ensuring food security. Biosensors have become pivotal in modern agriculture, and their performance has been further improved by advances in miniaturization and nanomaterial integration (Gangopadhyay *et al.,* 2024; Ali *et al.,* 2024).

Table 1: Different types of biosensors, its mechanism and application in agriculture

Type	Signal conversion	Typical material	Detection Approach	Agricultural use
Electrochemical sensors	Biochemical activity into electrical output	AuNPs, AgNPs, CNTs, magnetic nanoparticles	Monitoring changes in current, voltage, or impedance	Identification of pesticides, hormones, and soil contaminants
Optical Sensors	Biological interaction into optical response	Gold nanoparticles, quantum dots	Detection through fluorescence, absorbance, or color variation	Disease diagnostics, nucleic acid detection
Piezoelectric sensors	Mass variation into electrical frequency	Gold-coated quartz crystals	Frequency shift due to biomolecular binding	Pathogen and antigen–antibody analysis
Thermal Sensors	Biochemical reaction into heat change	Metallic Nanoparticles	Measurement of temperature differences	Enzyme activity and metabolic monitoring
Magnetic sensors	Magnetic property alteration into signal	Iron oxide, cobalt, nickel nanoparticles	Detection via magnetic field changes	Heavy metal and pollutant detection
Nanomechanical sensors	Mechanical stress into measurable signal	Nanowires and nanotubes	Cantilever bending or vibration changes	Biomolecule and pathogen sensing
Electronic nose system	Volatile compounds into electrical patterns	Nanosensors arrays	Pattern recognition of emitted gases	Crop disease and pest detection
Electronic tongue systems	Chemical composition into signal patterns	Nanocomposite-based sensors	Multi-sensor taste-like response analysis	Soil quality and water assessment

Designing of Biosensors

A biosensor is a bioanalytical device that combines a biological recognition element with a physicochemical transducer to detect specific analytes. It mainly consists of three components: a biorecognition element, a transducer, and a signal processing/output system. The biorecognition element, such as nucleic acids (DNA, RNA, PNA or aptamers), enzymes, or antibodies selectively interacts with the target analyte. In nucleic acid-based sensors, this recognition occurs through complementary base pairing. For effective performance, the biomolecules are immobilized on a surface in a way that maintains their activity usually by attaching them at one end to allow proper interaction with the target.

The transducer converts this biological interaction into a measurable signal, often electrical, through methods such as electrochemical, optical or piezoelectric detection. Among these, electrochemical transducers are commonly used due to their high sensitivity, low cost, and ability to work with small sample volumes. The generated signal is then amplified and processed so it can be displayed, stored and analyzed. This integrated system enables biosensors to provide rapid, sensitive and reliable detection for various applications.

Mechanism of Nanobiosensors in Disease Detection

Nanobiosensors detect disease biomarkers through a stepwise process in which biological interactions are converted into measurable signals. First, a biological sample containing the target analyte (such as proteins, DNA or pathogens) is introduced onto the sensor surface. The analyte is specifically recognized by bioreceptors like antibodies, enzymes or nucleic acid probes that are immobilized on nanomaterial-based platforms. The use of nanomaterials enhances binding efficiency due to their high surface area (Kumar *et al.,* 2023).

After recognition, a biochemical interaction occurs between the analyte and the bioreceptor, such as antigen–antibody binding or nucleic acid hybridization. This interaction produces changes at the sensor surface, including variations in charge or electron transfer (Kumar *et al.,* 2023).

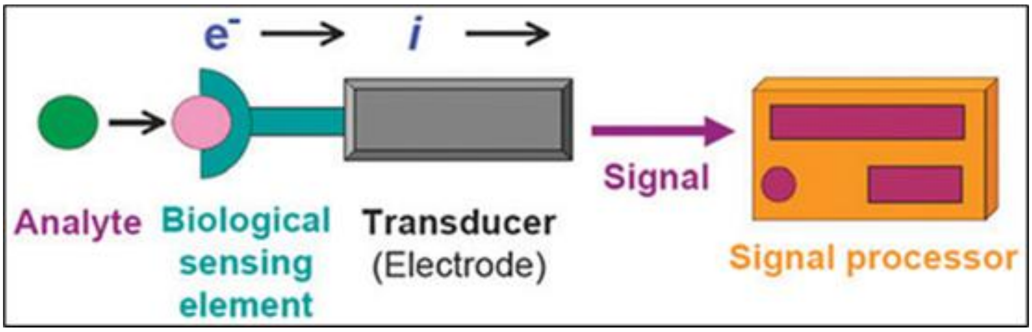

Figure 1: Schematic representation of a nanobiosensor incorporating an electrochemical transduction system along with other functional components.

These changes are then converted into a measurable electrical or optical signal by the transducer. Since the signal is usually weak, it is amplified and then processed using electronic systems to ensure accuracy. Finally, the processed signal is displayed as output, indicating the presence or level of the disease biomarker (Kumar *et al.,* 2023).

Applications of Nanobiosensors in Phytopathology

Nanobiosensors have become valuable tools in phytopathology for the quick and accurate detection of plant diseases and associated biomarkers. The use of nanomaterials such as quantum dots, nanowires and metal nanoparticles improves sensitivity and allows detection at very low concentrations. For instance, quantum dot-based systems utilize fluorescence techniques like

FRET to identify plant viruses, while nanowire and gold nanoparticle-based sensors are effective in detecting pathogens such as cucumber mosaic virus and *Pseudomonas syringae*. In addition, portable nanopore sequencing devices like MinION enable rapid identification of plant pathogens by directly analyzing genetic material, making on-site diagnosis more efficient. Beyond biosensors, nanotechnology is also applied in non-biosensor methods for identifying pesticides and toxins in agricultural samples. Colorimetric systems based on gold or silver nanoparticles detect pesticide residues through visible color changes, eliminating the need for biological recognition elements. Similarly, electrochemical nanosystems can directly sense toxic substances by producing measurable electrical signals upon interaction. These approaches offer simple, fast, and cost-effective solutions for monitoring crop health and maintaining food safety.

Non-biosensor nanotechnology approaches are also widely used for detecting pesticides and toxic substances in agricultural samples.

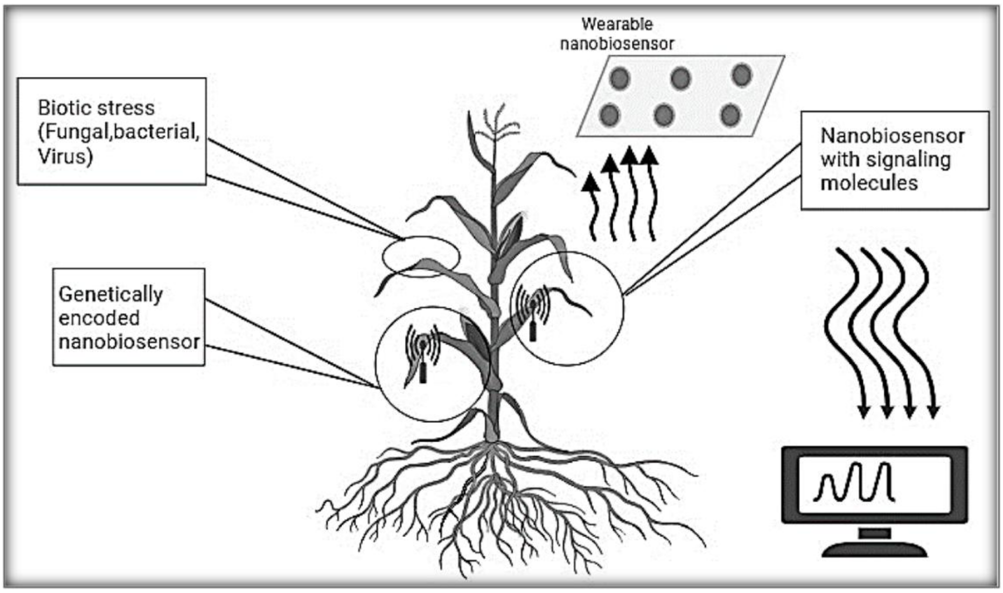

Figure 2: Nanomaterial-based sensors are used to detect plant diseases by identifying bacterial, fungal and viral pathogens

One common method involves nanoparticle-based colorimetric systems, where interactions between nanoparticles and pesticide molecules cause visible color changes, allowing quick and on-site detection without biological components. For example, gold nanoparticles can identify organophosphate pesticides through aggregation-induced color variation, while silver nanoparticles detect toxins by changes in optical properties. Additionally, electrochemical nanosystems without bioreceptors can directly interact with pesticide molecules to generate measurable electrical signals. These techniques are simple, cost-effective, and rapid, making them useful for monitoring pesticide residues and ensuring crop safety.

Table 2: Advances in Biosensor Application for Plant Pathogen Detection

Nanomaterial/Technology	**Role/Benefit in Biosensing**
Gold nanoparticles	Colorimetric, immunosensors, enhanced optical signal
Silver nanoparticles	SERS, fluorescence amplification, DNA detection
Quantum dots	Fluorescent imaging,multiplexed detection
Fluorescent polymeric nanoparticles	Improved signal stability, quantification
Magnetic nanoparticles	Magnetic separation, rapid automated detection
Nanochips/ nanoarrays	High-throughput, multiplexed pathogen detection
Nanotubes/ nanowires	Label-free, high-sensitivity electrical detection
Fiber-optic biosensors	Real-time, in-field monitoring Cantilever-basedassays

Limitations of Nanobiosensors Use in Phytopathology

Nanobiosensors offer great potential for plant disease detection but several limitations restrict their practical use in phytopathology. A major scientific challenge is the complexity of plant–pathogen systems, where plants respond similarly to both pathogen attacks and environmental stresses like drought, temperature changes, and soil variations, making accurate disease identification difficult (Lowry *et al.,* 2019; Mittal *et al.,* 2020).

Technically, the stability and sensitivity under field conditions remain problematic. Although nanobiosensors work effectively in laboratories, real agricultural environments with heat, moisture, soil chemicals and interference often reduce their accuracy and durability sometimes causing false readings. This is further complicated by the lack of standardization and calibration, as no universal protocols exist for sensor design and testing, leading to inconsistent and unreliable results (Kaushal and Wani, 2017; Kelli *et al.,* 2022). From a socio-economic perspective, high cost and limited accessibility of nanomaterials and fabrication techniques restrict their use, especially for small and marginal farmers (Prasad *et al.,* 2017; Patel and Geed, 2024). Additionally, data interpretation and integration challenges arise because nanobiosensors generate complex datasets that require advanced analytical tools and technical expertise, which are not easily available at the field level (Zhang *et al.,* 2023; Vaseashta, 2020).

Regulatory and biosafety concerns remain significant. Nanoparticles may accumulate in soil, water, and plant tissues and potentially enter the food chain, posing environmental and health risks. The absence of proper regulations and safety guidelines further limits their safe and large-scale application in agriculture (Rahman *et al.,* 2023; Prasad *et al.,* 2017).

Future of Nanobiosensors in Phytopathology

Nanobiosensors are expected to significantly improve plant disease detection and sustainable agriculture through applications in soil monitoring, moisture analysis, pathogen detection, and food safety (Giraldo *et al.,* 2019; Zhang *et al.,* 2023). In future agriculture, their integration with smart farming systems, IoT and GPS technologies will enable real-time crop monitoring and precise management of irrigation, fertilization, and pest control, improving resource efficiency (Vaseashta, 2020). The combination of AI and data analytics with nanobiosensors will enhance disease prediction and decision-making by analyzing complex field data, thereby reducing crop losses and improving productivity (Zhang *et al.,* 2023). Future devices are also expected to support multiplex and point-of-care detection, allowing simultaneous identification of multiple pathogens directly in the field without laboratory testing (Giraldo *et al.,* 2019).

Another important direction is the development of eco-friendly nanomaterials, particularly those derived from waste biomass, which can reduce cost and environmental impact while supporting sustainable sensor production (Bartolucci *et al.,* 2020; Rahman *et al.,* 2023). Improving stability and sensitivity under field conditions will also be essential for reliable disease detection in variable environmental conditions (Lowry *et al.,* 2019; Mittal *et al.,* 2020). In addition, the establishment of a strong regulatory framework and standardization is necessary for safe use, validation, and commercialization of nanobiosensors (Prasad *et al.,* 2017; Kelli *et al.,* 2022). Finally, interdisciplinary collaboration among scientists, engineers, and agricultural experts will be crucial to overcome challenges related to cost, scalability, and practical implementation in agriculture (Kaushal and Wani, 2017; Patel and Geed, 2024).

Conclusion

Nanotechnology represents a transformative approach in plant disease management by providing highly effective, multifunctional, and environmentally sustainable alternatives to conventional chemical pesticides (Lowry *et al.,* 2019; Zhang *et al.,* 2023). Nanoparticles exhibit broad-spectrum antimicrobial activity and can be engineered for targeted delivery, controlled release, and enhancement of plant immune responses (Mittal *et al.,* 2020). They have shown effectiveness against a wide range of plant pathogens, including fungi, bacteria, viruses, and nematodes, particularly through the use of silver, copper, zinc oxide nanoparticles, carbon-based nanostructures, and biogenic polymer carriers such as chitosan (Giraldo *et al.,* 2019; Bartolucci *et al.,* 2020).

Despite these advantages, several challenges remain in their application. Concerns related to nanoparticle toxicity, environmental accumulation, and effects on non-target organisms require careful consideration (Prasad *et al.,* 2017; Rahman *et al.,* 2023). In addition, the absence of strong regulatory frameworks, along with difficulties in scalability and the need for cost-effective and green synthesis methods, limits their practical application (Kelli *et al.,* 2022; Kaushal and Wani, 2017). These issues highlight the importance of further research and policy development to ensure safe and sustainable use. Future progress in this field will depend on improving field-level application and addressing existing limitations to enable effective implementation of nanotechnology in agriculture (Vaseashta, 2020; Patel and Geed, 2024).

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IRON SULFIDE THIN FILMS: GROWTH MECHANISMS AND FUNCTIONAL PROPERTIES

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1. Introduction

Iron sulfide (FeS) is an important transition metal chalcogenide that has emerged as a promising material for modern electronic and energy-related applications due to its earth abundance, low cost, non-toxicity, and chemical stability. In contrast to widely used semiconductor materials such as cadmium sulfide and lead sulfide, which pose serious environmental and health risks because of their toxic constituents [1], FeS offers a sustainable and environmentally benign alternative. This makes it particularly attractive for large-scale industrial applications, where environmental regulations and material safety are critical considerations. The use of FeS aligns well with the global shift toward green and sustainable materials for next-generation technologies.

FeS exhibits multiple polymorphic forms, including tetragonal mackinawite (FeS_{1-x}), hexagonal troilite (FeS), and non-stoichiometric pyrrhotite ($Fe_{1-x}S$, where $x = 0$–0.2). Among these, the mackinawite phase is most commonly observed in chemically deposited thin films because it can be synthesized at relatively low temperatures, typically below 100°C [2]. Structurally, mackinawite FeS consists of layered arrangements of iron atoms tetrahedrally coordinated with sulfur atoms, forming two-dimensional sheets. These layers are weakly bonded through van der Waals forces, leading to anisotropic structural, electrical, and optical properties. Such a layered structure is advantageous for charge transport and surface-related phenomena, which are critical in applications like catalysis and sensing. From an optoelectronic perspective, FeS is a narrow band gap semiconductor with an energy band gap ranging from 0.9 to 1.5 eV, depending on synthesis conditions and film quality. This range is very close to the optimal band gap of approximately 1.34 eV, as predicted by the Shockley–Queisser limit for maximum efficiency in single-junction solar cells [3]. In addition, FeS exhibits a high optical absorption coefficient of 10^4–10^5 cm^{-1} [4], enabling it to absorb a large fraction of incident solar radiation within a very thin layer of about 200–500 nm. This property is highly beneficial for reducing material consumption and fabrication costs in thin film photovoltaic devices while maintaining efficient light harvesting. The electrical properties of FeS thin films are highly tunable and depend strongly on factors such as stoichiometry, crystallinity, grain size, and defect concentration. The electrical conductivity typically varies from 10^{-3} to 10^{2} S/cm, allowing FeS to exhibit behavior ranging from semiconducting to metallic under certain conditions. Intrinsic defects such as sulfur vacancies and iron interstitials significantly influence the charge carrier concentration and mobility by introducing donor or acceptor levels within the band gap. This tunability of electrical properties enhances the versatility of FeS for different device applications.

The significance of FeS thin films lies in their multifunctionality and adaptability across a wide range of technological domains. In the field of photovoltaics, FeS serves as an efficient absorber layer due to its suitable band gap and high absorption coefficient. In energy storage systems, FeS is being explored as an electrode material in lithium-ion batteries and supercapacitors, where it offers high theoretical capacity and good electrochemical stability [5-8]. In sensing applications, FeS thin films demonstrate sensitivity to gases such as hydrogen sulfide, ammonia, and nitrogen oxides, making them suitable for environmental monitoring and industrial safety devices. Furthermore, FeS has shown promising catalytic activity in electrochemical reactions, particularly in the hydrogen evolution reaction, which is a key process in sustainable hydrogen production through water splitting. Its layered structure and active surface sites facilitate efficient charge transfer and catalytic performance. In addition, FeS thin films are being investigated for thermoelectric applications due to their moderate electrical conductivity and relatively low thermal conductivity, which are desirable for converting waste heat into electrical energy.

2. Synthesis by Chemical Bath Methods

Chemical synthesis techniques are widely employed for the deposition of FeS thin films due to their advantages of low cost, simplicity, scalability, and suitability for coating large-area as well as complex-shaped substrates. These methods do not require sophisticated vacuum systems or high processing temperatures, making them highly attractive for both laboratory-scale studies and industrial applications. Among the various chemical approaches, chemical bath deposition (CBD) is the most commonly used technique because of its ease of operation, reproducibility, and ability to produce uniform and adherent thin films with controlled properties.

In the CBD process, FeS thin films are deposited from an aqueous reaction bath containing a source of Fe^{2+} ions and a sulfur precursor. Typically, iron salts such as $FeCl_2$ or $FeSO_4$ are used as the metal ion source, while sulfur is supplied by compounds such as thiourea ($CS(NH_2)_2$) or sodium thiosulfate ($Na_2S_2O_3$) and thioacetamide. The choice of sulfur precursor significantly influences the kinetics of sulfide ion (S^{2-}) release and, consequently, the growth rate and morphology of the film. Thiourea is often preferred because it decomposes gradually under alkaline conditions, ensuring a controlled supply of sulfide ions.

To regulate the availability of Fe^{2+} ions and prevent rapid precipitation in the bulk solution, complexing agents such as ammonia (NH_3), ethylenediaminetetraacetic acid (EDTA), and triethanolamine (TEA) are added to the bath. These agents form stable coordination complexes with Fe^{2+} ions, thereby reducing their free concentration and slowing down the reaction rate. This controlled release mechanism is essential for promoting heterogeneous nucleation on the substrate surface rather than homogeneous precipitation in the solution, which leads to better film uniformity and adhesion. The deposition is typically carried out at temperatures ranging from 60°C to 90°C, where the sulfur precursor undergoes gradual decomposition to release S^{2-} ions. The pH of the solution is maintained in the alkaline range of 9–11 using NH_4OH or NaOH, as alkaline conditions favor the hydrolysis of the sulfur source and enhance the formation of sulfide ions. Substrates such as glass, quartz, or fluorine-doped tin oxide (FTO) are usually immersed vertically in the solution to ensure uniform film growth and to minimize the deposition of loosely bound particles. The deposition time generally varies from 30 minutes to 120 minutes, during which the film thickness increases from approximately 100 nm to 1000 nm. Initially, a thin nucleation layer forms on the substrate, followed by continuous growth through ion-by-ion and cluster-by-cluster mechanisms. As the deposition time increases, grain size typically increases from about 10–20 nm to 50–100 nm, leading to improved crystallinity.

FeS thin films deposited by CBD typically exhibit a dark grey, black, or brownish-black colour, depending on thickness, stoichiometry, and surface morphology. Thinner films may appear slightly translucent or brownish, while thicker films generally show a deep black appearance due to strong optical absorption. The colour of the film is an important qualitative indicator of film thickness and uniformity.

Several deposition parameters critically influence the structural and physical properties of FeS thin films. Precursor concentration is typically in the range of 0.01–0.1 M; higher concentrations increase growth rate but may cause non-uniform films. Complexing agent concentration controls ion release; excess complexing agent may suppress deposition. Higher temperature increases reaction kinetics and grain size. pH affects sulfide ion generation and film adhesion. Deposition time determines thickness and crystallinity. Mild stirring improves uniformity but excessive agitation may disturb film growth. Despite its advantages, the CBD method also has certain limitations. One of the main limitations is the possibility of homogeneous precipitation in the solution, which leads to particle formation instead of film deposition. This can reduce film quality and cause surface roughness. Another limitation is the difficulty in achieving precise stoichiometric control, especially in multicomponent systems, due to the complex interplay of reaction parameters. Additionally, films deposited by CBD may exhibit poor adhesion, pinholes, or cracking, particularly for thicker films, due to internal stress and poor substrate bonding. The method also offers limited control over film crystallinity compared to high-temperature techniques such as sputtering or chemical vapor deposition. Post-deposition annealing is often required at temperatures of 200–400°C to improve crystallinity, reduce defects, and enhance electrical and optical properties. Furthermore, reproducibility can sometimes be affected by slight variations in bath composition, temperature fluctuations, and contamination.

3. Reaction Mechanism and Growth

The formation of FeS thin films by CBD involves a complex sequence of chemical reactions and physicochemical processes that collectively govern nucleation, growth, and film formation. A critical aspect of this process is the controlled generation of sulfide ions (S^{2-}) from the sulfur precursor, in an alkaline medium. The success of CBD largely depends on maintaining a delicate balance between ion release, nucleation rate, and growth kinetics.

In an alkaline solution, sulphur source undergoes slow hydrolysis and decomposition, producing sulfide ions in a stepwise manner. The reaction pathway involves intermediate species such as isothiocyanate and ammonia, ultimately leading to the formation of S^{2-} ions. This gradual release is essential because a sudden high concentration of sulfide ions would cause rapid precipitation of FeS in the bulk solution rather than controlled deposition on the substrate surface. The generated sulfide ions react with Fe^{2+} ions present in the solution to form FeS. However, in the absence of complexing agents, this reaction proceeds very rapidly due to the high affinity between Fe^{2+} and S^{2-} ions, resulting in homogeneous precipitation. To avoid this, complexing agents such as ammonia, EDTA, or triethanolamine are introduced into the bath. These agents form stable complexes with Fe^{2+} ions, effectively reducing the concentration of free Fe^{2+} ions. As a result, Fe^{2+} ions are released slowly into the solution, ensuring that the reaction occurs in a controlled manner and favors heterogeneous nucleation on the substrate rather than bulk precipitation [9].

The growth mechanism of FeS thin films can be divided into several distinct but overlapping stages:

(i) Nucleation Stage

At the initial stage of deposition, FeS nuclei begin to form on energetically favorable sites on the substrate surface. These active sites reduce the energy barrier for nucleation. The nucleation density depends on factors such as temperature, pH, and ion concentration. Typically, nucleation occurs within the first few minutes of deposition, forming nanometer-sized clusters.

(ii) Ion-by-Ion Growth Mechanism

Once stable nuclei are formed, further growth occurs through the direct reaction of Fe^{2+} and S^{2-} ions at the substrate surface. In this mechanism, ions diffuse from the bulk solution to the surface and attach to the growing nuclei. This process results in the formation of a dense and uniform film. Ion-by-ion growth is dominant under conditions of low supersaturation and controlled ion release.

(iii) Cluster-by-Cluster Growth Mechanism

In addition to ion-by-ion growth, cluster-by-cluster growth may also occur. In this process, small FeS colloidal particles formed in the solution aggregate and subsequently adsorb onto the substrate surface. These clusters then coalesce with existing nuclei, contributing to film growth.

This mechanism becomes more significant at higher precursor concentrations or higher supersaturation levels and may lead to rougher film surfaces.

(iv) Grain Growth and Coalescence

As deposition proceeds, the initially formed small nuclei grow both laterally and vertically. Neighboring grains begin to merge, leading to grain coalescence and the formation of a continuous film. During this stage, grain boundaries are reduced, and crystallinity improves. Grain size typically increases from about 10–20 nm in the early stages to 50–100 nm with prolonged deposition times.

The rate of grain growth is strongly influenced by deposition parameters. Higher temperatures enhance ion mobility and surface diffusion, allowing atoms to rearrange into energetically favorable positions, thereby improving crystallinity and increasing grain size. Similarly, higher pH values accelerate the generation of sulfide ions, increasing the growth rate, but excessively high pH may lead to poor film quality due to rapid precipitation.

(v) Film Thickening and Stabilization

With continued deposition, the film thickness increases progressively, typically reaching 100–1000 nm depending on deposition time and bath composition. As the film becomes thicker, internal stresses may develop due to lattice mismatch, differential growth rates, or incorporation of defects. These stresses can influence adhesion and may lead to the formation of microcracks if not properly controlled.

4. Crystallographic Properties

Among the various characterization techniques, X-ray diffraction (XRD) is the most widely used and powerful tool for investigating the crystal structure, phase purity, preferred orientation, lattice parameters, and crystallite size of thin films. FeS thin films deposited by chemical methods such as CBD generally exhibit a tetragonal crystal structure corresponding to the mackinawite phase [10]. This phase is metastable but is preferentially formed under low-temperature synthesis conditions. The lattice parameters for tetragonal FeS are typically found to be $a = 3.68$ Å and $c = 5.03$ Å, which are consistent with standard crystallographic data. The structure consists of layered arrangements of Fe and S atoms, which contribute to anisotropic properties and influence diffraction peak intensities.

The XRD patterns of FeS thin films typically show distinct diffraction peaks corresponding to crystallographic planes such as (001), (101), (110), and (200). The presence of these peaks confirms the formation of polycrystalline films. In many cases, the (001) plane shows relatively higher intensity, indicating a preferred orientation along the c-axis, which is common in layered materials. The degree of preferred orientation depends on deposition conditions such as temperature, pH, and precursor concentration. In addition to the tetragonal mackinawite phase, secondary phases such as hexagonal troilite FeS may also be observed, particularly when the deposition temperature is increased or when post-deposition annealing is performed. The appearance of additional peaks in the XRD pattern indicates phase transformation or coexistence of multiple phases. This phase evolution is important because different phases exhibit different electrical and optical properties. The crystallite size of FeS thin films is commonly estimated using the Debye–Scherrer equation, which relates the broadening of XRD peaks to the size of coherently diffracting domains. For films prepared by CBD, the crystallite size typically lies in the range of 10–50 nm, reflecting nanocrystalline nature. In contrast, films deposited using techniques such as spray pyrolysis or subjected to thermal annealing can exhibit larger crystallite sizes, reaching up to 70–80 nm. An increase in crystallite size generally leads to reduced grain boundary scattering, thereby improving electrical conductivity. Peak broadening in XRD patterns is not only influenced by crystallite size but also by lattice strain. The microstrain (ε) in FeS thin films is typically of the order of 10^{-3}, indicating the presence of slight lattice distortions caused by defects, dislocations, and non-uniform growth. These distortions can affect the band structure and carrier transport properties. Another important structural parameter is the dislocation density (δ), which provides a measure of the number of defects present in the crystal. It is typically found in the range of 10^{14} to 10^{16} lines/m^2 for FeS thin films. High dislocation density indicates a larger number of defect sites, which can act as scattering centers for charge carriers, thereby reducing mobility and affecting electrical performance. The quality of crystallinity in FeS thin films is often assessed by analyzing the intensity and full width at half maximum, FWHM of XRD peaks. Sharper and more intense peaks indicate improved crystallinity and larger grain size, while broader peaks suggest smaller crystallites and higher defect concentration. The crystallinity of the films can be significantly enhanced by optimizing deposition parameters or by post-deposition thermal treatment.

Annealing of FeS thin films at temperatures in the range of 200–400°C leads to improved crystallinity, increased grain size, and reduction in microstrain and defect density. During annealing, atoms gain sufficient energy to rearrange into more stable configurations, resulting in better crystal ordering. However, excessive annealing temperatures may induce phase transformation from mackinawite to more stable phases such as troilite or pyrrhotite, which may alter the film properties.

5. Optical Properties

The optical properties of FeS thin films are of critical importance for their application in photovoltaic, optoelectronic, and photodetector devices, as these properties determine how effectively the material interacts with incident electromagnetic radiation. In particular, parameters such as absorption coefficient, optical band gap, transmittance, and reflectance govern the efficiency of light absorption, charge carrier generation, and overall device performance. FeS thin films exhibit strong optical absorption in the visible region, which is primarily attributed to their narrow band gap and high density of electronic states near the band edges. The absorption coefficient (α) is typically in the range of 10^4–10^5 cm^{-1}, indicating that incident photons are absorbed within a very short penetration depth. As a result, even thin films with thicknesses of only 200–500 nm are sufficient to absorb a significant fraction of incident solar radiation. This high absorption capability is particularly advantageous for thin film solar cells, as it reduces material consumption while maintaining high efficiency.

The optical band gap of FeS thin films is generally determined using Tauc plots derived from UV–Visible absorption spectra. The band gap values typically lie in the range of 0.9 eV to 1.5eV [11], depending on factors such as synthesis method, film thickness, crystallinity, and stoichiometry. This band gap range is highly suitable for solar energy conversion because it allows absorption of a large portion of the solar spectrum, particularly in the visible and near-infrared regions. Variations in the band gap are often observed and can be attributed to several factors. One important factor is quantum confinement, which becomes significant when the crystallite size approaches the exciton Bohr radius typically in the nanometer range. Smaller grain sizes (e.g., 10–20 nm) tend to exhibit slightly larger band gap values due to confinement effects, whereas larger grains (50–100 nm) show reduced band gap values closer to bulk behavior. Additionally, the presence of defect states, such as sulfur vacancies and interstitial iron atoms, introduces localized energy levels within the band gap, which can alter the effective optical transition energy. Changes in stoichiometry and phase composition also influence the band structure and optical response.

The transmittance of FeS thin films in the visible region is relatively low, typically in the range of 10–40%, due to strong absorption. However, as the wavelength increases toward the near-infrared region, transmittance generally improves because photon energies become insufficient to excite electrons across the band gap. The transmittance is also strongly dependent on film thickness; thinner films tend to exhibit higher transmittance, while thicker films appear more opaque. The reflectance of FeS thin films is moderate, usually ranging between 10% and 30%, and is influenced by surface morphology, film roughness, and refractive index contrast between the film and substrate. Smooth and dense films tend to exhibit lower scattering losses and more predictable optical behavior, while rough surfaces can increase scattering and reduce effective absorption. Another important optical parameter is the extinction coefficient (k) and refractive index (n), which together describe how light propagates through the material. These parameters are influenced by film density, configuration, and defect concentration. In general, improved crystallinity leads to more well-defined optical constants and reduced optical losses. The optical properties of FeS thin films can be effectively tuned by controlling deposition parameters such as precursor concentration, temperature, pH, and deposition time. For example, increasing grain size through higher deposition temperature or post-deposition annealing reduces grain boundary scattering and defect density, leading to improved optical absorption and a slight reduction in band gap. Similarly, increasing film thickness enhances absorption but reduces transmittance. Post-deposition annealing at temperatures of 200–400°C can further improve optical quality by reducing defects and enhancing crystallinity.

6. Electrical Properties

FeS thin films exhibit typical semiconducting behavior, with electrical conductivity values spanning a wide range from approximately 10^{-3} to 10^{2} S/cm. This large variation arises from differences in synthesis conditions, crystallinity, grain size, film thickness, and defect concentration. In chemically deposited films, particularly those prepared by low-temperature methods such as chemical bath deposition, the presence of structural imperfections and grain boundaries plays a dominant role in determining the electrical transport properties.

The electrical conductivity (σ) of FeS thin films is governed by both the charge carrier concentration (n) and mobility (μ), following the relation $\sigma = n\,e\,\mu$. Variations in any of these parameters can significantly alter the conductivity. Films with larger grain sizes and better crystallinity generally exhibit higher conductivity due to reduced scattering at grain boundaries, whereas films with smaller grains and higher defect density tend to show lower conductivity. The conduction mechanism in FeS thin films is primarily thermally activated, meaning that charge carriers require thermal energy to transition from the valence band to the conduction band or between localized states within the band gap. This behavior is typically analyzed using temperature-dependent conductivity measurements, which follow the Arrhenius relation. The activation energy for FeS thin films is generally found in the range of 0.1 to 0.5 eV, indicating the presence of shallow donor levels or defect states near the conduction band. Lower activation energy values are associated with higher conductivity, as charge carriers require less energy to participate in conduction. In addition to band conduction, hopping conduction can also occur in FeS thin films, especially in disordered or amorphous regions. In this mechanism, charge carriers move by hopping between localized states created by defects or impurities. This type of conduction becomes significant at lower temperatures or in films with high defect densities and poor crystallinity. FeS thin films are generally observed to exhibit n-type conductivity [12], where electrons act as the majority charge carriers. This behavior is primarily attributed to intrinsic defects such as sulfur vacancies and iron interstitials. Sulfur vacancies occur when sulfur atoms are missing from their lattice sites, leaving behind excess electrons that contribute to conduction. Similarly, iron interstitials introduce extra electrons into the system. These defects create donor energy levels just below the conduction band, facilitating electron excitation and enhancing conductivity.

The carrier concentration in FeS thin films typically lies in the range of 10^{16} to 10^{19} cm^{-3}, depending on the defect density and synthesis conditions [13]. Higher carrier concentrations are generally associated with increased conductivity but may also lead to reduced mobility due to enhanced scattering effects. The charge carrier mobility in FeS thin films is relatively low, typically in the range of 1 to 10 $cm^2/V \cdot s$. This is mainly due to scattering mechanisms such as grain boundary scattering, impurity scattering, and lattice vibrations. In polycrystalline films, grain boundaries act as potential barriers that hinder the charge carriers, thereby reducing mobility. Improving film crystallinity through higher deposition temperatures or post-deposition annealing can help reduce these defects and enhance mobility. Temperature also plays a significant role in determining electrical behavior. As temperature increases, conductivity generally increases due to enhanced carrier excitation and improved hopping probability. However, at very high temperatures, increased phonon scattering may limit mobility, leading to saturation or reduction in conductivity. Similarly, annealing at temperatures of 200–400°C can reduce defect density, increase grain size, and enhance conductivity.

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NANOCOMPOSITES AND HYBRID SMART MATERIALS

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Abstract

Nanocomposites and hybrid smart materials have emerged as a transformative class of advanced materials that combine nanoscale reinforcements with stimuli-responsive functionalities. These materials exhibit enhanced mechanical, electrical, thermal, and adaptive properties compared to conventional systems. The integration of nanotechnology with smart material systems has enabled the development of multifunctional materials capable of sensing, actuation, self-healing, and environmental responsiveness. This review provides a detailed analysis of the classification, synthesis methods, and applications of nanocomposites and hybrid smart materials. Emphasis is placed on recent advancements in hybridization strategies, sustainability considerations, and emerging technologies. Key challenges such as scalability, toxicity, and economic feasibility are also critically discussed. Finally, future research directions including AI-driven material design and bio-inspired systems are outlined.

Keywords: Nanocomposites, Smart Materials, Hybrid Materials, Stimuli-Responsive Systems, Nanotechnology, Self-Healing Materials, Multifunctional Materials.

1. Introduction

The advancement of nanotechnology has significantly transformed the field of materials science by enabling the manipulation of matter at the nanoscale, typically below 100 nm. At this scale, materials exhibit unique physical and chemical properties such as enhanced surface area, quantum confinement effects, and improved reactivity, which differ substantially from their bulk counterparts [1,2]. These novel characteristics have paved the way for the development of nanocomposites, a class of materials that combine nanoscale reinforcements with conventional matrices to achieve superior performance. Nanocomposites are defined as multiphase materials in which at least one phase has dimensions in the nanometer range. The incorporation of nanofillers such as carbon nanotubes, graphene, metal oxides, and nanoclays into polymeric, metallic, or ceramic matrices leads to significant improvements in mechanical strength, thermal stability, electrical conductivity, and chemical resistance [3–5]. These enhancements are primarily attributed to the high surface area-to-volume ratio and strong interfacial interactions between the matrix and the nanofillers [6]. In parallel, smart materials have emerged as an important class of materials capable of responding to external stimuli such as temperature, pressure, light, magnetic fields, and chemical environments [7,8]. These materials exhibit adaptive behaviors including shape memory, self-healing, and actuation, making them suitable for advanced technological applications [9].

The integration of nanocomposites with smart materials has led to the development of hybrid smart nanocomposites, which combine structural strength with functional responsiveness [10]. These materials are capable of performing multiple functions such as sensing, actuation, and self-repair within a single system [11]. The synergy between nanoscale reinforcement and smart functionality enables the design of materials with enhanced performance and multi-functionality [12]. The growing demand for high-performance materials in industries such as aerospace, automotive, electronics, and biomedical engineering has further accelerated research in this field [13,14]. For example, lightweight nanocomposites are used in structural components, while smart materials are employed in sensors and actuators for real-time monitoring systems [15].

Advancements in synthesis techniques and characterization methods have enabled precise control over the structure and properties of nanocomposites and hybrid materials [21,22]. Techniques such as electron microscopy and spectroscopy allow researchers to study materials at the nanoscale and optimize their performance [23]. Despite these advancements, several challenges remain, including issues related to nanoparticle dispersion, interfacial stability, scalability, and cost [19,21]. Additionally, concerns regarding the environmental and health impacts of nanomaterials have led to increased focus on sustainable and eco-friendly approaches [1].

2. Classification of Nanocomposites

Nanocomposites can be systematically classified based on the type of matrix material, the nature of nanofillers, and their structural organization. This classification is essential for understanding their properties and tailoring them for specific applications [2,21]. One of the most widely studied categories is polymer matrix nanocomposites (PMNCs), where polymers serve as the continuous phase and nanoparticles act as reinforcing agents. These materials are highly attractive due to their lightweight nature, flexibility, and ease of processing [3]. Common nanofillers used in PMNCs include carbon nanotubes, graphene, nanoclays, and silica nanoparticles [5,6]. The addition of these nanofillers enhances mechanical strength, thermal stability, and electrical conductivity [13].

Metal matrix nanocomposites (MMNCs) constitute another important class, where metals such as aluminum, magnesium, and titanium are reinforced with nanoparticles [14]. These materials are widely used in structural and aerospace applications due to their high strength, wear resistance, and thermal conductivity [15]. The presence of nanoscale reinforcements improves load transfer efficiency and reduces grain size, leading to enhanced mechanical performance [22].

Ceramic matrix nanocomposites (CMNCs) are characterized by their high hardness, excellent thermal stability, and resistance to chemical degradation [27]. These materials are commonly used in high-temperature applications such as turbines, engines, and protective coatings [14]. Nanoparticles such as alumina, silicon carbide, and zirconia are typically used as reinforcements in ceramic matrices [23].

Hybrid nanocomposites represent an advanced category that incorporates multiple types of nanofillers within a single matrix [16]. The combination of different nanomaterials leads to synergistic effects, resulting in improved mechanical, electrical, and thermal properties [6]. For instance, the integration of carbon nanotubes and graphene can significantly enhance both strength and conductivity [5].

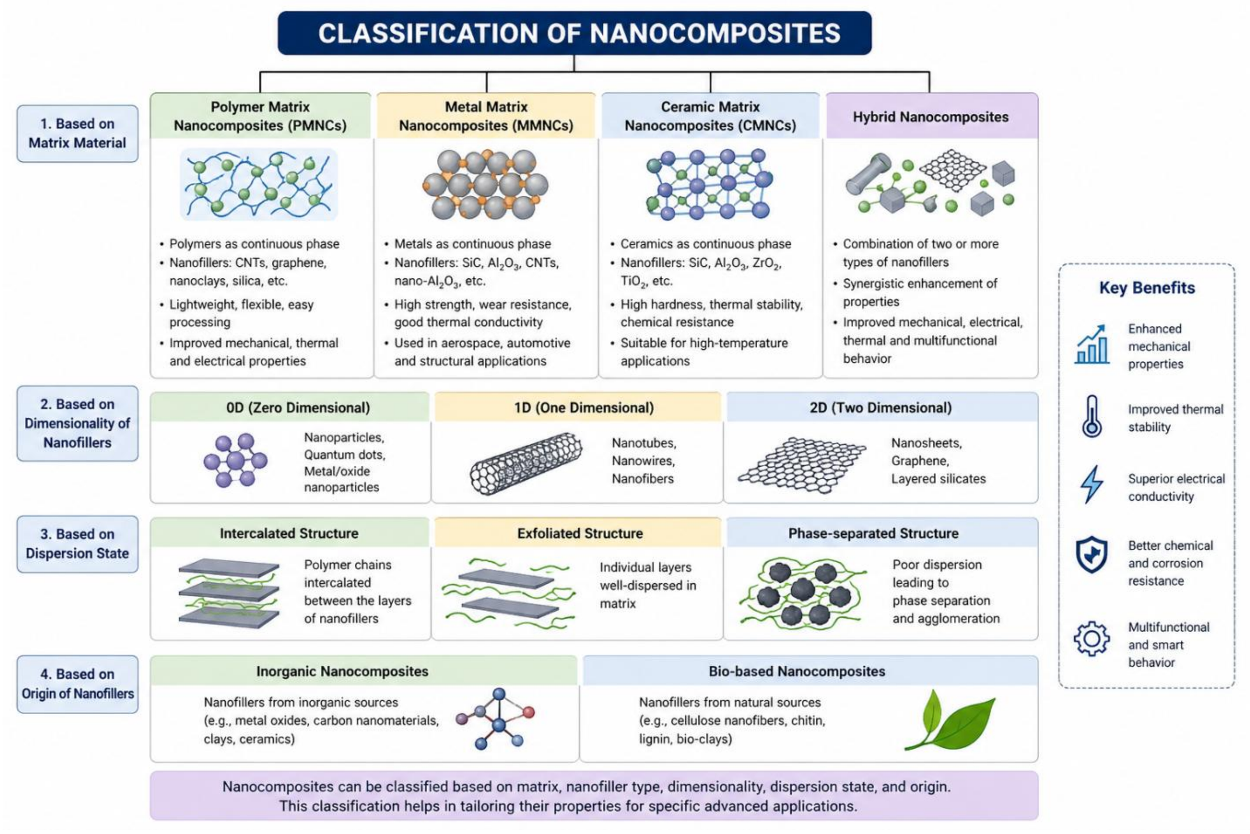

Figure 1: Classification of Nanocomposites

Nanocomposites can also be classified based on the dimensionality of nanofillers, including zero-dimensional nanoparticles, one-dimensional nanotubes or nanowires, and two-dimensional nanosheets such as graphene [5]. Each type of nanofiller contributes uniquely to the overall properties of the composite [30]. Another classification is based on the dispersion state of nanofillers within the matrix, such as intercalated, exfoliated, and phase-separated structures [19]. Exfoliated nanocomposites, where nanofillers are uniformly dispersed, generally exhibit superior properties due to increased surface area and stronger interfacial interactions [20]. Recent research has also focused on bio-based nanocomposites that utilize natural polymers and environmentally friendly nanofillers [1]. These materials offer sustainable alternatives and are gaining attention in applications such as packaging, biomedical devices, and environmental protection [8].

3. Smart Materials and Functional Behavior

Smart materials, also referred to as intelligent or responsive materials, are capable of sensing and responding to external stimuli in a controlled and reversible manner [7,9]. These materials can alter their physical or chemical properties in response to changes in environmental conditions, making them highly valuable for advanced engineering applications [18]. One of the most important classes of smart materials is shape memory materials, which can recover their original shape after deformation when exposed to a specific stimulus such as temperature [7]. Shape memory alloys and polymers are widely used in biomedical devices, aerospace systems, and robotics [8]. Piezoelectric materials represent another significant category, where mechanical stress generates an electric charge [9]. These materials are commonly used in sensors, actuators, and energy harvesting devices due to their ability to convert mechanical energy into electrical energy [28]. The incorporation of nanomaterials enhances their sensitivity and efficiency [5].

Magnetostrictive materials exhibit dimensional changes when subjected to magnetic fields, making them suitable for applications in actuators and vibration control systems [18]. Similarly, electroactive polymers change their shape or size in response to an electric field, enabling their use in soft robotics and artificial muscles [10]. Self-healing materials are an emerging class of smart materials that can repair damage autonomously [17]. This capability is achieved through mechanisms such as reversible chemical bonding or the release of healing agents from microcapsules embedded within the material [11]. These materials are particularly useful in structural applications where maintenance is challenging [15]. The integration of nanotechnology with smart materials has led to the development of hybrid smart nanocomposites with enhanced functionality [6]. Nanoparticles provide high surface area and improved interfacial interactions, which enhance the responsiveness and efficiency of smart materials [19]. Stimuli-responsive materials can react to various external triggers such as temperature, pH, light, and chemical signals [8]. For example, thermo-responsive polymers undergo phase transitions at specific temperatures, while pH-sensitive materials change their structure in response to acidity [3].

The functional behavior of smart materials is governed by their molecular structure and the interactions between their components [20]. Advanced characterization techniques are used to study these interactions and optimize material performance [23]. Applications of smart materials include biomedical devices, structural health monitoring systems, adaptive optics, and wearable electronics [12]. In biomedical applications, smart materials enable targeted drug delivery by releasing therapeutic agents in response to specific biological signals [8]. Despite their advantages, smart materials face challenges such as high cost, limited durability, and complexity in design [21]. Ongoing research aims to overcome these limitations through the development of new materials and improved fabrication techniques [22].

4. Synthesis Techniques

The synthesis of nanocomposites and hybrid smart materials is a crucial factor that directly influences their structural characteristics and functional performance. As discussed in earlier sections, the effectiveness of nanocomposites depends largely on the uniform dispersion of nanofillers and the strength of interfacial interactions [2,21]. Therefore, selecting an appropriate synthesis technique is essential for achieving desired material properties. Synthesis approaches are broadly categorized into top-down and bottom-up methods. In top-down approaches, bulk materials are broken down into nanoscale structures using physical or mechanical processes such as mechanical milling and lithography [21]. Mechanical milling is widely used in the production of metal and ceramic nanocomposites due to its simplicity and scalability [14,22]. However, this method may introduce defects and contamination, which can negatively affect the final properties of the material [23].

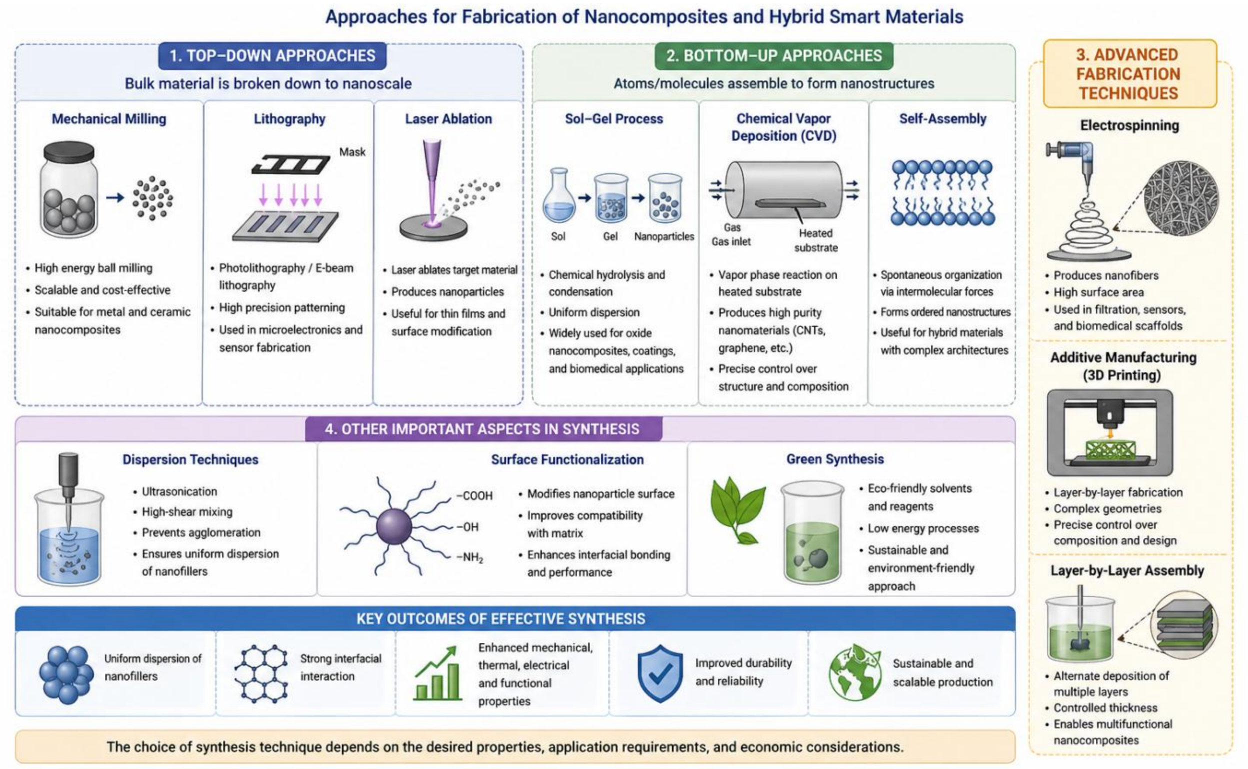

Figure 2: Synthesis techniques for Nanocomposites

Lithographic techniques, including photolithography and electron beam lithography, enable the fabrication of nanoscale patterns with high precision [24]. These methods are particularly useful in microelectronics and sensor fabrication but are limited by high cost and complexity [25]. In contrast, bottom-up approaches involve the assembly of materials from atomic or molecular precursors, allowing better control over particle size and morphology [26]. The sol–gel method is one of the most widely used techniques for synthesizing oxide-based nanocomposites, offering uniform dispersion and controlled composition [27]. Similarly, chemical vapor deposition (CVD) is employed for producing high-quality nanomaterials such as carbon nanotubes and graphene, which are widely used in hybrid systems [5, 28].

Self-assembly techniques rely on intermolecular forces to organize molecules into ordered nanostructures, making them particularly suitable for hybrid smart nanocomposites [29]. These methods enable the formation of complex architectures with enhanced functionality. Advanced fabrication techniques such as electrospinning and additive manufacturing (3D printing) have further expanded the possibilities for designing nanocomposites with tailored properties [30]. Electrospinning produces nanofibers with high surface area, while 3D printing allows precise control over geometry and material distribution. Achieving uniform dispersion of nanofillers remains a major challenge in synthesis. Techniques such as ultrasonication and surface functionalization are commonly used to improve dispersion and prevent agglomeration [6,20]. Surface modification enhances compatibility between the matrix and nanofillers, leading to improved interfacial bonding and overall performance [19]. In recent years, there has been a growing emphasis on green synthesis methods that minimize environmental impact [1]. These approaches utilize eco-friendly solvents and renewable materials, aligning with sustainability goals.

5. Hybrid Smart Nanocomposites

Hybrid smart nanocomposites represent a significant advancement in materials science, combining the benefits of nanocomposites with the adaptive functionalities of smart materials. As introduced in earlier sections, these materials integrate multiple nanofillers and stimuli-responsive components to achieve multifunctionality [6,10]. The concept of hybridization involves combining different types of nanomaterials within a single matrix to exploit their complementary properties [16]. For example, carbon nanotubes and graphene are often combined to enhance both mechanical strength and electrical conductivity [5]. Similarly, metal oxide nanoparticles can be incorporated to improve thermal stability and catalytic activity [27]. One of the key advantages of hybrid smart nanocomposites is their ability to respond to external stimuli such as temperature, light, pH, and magnetic fields [7,18]. This responsiveness is achieved through the incorporation of smart materials such as shape memory polymers, piezoelectric materials, and electro active polymers [9].

These materials exhibit multiple functionalities simultaneously, including sensing, actuation, and self-healing [17]. For instance, a hybrid nanocomposite used in structural applications may detect damage, initiate repair, and restore its original properties without external intervention [11]. The design of hybrid nanocomposites requires careful consideration of compatibility between different components. Interfacial interactions, dispersion, and processing conditions must be optimized to achieve desired performance [19]. Surface modification techniques are commonly used to improve compatibility and enhance bonding between different phases [20]. Hybrid smart nanocomposites have a wide range of applications in sensors, actuators, energy storage devices, and biomedical systems [9,12]. In sensor applications, these materials provide high sensitivity and fast response times due to their enhanced electrical properties [28].

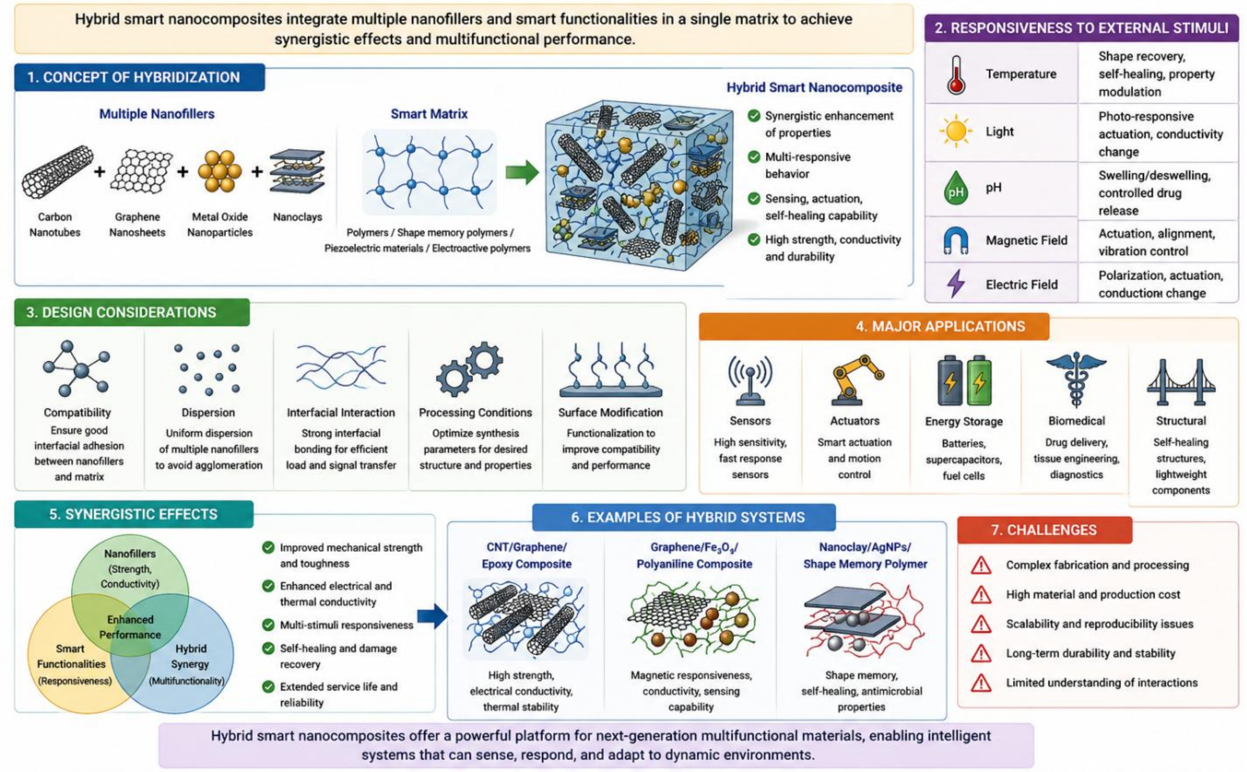

Figure 3: Hybrid Smart Nanocomposites

In energy applications, hybrid nanocomposites are used in batteries and supercapacitors to improve energy density and cycling stability [27]. The combination of different nanomaterials enables efficient charge transport and storage [14]. Biomedical applications include drug delivery systems and tissue engineering, where hybrid nanocomposites offer improved biocompatibility and controlled release of therapeutic agents [8]. These materials are also used in diagnostic devices due to their high sensitivity and specificity [3]. Self-healing hybrid nanocomposites are gaining attention for their ability to repair damage autonomously, thereby extending material lifespan and reducing maintenance costs [17]. These materials are particularly useful in aerospace and infrastructure applications [15]. Despite their advantages, hybrid nanocomposites face challenges such as complex fabrication processes, high cost, and scalability issues [21]. Research efforts are focused on developing cost-effective and scalable synthesis methods to overcome these limitations [1].

6. Applications of Nanocomposites and Hybrid Smart Materials

Nanocomposites and hybrid smart materials have gained significant attention due to their wide range of applications across multiple industries. Their unique combination of enhanced mechanical properties and intelligent functionality enables their use in advanced technological systems [13,14].

6.1 Biomedical Applications

In the biomedical field, nanocomposites are extensively used for drug delivery, tissue engineering, and diagnostic applications [8]. These materials enable targeted drug delivery systems, where therapeutic agents are released in response to specific biological stimuli, thereby improving treatment efficiency and reducing side effects [3]. Nanocomposite-based scaffolds are also used in tissue engineering to support cell growth and regeneration due to their biocompatibility and structural properties [12].

6.2 Energy Storage and Conversion

Nanocomposites play a crucial role in energy-related applications such as lithium-ion batteries, supercapacitors, and solar cells [27]. The incorporation of nanomaterials such as graphene and carbon nanotubes enhances electrical conductivity and surface area, leading to improved energy storage capacity and efficiency [5]. Hybrid nanocomposites are also used in fuel cells and energy harvesting systems due to their multifunctional properties [14].

6.3 Environmental Applications

Environmental protection is another important area where nanocomposites are widely applied. These materials are used in water purification, air filtration, and pollutant removal systems [1]. Their high surface area and catalytic activity enable efficient adsorption and degradation of contaminants [2]. Additionally, nanocomposite membranes are used for desalination and wastewater treatment processes [15].

6.4 Aerospace and Automotive Applications

In the aerospace and automotive industries, nanocomposites are used to develop lightweight and high-strength materials that improve fuel efficiency and reduce emissions [14]. These materials offer excellent mechanical properties, corrosion resistance, and durability, making them suitable for structural components [13]. Smart coatings with self-healing and anti-corrosion properties are also widely used in these sectors [17].

6.5 Sensors and Actuators

Hybrid smart nanocomposites are extensively used in sensors and actuators due to their high sensitivity and rapid response to external stimuli [9]. These materials are capable of detecting changes in temperature, pressure, and chemical composition, making them suitable for applications in healthcare, environmental monitoring, and industrial automation [28].

6.6 Flexible Electronics and Wearable Devices

The development of flexible electronics and wearable devices has been greatly enhanced by the use of nanocomposites [10]. These materials provide flexibility, durability, and improved electrical performance, enabling the fabrication of lightweight and portable electronic systems [12]. Applications include smart textiles, health monitoring devices, and flexible displays [30].

6.7 Construction and Infrastructure

Nanocomposites are increasingly used in the construction industry to improve the strength and durability of building materials [15]. Self-healing concrete and smart coatings are examples of innovative applications that enhance the lifespan of structures and reduce maintenance costs [17].

7. Challenges and Limitations

Despite the significant advancements in nanocomposites and hybrid smart materials, several challenges and limitations must be addressed to enable their widespread adoption. These challenges are related to synthesis, performance, scalability, cost, and environmental concerns [21].

7.1 Nanoparticle Dispersion and Agglomeration

One of the major challenges in nanocomposite fabrication is achieving uniform dispersion of nanoparticles within the matrix [19]. Due to their high surface energy, nanoparticles tend to agglomerate, leading to non-uniform distribution and reduced material performance [20]. Agglomeration can create stress concentration points, negatively affecting mechanical properties [13].

7.2 Interfacial Compatibility

The performance of nanocomposites is highly dependent on the interaction between the matrix and the nanofillers [6]. Poor interfacial bonding can lead to weak load transfer and reduced efficiency of reinforcement [30]. Surface functionalization techniques are often required to improve compatibility, but they add complexity to the fabrication process [5].

7.3 High Production Cost

The high cost of nanomaterials and advanced synthesis techniques remains a significant barrier to large-scale commercialization [21]. Materials such as carbon nanotubes and graphene are expensive to produce, limiting their widespread use in industrial applications [14].

7.4 Scalability Issues

While laboratory-scale synthesis of nanocomposites is well established, scaling up these processes for industrial production is challenging [22]. Maintaining uniformity and consistency in large-scale production requires advanced equipment and precise control over processing parameters [23].

7.5 Environmental and Health Concerns

The potential toxicity of nanomaterials poses risks to both human health and the environment [1]. The release of nanoparticles during production, use, or disposal can lead to environmental contamination [2]. Therefore, the development of eco-friendly and biodegradable nanocomposites is essential [8].

7.6 Durability and Reliability

Smart materials often face issues related to long-term durability and reliability [18]. Repeated exposure to external stimuli can degrade material performance over time, limiting their practical applications [15].

7.7 Standardization and Regulation

The lack of standardized testing methods and regulatory guidelines for nanocomposites is another major challenge [21]. This creates difficulties in evaluating material performance and ensuring safety across different applications [22].

7.8 Complexity in Design and Fabrication

The design and fabrication of hybrid smart nanocomposites involve multiple components and processes, making them complex and time-consuming [6]. Achieving the desired balance between structural and functional properties requires careful optimization [19].

Conclusion

Nanocomposites and hybrid smart materials represent a major advancement in materials science by combining enhanced structural performance with intelligent, stimuli-responsive behavior. Their unique ability to integrate nanoscale reinforcements with adaptive functionalities enables improved mechanical, thermal, and electrical properties along with capabilities such as sensing, actuation, and self-healing. The study of classification and synthesis methods highlights the importance of controlled fabrication and strong interfacial interactions in achieving optimal performance. Hybridization further enhances multi-functionality by creating synergistic effects between different material components. These materials have demonstrated wide applicability across fields such as biomedical engineering, energy systems, environmental protection, and advanced structural applications. However, challenges including dispersion issues, high production costs, scalability limitations, and environmental concerns must be addressed for broader adoption.

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DEVELOPMENT OF NOVEL PHYTOFORMULATIONS USING NANOENGINEERING TECHNOLOGY FOR ENHANCED BIOAVAILABILITY AND THERAPEUTIC EFFICACY

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Abstract

Phytopharmaceuticals which are formulated from medicinal plants have been evaluated for its remarkable activities like therapeutic potential, safety profile, and multi-target pharmacological actions. However, conventional herbal formulations have reported certain limitations compared to Phytopharmaceuticals like poor aqueous solubility, low permeability, rapid degradation, variable absorption, and limited bioavailability, which reduces their clinical performance. Nanoengineering technology overcomes these limitations by converting this phytoconstituents into advanced nanoscale delivery systems like liposomes, phytosomes, polymeric nanoparticles, nanoemulsions, solid lipid nanoparticles, nanostructured lipid carriers, and metallic green-synthesized nanoparticles this technology enhance dissolution, stability, targeted delivery, sustained release, and therapeutic efficacy of herbal bioactives. Recent Indian research has made notable efforts to formulate nanoformulations derived from curcumin, berberine, quercetin, neem, and ashwagandha to treat various diseases like cancer, diabetes, neurodegeneration, wound healing, and antimicrobial. International studies have made valuable contributions to emphasized smart nanocarriers, stimuli-responsive systems, and translational opportunities. In this chapter we have described the different principles of nanoengineering in Herbal Drug Delivery, different materials used for the formulation of phytopharmaceuticals, various preparation technology, evaluation methods, biomedical applications, regulatory compliances, and future aspects. Special contribution has been made for integration of traditional phytomedicine with modern nanotechnology for next-generation therapeutics. Nanoengineered phytopharmaceuticals depicts a promising platform to transform plant-derived molecules into clinically relevant medicines with enhanced patient compliance and accurate delivery.

Keywords: Nanoengineering, Phytopharmaceuticals, Herbal Drug Delivery, Nanocarriers, Phytomedicine, Controlled Release.

1. Introduction

From Ancient period of time Medicinal plants have been used in healthcare systems such as Ayurveda, Siddha, Unani, and Traditional Chinese Medicine. The phytoconstituents which are derived from Medicinal plants including alkaloids, flavonoids, polyphenols, terpenoids, tannins, glycosides, and saponins has been reported for various biological activities like antioxidant, anti-inflammatory, antimicrobial, anticancer, hepatoprotective, cardioprotective, and neuroprotective activities [1,2]. Despite these advantages, many herbal drugs have certain limitations like poor water solubility, instability under physiological conditions, low intestinal permeability, rapid metabolism, and inconsistent therapeutic response after oral administration [3]. These limitations have decreased the progression of many promising phytochemicals from traditional uses into scientifically validated pharmaceutical products.

To overcome this limitations Nanoengineering technology has been design and Manufacturing of materials or systems at the nanoscale (1–1000 nm) has been reported to improve Efficiency and effectiveness. In pharmaceutical sciences, nanoengineering technology has Transformed drug delivery by Facilitating encapsulation, protection, controlled release, tissue targeting, and enhanced cellular uptake of bioactive compounds [4]. When this nanoengineering technology is applied to phytomedicine this technology has prominently improve the pharmacokinetic and pharmacodynamic behaviour of herbal molecules. Nanocarriers helps to protect sensitive phytoconstituents from degradation caused due to oxidation, hydrolysis, and enzymatic degradation while also enhancing their retention time and bioavailability. [5].

Several advanced phytopharmaceuticals have been formulated in recent years. Liposomes are structurally derived phospholipid vesicles capable of encapsuling hydrophilic (water soluble) and lipophilic (fat soluble) herbal compounds. Phytosomes facilitate membrane permeability by complexing phytoconstituents with phospholipids. Polymeric nanoparticles release the drugs slowly over a longer period of time, whereas nanoemulsions improve the solubility of plant oils and extracts that have low water solubility. Solid lipid nanoparticles and nanostructured lipid carriers improve stability and scale-up feasibility [6-8].

India has contributed significantly in herbal nanotechnology due to its rich biodiversity and traditional medicinal knowledge. The development of nonpharmaceutical formulation of curcumin, berberine, neem, tulsi, aloe vera, and ashwagandha have been widely explored in Indian institutions for therapeutic outcomes [9,10]. Globally, interest is transforming toward precision medicine using stimuli-responsive and ligand-targeted nano-herbal systems [11,12].

For the effective development of novel phytopharmaceuticals requires careful selection of carrier materials, suitable preparation technology, reproducible characterization, toxicity assessment, and regulatory compliance. This chapter focuses on recent progress in nanoengineering technology for phytopharmaceuticals, summarizes materials and methods, discusses therapeutic applications, and outlines future directions for translation into commercial herbal medicines. Integration of natural products with nanoscale engineering may produce safer, smarter, and more effective therapies for chronic and infectious diseases [13-15].

2. Nanoengineering Concepts in Phytopharmaceuticals Development

Nanoengineering has been reported as an effective approach for enhancing the performance of phytopharmaceuticals by overcoming the common limitations of traditional herbal medicines, such as poor solubility, limited absorption, low stability, and variable therapeutic response. With the use of nanoscale delivery systems technology, plant-based bioactive compounds can be administered more effectively with improved therapeutic potentials [4,5].

Nanoengineering provides one key advantage like it reduces the particle size, which increases surface area and helps improve dissolution and absorption in the body. The nanoparticles which are Surface-functionalized can also direct herbal compounds toward specific tissues, resulting in better therapeutic action and fewer side effects. In addition, the phytoconstituents are protected from environmental and enzymatic degradation by encapsulating inside a nanocarriers, thereby improving its stability [4].

Nanoformulations are also capable of providing controlled and prolonged release of active compounds, which helps maintain effective drug levels for longer periods and decreases frequent dosing. In some pathological conditions, nanosized carriers may accumulate more accurately at target sites, improving localized treatment effects. Reduced systemic exposure can also minimize toxicity.

Overall, the safety, efficacy, and patient acceptability of herbal medicines can be improved by incorporating the active constituents into nanoengineering, supporting the advancement of next-generation phytoformulations for therapeutic use [5].

3. Materials Used in Novel Phytopharmaceuticals

For the formulation of nanoengineered phytopharmaceuticals different materials are used based on their functional role. To prepare lipid carriers like SLN, NLC, and liposomes, Lipids such as stearic acid, glyceryl monostearate, and lecithin are mainly used, which improve stability and controlled release. For nanoparticle formation and sustained drug delivery, Polymers such as chitosan, PLGA, and alginate are used. For the emulsification and stabilization of nano-system, surfactants such as Tween 80, Span 60, and Poloxamer are used. The phytosomes and liposomes are prepared using Phospholipids like phosphatidylcholine, which leads to increase absorption of herbal compounds. Metals such as silver, gold, and zinc oxide are utilized in green synthesized nanoparticles for antimicrobial and therapeutic purposes. Herbal actives including curcumin, quercetin, berberine, and eugenol act as the medicinal payload. Overall, the materials listed in table 1 are selected to improve solubility, stability, bioavailability, and therapeutic efficiency of phytoformulations.

Table 1: Materials Used for Nanoengineered Phytoformulations

Material Category	Examples	Role in Formulation
Lipids	Stearic acid, glyceryl monostearate, lecithin	SLN, NLC, liposomes
Polymers	Chitosan, PLGA, alginate	Nanoparticles, mucoadhesive systems
Surfactants	Tween 80, Span 60, Poloxamer	Emulsification, stabilization
Phospholipids	Phosphatidylcholine	Phytosomes, liposomes
Metals	Silver, gold, zinc oxide	Green synthesized nanoparticles
Herbal Actives	Curcumin, quercetin, berberine, eugenol	Therapeutic agents

4. Types of Nanoengineered Phytopharmaceuticals

For the targeted drug delivery and improved therapeutic efficacy of herbal bioactive compounds Several Nanoengineered phytopharmaceuticals have been developed. Liposomes, with a size range of 50–500 nm, are widely used as biocompatible carriers for compounds such as curcumin. Phytosomes (100–300 nm) improve membrane permeability and absorption, making them suitable for phytoconstituents like silymarin. Polymeric nanoparticles ranging from 100–400 nm provide sustained and controlled release of herbal drugs, as seen in berberine-loaded PLGA nanoparticles. Nanoemulsions (20–200 nm) are effective in improving the solubility of hydrophobic herbal oils, such as neem oil nanoemulsions. Solid lipid nanoparticles (SLN), with sizes between 50–300 nm, offer better physical stability and protection of sensitive phytochemicals, while nanostructured lipid carriers (NLC) provide higher drug loading capacity and improved release properties. Curcumin-loaded NLC is a common example. Overall, the systems listed in table 2 demonstrate the versatility of nanoengineering in developing advanced phytoformulations with enhanced therapeutic benefits.

Table 2: Novel Systems and Advantages

Formulation Type	Size Range	Major Advantage	Example
Liposomes	50–500 nm	Biocompatible carrier	Curcumin liposomes
Phytosomes	100–300 nm	Better absorption	Silymarin phytosomes
Polymeric nanoparticles	100–400 nm	Sustained release	Berberine PLGA NP
Nanoemulsions	20–200 nm	Solubilization	Neem oil nanoemulsion
SLN	50–300 nm	Stability	Quercetin SLN
NLC	80–400 nm	Higher loading	Curcumin NLC

5. Preparation Methods

For the development of nanoengineered phytopharmaceutical Various preparation methods are been utilised, depending on the nature of the herbal drug and carrier material. Solvent evaporation is the most commonly utilised technique in which the drug and polymer are dissolved in a volatile organic solvent, followed subsequently removal of the solvent result in formation of nanoparticles. This method is widely used for polymer-based delivery systems. In Nanoprecipitation technique a solution containing the drug and polymer is mixed with a nonsolvent phase, leading to rapid precipitation of nanosized particles. It is a simple and efficient method for producing uniform nanoparticles. Homogenization technique involves application of intense high mechanical pressure to reduce particle size and obtain stable nanoemulsions or lipid nanoparticles. In Ultrasonication technique the high-frequency sound waves strikes the larger molecules and breaks down into droplets or particles into nanosized systems, thereby improving dispersion and uniformity. In Microemulsion technique the components such as oil, water, surfactant, and co-surfactant are mixed together to form thermodynamically stable nanosized emulsions suitable for poorly soluble herbal compounds. Ionic gelation is generally used for natural polymers such as chitosan, where interaction with oppositely charged ions leads to nanoparticle formation under mild conditions. This method is suitable for sensitive phytoconstituents. For the preparation of metallic nanoparticles green synthesis using plant extracts has recently gained attention, where plant phytochemicals act as reducing and stabilizing agents in an eco-friendly manner. Overall, these methods play an important role in producing stable, effective, and targeted phytopharmaceuticals for advanced drug delivery applications [6,7].

6. Characterization Techniques

Characterization is a crucial step in the development of nanoengineered phytopharmaceuticals, as it helps evaluate the quality, stability, and performance of the prepared nanosystems (Table 3). Different analytical techniques are utilised to confirm particle properties, drug loading, compatibility, and release behaviour. The size of the Particle and polydispersity index (PDI) can be generally measured using dynamic light scattering (DLS). Particle size influences drug release, absorption, and cellular uptake, while PDI indicates the uniformity of particle distribution. Lower PDI values generally represent a more homogeneous formulation. Zeta potential is used to determine the surface charge of nanoparticles. It provides information about physical stability, as highly charged particles are less likely to aggregate during storage. The particle shape, surface texture, and morphology can be studied using Scanning electron microscopy (SEM) and transmission electron microscopy (TEM). These techniques provide comprehensive images of nanosized carriers. Entrapment efficiency measures the amount of herbal active compound successfully incorporated within the carrier system. High entrapment efficiency is desirable for better therapeutic performance. FTIR compatibility studies help identify possible interactions between phytoconstituents and excipients by analysing functional groups. DSC and XRD are used to determine thermal behaviour and crystalline or amorphous nature of the formulation. In vitro release studies are performed to assess the drug release pattern over time, while stability studies evaluate the effect of storage conditions on particle size, appearance, and potency. These characterization methods ensure the effectiveness and reliability of nanoengineered phytopharmaceuticals [8].

Table 3: Characterization Techniques for Nanoengineered Phytoformulations

Technique	Parameter Evaluated	Importance
DLS	Particle size, PDI	Determines size distribution and uniformity
Zeta Potential	Surface charge	Predicts formulation stability
SEM/TEM	Morphology, shape	Examines particle structure
Entrapment Efficiency	Drug loading	Measures active content
FTIR	Drug-excipient	Detects chemical interactions
DSC	Thermal behaviour	Assesses melting and stability
XRD	Crystallinity	Identifies crystalline/amorphous nature
In vitro Release	Release profile	Evaluates sustained drug release
Stability Studies	Storage stability	Confirms shelf-life and quality

7. Drug Delivery Applications

Nanoengineered phytopharmaceuticals have shown diverse potential in various therapeutic areas by improving solubility, stability, bioavailability, and targeted delivery of herbal bioactive compounds. These advanced systems help enhance treatment outcomes while reducing side effects associated with conventional formulations. In cancer therapy, nanoparticles loaded with phytochemicals such as curcumin, quercetin, and resveratrol have demonstrated improved cellular uptake, controlled release, and enhanced anticancer activity. Their nanosized nature also supports better accumulation at tumour sites. For diabetes management, berberine and gymnema-based nanoformulations have been investigated to improve oral absorption and glucose-regulating effects. Such systems may provide prolonged therapeutic action and better patient compliance. In neurological disorders, Ashwagandha nano-carriers are being explored for neuroprotective benefits and improved brain delivery of active constituents. These systems may help overcome poor permeability barriers. For antimicrobial therapy, neem and Tulsi mediated metallic nanoparticles have shown promising antibacterial and antifungal properties. These green synthesized systems are useful against resistant microorganisms. In dermal delivery, aloe vera nanogels are used for topical application due to their soothing, anti-inflammatory, and moisturizing effects with better skin penetration. For wound healing, herbal nanofibers and hydrogel systems provide sustained release of phytoconstituents, maintain a moist environment, and support faster tissue repair. Overall, nanoengineered phytoformulations represent an effective platform for modern herbal therapeutics [9-12].

Table 4: Drug Delivery Applications of Nanoengineered Phytoformulations

Activity	Herbal Actives	Nanoformulations	Major Benefit
Cancer	Curcumin, Quercetin, Resveratrol	Nanoparticles	Targeted delivery, enhanced anticancer effect
Diabetes	Berberine, Gymnema	Nanoformulations	Improved absorption, prolonged action
Neurological Disorders	Ashwagandha	Nano-carriers	Better brain delivery, neuroprotection
Antimicrobial Therapy	Neem, Tulsi	Metallic nanoparticles	Antibacterial and antifungal activity
Dermal Delivery	Aloe vera	Nanogels	Enhanced skin penetration, soothing effect
Wound Healing	Herbal extracts	Nanofibers, Hydrogels	Faster healing and sustained release

8. Challenges

Despite the growing potential of nanoengineered phytoformulations, several challenges must be addressed before large-scale commercial and clinical adoption. One of the major concerns is batch-to-batch variability of plant extracts. The chemical composition of herbal materials can vary depending on plant species, geographical source, harvesting season, cultivation conditions, and extraction methods, which may affect formulation consistency and therapeutic performance. Another important issue is standardization. Herbal extracts contain multiple active constituents, making it difficult to establish uniform quality parameters, dosage accuracy, and reproducible efficacy. Reliable standardization methods are essential for product acceptance and regulatory approval. Scale-up complexity is also a major limitation. Many nanoformulations perform well at laboratory level but face technical difficulties during industrial production, including particle size control, process reproducibility, equipment requirements, and storage stability. The need for long-term toxicity evaluation is equally important. Although many herbal compounds are considered safe, their behaviour may change after nanosizing or encapsulation. Detailed studies are required to assess long-term toxicity, biodistribution, and possible organ accumulation. Another challenge is regulatory ambiguity for herbal nanomedicines. In many countries, there are no clear and specific guidelines covering products that combine herbal medicines with nanotechnology, resulting in delays in approval and market entry. Finally, the cost of advanced manufacturing can be high due to specialized instruments, skilled manpower, quality control systems, and sophisticated processing methods. Addressing these challenges is essential for the successful translation of nanoengineered phytoformulations into practical healthcare products [11-13].

9. Future Perspectives

The future nanoengineered herbal preparations with contemporary technology has good future in coming drug discovery and development. AI-supported optimization and validation of nanoformulations can help the developer to produce the stable and effective nano-system. The smart stimuli responsive carriers can be used to deliver the herbal active at different rate with different pH, temperature and other conditions. The personalized nano-phytomedicine may give effective therapy for chronic diseases. 3D print supported herbal nano systems helps to give personalised pills, patches, or implants with accurate dosing. The clinical translation and global regulatory harmonization are the important and critical aspects for the safe commercialization and widespread adoption of herbal nanoformulations [14,15].

Conclusion

Nanoengineering technology has become a powerful approach for the design and development of novel phytopharmaceuticals in drug delivery. It has overcome the key challenges associated with herbal drugs such as poor solubility, instability, low absorption, and inconsistent bioavailability; nanoscale carriers can significantly improve therapeutic efficacy and safety. Liposomes, phytosomes, nanoemulsions, polymeric nanoparticles, SLN, and NLC systems have established targeted drug delivery and also enhanced well-structured outcomes for multiple diseases. Indian researchers have made notable contributions through herbal biodiversity-driven innovation, while international studies have advanced smart and targeted nanocarriers. Despite progress, issues related to standardization, toxicology, regulation, and industrial scalability remain critical. Future research should focus on evidence-based clinical studies, reproducible manufacturing, and interdisciplinary collaboration. The convergence of nanotechnology with phytomedicine offers immense potential to convert traditional herbal remedies into next-generation pharmaceuticals with global relevance.

Abbriviations

DLS: Dynamic Light Scattering, DSC: Differential Scanning Calorimetry, EPR: Enhanced Permeability and Retention, FTIR: Fourier Transform Infrared Spectroscopy, NLC: Nanostructured Lipid Carriers, NP: Nanoparticles, PDI: Polydispersity Index, PLGA: Poly(lactic-co-glycolic acid), SEM: Scanning Electron Microscopy, SLN: Solid Lipid Nanoparticles, TEM: Transmission Electron Microscopy, XRD: X-ray Diffraction, AI: Artificial Intelligence, API: Active Pharmaceutical Ingredient, CNS: Central Nervous System, GMP: Good Manufacturing Practice, HPLC: High Performance Liquid Chromatography, QbD: Quality by Design, ROS: Reactive Oxygen Species, USP: United States Pharmacopeia.

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NANOSCIENCE AND NANOTECHNOLOGY: AN INTRODUCTORY REVIEW

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Abstract

It would be proper to define nanotechnology as a relatively new area of science and technology that entails dealing with materials in sizes between 1nm to 100nm. There are some distinct properties that are attributed to materials which are dealt with on a nano-scale basis. Distinct properties that are associated with nano-scale materials include properties like strength, reactivity, conductivity, optics and many more. In essence, nanotechnology plays an important role in many different areas. Some of the areas which benefit from nanotechnology include medicine, electronics, energy, environment, agriculture, and many more. However, there are many ethical concerns about nanotechnology including its toxicity to the environment**.**

Introduction

Nanoscience and Nanotechnology are among the most fascinating and rapidly growing fields of modern science. The foundation of both lies in the study and application of materials at the nano scale. The term “nano” comes from the Greek word meaning dwarf or extremely small. In scientific measurement, a nanometer represents one-billionth of a meter (1 nm = 10–9m). To understand this scale, consider that the diameter of a single human hair is about 80,000 to 100,000 nanometers, which shows just how tiny the nano scale is Nanoscience can be defined as the study of the structure, properties [1], and behavior of materials at the nano scale. When materials are reduced to such an incredibly small size, they often exhibit unique physical, chemical, and biological properties that are not observed in their bulk form. For example, bulk gold appears yellowish and shiny, but at the nano scale, gold nanoparticles can display colors like red or purple due to changes in their optical properties. This demonstrates how size alone can drastically alter the characteristics of a nanomaterial [2].

On the other hand, Nanotechnology refers to the practical application of this scientific understanding. If Nanoscience provides the knowledge about how materials behave at the nano scale, Nanotechnology applies that knowledge to design and develop new products, tools, and technologies. In simpler terms, Nanoscience is the “theory” or “knowledge base,” while Nanotechnology is its “application.” For instance, Nanoscience explains that carbon nano tubes are extremely strong and lightweight, whereas Nanotechnology uses this knowledge to create advanced materials for aerospace, construction, and medical applications [3]. One of the most important aspects of Nanoscience is the high surfaceto- volume ratio of nanoparticles, which makes them more reactive and efficient compared to their bulk counterparts. Along with this, quantum effects become significant at the nano scale, leading to unusual electrical, optical, and magnetic behaviors. These characteristics make nanomaterials highly versatile and powerful for a wide range of uses. Nanoscience is the study, and nanotechnology is used of the familiar properties of materials smaller than 100nm nanometers to create new useful objects. This work is made possible by being able to manipulate structures at the size –scale of atoms [4]. Nano technology is an emerging, interdisciplinary are of research with important commercial applications, and will, most assured by, be a dominant different field techonolgy in new –world economies and shown in figure 1.

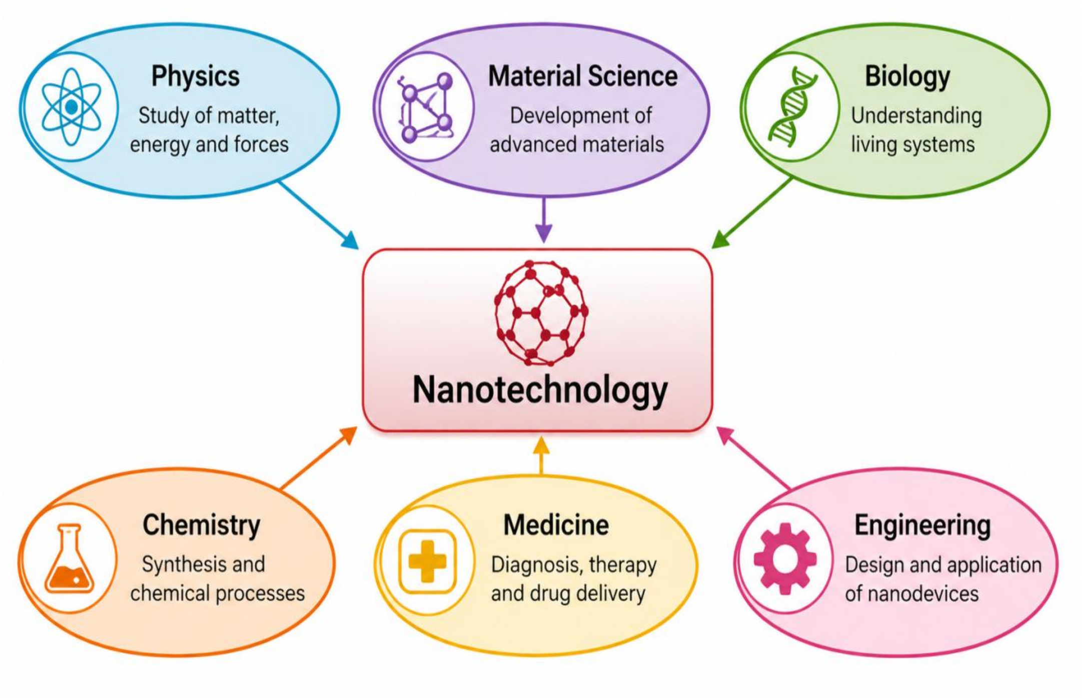

Figure 1: Different field of nanotechnology

This intense interest in the science of the nanomaterials, which confined within the atomic scales, stems from the fact that this nonmaterial exhibit fundamentally interesting unique properties with great potentials of next generation technologies in electronics, computing, optics, biotechnology medical imaging, medicine drug delivery, structural materials, aerospace, energy etc. Semiconductor nanoparticles II-VI semiconductor are thus a type of compound semiconductors composed of group II and VI elements. Which have wide and direct band gap structures, are very important in many fields, due to their tunable electrical and optical properties [5].

The physical properties depend on their crystallite sizes and they show size dependent electrical or optical properties in the quantum size region. Due to the fundament as well as technological importance, the modification in the energy band gap of semiconductors is the most attractive property [6].

Generally, nanomaterials have structured components with at least. One dimensional less than 100nm (1nm= 10^{-9}) and distinctly different physical and chemical properties in comparison to their micron size counterpart. In nanoparticles the various material properties such as electrical, Mechanical, optical magnetic etc, can be selectively controlled by engineering the size, morpholopy materials, using a variety of synthesis methods, in the various forms like thin films, powder quantum wires, quantum wells, quantum dots etc. Nanocrystals are characterized as atomic clusters and are called quantum confined systems [7]. The requirement for quantum confinement is that the size of the nanocrystals should be smaller than the excitation Bohr radius of the material

A *meter* is about the distance from the tip of your nose to the end of your hand (1 meter = 3.28 feet). One *thousandth* of that is a *millimeter*. Now take *one thousandth* of that, and you have a *micron*: a thousandth of a thousandth of a meter. Put another way: a *micron is a millionth of a meter*, which is the scale that is relevant to - for instance - building computers, computer memory, and logic devices [8] in fig 1.2. Now, let's go smaller, to the *nanometer*: A nanometer is one thousandth of a micron, and a thousandth of a millionth of a meter (a billionth of a meter). Imagine: one billion nanometers in a meter in figure 2 and 3.

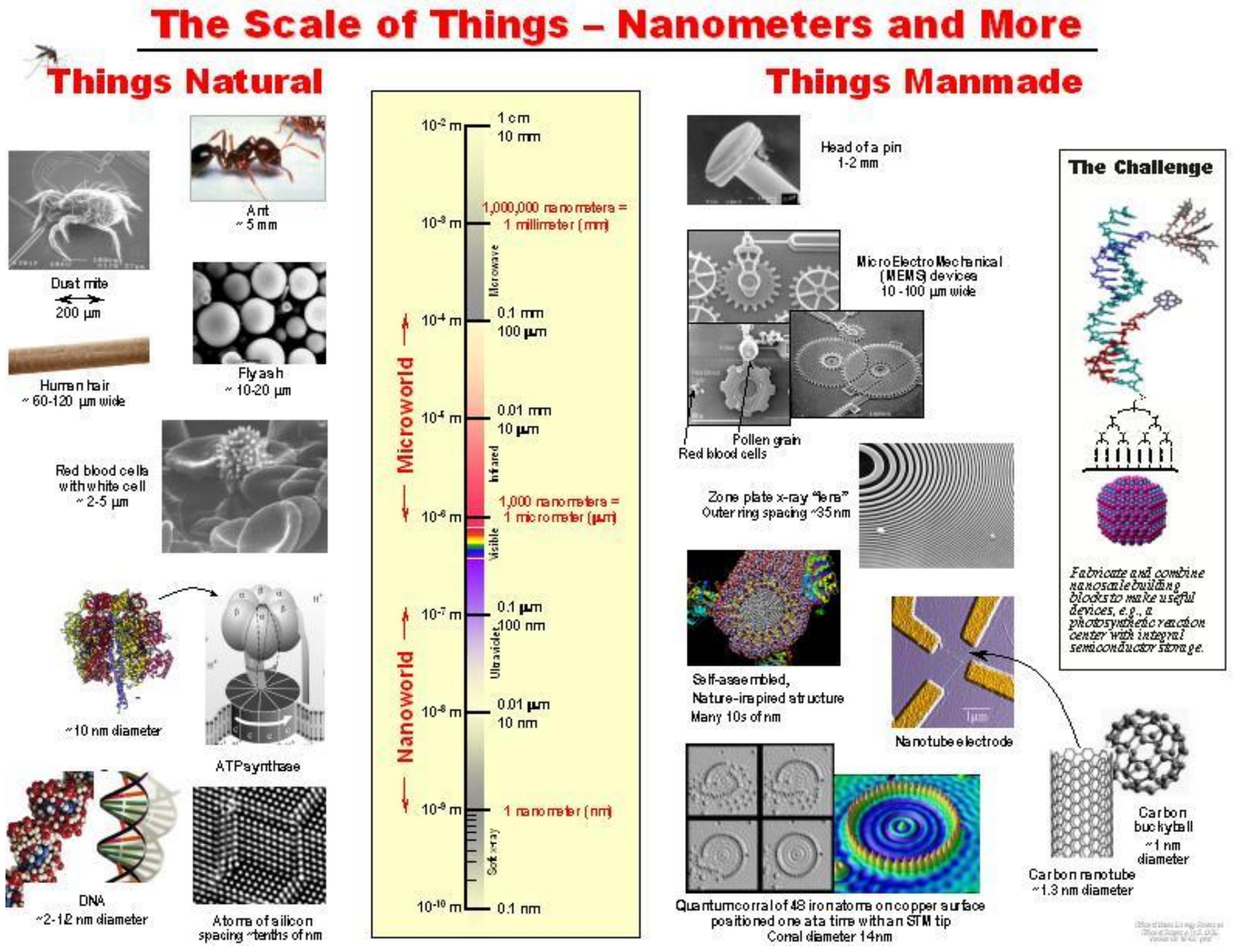

Figure 2: The Scale of things: Nanoworld and Microworld

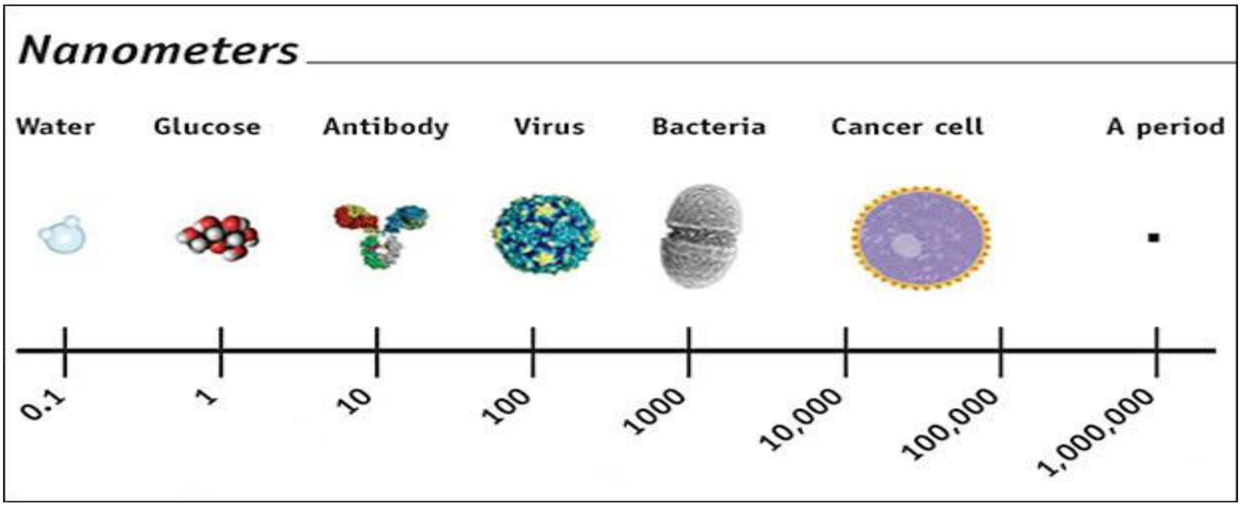

Figure 3: Different type of Nanometer Scale

History of Nanomaterials

The history of nanomaterials began immediately after the big bang when Nanostructures were formed in the early meteorites. Nature later evolved many other Nanostructures like sea shells, skeletons etc. Nanoscaled smoke particles were formed during the use of fire by early humans. The scientific story of nanomaterials however began much later. One of the first scientific report is the colloidal gold particles synthesized by Michael Faraday as early as 1857. Nanostructured catalysts have also been investigated for over 70 years. By the early 1940's, precipitated and fumed silica nanoparticles were being manufactured and sold in USA and Germany as substitutes for ultrafine carbon black for rubber reinforcements. Nanosized amorphous silica particles have found large-scale applications in many every-day consumer products, ranging from non-diary coffee creamer to automobile tires, optical fibers and catalyst supports [9]. In the 1960s and 1970's metallic nanopowders for magnetic recording tapes were developed. In 1976, for the first time, nanocrystals produced by the now popular inert- gas evaporation technique was published by Granqvist and Buhrman. Recently it has been found that the Maya blue paint is a nanostructured hybrid material. The origin of its color and its resistance to acids and biocorrosion are still not understood but studies of authentic samples from Jaina Island show that the material is made of needle-shaped palygorskite (clay) crystals that form a super lattice with a period of 1.4 nm, with intercalates of amorphous silicate substrate containing inclusions of metal (Mg) nanoparticles. The beautiful tone of the blue color is obtained only when both these nanoparticles and the super lattice are present, as has been shown by the fabrication of synthetic samples. New technologies require new materials with superior physical, chemical and mechanical properties. Materials science and engineering have provided us materials with widely varying properties made by changing the composition or altering the microstructure using thermo chemical-mechanical methods. Consequently, micro structural engineering and the study of structure–property correlation have become very important. The mechanism by which ultrafine microstructures affect the properties of solids could be better understood after the advent of the theory of lattice defects and dislocation theory, and the availability of advanced high-resolution microscopy techniques such as electron, atomic force and field ion microscopy. These developments have helped in understanding the correlation between the structure and properties of solids. The unique properties of materials due to ultrafine particle sizes were recognized early in the 20th century. The classic lecture by Richard P Feynman titled “There’s plenty of room at the bottom”, on 29 December 1959, at the annual meeting of the American Physical Society, opened up a whole new field, known as ‘nanotechnology’. He spoke about manipulating and controlling things on a small scale

In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

Due to his foresight, Feynman is often regarded as the first visionary of nanotechnology. Feynman’s profound vision resulted in a lot of discussion and interest among the research community on engineering at a very small scale. However, it took almost three decades for the research community to translate his vision into reality for want of proper tools and techniques. Eric Drexler, yet another visionary of nanotechnology, stretched the imagination further. He advocated that the power of chemistry be used to build molecular machines, and predicted the tremendous impact this would have on a wide spectrum of technologies. In his popular book, *Engines of Creation: The Coming Era of Nanotechnology*, he speaks about the power of an interdisciplinary approach to make commendable progress in nanoscience and nanotechnology [10].

The following statement by Drexler in 1986 still continues to be relevant.

Development of the ability to design protein molecules will, by analogy between features natural macromolecules and components of existing machines, make possible the construction of molecular machines. These machines can build second-generation machines which can perform extremely general synthesis of three-dimensional molecular structures, thus permitting construction of devices and materials to complex atomic specifications. This capability has implications for technology in general andin particular for computation and characterization, manipulation, and repair of biological materials.

Today nanophase engineering expands in a rapidly growing number of structural and functional materials, both inorganic and organic, allowing to manipulate mechanical, catalytic, electric, magnetic, optical and electronic functions. The production of nanophase or cluster-assembled materials is usually based upon the creation of separated small clusters which then are fused into a bulk-like material or on their embedding into compact liquid or solid matrix materials. e.g. nanophase silicon, which differs from normal silicon in physical and electronic properties, could be applied to macroscopic semiconductor processes to create new devices. For instance, when ordinary glass is doped with quantized semiconductor "colloids," it becomes a high-performance optical medium with potential applications in optical computing.

Conclusion

Nanotechnology is an interdisciplinary field that has revolutionized modern science and technology in a very big way. This field of nanotechnology is considered to be very transformational in nature, linking basic science with innovations through the use of materials that make use of nanotechnology. Applications of nanotechnology have been seen in every possible field of technology such as electronics, optics, biology, agriculture, environment, and food and medicine.

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