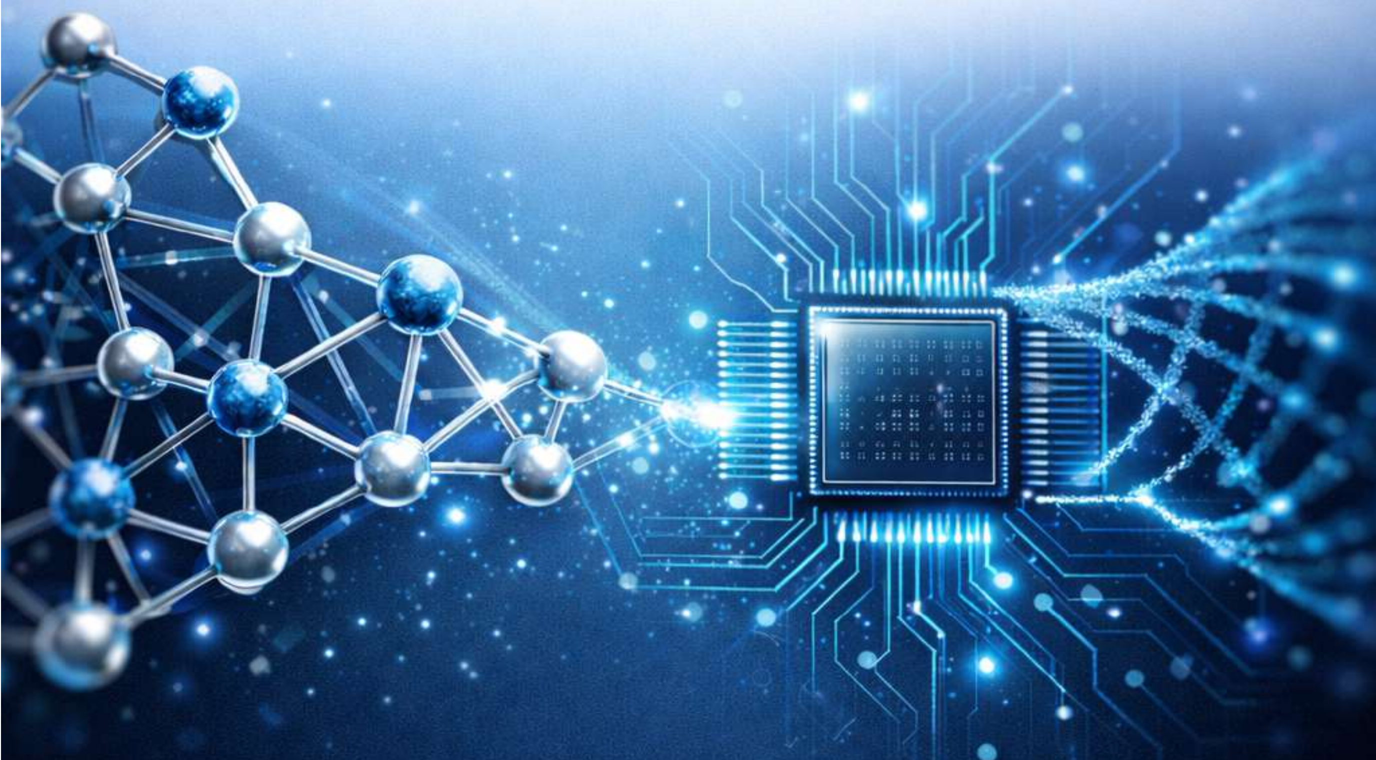
NANOTECHNOLOGY

Advances, Applications, and Challenges



Editors

Mr. Amol Pardeshi

Dr. Sandeep S. Kahandal

Ms. Monika Dixit

Dr. S. Muthurajan

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Nanotechnology: Advances, Applications, and Challenges

Editors

Mr. Amol Rajendrasing Pardeshi
Assistant Professor
Department of Physics,
Dada Patil Mahavidyalaya, Karjat, Ahilyanagar, (MH), India.

Dr. Sandeep S. Kahandal
Assistant Professor
Department of Chemistry
V.P.M.'s B.N. Bandodkar College of Science (Autonomous), Thane, affiliated to University of Mumbai, (MH), India.

Ms. Monika Shyamkumarji Dixit
Assistant Professor
Department of Physics,
Jagadamba Mahavidyalaya, Achalpur, India.

Dr. S. Muthurajan
Assistant Professor
Department of Marine Engineering,
Academy of Maritime Education and Training (AMET) Deemed to be University, Chennai, India.

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Email: naturelightpublications@gmail.com
Contact No: +91 9822489040 / 9922489040

Preface

Nanotechnology has emerged as one of the most transformative and interdisciplinary fields of the 21st century, bridging the gap between fundamental science and real-world applications. The edited volume "Nanotechnology: Advances, Applications, and Challenges" aims to present a comprehensive overview of recent developments, innovations, and critical concerns in this rapidly evolving domain. By integrating contributions from diverse research areas, this book highlights the profound impact of nanoscience and nanomaterials across multiple sectors, including energy, healthcare, agriculture, environment, and industry.

The chapters in this volume collectively explore the foundations and evolution of nanotechnology, offering insights into the synthesis, characterization, and functionalization of nanomaterials. Significant attention is given to industrial applications, particularly in textiles, construction, and the automotive sector, demonstrating how nanotechnology enhances material performance, durability, and efficiency. Furthermore, the book presents cutting-edge research on thin films such as Nickel Sulphide (NiS) and Nickel Selenide (NiSe), emphasizing their potential in photovoltaic and thermoelectric applications, which are critical for sustainable energy solutions.

In addition to technological advancements, this volume also addresses pressing global challenges. The environmental and health risks associated with nanomaterials are critically examined, ensuring a balanced perspective on their safe and responsible use. Emerging innovations such as nanotechnology-based smart sensors for agriculture, nanosensors in food safety, and rare-earth-ion-doped nanophosphors for bioimaging reflect the expanding scope of nanotechnology in improving quality of life and ensuring sustainability.

The book further explores recent progress in supercapacitor technology and renewable energy systems, underlining the role of nanomaterials in advancing energy storage and efficiency. By combining theoretical principles *with practical applications, this volume serves as a valuable resource for researchers, academicians, industry professionals, and students seeking to understand both the opportunities and challenges within the field.*

We hope this collection inspires further research, fosters interdisciplinary collaboration, and contributes to the responsible advancement of nanotechnology for the benefit of society and the environment..

Editors

Nanotechnology: Advances, Applications, and Challenge

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Nanotechnology: Advances, Applications, and Challenge

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Nanotechnology and Nanomaterials: Fundamentals, Evolution, and Multisectoral Industrial Applications

[1]E. Thenpandiyan

[2]T. Sathishpriya

[3]G. Pugazhmani

[4]K. Sakthimurugan

[1]Department of Physics, Academy of Maritime Education and Training, Kanathur, Chennai- 603 112, Tamil Nadu, India.

[2]Department of Science & Humanities (Physics), Loyola Institute of Technology, Palanchur, Chennai, India.

[3]Department of Nautical Science, Academy of Maritime Education and Training, Kanathur, Chennai- 603 112, Tamil Nadu, India.

[4]Department of Civil Engineering, C.K College of Engineering and Technology, Cuddalore, Tamil Nadu, India

Email: esthenpandiyan2@gmail.com

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Abstract

Nanotechnology has emerged as a transformative field within materials science, offering unprecedented control over matter at the nanometer scale and enabling the development of materials with unique and enhanced properties. Nanomaterials, typically defined by dimensions between 1 and 100 nm, exhibit distinct physical, chemical, and biological behaviors that differ significantly from their bulk counterparts due to size effects, large surface area, and high surface energy. This review presents an overview of the fundamental concepts of nanoscience and nanotechnology, tracing their historical evolution from early theoretical predictions to modern industrial applications. The interdisciplinary nature of nanotechnology, integrating physics, chemistry, biology, and engineering, has led to its widespread adoption across numerous sectors. Key applications discussed include computing, agriculture, food processing, bioprocessing, packaging, construction, transportation, healthcare, textiles, and chemical industries. The role of nanotechnology in improving performance, sustainability, safety, and efficiency across these industries is highlighted. Furthermore, the review emphasizes the growing importance of nanomaterials in addressing global challenges related to energy, environmental protection, and human health. Overall, this work underscores the significance of nanotechnology as a driving force for technological innovation and sustainable industrial development.

Keywords: Nanotechnology; computing; agriculture; civil construction; chemical; healthcare

Introduction

Advancements in materials science have significantly enhanced the quality of human life. Materials are an integral part of everyday activities and play a crucial role in essential sectors such as food, clothing, shelter, and transportation. Beyond improvements in conventional processing techniques and equipment, the development of novel materials has driven major progress in high-technology fields. Among these innovations, nanomaterials occupy a leading position in modern research and have attracted considerable attention from both academia and industry, making them one of the most valuable areas within materials science.

In the 1960s, Nobel laureate Richard Feynman proposed that precise control over matter at extremely small scales could result in materials with extraordinary and previously unattainable properties. His vision anticipated the diverse and unusual behaviors observed in materials when manipulated at the nanoscale. This idea laid the foundation for the concept of nanomaterials, which was formally introduced by Gleiter in 1981. Nanomaterials are defined as materials possessing crystalline or amorphous structures with dimensions in the nanometer range, including nanoparticles, nanowires, nanofilms, and nanostructured blocks. Due to their reduced size and distinctive structures, nanomaterials exhibit properties that differ markedly from those of bulk materials. For instance, copper may lose its electrical conductivity at very small dimensions, while silicon dioxide, typically an insulator, can exhibit semiconducting behavior at the nanoscale. These effects arise from unique characteristics such as extremely small particle size, large surface-to-volume ratio, and high surface energy [1, 2]. Nanoscience, which focuses on the study of materials and phenomena at the nanometer scale, has emerged as an interdisciplinary field bridging physics, chemistry, biology, and engineering. It has far-reaching implications for numerous scientific domains and industrial sectors.

Nanomaterials typically possess at least one dimension within the range of one billionth of a meter. According to the International Union of Pure and Applied Chemistry (IUPAC), nanoparticles are defined as particles with sizes between 1 and 100 nm. Materials with at least one dimension such as thickness, pore size, or surface features—within this range are also classified as nanomaterials [2, 3]. At this scale, materials demonstrate novel physical, chemical, and biological behaviors that differ from their bulk counterparts, enabling advanced applications in electronics, medicine, energy systems, and environmental remediation.

Nanotechnology is regarded as one of the most transformative technologies of the 21st century. It involves translating nanoscientific principles into practical applications through the observation, measurement, manipulation, assembly, and fabrication of matter at the nanoscale. The United States National Nanotechnology Initiative defines nanotechnology as science and engineering conducted at dimensions between 1 and 100 nm, where unique nanoscale phenomena allow for innovative applications across disciplines such as chemistry, physics, biology, medicine, engineering, and electronics [3]. This definition highlights two essential aspects: control at the nanoscale and the exploitation of novel properties that emerge at these dimensions.

The conceptual origins of nanotechnology trace back to Feynman's 1959 lecture, "There's Plenty of Room at the Bottom," delivered at the California Institute of Technology. In this talk, he envisioned the possibility of manipulating individual atoms and molecules, famously suggesting that the entire Encyclopedia Britannica could be written on the head of a pin. His ideas established the intellectual groundwork for modern nanotechnology. Later, in 1974, Japanese scientist Norio Taniguchi formally introduced the term "nanotechnology," defining it as the processing of materials through the manipulation of individual atoms or molecules [4]. While nanoscience focuses on understanding and studying phenomena at atomic and molecular scales, nanotechnology emphasizes the practical application of this knowledge to create functional systems and products [5].

Although several studies have documented the historical development of nanoscience and nanotechnology, a comprehensive summary outlining their progressive evolution remains limited. Therefore, it is essential to review and consolidate key milestones to gain a complete understanding of the growth and impact of this field.

Nanotechnology Applications

Applications of Nanotechnology Across Industries

Extensive analysis reveals that nanotechnology has introduced transformative applications across a broad range of industries. In many cases, multiple industrial sectors overlap under a single application area, highlighting the versatility of nanotechnology. The graphical abstract illustrates the diverse industries influenced by nanotechnological advancements, which are discussed in detail in the following sections [Figure 1].

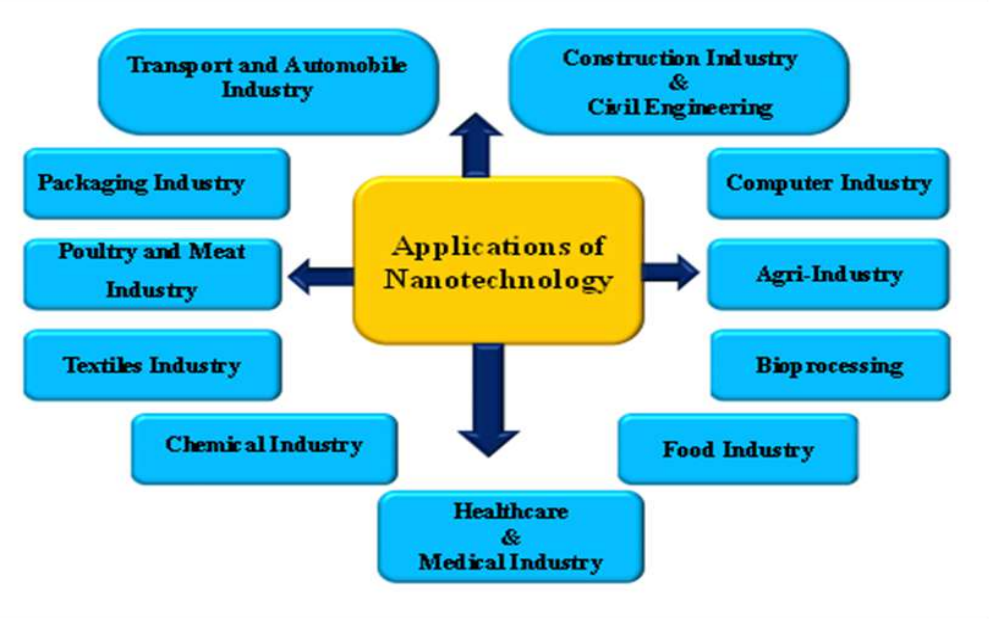

Figure 1 Applications of Nanotechnology Across Industries

- **Computer Industry**

Nanotechnology has evolved from foundational concepts in microengineering, physics, and materials science [6]. Miniaturization has long been a focus of the computer industry, where continuous efforts aim to develop compact, efficient, and high-performance devices. The replacement of conventional silicon-based components with carbon nanotubes and other nanostructures is actively being explored. The pioneering ideas of Feynman and Drexler have inspired the design of nanocomputers capable of unprecedented performance [7]. Devices such as laptops and smartphones have become significantly thinner and lighter, and nanotechnology is expected to further advance this trend, enabling even more sophisticated and portable computing technologies [8].

- **Agricultural Industries**

Agriculture plays a vital role in sustaining global economies and ensuring food security. However, changing climate patterns and global warming pose serious challenges to agricultural productivity [9]. To address these concerns, advanced and sustainable technologies are increasingly being adopted. Nanotechnology has emerged as an effective tool in improving agricultural practices, contributing to enhanced production, processing, storage, packaging, and transportation of agricultural products [10].

- **Bioprocessing Industries**

Nanotechnology has found increasing applications in the bioprocessing sector, particularly in food production and biomaterial manufacturing [8, 11]. Researchers are exploring the use of nanomaterials for pathogen detection, food quality monitoring, biosensors, smart and biodegradable packaging, and nano-encapsulation of bioactive compounds. These innovations support safer food production while addressing societal, ethical, and environmental considerations [12, 13]. Nanotechnology-based sensors improve the sensitivity and reliability of food quality assessments [14], while reduced energy consumption in production processes contributes positively to environmental sustainability [15].

- **Food Industry**

The food industry has widely adopted nanotechnology for applications including food processing, packaging, preservation, and safety monitoring [16]. Nanocomposite materials are used in packaging due to their superior barrier properties, while nanoparticles serve as antimicrobial agents to extend shelf life and prevent microbial contamination. Additionally, nanosensors are employed to detect pathogens and ensure food safety throughout the production and storage chain [17, 18].

- **Poultry and Meat Industry**

The poultry and meat sectors represent a significant portion of the global food industry but face challenges related to foodborne diseases. Nanobiotechnology offers effective solutions by enabling rapid pathogen detection and improving hygiene and safety standards. Nano-enabled disinfectants, biosensors, packaging materials, and protective equipment enhance product traceability, safety, and quality, reducing contamination risks before products enter the supply chain [19, 20].

- **Packaging Industry**

The packaging industry is undergoing continuous improvement in response to growing environmental concerns. Nanotechnology supports the development of eco-friendly, biodegradable packaging materials that ensure food safety while reducing environmental impact. Nanostructured biopolymers are increasingly replacing conventional plastic materials to promote sustainability [21].

- **Construction Industry and Civil Engineering**

Nanomaterials are increasingly incorporated into construction materials to improve sustainability, strength, durability, and workability [22]. Nanoparticles such as nano-silica enhance cement performance by improving compressive strength, pore structure, and durability. Nanotechnology has also enabled innovations such as smart windows, vacuum insulation panels, and phase-change materials that improve energy efficiency and indoor air quality [23]. Additional benefits include enhanced fire resistance, sound insulation, corrosion resistance, and reduced maintenance requirements [24].

- **Transport and Automobile Industry**

The automotive industry continues to evolve through the adoption of nanotechnology-based manufacturing methods. Nanomaterials enhance mechanical performance, durability, and self-repair capabilities while reducing production costs. Although initial investments are high, nano-enabled vehicles demonstrate improved longevity and reduced failure rates, making nanotechnology a promising driver of future automotive innovation [25].

- **Healthcare and Medical Industry**

Nanotechnology has revolutionized healthcare through the emergence of nanomedicine. It enables advanced diagnostic tools, targeted drug delivery systems, improved imaging techniques, and innovations in genomics, tissue engineering, and gene therapy [26]. These applications have significantly enhanced disease prevention, diagnosis, and treatment, positioning nanomedicine as a major research focus for future biomedical advancements [27].

- **Textile Industry**

The textile industry has embraced nanotechnology to enhance fabric durability, comfort, and functionality. Nanoparticle coatings improve properties such as water repellence, antibacterial activity, wrinkle resistance, flame retardancy, and dye affinity. These enhancements remain effective even after repeated washing, offering long-lasting performance improvements over conventional textiles [28, 29].

- **Chemical Industries**

Nanotechnology has broad applications in chemical industries, enabling structural and functional modifications of polymers and other materials. It supports advancements in energy production, catalysis, coatings, textiles, and water purification [30-31]. Nanoparticles, including silver and magnetic nanomaterials, are widely used for efficient catalysis and environmental remediation, particularly in removing contaminants from water sources [32].

Conclusion

Nanotechnology has emerged as one of the most influential scientific and technological advancements of the 21st century, fundamentally transforming both research and industrial practices. The unique properties of nanomaterials arising from their nanoscale dimensions, large surface area, and altered physicochemical behavior have enabled innovative solutions across diverse sectors. From enhancing computing efficiency and agricultural productivity to improving food safety, construction durability, transportation performance, and healthcare outcomes, nanotechnology has demonstrated its vast potential to address global challenges.

The widespread integration of nanomaterials into industries such as packaging, textiles, chemical processing, and environmental remediation further highlights their role in promoting sustainability, energy efficiency, and improved product performance. In particular, the development of eco-friendly materials, advanced sensors, smart coatings, and targeted medical therapies underscores the societal and economic significance of nanotechnology.

Despite these advancements, continued research is essential to fully exploit the capabilities of nanomaterials while addressing concerns related to safety, scalability, cost, and environmental impact. A clear distinction between nanoscience and nanotechnology, along with a thorough understanding of their historical evolution, is crucial for guiding future innovations. Overall, nanotechnology stands as a powerful enabling platform that will continue to shape the future of science, industry, and sustainable development.

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Applications In Textile, Construction, and Automotive Industries

[1]Dr. Muthurajan S
[2]Gold Beulah Patturose J
[1]Assistant Professor, Department of Marine Engineering, AMET University, Chennai, India.
[2]Assistant Professor, Department of AIDS, St. Joseph's Institute of Technology, Chennai, India.
Email: beulahpattu@gmail.com

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Abstract

This chapter provides a comprehensive review of advanced materials and technologies shaping modern applications in the textile, construction, and automotive sectors. Recent breakthroughs in nanotechnology, structural composites, and smart textiles have driven significant enhancements in performance, sustainability, and multifunctionality. By integrating nanoscale reinforcements and engineered fibre architectures, industry challenges related to weight reduction, durability, thermal and mechanical properties are being successfully addressed. The chapter outlines cross-sector technological synergies, such as nano-enhanced composites and smart fabric systems, demonstrating how materials innovations are powering next-generation industrial applications.

Keywords: Advanced materials, nanotechnology, smart textiles, structural composites, automotive composites, construction materials, sustainability

Introduction

The rapid evolution of global industries has significantly increased the demand for advanced materials that offer improved performance, sustainability, and multifunctionality. Traditional materials like metals, wood, and conventional polymers are being supplemented or replaced by novel materials engineered at micro and nano scales. These innovations have profound implications for the textile, construction, and automotive industries sectors where performance, efficiency, and environmental considerations are paramount. Recent research shows how nanotechnology, structural composites, and smart textiles are transforming these industries by enhancing mechanical properties, enabling lightweight design, and introducing novel functionalities.

Objectives

The primary objectives of this chapter are

- To analyse the role of advanced materials in modern industrial applications.
- To illustrate key technologies revolutionizing textile, construction, and automotive products.
- To identify performance benefits and sustainability advantages of these emerging materials.
- To highlight contemporary research progress and future directions.

Materials and Methods

This review synthesizes findings from peer-reviewed journals, high-impact articles, and recent industrial reports (2024–2026). It covers developments in nanotechnology, structural composites, technical and smart textile systems, and their intersection with construction and automotive engineering. Studies focusing on performance metrics, manufacturing methodologies, and sustainability considerations are emphasized.

Applications in the Textile Industry

- **Smart and Technical Textiles**

Smart textiles integrate functional materials (e.g., sensors, conductive fibres) to provide responsive behaviour to environmental stimuli. These textiles are crucial for wearables, protective clothing, and adaptive performance fabrics. Nanotechnology enables enhanced properties such as antimicrobial activity, water repellence, and self-cleaning functions.

- **Structural Textile Composites**

Textile structural composites, made by embedding textile fibres (glass, carbon, aramid) within matrices, offer exceptional strength-to-weight ratios and enhanced durability. These materials serve as reinforcements in load-bearing applications and are increasingly used in high-performance sectors.

- **Nanotechnology in Fabrics**

Nanomaterials such as nanoparticles and nanofibers bring functionalities like UV protection, antibacterial action, and enhanced mechanical behaviour into textiles. By applying coatings or built-in nanostructures, fabrics gain new capabilities without compromising comfort or flexibility.

Applications in the Construction Industry

- **Smart and Functional Construction Textiles**

High-performance textiles are used in geotextiles for soil reinforcement, filtration systems, and structural meshes. Smart textiles further incorporate sensors for structural health monitoring, enabling real-time assessment of stress and deformation.

- **Nanocomposite Construction Materials**

Nanocomposites incorporating nanofillers enhance concrete strength, reduce permeability, and improve resistance against environmental degradation. These materials contribute to longer service life and greater structural resilience.

- **Sustainability in Construction**

The use of natural fibres and bio composites supports sustainability goals by reducing reliance on energy-intensive materials and lowering carbon emissions throughout the lifecycle of building components.

Applications in the Automotive Industry

Lightweight Structural Composites

Lightweight composites are essential for reducing vehicle weight, improving fuel efficiency, and lowering emissions. Automotive manufacturers increasingly replace steel with carbon fibre and glass fibre composites for body panels, chassis components, and interior parts.

Eco-Friendly Materials

Recent developments include bamboo fibre composites reinforced with biodegradable polymers, offering sustainable alternatives to traditional plastics in automotive interiors while meeting strength and thermal stability requirements.

Integration of Smart Textiles

Smart and conductive textiles are incorporated into automotive seating, safety systems (e.g., airbag fabrics), and user interaction systems that adapt to occupant comfort and monitoring needs.

Cross-Sector Synergies

Advanced materials such as nanocomposites and engineered textiles demonstrate significant cross-sector applications. The automotive industry benefits from textile composites initially developed for aerospace; construction adopts fibre reinforcement concepts from automotive composites; and smart textile technologies find overlapping uses in wearables and infrastructure sensing.

Challenges and Future Trends

- **Manufacturing and Scalability**

Scalable production of advanced composite materials remains a challenge due to cost, process complexity, and quality control requirements.

- **Sustainability and Lifecycle Impact**

Lifecycle analysis, recycling infrastructure, and sustainable sourcing of raw materials are critical for aligning advanced materials with global environmental targets.

Emerging Research Directions

Future trends include multifunctional composites with integrated sensing, self-healing capabilities, and stronger bio-derived nanomaterials that combine performance with circular economy principles.

Conclusion

Advanced materials, including smart textiles, structural composites, and nanotechnology-enhanced systems, are transforming textile, construction, and automotive industries. These innovations improve performance, sustainability, and functional adaptability while addressing key industry challenges such as weight reduction and environmental resilience. Continued interdisciplinary research and industrial collaboration will further accelerate the integration of these materials into next-generation products.

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Health and Environmental Risks of Nanomaterials

Anurag Chourasia

Assistant Professor, Quantum School of Health Science, Quantum University

Email: anurag.research01@gmail.com

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Abstract

The rapid advancement of nanotechnology has introduced unprecedented opportunities across multiple sectors, yet simultaneously raised significant concerns regarding potential health and environmental risks associated with nanomaterial exposure. This chapter provides a comprehensive examination of the toxicological profiles, exposure pathways, and ecological impacts of engineered nanomaterials. We explore the unique physicochemical properties that govern nanomaterial behavior in biological and environmental systems, including size-dependent reactivity, surface chemistry, and cellular uptake mechanisms. The discussion encompasses occupational and consumer exposure scenarios, health effects observed in experimental studies, and environmental accumulation patterns. Particular attention is devoted to challenges in risk assessment methodologies and current regulatory frameworks. The chapter evaluates safe-by-design principles in nanomaterial development and protective strategies for workers, consumers, and ecosystems. By synthesizing current scientific understanding with regulatory perspectives, this chapter aims to foster informed decision-making in nanotechnology development while ensuring human and environmental safety remains paramount.

Keywords: Nanotoxicology, environmental impact, risk assessment, occupational exposure, safe-by-design

Introduction

The emergence of nanotechnology as a transformative force across industries has fundamentally altered our approach to material science, manufacturing, and product development. Nanomaterials, defined as materials with at least one dimension measuring between 1 and 100 nanometers, exhibit unique properties that differ markedly from their bulk counterparts, enabling revolutionary applications in medicine, electronics, energy, and consumer products (Maynard & Aitken, 2023).

However, these same size-dependent properties that make nanomaterials valuable also raise critical questions about their potential impacts on human health and environmental systems. The exponential growth in nanomaterial production has outpaced our understanding of their long-term consequences, creating an urgent need for comprehensive risk assessment and management strategies (Oberdörster et al., 2024).

The nano-scale dimension introduces fundamentally different physical, chemical, and biological interactions compared to conventional materials. Increased surface area to volume ratios, enhanced reactivity, and the ability to cross biological barriers create both opportunities and challenges (Nel et al., 2023). Understanding these dual-edged characteristics becomes essential as nanomaterials increasingly permeate everyday products, from cosmetics and textiles to food packaging and medical devices. The scientific community faces considerable challenges in establishing standardized protocols for assessing nanomaterial safety, as traditional toxicological testing methods often prove inadequate when applied to nanomaterials (Stone et al., 2023). This chapter examines the multifaceted dimensions of nanomaterial risk, integrating toxicological evidence with environmental fate studies and regulatory developments (Fadeel & Garcia-Bennett, 2024).

Physicochemical Properties and Toxicity Mechanisms

The toxicological behavior of nanomaterials fundamentally depends on their physicochemical characteristics. Particle size represents the most obvious distinguishing feature, with smaller nanoparticles generally exhibiting greater biological reactivity and ability to penetrate cellular membranes (Monopoli et al., 2023). Studies demonstrate that particles below 10 nanometers can translocate across epithelial barriers and potentially reach distant organs including the brain. However, size alone insufficiently predicts toxicity, as surface area and surface chemistry emerge as equally critical determinants. The dramatically increased surface area to mass ratio provides abundant sites for molecular interactions and generation of reactive oxygen species that trigger cellular stress responses (Xia et al., 2023).

Oxidative stress emerges as a predominant mechanism underlying nanomaterial toxicity across diverse material types. The generation of reactive oxygen species triggers cascades that can overwhelm antioxidant defenses and damage cellular components including lipids, proteins, and DNA (Li et al., 2023). Inflammation constitutes another fundamental response, mediated through immune cell activation and pro-inflammatory cytokine release. The inflammasome pathway has emerged as key in nanomaterial recognition, leading to chronic inflammation that may contribute to fibrosis and other pathological outcomes (Boraschi et al., 2023). Shape and crystal structure add complexity, with fiber-like nanomaterials raising concerns due to structural similarity to asbestos fibers, potentially triggering similar pathogenic mechanisms in lung tissue (Poland et al., 2023).

Human Health Risks and Exposure Pathways

Human exposure to engineered nanomaterials occurs through multiple pathways, with occupational settings representing the most significant source of direct contact. Workers involved in nanomaterial synthesis and processing face potential inhalation exposure to airborne nanoparticles, dermal contact, and possible ingestion (Schulte et al., 2024). Inhalation represents the primary concern, as respirable nanoparticles deposit throughout the respiratory tract with patterns influenced by particle size and shape. The respiratory system emerges as a primary target organ, with evidence documenting pulmonary inflammation, oxidative stress, and fibrotic responses following exposure (Miller et al., 2024). Carbon nanotubes, particularly long rigid fibers, have shown capacity to induce asbestos-like pathological changes in animal models (Donaldson et al., 2023).

Consumer exposure affects broader populations through diverse products. Cosmetics and personal care products containing nanoscale titanium dioxide, zinc oxide, or silver represent widespread sources of dermal exposure (Lorenz et al., 2024). Food contact materials may release nanomaterials into food products, creating oral exposure pathways. Systemic distribution following exposure represents a critical consideration, as certain nanoparticles can translocate from lungs to bloodstream and distribute to liver, spleen, kidneys, and potentially the brain (Geiser & Kreyling, 2023). Cardiovascular effects have been documented, including endothelial dysfunction and thrombotic tendencies, consistent with epidemiological observations linking particulate air pollution to cardiovascular events. Reproductive and developmental toxicity represent growing concerns, with some nanomaterials demonstrating ability to cross placental barriers (Campagnolo et al., 2024).

Environmental Fate and Ecological Impacts

The environmental journey of nanomaterials involves complex transformation processes that modify their properties and influence ecological impacts. Manufacturing facilities, wastewater treatment plants, and product weathering contribute to environmental releases (Keller & Lazareva, 2023). Once released, nanomaterials undergo transformations including agglomeration, dissolution, surface oxidation, and interaction with natural organic matter. These transformations vary with environmental conditions such as pH, ionic strength, and presence of organic ligands (Lowry et al., 2024). Aquatic systems receive particular attention due to their role as receiving waters. Nanoparticles interact with suspended particles, sediments, and organisms through diverse mechanisms, with some demonstrating persistence while others undergo rapid transformation (Lead & Batley, 2024).

Soil ecosystems represent another critical compartment where nanomaterials may accumulate. Soil properties including organic matter content and pH influence nanomaterial behavior and effects (Judy et al., 2024). Studies report altered microbial community structure following nanomaterial exposure, with potential consequences for nutrient cycling. Ecological toxicity manifests across multiple organizational levels. Aquatic invertebrates demonstrate various sensitivities including mortality, reproductive impairment, and behavioral changes (Hua et al., 2023). Fish exhibit responses ranging from gill damage to neurotoxicity depending on nanomaterial type and exposure conditions. The concept of trophic transfer raises particular concern, with evidence indicating some nanomaterials can pass from prey to predators and potentially accumulate in higher trophic levels (Markus et al., 2024).

Risk Assessment and Regulatory Frameworks

Assessing risks posed by nanomaterials requires adapting traditional toxicological frameworks to accommodate unique nanoscale characteristics. Conventional risk assessment paradigms encounter numerous challenges when applied to nanomaterials (Hansen et al., 2024). Dose metrics represent a fundamental challenge, as mass-based measurements may poorly correlate with biological effects compared to surface area or particle number. The transformation of nanomaterials in biological systems necessitates consideration of both pristine materials and their transformed states (Oomen et al., 2023). Exposure assessment faces significant methodological hurdles from analytical challenges. Detecting and quantifying nanomaterials in complex matrices pushes limits of current techniques, and distinguishing engineered nanomaterials from naturally occurring nanoparticles requires sophisticated approaches (Montaño et al., 2024).

Regulatory frameworks worldwide are evolving to address nanotechnology-specific considerations, though approaches vary across jurisdictions. The European Union has implemented nano-specific requirements including mandatory notification systems and adapted testing requirements under REACH (Rasmussen et al., 2024). The United States takes a case-by-case approach across different regulatory agencies. International organizations work to harmonize testing methods and promote regulatory cooperation (OECD, 2023). The development of standardized testing protocols specifically designed for nanomaterials represents a critical step. International standards organizations have developed protocols addressing characterization, sample preparation, and toxicity testing (ISO/TR 13121, 2023). Alternative testing strategies including in vitro assays and computational models receive increasing attention as means to reduce animal testing while providing mechanistically relevant data (Arts et al., 2023).

Safe-by-Design and Risk Management

The concept of safe-by-design represents a proactive approach to minimizing risks by incorporating safety considerations throughout the innovation process. Rather than relying solely on protective measures implemented after development, safe-by-design seeks to engineer safety into nanomaterials from the outset (Hjorth et al., 2023). This requires early-stage consideration of how material properties influence hazard potential, with deliberate choices regarding size distribution, surface chemistry, and shape to minimize adverse effects while maintaining functionality (Soeteman-Hernández et al., 2024). Surface modification represents a powerful tool, as coating nanomaterials with biocompatible polymers can reduce cellular uptake and enhance colloidal stability (Weber et al., 2023).

Occupational health measures remain essential for protecting workers. Engineering controls including ventilation and closed systems represent the preferred approach to minimizing exposures (Kuempel et al., 2023). Personal protective equipment serves as a final defense when other controls prove insufficient. Life cycle thinking extends consideration beyond manufacturing to environmental releases during production, potential exposures during product use, and fate following disposal (Caballero-Guzman et al., 2023). Products may release particles during use or weathering, creating consumer and environmental exposures. End-of-life management represents a challenge, as conventional waste treatment may not effectively contain nanomaterials. These life cycle considerations inform efforts to develop more sustainable nanotechnologies (Arvidsson et al., 2024).

Conclusions

The health and environmental risks associated with nanomaterials present complex challenges requiring continued scientific investigation, thoughtful regulation, and responsible innovation practices. While substantial progress has been made in understanding how nanomaterial properties influence toxicity and environmental behavior, significant knowledge gaps remain regarding long-term effects and ecosystem-level impacts. The field has matured toward more nuanced, material-specific risk assessments that recognize the diversity of nanomaterial types. Safe-by-design principles offer promising pathways for developing nanomaterials that maintain beneficial properties while minimizing hazard potential. Effective risk management requires integration of scientific knowledge with regulatory frameworks, occupational health practices, and life cycle considerations. As nanotechnology continues advancing, maintaining vigilance regarding potential risks while fostering beneficial innovation represents an ongoing imperative for the scientific community, industry, and regulatory authorities.

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Comparison of Nickel Sulphide (NiS) Thin Films for Photovoltaic Applications Prepared by Different Methods

Dr. K.A. Jamal Basha

Department of Physics, Government College for Men (A), Kadapa-516004, AP, India.

Email: jbluckys1531@gmail.com

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Abstract

Nickel sulphide ($Ni–S_x$) thin films are increasingly seen as promising multifunctional materials due to their phase-dependent electrical conductivity, adjustable band gap, excellent electrochemical activity, and catalytic abilities. The Ni–S system exhibits diverse polymorphs, including NiS, NiS_2, Ni_3S_2, and other non-stoichiometric phases, enabling applications in photovoltaics, supercapacitors, lithium-ion batteries, hydrogen evolution catalysis, sensors, and optoelectronics. This chapter offers a thorough review of synthesis methods, structural characterisation techniques (XRD, SEM, TEM), optical band gap measurement via Tauc analysis, electronic band structure considerations, and a comparison of chemical bath deposition (CBD) and physical vapour deposition (PVD) processes. It also explores challenges related to phase control, defect engineering, and stability, along with future prospects in flexible electronics and hybrid heterostructures.

Keywords: Nickel sulphide, NiS, NiS_2, Ni_3S_2, Thin films, XRD, Tauc plot, Band gap, Chemical bath deposition, Physical vapour deposition, Energy storage.

Introduction

Transition metal chalcogenides (TMCs) are an expanding class of materials characterised by tunable electrical and optical properties [5–13]. Notably, nickel sulphide ($Ni–S_x$) stands out due to its multiple stoichiometric forms, capacity to transition from metallic to semiconducting states, high electrochemical activity, Remarkable catalytic efficiency, and their structural versatility. These $Ni–S_x$ compounds include diverse phases such as NiS (hexagonal), NiS_2 (cubic pyrite), Ni_3S_2 (rhombohedral), and Ni_7S_6 [4–6]. The thin-film variants of these materials hold particular promise for integration into various devices.

Crystal Chemistry and Phase Diagram of Ni–S System

Polymorphism

The Ni–S binary system is complex and contains multiple stable and metastable phases [4].

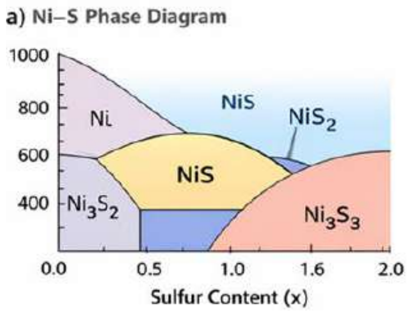

Figure 1. Phase Diagram of Ni–S_x thin films.

S.NO	Compound	Phase	Electrical Nature
1	NiS	Hexagonal (millerite)	Metallic
2	NiS_2	Cubic (pyrite)	Semiconductor
3	Ni_3S_2	Rhombohedral	Metallic

Table 1: Phase related nature of Compound

Thin Film Deposition Techniques

Chemical Bath Deposition (CBD)

Chemical Bath Deposition (CBD) is one of the most widely used solution-based techniques for preparing nickel sulphide (NiS) thin films due to its simplicity, scalability, and low fabrication cost. The method relies on controlled chemical reactions occurring in an aqueous solution containing nickel precursor salts and sulfur-releasing agents, where thin film growth takes place through slow ionic precipitation onto a substrate surface. In this process, nickel ions (Ni +2) react with sulfide ions (S-2) generated in situ, resulting in the formation of nickel sulphide according to the reaction:

$$Ni^{2+} + S^{2-} \rightarrow NiS$$

The deposition mechanism involves nucleation followed by ion-by-ion growth or cluster-by-cluster aggregation, depending on bath chemistry and reaction kinetics. Complexing agents are typically introduced to regulate the release rate of metal ions, thereby preventing rapid bulk precipitation and enabling uniform film formation on immersed substrates. Literature reports indicate that parameters such as bath temperature, solution pH, precursor concentration, and deposition duration critically influence film thickness, crystallinity, and stoichiometry [10–12]. One of

CBD's main benefits is that it works at comparatively low temperatures, typically below 100 °C making it suitable for substrates that are sensitive to temperature, such glass and polymers. Furthermore, the technique greatly lowers production costs by enabling uniform coating across enormous surface regions without the need for complex vacuum equipment. Because of these qualities, CBD is especially appealing for the large-scale production of absorber layers in optoelectronic coatings, electrochemical electrodes, and solar systems.

Furthermore, CBD-grown NiS films often display nanocrystalline structures characterised by small grain sizes. This structural feature manifests in X-ray diffraction patterns as broadened diffraction peaks, reflecting reduced crystallite dimensions and increased lattice strain [11]. While such nanoscale features can enhance surface area and catalytic activity, they may simultaneously introduce defect states that influence optical band gap and electrical transport properties.

Physical Vapour Deposition (PVD)

A popular vacuum-based method for creating high-quality nickel sulphide ($Ni–S_x$) thin films with excellent crystallinity, compositional control, and robust substrate adherence is physical vapour deposition (PVD). In contrast to solution-based techniques, PVD uses controlled vacuum conditions to physically transfer material from a solid source to a substrate through vaporisation and condensation. Using thermal evaporation, electron-beam evaporation, or sputtering techniques, nickel or nickel sulphide targets are vaporised during the deposition process. The vaporised species then react with sulphur vapour or a reactive gas environment to form nickel sulphide films on the substrate surface. During reactive deposition, the overall reaction can be written as

Ni (vapor)+S (vapor)→NiS (vapor)

The vacuum environment is essential for reducing contamination and providing exact control over the microstructure, stoichiometry, and film thickness. The dynamics of film growth are greatly influenced by parameters such working pressure, plasma power, substrate temperature, and deposition rate. Higher substrate temperatures encourage adatom surface diffusion, which improves dense film morphology and crystalline ordering. Therefore, when compared to their chemically deposited equivalents, PVD-grown nickel sulphide films frequently show well-defined grain morphologies and improved phase purity. [13,14]

Spray Pyrolysis and Other Techniques

Spray pyrolysis is another common approach, particularly for high-temperature synthesis, producing crystalline films with enhanced grain size. In this technique, precursor solutions are atomized onto heated substrates, causing rapid solvent evaporation and film formation. The substrate temperature can induce phase transitions, often resulting in films with different stoichiometries (e.g., Ni_3S_2) and morphological features [6, 7,8].

Other methods include pulsed laser deposition (PLD), sputtering, successive ionic layer adsorption and reaction (SILAR) [12], and hydrothermal approaches. These techniques can yield high-quality films but require more specialized equipment compared to CBD.

Structural and Phase Properties of NiS Films

Crystal Structure, Size and Strain

X-ray diffraction (XRD) is the predominant tool used to determine phase and crystallinity of NiS thin films. CBD-derived NiS films typically exhibit a hexagonal α-NiS phase (space group $P6_3/mmc$) with lattice parameters close to reported bulk values [4, 8]. Variations in deposition time and solution chemistry can influence crystallite size and preferred orientation. Secondary phases such as Ni_3S_2 or NiS_2 are sometimes observed in high-temperature methods or when the S/Ni ratio deviates from unity, indicating phase sensitivity to stoichiometry and thermal budget [6].

Crystallite size is commonly estimated using the Scherrer equation from XRD peak broadening, with values ranging from ~7 nm to ~35 nm depending on deposition method and parameters. Longer deposition times generally promote grain growth but may also introduce strain and dislocations due to lattice mismatch and defect accumulation.

XRD confirms phase formation. Crystallite size calculated using the Scherrer equation [16]:

$$L_c = \frac{0.9\lambda}{\beta \cos\theta}$$

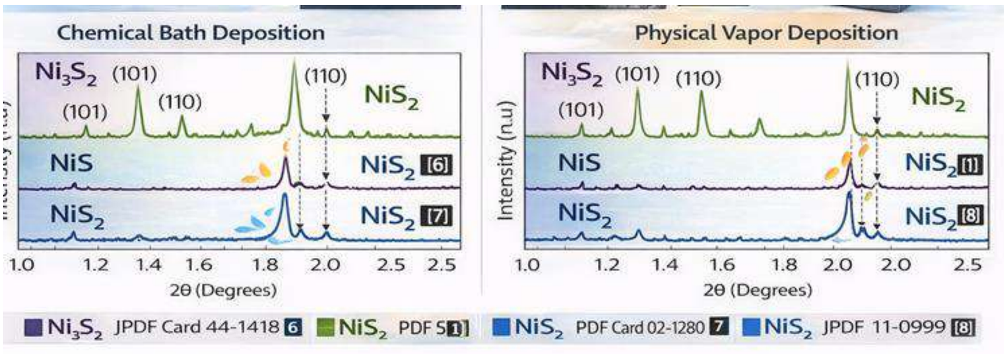

Figure 2. XRD patterns of Ni–S_x thin films (CBD vs PVD) [6,7,8,11].

S. No	Deposition Method	Key Parameters	Phase and Preferred Orientation	Crystallite Size (nm)	Results	Ref.
1	CBD	80 °C, 60–150 min	Hexagonal α-NiS, (010)	7–19	Grain size increases with deposition time	Basha et al. (2022)
2	CBD	70 °C, 2 h	Hexagonal α-NiS, (101)	12–18	Uniform polycrystalline films	Nwauzor et al. (2023)
3	Spray Pyrolysis	300–450 °C	Hexagonal / Ni_3S_2 (at high T), (110)	20–35	Phase transition at elevated T	Gahtar et al. (2020)
4	Spray Pyrolysis	350 °C	Hexagonal α-NiS, (012)	25	Dense morphology	Gahtar et al. (2021)
5	CBD (Al-doped)	75°C,90 min	Hexagonal α-NiS, (010)	10–22	Doping modifies crystallinity	Ugwu et al. (2025)
6	CBD (Zn-doped)	85 °C	Hexagonal α-NiS, (011)	15–28	Zn incorporation without phase change	Younus et al. (2023)

Table 2: Summary of Synthesis Parameters and Structural Properties

Morphology and Surface Characteristics (SEM/TEM)

Surface morphology profoundly impacts the optical absorption and electronic transport of NiS thin films. Scanning electron microscopy (SEM) studies report a range of features from Aggregated nano-grains, Flower-like clusters, Compact hexagonal grains, Porous and dendritic structures. Optimized CBD films exhibit homogeneous and crack-free surfaces, while high-temperature deposition methods often yield dense microstructures with larger grain sizes [5, 7]. Atomic force microscopy (AFM) adds insight into surface roughness and three-dimensional features, linking them to film thickness and deposition kinetics. Rougher surfaces with larger grain boundaries tend to increase light scattering, which may benefit photovoltaic applications but can impede carrier transport.

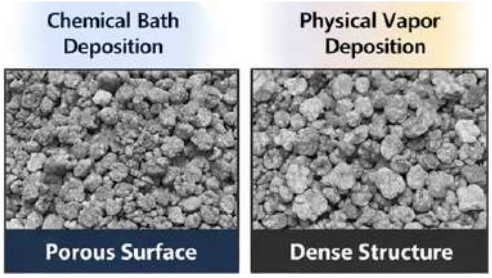

Figure 3. SEM images of Ni–S_x thin films (CBD vs PVD) [7,11].

S.No	Deposition method	Morphology	Grain Shape	Surface Quality	Results	Ref.
1	CBD	Compact grains	Hexagonal	Uniform	Photovoltaic absorber	Basha et al.
2	CBD	Nanograins	Spherical	Crack-free	Optoelectronic films	Nwauzor et al.
3	Spray	Granular / dense	Polyhedral	Dense	Supercapacitor	Gahtar et al. (2021)
4	Zn-doped	Fine grains	Nanocrystalline	Smooth	Band-gap tuning	Younus et al.
5	Al-doped	Slight agglomeration	Irregular	Stable	Enhanced conduction	Ugwu et al.

Table 3: Morphological Characteristics

Optical Properties and Band Gap

Optical characterization using UV–Vis spectroscopy reveals that NiS thin films show direct band gap behavior

Absorption Coefficient

The absorption coefficient was calculated using the following formula.

$$\alpha = -\frac{lnT}{d}$$

where the α is absorption coefficient of film, T is transmittance, d denotes the thickness of film.

Tauc Plot Analysis

The energy band gap of the film was evaluated using the Tauc's relation between the absorption coefficient and band gap,

$$(\alpha h\upsilon)^2 = A(h\upsilon - E_g)$$

where A is constant of proportionality and hυ, the photon energy. From Fig. 6 the plot of 〖(αhυ) 〗^2 versus hυ indicated a straight line and the tangent of its linear part onto the horizontal energy axis gave the value of optical band gap.

n = 2 (direct), n = 1/2 (indirect)

Band gap values for NiS thin films range from ~1.8 to ~2.5 eV, influenced by phase composition, crystallite size, and defect states. CBD-derived films generally show band gaps around ~2.0–2.3 eV, making them suitable as visible light absorbers [4, 9]. Doping (e.g., Zn incorporation) offers a route to engineer band gaps within desired ranges without fundamentally altering the underlying crystal structure, a strategy demonstrated in several studies [9].

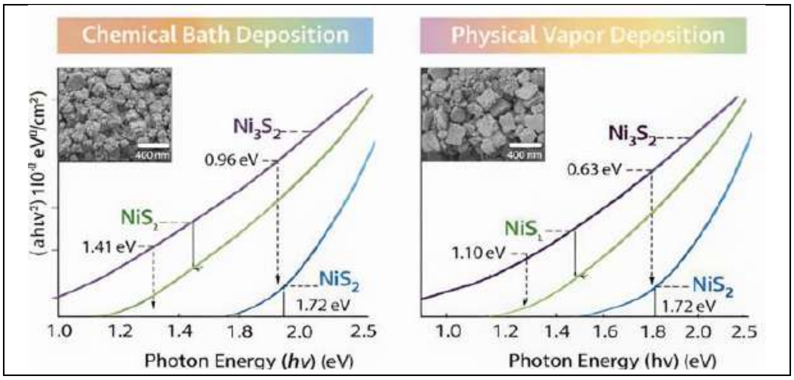

Figure 4. Comparative Tauc plots of Ni–S_x thin films (CBD vs PVD)

S.No	Deposition Method	Band Gap (eV)	Transition Type	Absorption Edge (nm)	Optical Behavior	Results	Ref.
1	CBD	1.93–2.09	Direct	593–642	High absorption	Band gap minimum at optimal deposition time	Basha et al. (2022)
2	CBD	~2.30	Direct	~540	Moderate transparency	Suitable for optoelectronics	Nwauzor et al. (2023)
3	Zn-doped CBD	2.1–2.4	Direct	Tunable	Improved absorption	Band gap engineered via Zn	Younus et al. (2023)
4	Spray Pyrolysis	2.0–2.3	Direct	Variable	Strong visible absorption	Temperature dependent	Gahtar et al. (2020)

5	Thin film (ab initio supported)	~1.8–2.2	Mixed	—	Metallic tendencies	d-band contributions	Metallic study (2015)

Table 4: Optical Properties of NiS Thin Films

Electrical Transport Properties

Electrical measurements indicate that NiS thin films can exhibit semiconducting behavior with comparatively high conductivity (tens of S cm^{-1}) relative to many other chalcogenides. Conductivity typically increases with improved crystallinity and reduced grain boundary scattering. Temperature-dependent conductivity follows an Arrhenius formula

$$\sigma = \sigma_{\circ}\ e^{\frac{-E}{KT}}$$

Activation energies extracted from such studies are often low (~0.1–0.3 eV), consistent with shallow trap states and efficient charge carrier transport [10,18,19]. Dopants such as Al and Zn influence carrier concentrations and mobility, enabling property tuning for specific device requirements.

S.No	Method	Conductivity (S cm^{-1})	Activation Energy (eV)	Transport Mechanism	Results	Ref.
1	CBD	Up to 48	0.16	Thermally activated	Maximum conductivity at optimized time	Basha et al. (2022)
2	CBD	Moderate	0.2–0.3	Semiconductor	Grain boundary limited	Nwauzor et al. (2023)
3	Spray Pyrolysis	High	0.15	Polaron hopping	Supercapacitor electrodes	Gahtar et al. (2021)
4	Al-doped CBD	Increased vs. undoped	0.12–0.22	Impurity-mediated	Doping enhances carrier density	Ugwu et al. (2025)
5	Thin film	Metallic-like	—	Band conduction	Supported by DFT	Metallic study (2015)

Table 5: Electrical Properties and Transport Mechanisms

Conclusions

Nickel sulphide thin films offer exceptional versatility due to their polymorphism and tunable electronic properties. While CBD provides a cost-effective route for large-scale production, PVD ensures superior crystallinity and phase control. Continued research into defect engineering, heterostructure design, and stability enhancement will further expand their applications in next-generation energy and optoelectronic devices. Accurate correlation between synthesis conditions and characterization results is essential for optimizing performance in energy storage, catalysis, and optoelectronic applications.

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Recent Advances in Supercapacitor Technology: A Comprehensive Review

Dr. Sandip V Patil

Department of Physics, Shri Pancham Khemraj Mahavidyalaya (Autonomous), Sawantwadi, Ratnagiri, (MH), India.

Email: spkphysics.svp@gmail.com

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Abstract

Supercapacitors (SCs), also known as electrochemical capacitors, have gained increasing attention as advanced energy storage devices due to their high-power density, rapid charge–discharge capability, and long cycle life. However, their relatively low energy density compared with batteries remains a key limitation. Recent research has focused on improving electrode materials, electrolytes, and device configurations to overcome these challenges. This review summarizes recent advances in supercapacitor technology, emphasizing electrode material development, electrolyte innovations, novel device architectures, and emerging research trends. The challenges and future prospects of supercapacitors are also discussed.

Keywords: SCs, electrolytes, electrical double layer capacitors, carbon-based materials

Introduction

The growing demand for efficient, reliable, and sustainable energy storage systems has intensified research into supercapacitors for applications such as electric vehicles, renewable energy systems, portable electronics, and wearable devices. Unlike conventional batteries, supercapacitors store energy through electrostatic charge accumulation or fast surface redox reactions, enabling high power density and excellent cycling stability [1]. Nevertheless, achieving higher energy density without sacrificing power performance remains a major research challenge [2].

Fundamentals of Supercapacitors

Types of Supercapacitors

Supercapacitors are generally classified into three categories:

- **Electrical Double Layer Capacitors (EDLCs):** Energy storage occurs via electrostatic charge separation at the electrode–electrolyte interface, typically using carbon-based materials [1]. Electrical Double Layer Capacitors (EDLCs) store energy through electrostatic charge separation at the electrode–electrolyte interface without involving any chemical reactions. When a potential is applied, electrons accumulate on the surface of the carbon-based electrode, while oppositely charged ions from the electrolyte migrate and adsorb onto the electrode surface. This process forms an electrical double layer consisting of two parallel layers of charge separated by a very small distance. The energy storage mechanism in EDLCs is purely physical and depends strongly on the large specific surface area and high electrical conductivity of carbon materials such as activated carbon, carbon nanotubes, and graphene. Because no Faradaic reactions occur, EDLCs exhibit extremely fast charge–discharge rates, excellent cycling stability, and high-power density, although their energy density is relatively low.
- **Pseudo capacitors:** Charge storage involves fast and reversible Faradaic redox reactions using metal oxides or conducting polymers [3]. Pseudo capacitors store energy through fast and reversible Faradaic redox reactions occurring on or near the surface of the electrode material. Upon charging, electrolyte ions interact with the electrode and undergo electron transfer reactions, leading to charge storage through surface redox processes, intercalation, or electro sorption. Unlike battery-type reactions, these Faradaic processes are highly reversible and occur without significant phase transformation of the electrode material. As a result, pseudo capacitors provide much higher specific capacitance and energy density than EDLCs. Common pseudocapacitive materials include transition metal oxides such as manganese dioxide and ruthenium dioxide, as well as conducting polymers like polyaniline and polypyrrole. However, repeated redox cycling can cause structural degradation, leading to comparatively lower cycle life than EDLCs.
- **Hybrid Supercapacitors:** These combine EDLC and pseudocapacitive electrodes to achieve a balance between energy and power density [5]. Hybrid supercapacitors combine the charge storage mechanisms of EDLCs and pseudo capacitors to achieve a balance between high power density and improved energy density. In typical asymmetric hybrid supercapacitors, one electrode is made of a carbon-based EDLC material, while the other electrode consists of a pseudocapacitive material such as a metal oxide or conducting polymer. This configuration allows the device to operate over a wider voltage window, thereby significantly increasing energy density. In another approach, hybrid electrodes are fabricated by integrating carbon materials with pseudocapacitive components within a single electrode, enabling simultaneous electrostatic

charge storage and Faradaic reactions. Through this synergistic mechanism, hybrid supercapacitors overcome many limitations of individual systems and are considered promising candidates for next-generation energy storage applications.

Performance Parameters

The performance of supercapacitors is evaluated using metrics such as specific capacitance, energy density, power density, and cycling life. Strategies to improve these parameters include increasing electrode surface area, optimizing pore structure, and expanding the operating voltage window [2].

Recent Advances in Electrode Materials

1. Carbon-Based Materials

Carbon materials are widely used due to their high conductivity, chemical stability, and large surface area. Recent developments include graphene, carbon nanotubes, and reduced graphene oxide with hierarchical pore structures to enhance ion transport and charge storage [9]. Multiscale reduced graphene oxide structures have demonstrated significant improvements in both energy and power density [4].

Activated carbon is the most commercially adopted carbon material for supercapacitor electrodes because of its extremely high surface area, which typically exceeds 1000 $m^2 g^{-1}$. It is commonly derived from biomass or polymer precursors through chemical or physical activation processes. The presence of micro- and mesopores provides abundant active sites for ion adsorption, resulting in high capacitance. However, excessive microporosity can hinder ion diffusion at high charge–discharge rates, limiting power performance. To address this, recent research focuses on optimizing hierarchical pore structures to improve ion accessibility and rate capability.

Carbon nanotubes (CNTs) have attracted significant attention due to their one-dimensional tubular structure, excellent electrical conductivity, and mechanical strength. CNTs provide efficient electron transport pathways and form interconnected conductive networks that reduce internal resistance. Although their specific surface area is lower than that of activated carbon, their open pore structure facilitates rapid ion diffusion, leading to high power density and excellent cycling stability. CNTs are often used in combination with other carbon materials or pseudocapacitive compounds to enhance overall capacitance.

Graphene and graphene-derived materials, such as graphene oxide and reduced graphene oxide, represent a major advancement in supercapacitor electrode design. Graphene possesses a two-dimensional structure with exceptionally high theoretical surface area and superior electrical conductivity. However, restacking of graphene sheets reduces accessible surface area and limits performance. To overcome this issue, strategies such as introducing spacers, creating three-dimensional graphene frameworks, and forming composites with metal oxides or conducting polymers have been developed. These approaches significantly enhance ion transport and charge storage capability.

Porous carbon materials and biomass-derived carbons have emerged as sustainable alternatives for supercapacitor electrodes. Biochar obtained from agricultural waste, cellulose, or lignin offers tunable porosity and surface functionality through controlled activation and heteroatom doping. The incorporation of heteroatoms such as nitrogen, sulfur, or phosphorus improves surface wettability, electrical conductivity, and pseudocapacitive behavior, thereby enhancing overall electrochemical performance.

2. Metal Oxides and Mixed Oxides

Transition metal oxides such as MnO_2, $NiCo_2O_4$, and RuO_2 exhibit high pseudo capacitance due to multiple oxidation states [3]. Recent research has focused on nano structuring and composite formation to address issues such as low conductivity and poor cycling stability [5].

Among metal oxides, manganese dioxide (MnO_2) is the most widely studied material due to its low cost, high theoretical capacitance (approximately 1370 F/g), and environmental friendliness. MnO_2 exhibits excellent pseudocapacitive behavior through a mechanism involving reversible ion intercalation and deintercalation, typically in aqueous electrolytes. However, MnO_2 suffers from poor electrical conductivity, which can limit its performance, particularly at high charge/discharge rates. To mitigate this issue, MnO_2 is often combined with conductive materials such as carbon-based substances or conducting polymers to form hybrid composites that enhance electrical conductivity and structural stability.

Ruthenium oxide (RuO_2) is another widely studied metal oxide with exceptional pseudocapacitive properties, providing both high capacitance and high voltage operation. Ruthenium oxide has a higher theoretical capacitance (up to 1000 F/g) than MnO_2 and maintains a relatively high energy density. Its performance, however, is limited by its high cost and the relatively scarce availability of ruthenium. Despite these drawbacks, RuO_2 is commonly used in high-performance supercapacitors, particularly in aerospace and military applications, where high energy and power densities are crucial.

To address the limitations of individual metal oxides, mixed metal oxides have been developed to combine the beneficial properties of different metals and achieve enhanced electrochemical performance. For instance, nickel-cobalt oxide ($NiCo_2O_4$) has gained attention due to its excellent electrochemical stability, high conductivity, and superior capacitance. The synergistic effects between nickel and cobalt ions in the mixed oxide structure allow for enhanced redox reactions, leading to a significant increase in specific capacitance and cycling stability. Mixed metal oxides like $NiCo_2O_4$ can be synthesized through various methods such as

hydrothermal, sol-gel, or chemical vapor deposition, offering tunable electrochemical properties depending on the composition and morphology.
Other notable mixed oxides include nickel-manganese oxide ($NiMn_2O_4$), cobalt-manganese oxide ($CoMn_2O_4$), and nickel-iron oxide ($NiFe_2O_4$). These composite materials often exhibit enhanced conductivity, higher capacitance, and greater electrochemical stability compared to pure metal oxides. For example, Co_3O_4 and NiO have been combined in hybrid systems to improve both energy and power densities, while nickel-iron oxide composites have been explored for their improved electrochemical activity and longer cycling life in alkaline electrolytes.

3. Conducting Polymers

Conducting polymers, including polyaniline and polypyrrole, offer high theoretical capacitance and flexibility. However, mechanical degradation during cycling limits their lifespan. Recent studies have employed nanocomposite and surface-coating strategies to improve structural stability and electrochemical performance [2].
Among the various conducting polymers, polyaniline (PANI), polypyrrole (PPy), poly(3,4-ethylenedioxythiophene) (PEDOT), and polyacetylene are the most widely studied for supercapacitor applications. These polymers exhibit excellent electrochemical activity due to their delocalized π-electrons, which facilitate the transfer of charge during the redox process. Additionally, conducting polymers can undergo significant volume changes during the charging and discharging cycles without undergoing phase transitions, contributing to their high capacitance and cycle stability. Polyaniline (PANI) is one of the most extensively researched conducting polymers due to its ease of synthesis, high conductivity, and environmental stability. The energy storage mechanism of PANI is based on the protonation-deprotonation process, where the polymer undergoes reversible changes in oxidation state during charge/discharge cycles. PANI's ability to store charge through both electrostatic and Faradaic processes allows it to achieve higher capacitance than traditional carbon electrodes. However, pure PANI suffers from poor conductivity, which limits its performance. To address this, PANI is often doped with various counterions (e.g., sulfate, chloride) or combined with carbon-based materials (such as activated carbon or graphene) to improve its conductivity and overall electrochemical performance.
Polypyrrole (PPy), another widely studied conducting polymer, has similar electrochemical properties to PANI but is more stable in aqueous electrolytes and can be easily synthesized through electrochemical polymerization. PPy's ability to undergo reversible redox reactions allows it to store charge at high efficiency, resulting in high specific capacitance. However, PPy also suffers from poor cycling stability and low conductivity. To enhance its performance, PPy is often combined with carbon materials like carbon nanotubes (CNTs) or graphene, which not only

improve its conductivity but also enhance mechanical stability and structural integrity during cycling.

Poly(3,4-ethylenedioxythiophene) (PEDOT) is another promising conducting polymer due to its high stability, high conductivity, and excellent electrochemical performance. PEDOT forms stable films that are conductive and highly stable during long charge/discharge cycles, making it an attractive choice for supercapacitors. It is often doped with polystyrene sulfonate (PSS) to enhance its solubility and processability, which significantly improves its electrochemical performance. PEDOT's high conductivity and stability make it particularly useful for high-performance supercapacitors, but like other conducting polymers, it requires composite formation with carbon materials to enhance its mechanical properties and cycling stability.

While conducting polymers offer excellent electrochemical properties, they also face several challenges that hinder their widespread use in supercapacitors. These challenges include poor conductivity (especially in the undoped state), low cycling stability due to mechanical degradation, and slow ion diffusion within the polymer matrix. To address these limitations, composite materials have been developed by combining conducting polymers with carbon nanomaterials (e.g., carbon nanotubes, graphene) or metal oxides. These composites not only improve conductivity and stability but also enhance the surface area and ion accessibility, leading to improved capacitance and cycling stability.

Hybrid electrode systems, such as PANI-carbon nanotube composites or PEDOT-graphene composites, have shown enhanced performance in supercapacitors by taking advantage of the high surface area and conductivity of carbon materials, while benefiting from the pseudocapacitive behavior of the conducting polymers. These hybrid systems also improve mechanical properties and structural integrity, making them more durable under extended charge/discharge cycles.

4. Emerging Nanomaterials

Metal–organic frameworks (MOFs), MXenes, and other two-dimensional materials have attracted attention due to their tunable porosity and high electrical conductivity. MOF-derived carbon and composite electrodes have shown promising electrochemical performance in recent studies [4,6].

Metal–Organic Frameworks (MOFs) are a class of materials consisting of metal ions or clusters coordinated to organic ligands, forming highly porous crystalline structures. MOFs exhibit remarkable tunable porosity and high surface areas (typically exceeding 1000 m^2/g), which are crucial for maximizing the electrostatic charge storage capacity of supercapacitors. The high surface area of MOFs provides abundant sites for ion adsorption, leading to high capacitance values. Moreover, the metal centers in MOFs can undergo reversible redox reactions, which add an additional pseudocapacitive charge storage mechanism. As a result, MOFs combine electrostatic capacitance and pseudo capacitance, offering both high energy density and good cycling stability. However, one of the main challenges associated with MOFs as supercapacitor electrodes is their poor electrical conductivity, which limits their power performance. To overcome this, recent studies have focused on MOF-derived carbon materials, where the organic ligands of the MOF are carbonized to form conductive carbon frameworks. These composites exhibit improved electrical conductivity and enhanced electrochemical performance, making them ideal candidates for high-performance supercapacitors. In addition, MOF-based composites with carbon nanotubes (CNTs), graphene, or conducting polymers have been developed to improve electrical conductivity, structural stability, and mechanical properties, resulting in significantly enhanced energy storage performance.

MXenes, a family of two-dimensional transition metal carbides, nitrides, and carbonitrides, have gained significant attention in recent years due to their high conductivity, hydrophilic surface properties, and excellent electrochemical performance. MXenes are synthesized by selective etching of metal atoms from bulk transition metal carbides or nitrides, creating highly conductive 2D sheets with abundant surface functional groups, such as hydroxyl (-OH), oxygen (-O), and fluorine (-F) groups. These functional groups not only enhance the electrophilicity of MXenes, improving their interaction with the electrolyte ions, but also allow for easy dispersion in aqueous and organic solvents, which is crucial for fabricating uniform electrode materials. Due to their high electronic conductivity and ion-intercalation capability, MXenes exhibit exceptional power density, rate performance, and long cycle life in supercapacitor devices. In addition, MXenes are highly flexible and mechanically robust, making them ideal for use in flexible supercapacitors. Recent studies have demonstrated that MXene-based supercapacitors, either alone or in combination with other materials like carbon nanotubes (CNTs) or conducting polymers, exhibit superior capacitance, rate capability, and cycling stability. However, challenges such as low energy density and instability under prolonged cycling remain, which researchers are actively addressing through surface modification and composite strategies.

In addition to MOFs and MXenes, two-dimensional (2D) materials such as graphene, transition metal dichalcogenides (TMDs), and black phosphorus have also been extensively explored for supercapacitor electrodes. Graphene, with its exceptionally high electrical conductivity and large surface area, has long been considered a leading candidate for high-performance supercapacitors. However, its tendency to restack into compact layers limits its pore accessibility and ion diffusion, which can reduce its capacitance. To overcome this, graphene-based composites with metal oxides, conducting polymers, or carbon nanotubes have been developed, enhancing its capacitance and cycling stability. Other 2D materials like TMDs (e.g., MoS_2, WS_2) exhibit layered structures that allow for efficient ion intercalation and offer high surface area and good electrical conductivity. Black phosphorus, a 2D material with high theoretical capacitance, has also shown promise as an electrode material. Although 2D materials generally offer high surface area, their practical applications in supercapacitors are often limited by challenges in material synthesis, scalability, and long-term stability.

Advances in Electrolytes

1. Aqueous Electrolytes

Aqueous electrolytes are the most commonly used electrolytes in supercapacitor systems due to their high ionic conductivity, low cost, and environmental friendliness. Aqueous electrolytes offer high ionic conductivity and low cost but are limited by narrow voltage windows due to water decomposition [1]. In supercapacitors, the electrolyte serves as the medium through which ions move between the positive and negative electrodes during charge and discharge processes, facilitating charge storage through either electrostatic adsorption (in EDLCs) or Faradaic redox reactions (in pseudo capacitors). Aqueous electrolytes typically consist of water as the solvent, combined with a variety of salts or acids that provide the necessary ions for charge transfer, such as sulfuric acid (H_2SO_4), potassium hydroxide (KOH), and sodium sulfate (Na_2SO_4).

One of the major advantages of aqueous electrolytes is their high ionic conductivity, which significantly reduces internal resistance and allows for fast charge/discharge cycles, resulting in supercapacitors with high power density. In comparison to organic or ionic liquid-based electrolytes, aqueous electrolytes also offer a safer and more cost-effective option, as water is abundant, non-toxic, and less prone to flammability. Additionally, the wide availability of aqueous electrolytes and their simple preparation methods make them ideal for use in commercial supercapacitors.

2. Ionic Liquids and Water-in-Salt Electrolytes

Ionic liquids and water-in-salt electrolytes enable wider voltage windows and improved energy density while maintaining reasonable safety and stability [1].

As energy storage devices evolve, the need for advanced electrolytes with wider voltage windows, higher conductivity, and enhanced thermal and electrochemical stability has led to the exploration of ionic liquids (ILs) and water-in-salt electrolytes. These electrolytes provide significant advantages over conventional aqueous electrolytes in terms of energy density, safety, and operating conditions, making them highly attractive for next-generation supercapacitors.

- **Ionic Liquids (ILs)**

Ionic liquids are organic salts that are liquid at ambient temperature, typically composed of bulky cations and anions. They exhibit high ionic conductivity, wide electrochemical stability windows, and non-volatility, making them ideal candidates for use in high-energy-density supercapacitors. One of the main advantages of ionic liquids is their wider voltage stability window compared to traditional aqueous electrolytes. In aqueous systems, water electrolysis limits the operational voltage to around 1.23 V, but ionic liquids can support voltage windows exceeding 3 V, significantly improving the energy density of supercapacitors.

Additionally, ionic liquids possess low vapor pressure, which makes them inherently safer than organic solvents used in conventional non-aqueous electrolytes. This property reduces the risk of leakage and flammability, offering enhanced safety for applications in flexible electronics, portable devices, and electric vehicles. Furthermore, ILs are often non-toxic and can be synthesized from a variety of natural and renewable sources, making them more environmentally friendly than other electrolyte types.

Despite these advantages, the high viscosity of many ionic liquids can hinder ion mobility, leading to reduced power density and limiting their rate performance. However, ongoing research focuses on optimizing the viscosity of ILs by designing new ionic liquids with lower viscosities and improving ion pairing characteristics. Another challenge is the cost of ILs, which can be higher than traditional aqueous electrolytes, although this is mitigated by their longer lifespan and greater electrochemical stability, which can reduce the need for frequent replacements.

Common ionic liquids used in supercapacitors include those based on the imidazolium, pyridinium, or phosphonium cations, paired with anions such as tetrafluoroborate (BF_4), hexafluorophosphate (PF_6), and bis (trifluoromethyl sulfonyl) imide (TFSI). These ILs offer wide electrochemical stability, low volatility, and high ionic conductivity, making them particularly useful in high-performance supercapacitor applications.

- **Water-in-Salt Electrolytes**

Water-in-salt electrolytes are a relatively new class of aqueous electrolytes designed to expand the voltage stability window of conventional water-based electrolytes. These electrolytes are formed by dissolving a high concentration of salts (such as $LiClO_4$, $NaSO_4$, or KOH) in water to create a highly concentrated solution. The high ionic concentration suppresses the typical problem of water electrolysis at low voltages, shifting the electrochemical stability window of water to higher voltages (up to 3 V or more), thus significantly improving the energy density of supercapacitors.

Water-in-salt electrolytes offer several key benefits, including environmental friendliness, low cost, and high ionic conductivity. Because water is the solvent, these electrolytes retain the advantages of aqueous electrolytes, such as high ion diffusivity and low resistance, while overcoming their inherent voltage limitation. Furthermore, the safety of water-based systems is preserved, as the risk of toxicity and flammability associated with organic solvents or ionic liquids is reduced.

However, water-in-salt electrolytes also face certain challenges. One of the main drawbacks is their high viscosity, which can lead to slow ion transport and lower power density compared to other non-aqueous electrolytes. Additionally, the preparation of water-in-salt electrolytes requires careful optimization of the salt concentration to balance the viscosity and ionic conductivity while maintaining stability. The high salt concentrations can also make it difficult to maintain long-term electrochemical stability, especially at elevated temperatures or under high charging currents.

Recent advances in water-in-salt systems have shown that by tuning the concentration of salts and utilizing specific salt mixtures, the performance can be greatly enhanced. For instance, using water-in-salt electrolytes with lithium salts like LiTFSI or $LiPF_6$ has shown promising results in hybrid supercapacitors. These systems exhibit wider operating voltage windows and enhanced electrochemical performance without compromising the environmental advantages of aqueous solutions.

3. Solid-State Electrolytes

Solid-state electrolytes have gained attention for flexible and wearable supercapacitors due to their improved safety and mechanical stability. However, challenges such as high interfacial resistance and limited ionic conductivity remain [7].

- **Polymer-Based Solid-State Electrolytes**

Polymer electrolytes (PEs) are one of the most extensively studied types of solid-state electrolytes due to their flexibility, lightweight nature, and ease of processing. Poly (ethylene oxide) (PEO) is one of the most commonly used polymers, as it provides high ionic conductivity when complexed with lithium salts (e.g., $LiPF_6$, LiTFSI) or sodium salts. However, PEO-based electrolytes suffer from low ionic conductivity at room temperature, mainly due to the crystallization of the polymer backbone, which impedes ion mobility. To overcome this limitation, recent advancements have focused on plasticizing agents (such as acrylonitrile) and ionic liquid additives to enhance ion transport and improve conductivity. Additionally, block copolymers, which consist of distinct polymer segments, have been developed to provide better mechanical stability and ionic conductivity at ambient temperature.

Recent research has also explored the use of cross-linked polymer networks and gel polymer electrolytes, which combine the flexibility of polymers with the ion conductivity of liquid electrolytes. Polymer-in-salt electrolytes (where a high concentration of salt is incorporated into the polymer matrix) have emerged as an attractive option to improve ionic conductivity. Additionally, the development of fluorinated polymers such as poly (vinylidene fluoride) (PVDF) and polytetrafluoroethylene (PTFE) has led to better thermal stability and enhanced electrochemical performance in solid-state supercapacitors.

- **Inorganic-Based Solid-State Electrolytes**

Inorganic solid-state electrolytes, such as ceramic materials and solid-state glasses, offer significantly higher ionic conductivities compared to their polymer counterparts, especially in the context of high-performance supercapacitors. Materials such as Li_3PS_4, Li_3PO_4, and NASICON-type (sodium superionic conductor) structures are widely studied for their high ionic conductivities and thermal stability. These inorganic electrolytes generally offer better mechanical stability and higher electrochemical stability windows than polymer-based systems, which is crucial for high-voltage supercapacitors. However, they face challenges related to processing, brittleness, and interface compatibility with electrodes, which can lead to poor contact resistance and degraded performance over cycling.

Recent advances have focused on improving the interface properties of inorganic electrolytes through nano structuring, doping, and coating strategies. For example, Li_3PS_4-based electrolytes have been modified by doping with various elements such as phosphorus, sulfur, or boron to improve ionic conductivity and reduce the brittleness of the material. Additionally, solid-state electrolyte/electrode interfaces can be enhanced by interlayer engineering using materials like graphene oxide, carbon nanotubes (CNTs), and conducting polymers, which help in bridging the gap between the electrolyte and electrode materials, leading to improved charge/discharge efficiency and cycling stability.

- **Composite Solid-State Electrolytes**

To combine the benefits of both polymer and inorganic electrolytes, researchers have developed composite solid-state electrolytes, which incorporate both organic and inorganic components. These composite materials often involve polymer matrices reinforced with inorganic fillers such as ceramic particles or nanotubes. The addition of inorganic materials enhances the ionic conductivity of the polymer electrolyte, while the polymer matrix provides mechanical flexibility, easy processability, and improved interface properties.

For instance, composite electrolytes based on PEO and Li_3PS_4 or Li_3PO_4 have shown significant improvements in ionic conductivity and electrochemical stability. The inorganic components help to boost ionic transport and reduce crystallization in polymer matrices, while the polymer components improve processability and mechanical flexibility. Another promising direction is the development of all-solid-state supercapacitors using these composite electrolytes, which combine the mechanical advantages of solid-state systems with the high performance of liquid electrolytes.

Device Architectures and Engineering

1. Asymmetric and Hybrid Supercapacitors

Asymmetric configurations, where different materials are used for the positive and negative electrodes, allow full utilization of the electrochemical potential window and significantly improve energy density [1,5].

2. Flexible and Wearable Supercapacitors

Flexible supercapacitors based on polymer electrolytes and nanostructured electrodes have been developed for wearable electronics and smart textiles, offering lightweight and mechanical durability [7].

Emerging Trends and Future Directions

Recent research trends include the use of sustainable biochar-derived materials for eco-friendly supercapacitors [8], solid-state devices capable of operating under extreme temperatures [7], and scalable fabrication techniques such as hydrothermal synthesis and chemical vapor deposition [5]. Environmental sustainability and cost reduction are also becoming major research priorities.

Challenges and Opportunities

Despite significant progress, supercapacitors still face challenges such as low energy density, high material costs, and difficulties in large-scale manufacturing. Future research should focus on multifunctional composite materials, improved electrolyte–electrode interfaces, and green fabrication approaches to enable widespread commercialization [2,3].

Conclusion

Recent advances in supercapacitor technology have demonstrated remarkable improvements in materials, electrolytes, and device configurations. Carbon-based nanomaterials, metal oxides, conducting polymers, and hybrid systems have collectively contributed to enhanced electrochemical performance. Continued interdisciplinary research is essential to overcome existing limitations and expand the practical applications of supercapacitors in next-generation energy storage systems.

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Nanotechnology-Based Smart Sensors for Early Prediction of Crop Stress in Paddy Fields

[1]Albino Wins J

[2]Dharshinn M

[3]M. Murugan

[1]P. Leema Rose

[1]Department of Botany, Holy Cross College (Autonomous), Nagercoil -4, Tamilnadu, India.

[2]Agricultural College and Research Institute, Tamil Nadu Agricultural University (TNAU), Coimbatore, Tamilnadu, India.

[3]Department of Biomedical Engineering, Noorul Islam Centre for Higher Education, Kumaracoil, Tamilnadu, India

Email: winsbt@gmail.com

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Abstract

Rice (*Oryza sativa* L.) is one of the most important staple crops globally and plays a central role in food security, particularly in Asian countries. Paddy cultivation is highly sensitive to environmental variations, soil nutrient imbalances, pathogen infections, and climatic fluctuations. Conventional crop monitoring methods depend mainly on visual symptoms and laboratory analyses, which often detect stress only after physiological damage has progressed.

Recent developments in nanotechnology have led to the emergence of smart sensors capable of detecting subtle biochemical and physiological changes in plants and soil at very early stages. Nanotechnology-based smart sensors offer high sensitivity, rapid response, portability, and real-time monitoring capability. These sensors can detect parameters such as nutrient levels, moisture stress, phytohormones, reactive oxygen species, and pathogen biomarkers.

Integration of nanosensors with Internet of Things (IoT), wireless communication, and data analytics has strengthened precision agriculture and early stress prediction systems. This chapter discusses the principles, types, working mechanisms,

applications, advantages, limitations, and future prospects of nanotechnology-based smart sensors in paddy fields.

Keywords: Smart sensors, Paddy fields, Crop stress, Precision agriculture, Rice cultivation, Stress monitoring

Introduction

Rice is cultivated under diverse agro-ecological conditions, ranging from irrigated lowlands to rain-fed uplands. Paddy fields are dynamic ecosystems where soil, water, microorganisms, and plant roots interact continuously. These interactions make rice plants highly sensitive to environmental disturbances.

Several stress factors affect rice production, including drought, flooding, salinity, nutrient deficiencies, heavy metal toxicity, pests, and diseases. Climate change has further intensified the frequency and severity of these stresses, making early detection increasingly important.

Traditional methods of crop stress detection include visual observation of symptoms, soil and water chemical analysis and

laboratory-based biochemical assays. These approaches are often time-consuming and detect stress only after significant damage occurs. Smart sensing technologies provide real-time monitoring and early warning systems. The incorporation of nanotechnology into sensor development has significantly improved detection sensitivity and reliability, enabling the identification of stress at molecular and biochemical levels before visible symptoms appear.

Concept of Crop Stress in Paddy Fields

Crop stress refers to any environmental or biological factor that adversely affects plant growth, metabolism, or productivity. In paddy fields, stress is complex due to fluctuating water levels and soil chemistry.

- **Abiotic Stress**

Abiotic stresses include drought or water scarcity, salinity in coastal and irrigated regions, temperature extremes, nutrient deficiency or toxicity and heavy metal contamination. These stresses interfere with photosynthesis, respiration, nutrient uptake, and enzyme activity. For example, salinity reduces osmotic potential and leads to ion toxicity, while drought affects stomatal conductance and carbohydrate synthesis.

- **Biotic Stress**

Biotic stresses are caused by fungal pathogens (blast disease), bacterial infections (bacterial leaf blight), viral diseases and insect pests and nematodes.These stresses trigger early biochemical responses such as production of defense enzymes, phenolic compounds, and reactive oxygen species, which can be detected using nanosensors.

- **Need for Early Stress Prediction**

Early stress detection allows timely irrigation and nutrient management, reduced pesticide application, prevention of yield loss and efficient resource utilization. Thus, predictive monitoring systems are essential for sustainable rice cultivation.

Nanotechnology and Smart Sensors: An Overview

Nanotechnology involves the manipulation of materials at the nanoscale (1–100 nm), where materials exhibit unique physical and chemical properties such as high surface area, enhanced reactivity, and improved electrical conductivity.

Smart sensors consist of three major components:

- Recognition element (detects target substance)
- Transducer (converts signal into measurable form)
- Data processing unit (analyzes and transmits information)

Nanomaterials improve sensor performance by:

- Increasing sensitivity
- Reducing detection limits
- Enabling miniaturization
- Improving response time

These features make nanosensors suitable for agricultural field applications.

Types of Nanomaterials Used in Smart Sensors

- **Metal and Metal Oxide Nanoparticles**

Gold, silver, zinc oxide, and titanium dioxide nanoparticles are widely used in the development of nanosensors because of their unique physicochemical properties. These nanoparticles possess high catalytic activity, which enhances reaction efficiency and improves signal detection in sensing systems. They also exhibit good electrical conductivity, allowing rapid transfer of electrons and increased sensitivity in electrochemical sensors. In addition, their stability under varying environmental conditions makes them suitable for field applications, including flooded and variable paddy field environments. Among these, gold nanoparticles are particularly important in biosensor development because they provide a stable surface for the immobilization of enzymes, antibodies, and DNA molecules. This property enables highly sensitive detection of plant pathogens, toxins, and other biomolecules, making gold nanoparticles valuable components in early crop stress and disease monitoring systems.

- **Carbon-Based Nanomaterials**

Carbon nanotubes and graphene are widely used in nanosensor development due to their exceptional physicochemical properties. These materials possess high mechanical strength, which provides durability and stability in sensor devices under field conditions. They also exhibit excellent electrical conductivity, enabling rapid electron transfer and improved sensitivity in electrochemical detection systems. Another important characteristic is their large surface area, which allows greater interaction with target molecules and enhances detection efficiency. Because of these properties, carbon nanotubes and graphene are commonly used in electrochemical sensors for detecting plant metabolites, nutrient levels, and environmental pollutants, thereby helping in the early identification of crop stress in agricultural systems.

- **Polymer-Based Nanomaterials**

Conducting polymers and nanocomposites are flexible, durable and resistant to environmental degradation. They are used in wearable plant sensors and flexible soil probes.

- **Quantum Dots**

Quantum dots are semiconductor nanocrystals that exhibit strong fluorescence and are useful in optical biosensing, imaging plant tissues and detecting disease biomarkers

Nanotechnology-Based Smart Sensors for Crop Stress Detection

Nanotechnology-based smart sensors play a vital role in monitoring crop health by detecting early physiological and environmental changes in paddy fields. These sensors can measure physical, chemical, and biological parameters at very low concentrations, enabling farmers and researchers to identify stress conditions before visible symptoms appear. Depending on the monitoring target, smart sensors used in rice cultivation can be broadly categorized into soil-based nanosensors, plant-based nanosensors, nanobiosensors for disease detection, and environmental nanosensors.

- **Soil-Based Nanosensors**

Soil-based nanosensors are designed to continuously monitor soil conditions that directly influence crop growth and productivity. These sensors are capable of detecting moisture levels, which help determine irrigation requirements and prevent water stress. They also measure soil pH and salinity, both of which are critical in paddy fields where prolonged waterlogging may alter soil chemistry.

In addition, nanosensors can estimate nutrient concentrations such as nitrogen, phosphorus, and potassium in real time. This helps in precise fertilizer application, reducing nutrient wastage and environmental pollution. Some advanced nanosensors are also capable of detecting heavy metal contamination, which is increasingly important in areas affected by industrial effluents or polluted irrigation water. By providing real-time data, soil nanosensors assist in optimizing irrigation scheduling and nutrient management, thereby improving crop productivity and sustainability.

- **Plant-Based Nanosensors**

Plant-based nanosensors are directly associated with plant tissues and are used to monitor physiological processes within the plant. These sensors can detect chlorophyll fluorescence, which serves as an important indicator of photosynthetic efficiency and plant health. Changes in sugar transport and carbohydrate metabolism can also be measured, providing early signals of metabolic disturbances caused by stress.

Furthermore, nanosensors can detect stress hormones such as abscisic acid, which accumulates in plants under drought or salinity stress. Reactive oxygen species, which are produced during oxidative stress, can also be monitored using specialized nanosensors. Since these physiological indicators appear much earlier than visible symptom.

- **Nanobiosensors for Disease Detection**

Nanobiosensors are specialized devices that combine biological recognition elements with nanomaterials to detect plant pathogens at very early stages. These sensors commonly use enzymes, antibodies, or DNA probes as recognition molecules to identify specific fungal, bacterial, or viral pathogens.

Because nanomaterials enhance sensitivity and signal amplification, nanobiosensors can detect extremely low concentrations of pathogen biomarkers. Early identification of diseases such as bacterial blight, sheath blight, or blast disease allows farmers to take preventive measures before the infection spreads widely. This reduces crop losses and minimizes the excessive use of pesticides.

- **Environmental Nanosensors**

Environmental nanosensors are used to monitor atmospheric and climatic conditions that influence rice growth and stress development. These sensors measure temperature, humidity, gas emissions such as ammonia and carbon dioxide, and solar radiation levels.

Environmental factors strongly affect physiological processes such as transpiration, photosynthesis, and disease incidence. Continuous monitoring of these parameters helps in predicting stress conditions and planning suitable management strategies, including irrigation timing and pest control measures.

Integration with IoT and Data Analytics

Modern smart agriculture systems integrate nanosensors with Internet of Things (IoT) technology to enable real-time data collection and remote monitoring. IoT-enabled nanosensors transmit field data to mobile devices, computers, or cloud-based platforms through wireless networks.

The collected data can be analyzed using advanced data analytics and machine learning algorithms to predict stress occurrence, recommend irrigation schedules, identify potential disease outbreaks, and optimize fertilizer application. Such predictive models support precision agriculture by enabling farmers to make informed decisions based on real-time field conditions. As a result, IoT-integrated sensing systems improve resource-use efficiency, reduce labor requirements, and enhance farm management practices.

Advantages of Nanotechnology-Based Smart Sensors

Nanotechnology-based smart sensors offer several advantages over conventional monitoring methods. One of the most significant benefits is their high sensitivity and accuracy, which allows detection of stress at molecular or biochemical levels before visible symptoms appear. Early detection enables timely intervention and reduces crop losses.

Another important advantage is real-time monitoring, which allows continuous observation of field conditions without frequent manual sampling. This reduces labor requirements and improves operational efficiency. Smart sensors also support efficient utilization of water, fertilizers, and pesticides, thereby reducing production costs and environmental impact.

Overall, the use of nanosensors in paddy cultivation contributes to increased crop productivity, improved grain quality, and sustainable agricultural practices.

Conclusion

Nanotechnology-based smart sensors provide a promising approach for early prediction of crop stress in paddy fields. These sensors enable real-time monitoring of environmental and physiological parameters, allowing farmers to take timely preventive measures. Although challenges related to cost and scalability remain, ongoing advancements in nanotechnology and digital agriculture are expected to make smart sensing technologies more accessible and widely adopted in the future.

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Environmental and Energy Applications

[1]R. Deivanayaki

[2]Dr. S. Muthurajan

[3]Dr. Arul Kulandaivel

[1]Research Scholar - EEE Dept., AMET University - Kanathur, Chennai - 603112.

[2]Assistant Professor - Marine Dept., AMET University - Kanathur, Chennai - 603112.

[3]Director and Professor – Robotics and Automation Engineering, Dhaanish Ahmed Institute of Technology, Coimbatore - 641105.

Email: deivanayakiphd@ametuniv.ac.in

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Abstract

Nanotechnology presents transformative opportunities for addressing global environmental degradation and energy sustainability challenges. By precisely engineering materials at the nanoscale, researchers have developed advanced catalysts, adsorbents, membranes, sensors and energy systems that outperform traditional technologies. This chapter presents a comprehensive review of nanotechnology's role in environmental protection and energy innovation, including water treatment, air and soil remediation, pollutant sensing, renewable energy conversion, energy storage and carbon mitigation. Special emphasis is given to recent breakthroughs, sustainability considerations, environmental risks and future research pathways.

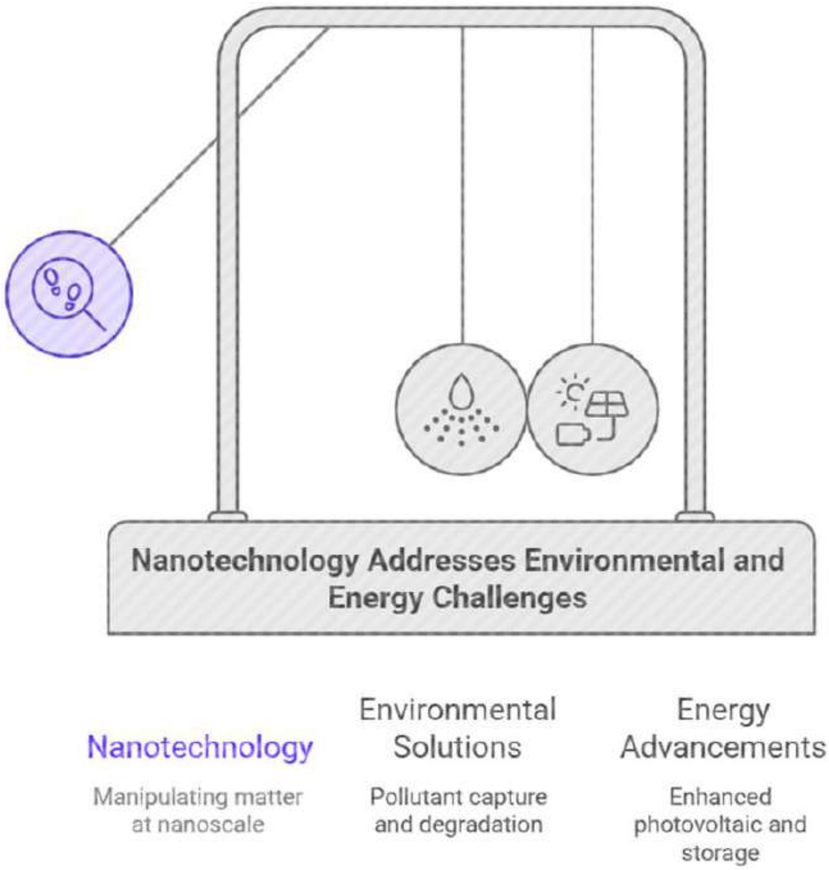
Keywords: Nanobiosensors, traditional technologies, carbon mitigation, supercapacitors

Introduction

Environmental pollution and energy demand are among the defining challenges of the twenty-first century. Rapid industrialization, urban growth, and reliance on fossil fuels have resulted in contaminated water systems, poor ambient air quality, soil degradation, and climate change driven by greenhouse gas emissions. Simultaneously, there is a critical need to transition to low-carbon and sustainable energy solutions.

Nanotechnology, the science of manipulating matter at dimensions of 1–100 nm offers unparalleled advantages in addressing these challenges due to the unique physical and chemical properties of nanomaterials, such as high surface area, tunable surface chemistry, quantum effects and enhanced reactivity. These properties enable improved pollutant capture, catalytic activity and energy conversion efficiencies that are unattainable with bulk materials.

In environmental contexts, nanomaterials have been widely explored to remove heavy metals, emerging contaminants and persistent organic pollutants from water and soil, as well as to degrade toxic species in air. In energy domains, nanotechnology enhances photovoltaic performance, advances hydrogen production and transforms electro-chemical energy storage. This chapter reviews advances across these areas and highlights recent developments from the scientific literature.



Fundamental Principles of Nanomaterials

Nanomaterial Properties

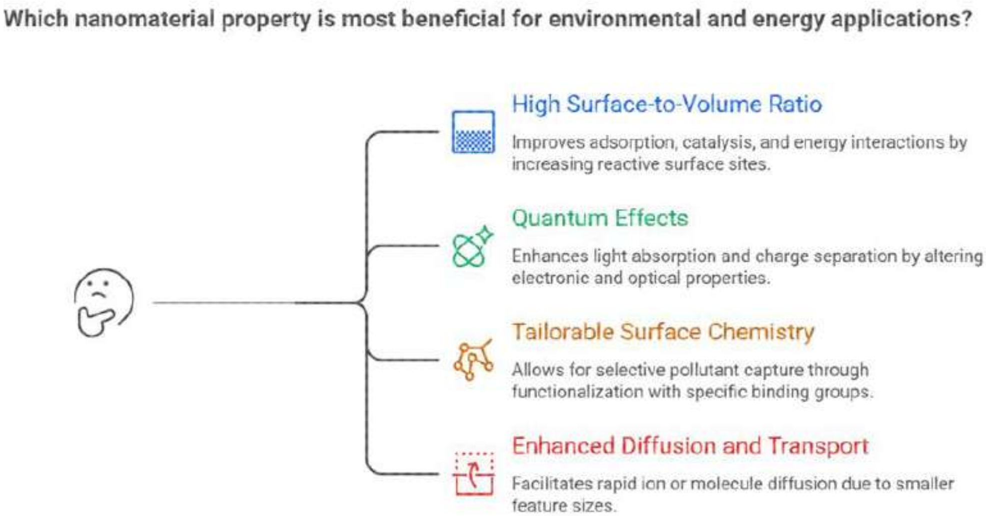
Nanomaterials exhibit several advantageous characteristics for environmental and energy applications:

- **High Surface-to-Volume Ratios:** Increased reactive surface sites improve adsorption, catalysis, and energy interactions.
- **Quantum Effects:** Alter electronic and optical properties, enabling enhanced light absorption and charge separation.
- **Tailorable Surface Chemistry:** Allows for functionalization with specific binding groups for target pollutant capture.
- **Enhanced Diffusion and Transport:** Smaller feature sizes facilitate rapid ion or molecule diffusion.

Common nanomaterials include metal and metal-oxide nanoparticles (e.g., TiO_2, Fe_3O_4), carbon allotropes (graphene, carbon nanotubes), quantum dots, nanocomposites, and metal–organic frameworks (MOFs).

Synthesis and Functionalization

The synthesis of nanomaterials employs techniques such as sol-gel, chemical vapor deposition, hydrothermal growth, and green synthesis. Surface functionalization with organic ligands, polymers, or biomolecules enables selective binding to specific contaminants or enhanced stability under operational conditions.



Nanotechnology in Environmental Remediation

1. Water Treatment Technologies

Water pollution remains a pervasive global issue, with heavy metals, organic chemicals, pathogens, and emerging contaminants (e.g., PFAS) threatening potable water sources.

- **Nano-Enabled Adsorbents**

Nanoparticles with high surface areas, such as iron-oxide and carbon-based nanostructures, have shown exceptional capacity for capturing heavy metals and dissolved pollutants. They can be engineered to selectively bind target species through surface functional groups.

- **Nanocomposite Membranes**

Nanostructured membranes — incorporating materials like carbon nanotubes or graphene oxide — increase permeability, fouling resistance, and rejection rates, leading to improved desalination and wastewater purification performance.

- **Photocatalytic Nanomaterials**

Semiconducting nanomaterials (e.g., TiO_2 and doped TiO_2) under light exposure produce reactive species that break down organic contaminants via advanced oxidation processes.

- **Nanotech in PFAS Degradation**

Emerging research highlights the application of metal nanoclusters and nanostructures to break down persistent contaminants such as per- and polyfluoroalkyl substances (PFAS) using sunlight-driven mechanisms, offering energy-efficient approaches to treat resistant pollutants. Recent work demonstrates effective PFAS bond disruption using sunlight and silver nanoclusters.

Recent comprehensive surveys detail cutting-edge nanotechnology approaches for heavy metals and sustainable water treatment.

2. Air Pollution Control

Nanotechnology has contributed to air purification through:

- **Nanocatalysts for NO_x and VOC Removal:** Catalytic materials with nanoscale features facilitate oxidation/reduction reactions for harmful pollutants.
- **Nanofiber Filters:** Capable of capturing ultrafine particulate matter effectively.
- **Photocatalytic Coatings:** Applied to surfaces that degrade airborne pollutants under irradiation.

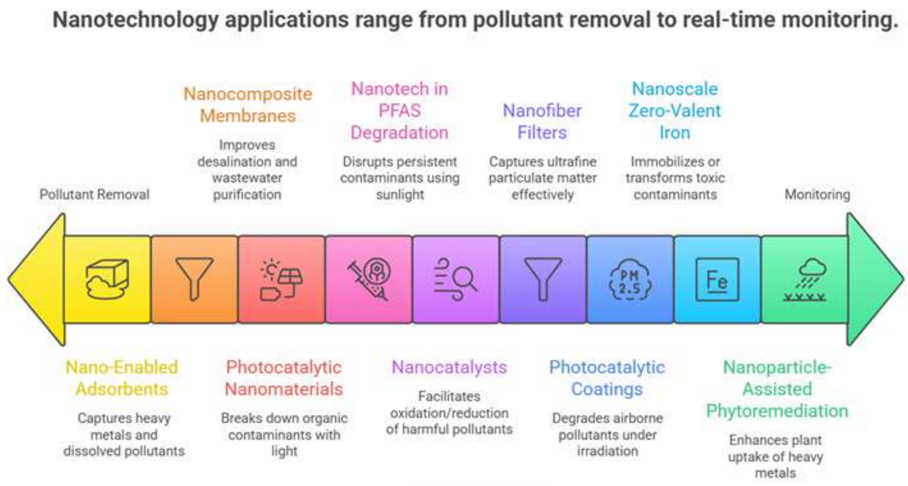
Nanotechnology also enables environmental sensors to detect trace pollutant concentrations with high sensitivity.

3. Soil Remediation

Nanoremediation has gained traction for remediating contaminated soils and groundwater. Nanoscale zero-valent iron (nZVI) and other reactive nanoparticles immobilize or transform toxic contaminants. Nanoparticle-assisted phytoremediation enhances plant uptake of heavy metals and supports ecosystem restoration.

4. Monitoring and Sensing

High-performance nanobiosensors based on quantum dots and carbon nanotubes enable the detection of pollutants at extremely low concentrations in environmental matrices, facilitating real-time monitoring of water and air quality.



Nanotechnology in Renewable Energy

1. Solar Energy Conversion

Photovoltaic (PV) technologies have been revolutionized by nanostructuring.

- **Nanostructured Silicon and Perovskites**

Nanostructuring increases light trapping and enhances charge carrier separation, leading to greater efficiencies in silicon cells. Perovskite solar cells, often incorporating nanomaterials, have achieved rapid efficiency improvements.

- **Quantum Dot Solar Cells**

Quantum dots provide tunable bandgaps, allowing multi-junction PV designs and potentially higher efficiencies.

2. Hydrogen Production and Fuel Cells

Nanocatalysts such as platinum nanoparticles improve reaction kinetics in water-splitting systems and fuel cells. The development of cost-effective, stable nanocatalysts is crucial for scalable green hydrogen generation.

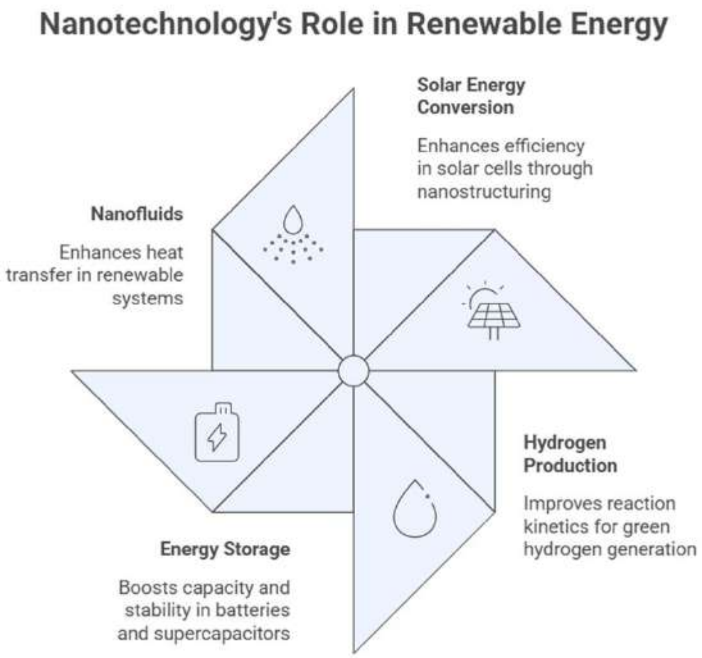
3. Energy Storage

Nanotechnology advances energy storage systems:

- **Lithium-Ion Batteries:** Nanoscale electrode materials enhance charge capacity, cycling stability, and rate capability.
- **Supercapacitors:** Nanocarbon structures (graphene, nanotubes) improve both energy and power densities.
- **Emerging Battery Technologies:** Sodium-ion and solid-state batteries benefit from tailored nanostructures that facilitate ion transport and structural integrity.

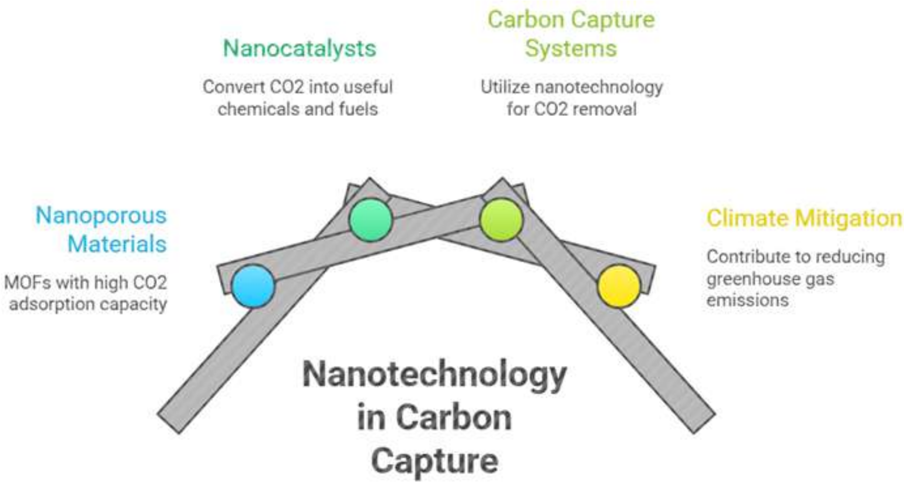
4. Nanofluids in Renewable Systems

Recent reviews highlight how nanofluids enhance heat transfer and energy conversion in renewable systems, such as solar thermal and geothermal applications.



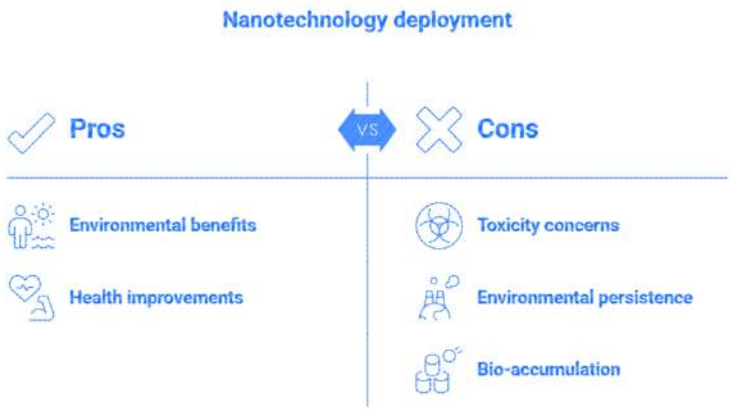
Carbon Capture and Climate Mitigation

Nanoporous materials like metal–organic frameworks (MOFs) demonstrate high capacities for CO_2 adsorption, offering pathways for carbon capture and utilization systems. Nanocatalysts also play roles in converting CO_2 into useful chemicals and fuels.



Sustainability and Environmental Impact

While nanotechnology provides significant benefits, environmental and health concerns include potential nanoparticle toxicity, environmental persistence and bio-accumulation. Lifecycle analysis and green synthesis methods are imperative for sustainable nanotechnology deployment.



Challenges and Future Perspective

➢ **Scalability and Manufacturing**

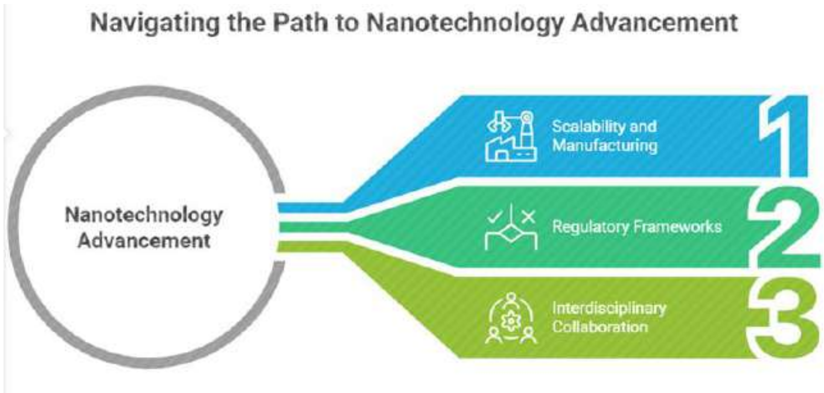
Mass production of nanomaterials at reasonable cost remains a central challenge. Further research must focus on scalable synthesis, reproducible material performance, and integration with existing infrastructure.

➢ **Regulatory Frameworks**

Standardization and regulation are needed to ensure safe use and disposal of nanomaterials, balancing innovation with environmental protection.

➢ **Interdisciplinary Collaboration**

Advancing nanotechnology applications requires collaboration across materials science, environmental engineering, energy systems, and policy domains to bridge laboratory innovation with field implementation.



Conclusion

Nanotechnology stands at the forefront of environmental protection and sustainable energy solutions. From water purification to advanced energy systems, nanoscale innovations offer transformative capabilities. However, responsible deployment, environmental risk assessment, and sustainable material lifecycles must guide future research to ensure ecological and societal benefits.

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Chemical Growth of NiSe Thin Films with Tunable Electrical and Thermoelectric Properties

[1]Prashant A. Chate

[2]Dattatray J. Sathe

[1]Dept. of Chemistry, J.S.M. College, Alibag (M.S.) India

[2]Dept. of Chemistry, KIT College of Engg. (Autonomous), Kolhapur (M.S.) India.

Email: pachate04@rediffmail.com

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Introduction

Nickel selenide (NiSe) is a transition-metal chalcogenide that is part of the broader family of II–VI and IV–VI compound semiconductors, which have attracted significant research interest due to their diverse structural, optical, electrical, and thermal properties. As with many metal chalcogenides, NiSe and related selenium-based compounds exhibit narrow to moderate band gaps and strong optical absorption across the visible spectrum, making them suitable for optoelectronic and energy-related applications [1-2]. Transition-metal selenides are especially appealing because of their tunable electrical conductivity, good chemical stability under various environmental conditions, and strong charge transport characteristics, features that have been exploited in applications ranging from photovoltaic systems and electrochemical sensors to energy storage devices and thermoelectric generators [3-4].

Nickel selenide exists in several stoichiometric and non-stoichiometric phases such as NiSe, $NiSe_2$, and $Ni_{1-x}Se$, which can be accessed by varying the Ni:Se ratio during synthesis. At equal Ni and Se atomic ratios, NiSe is formed, while a lower Ni fraction favors the formation of $NiSe_2$, $Ni_{1-x}Se$ phases also occur due to slight deviations from stoichiometry in practical samples [5-6]. Among these, stoichiometric NiSe has been widely investigated because of its relatively stable crystal structure and semiconducting behavior. Bulk NiSe crystallizes predominantly in a hexagonal nickel-arsenide-type structure (space group $P6_3/mmc$), where each Ni atom is octahedrally coordinated by Se atoms [7-8]. This crystal structure strongly influences its anisotropic electrical transport and optical transitions, as the layered arrangement and Ni–Se bonding modulate the band dispersion and carrier mobility along different crystallographic directions [9].

In thin film form, NiSe often exhibits polycrystalline nature with tunable microstructure, enabling the tailoring of its physical properties for specific device applications. The increasing demand for low cost, scalable, and environmentally benign semiconductor materials has driven research toward solution-processed thin films. NiSe thin films synthesized via chemical routes offer several advantages, including low processing temperatures, procedural simplicity, cost effectiveness, and excellent compatibility with large area substrates. These advantages make NiSe thin films particularly suitable for next generation optoelectronic and energy related technologies.

The thin film configuration allows precise control over material thickness, surface morphology, grain size, and crystallographic orientation, which in turn strongly influence functional properties such as optical absorption, charge transport, and thermoelectric performance in semiconductors and chalcogenides. In solution-deposited thin films, parameters such as deposition temperature, solution pH, precursor concentration, and deposition time significantly affect film microstructure, coverage, and connectivity, thereby enabling targeted tuning of structural and functional characteristics [10]. Thin films also exhibit a high surface-to-volume ratio, which enhances surface energy and reactivity compared to bulk counterparts and makes them advantageous for sensing and catalytic applications. Furthermore, reduced dimensionality in thin films can lead to quantum confinement effects, where band gap widening and modified optical transitions occur as a result of spatial confinement of charge carriers in the nanoscale regime. The ability to integrate thin films into multilayer heterostructures and flexible device architectures further broadens their application potential in optoelectronics, photovoltaics, sensors, and energy conversion systems. Extensive research has been conducted on the synthesis and characterization of NiSe thin films using various techniques such as chemical bath deposition (CBD) [11], electrodeposition [12], thermal evaporation [13], sputtering, and spray pyrolysis. Among these, CBD has emerged as one of the most widely used techniques due to its simplicity and low cost.

Hankare et al [14] reported the successful deposition of NiSe thin films by a chemical method and investigated their structural, optical, and electrical properties. Their study revealed polycrystalline hexagonal NiSe films with direct band gaps around 1.6–1.8 eV, suitable for optoelectronic applications.

Recent studies have extended the investigation of NiSe thin films to include thermoelectric properties, highlighting their potential for energy harvesting applications. Although the thermoelectric performance of NiSe is still under exploration, the inherently low thermal conductivity of chalcogenides combined with reasonable electrical conductivity makes NiSe a promising candidate for thermoelectric optimization. This chapter provides a comprehensive overview of NiSe thin films with a focus on synthesis via chemical bath deposition, crystallographic characterization, optical behavior, electrical transport, and thermoelectric properties. Emphasis is placed on correlating synthesis parameters with material properties and highlighting the potential of NiSe thin films for future technological applications.

Synthesis of NiSe Thin Films by Chemical Bath Deposition

Chemical bath deposition is a wet chemical thin film growth technique based on controlled precipitation of a compound from an aqueous solution onto a suitable substrate. The fundamental requirement of CBD is to create a supersaturated ionic product in the solution such that heterogeneous nucleation on the substrate surface is favored over homogeneous nucleation in the bulk solution. This is achieved through the use of complexing agents, controlled pH, and regulated temperature. In CBD, the metal ions are temporarily bound to ligands (complexing agents), which slows down their reaction with chalcogenide ions. As the reaction proceeds gradually, the metal chalcogenide compound nucleates and grows directly on the substrate, forming a uniform and adherent thin film. Because of its simplicity, low processing temperature, and scalability, CBD is extensively used for depositing metal chalcogenide semiconductors such as CdS, ZnSe, PbSe, and NiSe [15-17].

Proper substrate cleaning is a critical step in obtaining high-quality NiSe thin films. Common substrates include microscope glass slides, quartz, and conductive substrates such as fluorine-doped tin oxide. The substrates are typically cleaned ultrasonically in successive baths of acetone, ethanol, and deionized water for 10–15 minutes each to remove organic contaminants and surface impurities. After cleaning, the substrates are dried in ambient air or nitrogen flow. Clean and hydrophilic surfaces promote uniform nucleation and strong adhesion of the deposited NiSe films.

The selection of chemical precursors plays a decisive role in determining film composition and quality. Nickel salts such as nickel sulfate, nickel chloride, or nickel nitrate are commonly used as sources of Ni^{2+} ions. Selenium is typically introduced through sodium selenosulfate, which acts as a slow-releasing source of Se^{2-} ions under alkaline conditions. Complexing agents such as triethanol amine, ammonia, ethylene diamine tetra acetic acid, or sodium citrate are added to regulate the availability of free Ni^{2+} ions in the bath. These agents form stable complexes with nickel ions, preventing rapid precipitation and enabling controlled film growth. The choice and concentration of the complexing agent significantly influence the deposition rate, film thickness, and crystallinity.

The formation of NiSe thin films in CBD involves a series of chemical reactions occurring in the solution and at the substrate surface. In alkaline medium, sodium selenosulfate decomposes slowly generate Se-2 ions. Simultaneously, nickel ions released from the nickel–complex interact with selenide ions near the substrate surface to give NiSe thin film. The controlled release of both Ni^{2+} and Se^{2-} ions ensures that nucleation predominantly occurs on the substrate rather than in the bulk solution. This mechanism leads to uniform film growth with minimal particle agglomeration.

Solution pH is one of the most critical parameters in CBD. Alkaline conditions are generally required for the slow release of Se^{2-} ions from selenosulfate. At low pH values, insufficient Se^{2-} ions are available, resulting in poor or incomplete film formation. At excessively high pH, rapid precipitation may occur, leading to rough and poorly adherent films. Optimized pH values typically result in uniform, compact, and stoichiometric NiSe thin films. Deposition temperature affects reaction kinetics, nucleation density, and grain growth. Higher temperatures accelerate the decomposition of selenosulfate and increase ionic mobility, leading to improved crystallinity and larger grain sizes. However, excessively high temperatures can cause rapid homogeneous precipitation. CBD of NiSe thin films is commonly carried out in the temperature range of 25–80°C. Deposition time directly controls film thickness. Short deposition times result in thin and discontinuous films, while prolonged deposition leads to thicker films with improved coverage. However, excessively long deposition may introduce stress, cracking, or peeling of the film. Therefore, an optimized deposition time is essential to balance thickness and film quality. The concentration of nickel and selenium precursors influences nucleation rate and film stoichiometry. Higher precursor concentrations generally increase deposition rate and thickness but may lead to non-uniformity and increased defect density. Optimized concentrations promote smooth, homogeneous films with controlled grain size.

As-deposited NiSe thin films obtained by CBD are often polycrystalline with moderate crystallinity. Post-deposition treatments such as thermal annealing in inert or chalcogen-rich atmospheres are commonly employed to improve crystallinity, reduce defects, and enhance electrical conductivity. Annealing promotes grain growth and phase stabilization, which directly impacts optical and electrical properties.

The major advantages of CBD include low-cost processing, simplicity, low-temperature deposition, and suitability for large-area coatings. Additionally, CBD allows easy control of film composition through bath chemistry. However, limitations such as relatively lower crystallinity compared to vacuum-based techniques and challenges in precise thickness control remain. These limitations can be mitigated through careful optimization of deposition parameters and post-deposition treatments

Crystallographic and Microstructural Characteristics of NiSe Thin Films

The crystallographic and microstructural properties of NiSe thin films synthesized by chemical routes are central to understanding their physical behavior and technological relevance. X-ray diffraction (XRD) analysis carried out using Cu Kα radiation (λ = 1.5406 Å) reveals that the NiSe thin films crystallize predominantly in the hexagonal NiAs-type structure with space group $P6_3/mmc$. The diffraction patterns display well-resolved reflections at 2θ values of approximately 31.2°, 34.4°, 47.6°, and 56.4°, which are indexed to the (100), (002), (101), and (102) planes, respectively. The lattice parameters, determined from the indexed diffraction peaks, are found to be a = 3.62 Å and c = 5.32 Å, in close agreement with reported bulk values for hexagonal NiSe [18]. Using these lattice constants, the unit cell volume for the hexagonal structure was calculated using the standard relation yielding a value of approximately 60.3 $Å^3$. This value closely matches reported crystallographic data, indicating that the intrinsic crystal framework of NiSe is preserved despite the low-temperature chemical growth process. Minor deviations in lattice parameters and unit-cell volume are attributed to residual strain and point defects inherent to chemically deposited thin films. The average crystallite size (D), estimated using the Debye–Scherrer equation applied to the most intense diffraction peak, is approximately 22-50 nm, confirming the nanocrystalline nature of the NiSe thin films. Based on this crystallite size and assuming approximately spherical crystallites, the average crystallite volume is calculated to be 5.6×10^{-24} m^3, reflecting a large surface-to-volume ratio. Such nanoscale crystallite volumes are particularly advantageous for surface-dominated applications such as electrocatalysis and electrochemical energy storage. The microstrain present within the NiSe lattice, evaluated from XRD peak broadening, is estimated to be 2.6×10^{-3}, indicating moderate lattice distortion. This microstrain arises from defects such as selenium vacancies, nickel interstitials, and grain boundary effects introduced during chemical deposition. Owing to the anisotropic nature of the hexagonal NiAs-type structure, strain accommodation is often more pronounced along the c-axis, which can influence charge transport and defect-mediated conduction. The dislocation density representing the density of line defects within the crystal lattice, was estimated from the crystallite size and found to be approximately 2.1×10^{15} m^{-2}. This relatively high dislocation density is characteristic of nanocrystalline thin films synthesized at low temperatures and reflects a balance between crystalline order and defect concentration. While high dislocation density can increase carrier scattering, it can also enhance electrochemical reactivity by providing additional active sites.

The coexistence of nanocrystallinity, moderate lattice strain, and controlled defect density places NiSe as an intermediate member of the nickel chalcogenide family, offering a favorable balance between structural stability and functional performance for applications in energy conversion, electrochemical storage, sensing, and electronic devices.

Optical Properties of NiSe Thin Films

The optical response of nickel selenide (NiSe) thin films is a key determinant of their suitability for optoelectronic, photothermal, and energy-conversion applications. Owing to strong hybridization between Ni 3d and Se 4p orbitals, NiSe exhibits a complex electronic structure that gives rise to broadband optical absorption and narrow band gap behavior. In chemically synthesized thin films, optical properties are strongly influenced by crystallographic phase, stoichiometry, crystallite size, and defect density.

The optical absorption behavior of NiSe thin films is typically investigated using UV–visible spectroscopy in the wavelength range of 300–1100 nm. The absorbance values are high in the ultraviolet and visible regions and gradually decrease toward the near-infrared region. The absorption coefficient (α), calculated from absorbance and film thickness, typically lies in the range of 1.2×10^4 to 6.8×10^5 cm^{-1} in the visible region (400–700 nm). Such high absorption coefficients indicate that NiSe thin films can efficiently absorb incident photons even at relatively small thicknesses (300–600 nm). The absorption edge is observed around 780–900 nm, depending on synthesis conditions, reflecting the narrow band gap nature of NiSe. UV-Vis transmittance spectra of NiSe thin films show low optical transparency in the visible region, with transmittance values typically ranging from 12% to 38%, depending on film thickness and surface morphology. The transmittance gradually increases in the near-infrared region, reaching values of 45–55% beyond 900 nm. The low transmittance in the visible region is consistent with the strong absorption and narrow band gap of NiSe. The optical band gap of NiSe thin films is commonly estimated using the Tauc relation:

$$(\alpha h\nu)1/2 = A(h\nu - Eg)$$

which corresponds to an indirect allowed transition. Tauc plots of (αhν)1/2 versus photon energy (hν) for NiSe thin films typically show a well-defined linear region in the photon energy range of 1.1–1.6 eV [19]. Extrapolation of this linear region to the energy axis yields an optical band gap (Eg) in the range of 1.25–1.40 eV, with a representative value of 1.32 eV for nanocrystalline, chemically deposited NiSe thin films [20]. The relatively narrow band gap enables NiSe to absorb a large fraction of the solar spectrum, making it suitable for photovoltaic-assisted electrochemical systems and photothermal applications. Slight variations in the band gap are commonly observed and are attributed to differences in crystallite size, microstrain, and selenium vacancy concentration. The absorption edge of NiSe thin films is relatively broad, indicating significant band tailing due to localized states. The Urbach energy which characterizes the width of the exponential absorption tail, is typically found in the range of 180–260 meV for chemically synthesized NiSe thin films. Higher Urbach energy values reflect increased disorder and defect density, consistent with nanocrystalline growth and moderate microstrain. The refractive index of NiSe thin films, derived from transmittance and reflectance data, typically lies in the range of 2.1–2.7 in the visible region, while the extinction coefficient varies from 0.45 to 1.10. The wavelength dependence of n shows normal dispersion behavior, with higher values at longer wavelengths. The optical conductivity, calculated from the extinction coefficient, increases with photon energy and reaches values on the order of 10^{13}–10^{14} s^{-1} in the visible region. These values are consistent with the narrow band gap and high density of electronic states in NiSe.

Electrical and Thermoelectric Properties of NiSe Thin Films

NiSe thin films exhibit a unique combination of electrical and thermoelectric properties arising from their narrow band gap, high carrier concentration, and defect-mediated transport mechanisms. As a transition metal chalcogenide with a hexagonal NiAs-type crystal structure, NiSe shows mixed metallic–semiconducting behavior, making it particularly attractive for applications where both efficient charge transport and thermal-to-electrical energy conversion are required. Chemical synthesis routes further enhance these properties by enabling precise control over crystallite size, microstrain, and defect density at low processing temperatures.

The electrical conductivity of chemically synthesized NiSe thin films typically lies in the range of 10^{-1}–10^{2} S cm^{-1} at room temperature. These values are significantly higher than those of many conventional metal chalcogenide semiconductors, reflecting the narrow band gap and high intrinsic carrier concentration of NiSe. Temperature-dependent conductivity measurements reveal a monotonic increase in conductivity with temperature, confirming semiconducting transport behavior. The conductivity follows the Arrhenius relation with activation energy values typically in the range of 0.08–0.22eV. Such low activation energies indicate that electrical conduction is dominated by shallow donor levels associated with selenium vacancies and defect-assisted hopping between localized states. At lower temperatures, grain boundary scattering plays a significant role, while at higher temperatures, bulk-controlled conduction becomes dominant.

Hall effect measurements show that NiSe thin films predominantly exhibit n-type conductivity [21], consistent with the negative Seebeck coefficient observed in thermoelectric measurements. The carrier concentration generally lies between 10^{18} and 10^{20} cm^{-3}, depending on film stoichiometry and synthesis conditions. These relatively high carrier densities are responsible for the enhanced electrical conductivity but also influence thermoelectric parameters such as the Seebeck coefficient. The Hall mobility of NiSe thin films typically ranges from 0.5 to 15 cm^2 V^{-1} s^{-1}. Mobility is limited by carrier scattering at grain boundaries, dislocations, and point defects, which are inherent to nanocrystalline films synthesized via chemical routes. Films with larger crystallite sizes, lower dislocation density, and reduced microstrain exhibit improved mobility and reduced resistive losses.

The Seebeck coefficient is a key parameter linking electrical and thermoelectric behavior. NiSe thin films exhibit negative Seebeck coefficients, confirming electrons as the majority charge carriers. At room temperature, typical Seebeck coefficient values fall in the range of –20 to –80 μV K^{-1}, increasing in magnitude with temperature to –90 to –150 μV K^{-1} at ~500 K. The moderate magnitude of the Seebeck coefficient is a direct consequence of the high carrier concentration. As temperature increases, enhanced carrier energy filtering and increased carrier diffusion lead to an improvement in Seebeck coefficient. The simultaneous increase in both conductivity and Seebeck coefficient with temperature is particularly beneficial for thermoelectric performance.

The thermoelectric power factor represents the electrical contribution to thermoelectric efficiency. Due to their relatively high electrical conductivity, NiSe thin films exhibit promising power factor values despite their moderate Seebeck coefficient. At room temperature, power factor values typically range from 0.2 to 1.5 μW cm^{-1} K^{-2}, increasing to 2–4 μW cm^{-1} K^{-2} at elevated temperatures (450–500 K). This enhancement arises from the combined effect of increased carrier mobility, higher electrical conductivity, and enhanced Seebeck coefficient magnitude. Optimized microstructure plays a crucial role in maximizing power factor by balancing carrier concentration and scattering mechanisms. For NiSe thin films, figure of merit values typically ranges from 0.05 to 0.12 at room temperature, increasing to 0.15–0.35 at temperatures around 450–500 K. Although these values are modest compared to state-of-the-art thermoelectric materials, they are notable for films synthesized via simple, low-cost chemical routes and can be further enhanced through defect engineering and heterostructure design.

Conclusion

Chemically synthesized NiSe thin films exhibit nanocrystalline hexagonal structure, narrow band gap behavior, and thermally activated n-type electrical transport. The films show a favorable balance of high electrical conductivity, negative Seebeck coefficient, and reduced thermal conductivity, leading to improved thermoelectric performance at elevated temperatures. These results demonstrate that low-cost chemical routes enable effective tuning of structure–property relationships in NiSe thin films, making them promising for energy conversion and electronic applications.

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Synthesis And Characterization of Nanomaterials

[1]P. Gowthaman

[2]A Thanikasalam

[3]Arul Kulandaivel

[1]Research Scholar, Department of Mechanical Engineering, AMET University, Chennai, India

[2]Assistant Professor, Department of Marine Engineering, AMET University, Chennai, India

[3]Professor, Department of Robotics & Automation Engineering, Dhaanish Ahmed Institute of Technology, Coimbatore, India.

Email: gowthamanphd@ametuniv.ac.in

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Abstract

Nanomaterials have attracted significant scientific and technological interest due to their unique physical, chemical, mechanical, optical, and electronic properties, which differ substantially from their bulk counterparts. These extraordinary properties arise primarily from their nanoscale dimensions and large surface-area-to-volume ratio. The synthesis of nanomaterials with controlled size, shape, composition, and morphology is crucial for tailoring their properties for specific applications. The precise characterization of nanomaterials, which enables understanding of their structural, chemical, and functional attributes. This chapter provides a comprehensive overview of the fundamental principles, synthesis techniques, and characterization methods of nanomaterials. Various physical, chemical, and biological synthesis routes are discussed along with their advantages, limitations, and applications. Additionally, advanced characterization techniques such as X-ray diffraction, electron microscopy, spectroscopy, and thermal analysis are elaborated. The chapter concludes with emerging trends, challenges, and future prospects in nanomaterials research.

Keywords: Nanomaterials, synthesis methods, characterization techniques, nanoparticles, electron microscopy, spectroscopy.

Introduction

Nanomaterials are materials with at least one dimension in the range of 1–100 nm. At this scale, materials exhibit exceptional physical, chemical, electrical, magnetic, and optical properties that differ significantly from those of their bulk counterparts. The origin of these novel properties lies in quantum confinement effects, increased surface energy, and altered atomic coordination [1]. The rapid development of nanoscience and nanotechnology has led to wide-ranging applications in electronics, energy storage, biomedical engineering, environmental remediation, catalysis, sensors, and structural materials. The performance of nanomaterials strongly depends on their size, morphology, surface chemistry, and crystallinity. Therefore, precise control over synthesis parameters and accurate characterization techniques are essential. In recent years, nanomaterials have played a significant role to innovations to enhance human life and development. The implementation of green technologies utilizing nanomaterials represents a promising approach to reducing the risks of global warming and climate change as nanoscale systems demonstrate enhanced functional performance over conventional bulk materials [2]. Green-synthesized nanomaterials, derived from plant extracts or microbial processes, demonstrate superior performance in low-emission agriculture, environmental remediation, and CO_2 sequestration due to their enhanced surface area, high reactivity, and eco-friendly nature. These materials enhance climate-resilient agricultural practices by improving the targeted delivery of agrochemicals and minimizing emissions, while photocatalysts such as TiO_2 promote the conversion of greenhouse gases into value-added fuels. Furthermore, scalability and comprehensive toxicity evaluations are essential for their safe deployment in global sustainability initiatives [3].

Classification of Nanomaterials

Nanomaterials can be categorized into zero-dimensional (0D) nanoparticles and quantum dots, one-dimensional (1D) nanowires and nanotubes, two-dimensional (2D) nanosheets and thin films and three-dimensional (3D) nanostructured bulk materials. Based on their composition, these nanoparticles can be categorized as metallic, ceramic, polymeric, carbon-based, or hybrid, and each category exhibits distinct features suitable for specific applications.

Based on Dimensionality

1. Zero-dimensional (0D)

Zero-dimensional (0D) nanomaterials are structures in which all three spatial dimensions are confined to the nanoscale, typically below 100 nm. Due to this complete dimensional confinement, these materials exhibit unique size-dependent physical, chemical, and optical properties that differ significantly from their bulk counterparts [4].

Nanoparticles are small particulate systems composed of metals, ceramics, polymers, or carbon-based materials. The high surface-to-volume ratio enhances surface reactivity, catalytic activity, and adsorption capacity, making them highly suitable for applications in catalysis, drug delivery, sensors, coatings, and environmental remediation. Quantum dots are semiconductor nanoparticles that exhibit strong quantum confinement effects. This leads to discrete energy levels and tunable optical properties, allowing their emission wavelength to be precisely controlled by changing particle size. As a result, quantum dots are widely employed in optoelectronics, bioimaging, photovoltaics, light-emitting diodes (LEDs), and photodetectors.

2. One-dimensional (1D)

One-dimensional (1D) nanomaterials are characterized by nanoscale dimensions in two directions, while the third dimension extends to the microscale or beyond. This anisotropic structure results in a high aspect ratio, which imparts exceptional mechanical, electrical, thermal, and optical properties, distinguishing them from bulk materials. Nanowires are elongated nanostructures with diameters typically in the nanometer range and lengths extending up to several micrometers. Their high electrical conductivity, enhanced charge transport, and quantum confinement effects make them highly suitable for applications in nanoelectronics, sensors, energy storage devices, and photovoltaic systems. Nanotubes, particularly carbon nanotubes (CNTs), consist of cylindrical hollow structures formed by rolled atomic layers. They exhibit extraordinary mechanical strength, thermal conductivity, and electrical properties, making them ideal for applications in composite reinforcement, field-emission devices, nanoelectronics, drug delivery, and biosensors [5].

3. Two-dimensional (2D)

Two-dimensional (2D) nanomaterials are characterized by nanoscale thickness while extending laterally in two dimensions. This unique structural configuration results in exceptionally high surface area, strong in-plane bonding, and distinctive electronic, mechanical, and thermal properties, making them fundamentally different from bulk materials. Nanosheets are ultrathin layered structures, typically a few atomic layers thick, that exhibit high flexibility, excellent mechanical strength, and enhanced surface reactivity. Their large surface-to-volume ratio and tunable surface chemistry enable applications in catalysis, energy storage, sensors, membrane filtration, and biomedical fields. Thin films consist of nanoscale layers of materials deposited onto substrates, offering precise control over thickness, composition, and microstructure. They are widely used in microelectronics, optoelectronic devices, protective coatings, photovoltaic cells, and biomedical coatings, where tailored surface and functional properties are essential [6].

4. Three-dimensional (3D)

Three-dimensional (3D) nanomaterials are characterized by complex architectures in which nanoscale building blocks are interconnected in all three spatial dimensions. This structural integration results in enhanced mechanical stability, large surface area, tunable porosity, and multifunctional properties, enabling superior performance across a wide range of applications. Nanocomposites are materials composed of nanoscale fillers uniformly dispersed within a continuous matrix, which may be polymeric, metallic, or ceramic in nature. The incorporation of nanofillers significantly improves mechanical strength, stiffness, thermal stability, electrical conductivity, and barrier properties compared to conventional composites. As a result, nanocomposites are extensively used in aerospace, automotive components, electronics, biomedical devices, packaging, and structural applications [7].

Nanoporous materials consist of a three-dimensional network of interconnected pores with nanoscale dimensions. These materials exhibit exceptionally high surface area, tunable pore size distribution, and enhanced mass transport properties. Such features make nanoporous materials ideal for applications in catalysis, adsorption, gas separation, energy storage, filtration, sensing, and environmental remediation.

Based on Composition:

1. Metal-Based Nanomaterials

Metal-based nanomaterials consist of metallic elements engineered at the nanoscale, exhibiting unique physicochemical properties due to their high surface-to volume ratio, quantum size effects, and enhanced surface reactivity. These properties significantly differ from those of their bulk counterparts, enabling their widespread application in diverse scientific and technological fields.Copper (Cu) nanoparticles possess high electrical and thermal conductivity, making them suitable for applications in conductive inks, printed electronics, catalysts, and antimicrobial coatings. Their relatively low cost compared to noble metals further promotes their use in industrial-scale applications. Iron (Fe) nanoparticles, particularly magnetic iron oxide nanoparticles, exhibit superparamagnetic behavior, enabling applications in magnetic resonance imaging (MRI), targeted drug delivery, hyperthermia therapy, magnetic separation, and environmental remediation. Their magnetic properties allow precise external control, making them highly effective in biomedical and environmental technologies. Aluminum (Al) nanoparticles are characterized by high reactivity, low density, and excellent oxidation resistance when properly stabilized. They are widely used in energetic materials, propellants, explosives, catalysis, protective coatings, and lightweight structural materials due to their enhanced energy release and mechanical properties [8].

2. Ceramic Nanomaterials

Ceramic nanomaterials are inorganic, non-metallic materials engineered at the nanoscale, exhibiting exceptional mechanical strength, thermal stability, chemical resistance, and unique optical and electrical properties. Due to their high surface area, enhanced reactivity, and size-dependent behavior, ceramic nanomaterials have gained significant attention for applications in electronics, energy, healthcare, environmental remediation, and structural engineering.

Aluminum oxide (Al_2O_3) nanoparticles possess high hardness, excellent wear resistance, superior thermal stability, and strong dielectric properties. These characteristics make them suitable for applications in protective coatings, polishing agents, cutting tools, biomedical implants, and electronic substrates. Titanium dioxide (TiO_2) nanoparticles exhibit outstanding photocatalytic activity, strong UV absorption, and chemical stability. They are extensively utilized in environmental purification, self-cleaning coatings, solar cells, water treatment, air purification systems, and as pigments in paints, cosmetics, and sunscreens [9].

3. Carbon-Based Nanomaterials: Carbon Nanotubes, Graphene, Fullerenes

Fullerenes (C60) are spherically structured carbon nano molecules composed of sp2 hybridized carbon atoms with unique electronic and mechanical properties. The spherical structure is made up of around 28 to 1500 carbon atoms, with diameters ranging from 8.2 nm for single layers to 4 - 36 nm for multilayered fullerenes [10] Nanomaterials consisting of hollow, globular carbon cages, categorized by fullerenes, possess outstanding electrical transport characteristics, robust mechanical integrity, and adaptable chemical functionality, making them highly attractive for diverse commercial applications [11].Graphene is a monoatomic layer of carbon atoms arranged in a two dimensional honeycomb lattice, presenting an ultrathin thickness on the order of 1 nm [12].

Carbon nanotubes (CNTs) are formed by rolling a graphene nanosheet with a hexagonal honeycomb lattice into seamless cylindrical structures. Single-walled CNTs typically exhibit diameters as small as ~0.7 nm, whereas multi-walled CNTs can reach diameters of up to ~100 nm, with lengths extending from a few micrometers to several millimeters. The tube ends may be open or capped by hemispherical fullerene-like structures, resulting in either hollow or closed morphologies [13]. The rolled-graphite like architecture of CNTs endows them with remarkable mechanical robustness and exceptional electrical transport properties [14].

Synthesis of Nanomaterials

Nanomaterial synthesis aims to control particle size, morphology, surface chemistry, and crystallinity. The synthesis approaches are broadly categorized into top down and bottom-up methods.

1. Top-Down Synthesis Approaches

Top-down methods involve the physical breakdown of bulk materials into nanoscale dimensions. It approaches the systematic reduction of bulk materials into nanoscale structures using physical, mechanical, or lithographic techniques. In this approach, large-scale solid materials are progressively broken down into smaller particles until nanometer dimensions are achieved. The fundamental principle behind top-down processing is size reduction through external energy input, such as mechanical force, thermal energy, or electromagnetic radiation [15].

2. Bottom-Up Synthesis Approaches

Bottom-up methods assemble nanostructures from atomic or molecular precursors, allowing better control over size and morphology. It approaches the construction of nanomaterials from atomic, molecular, or ionic building blocks through chemical, physical, or biological processes. Unlike top-down techniques, which break down bulk materials, bottom-up methods assemble nanostructures in a controlled manner, allowing precise control over particle size, morphology, composition, and crystallinity.

Characterization of Nanomaterials

Characterization of nanomaterials refers to the systematic analysis and measurement of their structural, morphological, chemical, optical, electrical, mechanical, and thermal properties. Since nanomaterials exhibit size-dependent and surface dominated behaviours, precise characterization is essential to understand their structure property–performance relationships and to optimize them for specific applications. Nanomaterial characterization helps in determining particle size, shape, surface area, crystal structure, elemental composition, bonding nature, surface charge, stability, and functional properties. These parameters strongly influence their reactivity, toxicity, mechanical strength, optical response, catalytic efficiency, and biological interactions [16].

Structural Characterization Techniques

Structural characterization techniques are essential tools used to analyze the crystal structure, phase composition, lattice parameters, crystallite size, and atomic arrangement of materials. In nanomaterials research, these techniques provide crucial insights into how atomic-scale structure influences physical, chemical, and mechanical properties.

1. X-Ray Diffraction (XRD)

X-ray diffraction (XRD) is a powerful non-destructive analytical technique used to identify the crystal structure, phase composition, lattice parameters, crystallite size, and degree of crystallinity of materials. It is one of the most widely employed tools for structural characterization of crystalline and semi-crystalline materials, especially in nanomaterials research. XRD is based on the constructive interference of monochromatic X-rays scattered by periodic atomic planes within a crystalline material. The resulting diffraction pattern serves as a structural fingerprint of the material [17].

2. Transmission Electron Microscopy (TEM)

Transmission Electron Microscopy (TEM) is a powerful high-resolution imaging and analytical technique used to investigate the internal structure, morphology, crystallography, and elemental composition of materials at the nanoscale and atomic scale. Owing to its extremely high spatial resolution (down to ~0.1 nm), TEM is one of the most important tools in nanomaterials characterization. TEM operates by transmitting a high-energy electron beam through an ultrathin specimen, generating detailed images and diffraction patterns that reveal the material's microstructural features [18].

3. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is a widely used high-resolution surface imaging technique that provides detailed information about the surface morphology, topography, microstructure, and composition of materials. SEM offers nanometer-scale resolution and a large depth of field, making it ideal for studying nanomaterials, composites, polymers, ceramics, metals, and biological samples [19].

Spectroscopic Characterization

1. Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) is a powerful analytical technique used to identify chemical bonds, functional groups, and molecular interactions within a material. It works by measuring the absorption of infrared (IR) radiation by a sample, producing a spectrum that represents the vibrational transitions of molecular bonds. FTIR is widely used in nanomaterials characterization, polymer science, pharmaceuticals, biochemistry, environmental science, and surface chemistry to analyze chemical composition and bonding structure [20].

Thermal Characterization

1. Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) is a thermal characterization technique used to measure the change in mass of a material as a function of temperature or time under controlled atmosphere. It provides valuable information regarding thermal stability, decomposition behavior, compositional analysis, oxidation resistance, moisture content, and volatile components of materials. TGA is widely applied in the characterization of polymers, nanomaterials, composites, ceramics, pharmaceuticals, and biomaterials [21].

2. Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) is a thermal analysis technique used to measure the difference in heat flow between a sample and a reference as a function of temperature or time under controlled conditions. It provides critical information regarding phase transitions, melting behavior, crystallization, glass transition temperature, heat capacity, and thermal stability of materials. DSC is widely employed in the characterization of polymers, nanomaterials, composites, pharmaceuticals, biomaterials, metals, and ceramics [22].

Conclusion

The synthesis and characterization of nanomaterials form the backbone of nanotechnology. Advanced synthesis methods enable precise control over nanostructure, while modern characterization tools provide deep insights into their properties. Continued innovation in this field will drive breakthroughs across engineering, healthcare, energy, and environmental sectors. The design, development, and application of next-generation materials, the combination of materials science, nanotechnology, and advanced manufacturing constitutes a paradigm shift. The material selection and optimization are made possible by the fundamental understanding of structure-property processing-performance linkages provided by materials science. By providing exact control over material behaviour at the atomic and molecular dimensions, using nanotechnology had improved mechanical, thermal, electrical, and functional qualities that are not possible with traditional materials. Modern manufacturing methods serve as a link between advances in the lab and practical uses. In line with the objectives of intelligent and sustainable manufacturing, these methods not only enhance material performance but also encourage effective resource utilization, design flexibility, and scalability.

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Nanosensors in Food Safety and Quality Control

Mrs. Kavita Vinay Palve

Asst. Prof., Ashoka College of Education, Nashik, Maharashtra, India

Email: kavitanevkar88@gmail.com

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Abstract

Food safety and quality control are critical components of public health and global trade. Conventional analytical techniques such as chromatography, culture-based microbial assays, and immunological methods, although reliable, are often time-consuming, labor-intensive, and require sophisticated laboratory infrastructure. In recent years, nanosensor technology has emerged as a transformative tool in food analysis due to its high sensitivity, rapid detection capability, portability, and potential for real-time monitoring.

Nanosensors utilize nanomaterials such as gold nanoparticles, carbon nanotubes, graphene, quantum dots, and magnetic nanoparticles to detect chemical contaminants, pathogens, toxins, allergens, pesticides, and spoilage indicators at extremely low concentrations.

This chapter explores the principles, classifications, mechanisms, and applications of nanosensors in food safety and quality control. Various types of nanosensors—including electrochemical, optical, piezoelectric, and nano-biosensors—are discussed with emphasis on their working principles and detection strategies. Applications in detecting foodborne pathogens (e.g., Salmonella, Listeria), pesticide residues, heavy metals, mycotoxins, and adulterants are examined. The integration of nanosensors with smart packaging systems and Internet of Things (IoT)-based monitoring platforms is also highlighted.

Despite their immense potential, challenges such as regulatory concerns, toxicity risks, commercialization barriers, cost, and standardization remain significant. The chapter concludes with future perspectives emphasizing miniaturization, multiplex detection, wearable food sensors, and AI-integrated diagnostic systems. Nanosensors represent a promising frontier in ensuring safer, higher-quality food systems and supporting sustainable global food security.

Keywords: Nanosensors; Food Safety; Nanotechnology; Pathogen Detection; Smart Packaging

Introduction

Ensuring food safety and quality is a global priority due to increasing food borne illnesses, globalization of food trade, and rising consumer awareness. According to the World Health Organization, millions of people suffer annually from food borne diseases caused by microbial contamination, toxins, and chemical residues.

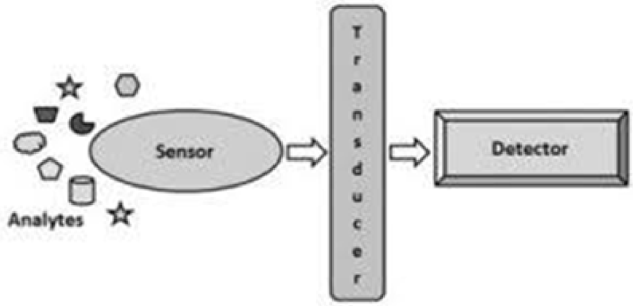
Traditional methods such as microbial culturing, chromatography (HPLC, GC-MS), and ELISA provide accurate results but require trained personnel, sophisticated laboratories, and extended analysis time.

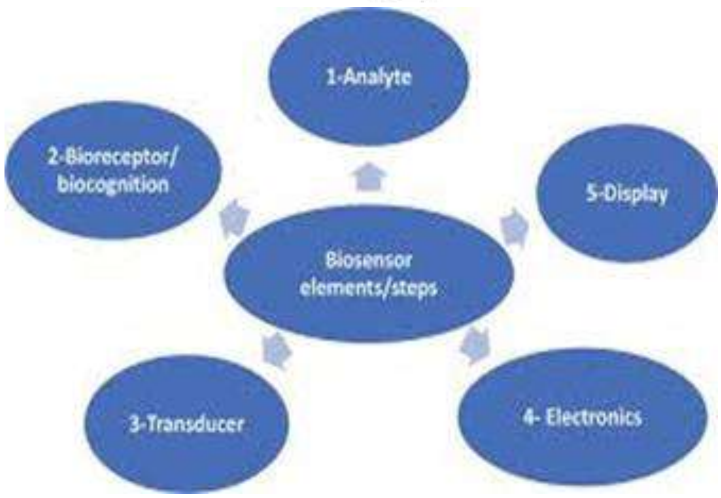
Nanotechnology has introduced innovative solutions in food monitoring systems. Nan sensors—devices that detect biological or chemical analytes using nanomaterials—offer enhanced sensitivity due to their high surface-to-volume ratio and unique physicochemical properties. These sensors enable rapid, on-site, and real-time detection, significantly improving food safety management systems.

Concept and Working Principle of Nanosensors

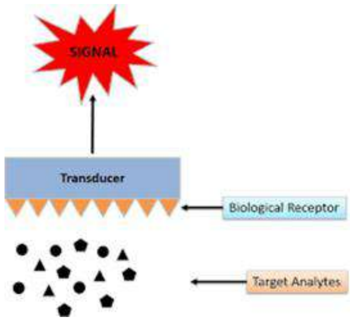
A nanosensor is a sensing device incorporating nanomaterials to detect and quantify target analytes. The fundamental components include:

1. **Recognition Element:** Antibodies, enzymes, DNA probes, aptamers





2. **Transducer:** Converts biological interaction into measurable signal



3. **Signal Processor:** Amplifies and displays output

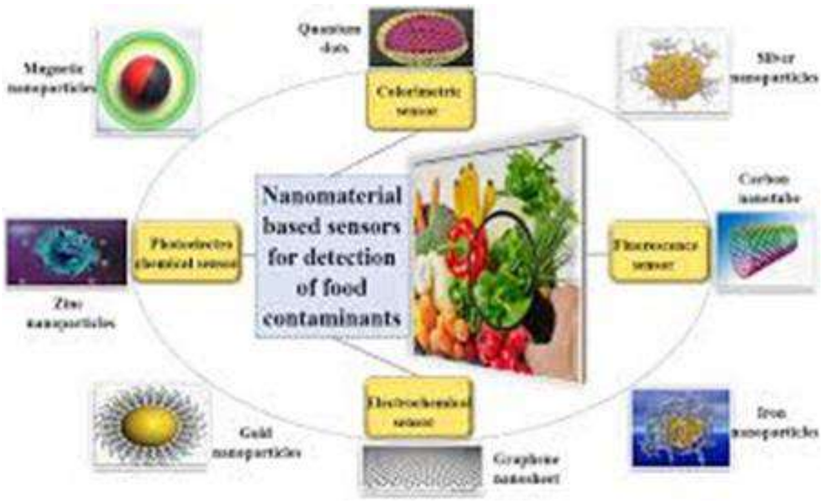
Mechanism of Detection

When a target molecule (e.g., pathogen antigen or pesticide residue) interacts with the recognition element immobilized on nanomaterials, a physical or chemical change occurs. This change may involve:

- Electrical signal variation
- Optical signal shift
- Mass change
- Fluorescence emission

The nanoscale properties enhance signal amplification, allowing detection at very low concentrations (ppm to ppt levels).

Types of Nanosensors in Food Safety



1. **Electrochemical Nanosensors**

These sensors measure changes in electrical parameters such as current, voltage, or impedance. Nanomaterials like gold nanoparticles and carbon nanotubes enhance conductivity and sensitivity.

Applications:

- Detection of heavy metals (lead, mercury)

- Pesticide residue monitoring
- Pathogen identification

2. Optical Nanosensors

Optical nanosensors rely on fluorescence, colorimetric changes, or surface plasmon resonance (SPR). Gold nanoparticles exhibit visible color change upon aggregation, making them useful for rapid detection of contaminants.

Applications:

- Detection of toxins
- Monitoring food spoilage indicators
- Mycotoxin detection

3. Piezoelectric Nanosensors

These sensors measure mass changes on a quartz crystal surface due to analyte binding. Even small molecular interactions cause detectable frequency shifts.

Applications:

- Bacterial detection
- Adulteration analysis

4. Nano-Biosensors

Nano-biosensors combine biological elements with nanomaterials for highly selective detection.

Examples:

- Enzyme-based nanosensors
- DNA nanosensors
- Immuno-nanosensors

Nanomaterials Used in Food Nanosensors

1. Gold Nanoparticles (AuNPs)

- High stability
- Excellent conductivity
- Colorimetric detection capability

2. Carbon Nanotubes (CNTs)

- High mechanical strength
- Superior electrical properties

3. Graphene

- Large surface area
- High electron mobility

4. Quantum Dots

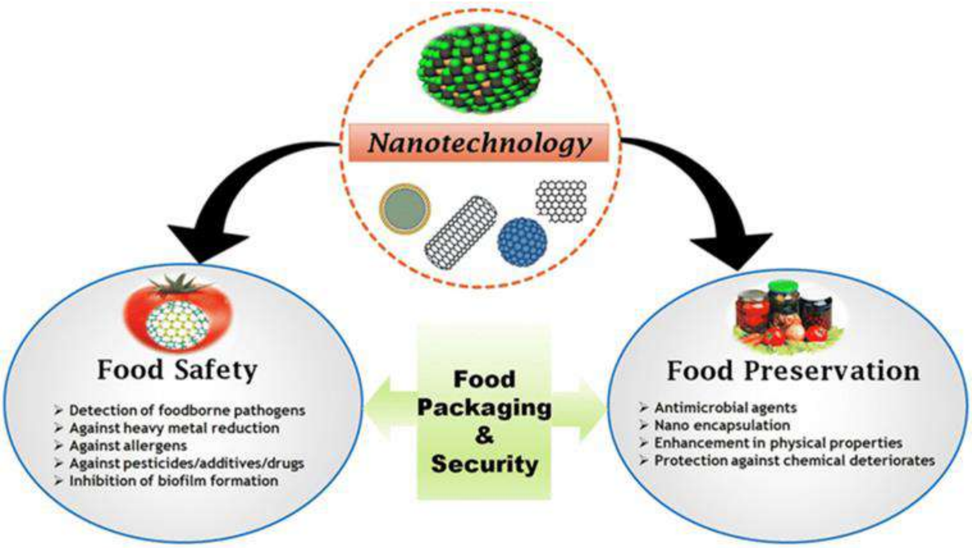
- Strong fluorescence

- Photostability

5. Magnetic Nanoparticles

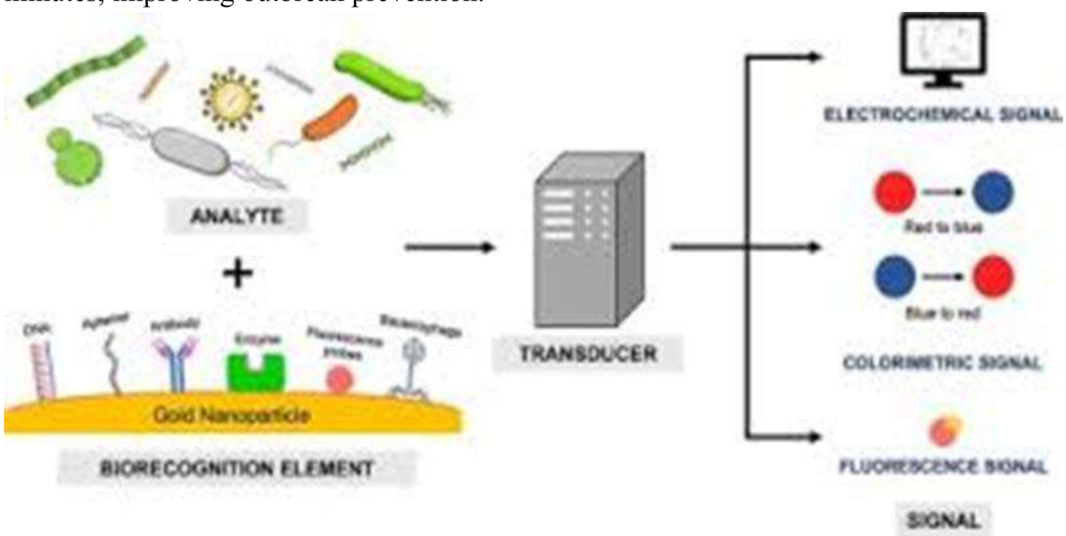
- Target separation
- Rapid detection enhancement

Applications in Food Safety



1. Detection of Foodborne Pathogens

Pathogens such as Salmonella, Escherichia coli, and Listeria monocytogenes are major causes of foodborne illness. Nanosensors enable rapid detection without extensive culturing. Electrochemical nanosensors can detect bacterial DNA within minutes, improving outbreak prevention.



2. Detection of Chemical Contaminants

Nanosensors detect pesticide residues, antibiotics, veterinary drug residues, and heavy metals. Graphene-based sensors are widely used for detecting organophosphate pesticides.

3. Mycotoxin Detection

Mycotoxins such as aflatoxins are toxic metabolites produced by fungi. Nano-biosensors allow highly sensitive detection even at trace levels.

4. Allergen Detection

Food allergens like peanut proteins can be detected using immuno-nanosensors, preventing allergic reactions in sensitive individuals.

5. Detection of Food Adulteration

Nanosensors help detect adulterants in milk, oils, spices, and beverages. Gold nanoparticle-based colorimetric sensors are widely used for rapid field analysis.

6. Nanosensors in Smart Packaging

Smart packaging integrates nanosensors into food packaging materials to monitor freshness and contamination.

Examples include:

- Oxygen and carbon dioxide nanosensors
- pH-sensitive nanosensors
- Temperature monitoring nano-indicators

These sensors provide visual indicators of spoilage and improve supply chain monitoring.

Advantages of Nanosensors

- High sensitivity and specificity
- Rapid detection
- Portability
- Low sample requirement
- Real-time monitoring
- Cost-effective in long term

Challenges and Limitations

Despite promising applications, several challenges remain:

- Toxicity concerns of nanomaterials
- Regulatory approval processes
- High initial development cost
- Stability and reproducibility issues
- Consumer acceptance

Standardization and validation of nanosensor-based methods are required before widespread commercialization.

Regulatory and Safety Considerations

Regulatory agencies are developing guidelines for nanotechnology applications in food systems. Risk assessment must evaluate:

- Migration of nanoparticles into food
- Environmental impact
- Long-term health effects

Clear regulatory frameworks are essential for safe integration into food industries.

Future Perspectives

Future research focuses on:

- Multiplex detection systems
- AI-integrated nanosensors
- Wearable food quality sensors
- Smartphone-based detection systems
- Integration with Internet of Things (IoT)

Miniaturization and automation will further enhance field-level applications. Development of biodegradable and eco-friendly nanomaterials will improve sustainability.

Conclusion

Nanosensors represent a revolutionary advancement in food safety and quality control. Their high sensitivity, rapid detection capability, and adaptability to smart systems make them superior to conventional analytical methods. Applications range from pathogen detection and chemical contamination monitoring to smart packaging and real-time supply chain tracking. Although regulatory and safety challenges remain, continuous research and technological improvements are paving the way for commercial adoption. Nanosensors hold significant potential in enhancing global food security, reducing foodborne illness, and improving consumer confidence in food products.

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Rare-Earth-Ion-Doped Nanophosphors for Advanced Bioimaging Applications

[1]Jitendra Pal Singh

[2]Rohit Kumar

[1]Department of Physics, School of Sciences, IFTM University, Moradabad-244102, India

[2]Department of Chemistry, School of Sciences, IFTM University, Moradabad-244102, India

Email: paljitendra124@gmail.com

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Abstract

Rare-earth-ion-doped nanophosphors have been shown to be highly promising luminescent materials for advanced bioimaging applications because of their unique optical properties, such as broad emission bands, long luminescence lifetimes, large Stokes/anti-Stokes shifts, high photostability, and low photobleaching. The doping of trivalent rare-earth ions such as Er^{3+}, Yb^{3+}, Nd^{3+}, Eu^{3+}, and Tb^{3+} into suitable inorganic host materials enables the generation of upconversion luminescence in the visible to near-infrared (NIR) spectral regions. In particular, NIR-emitting and up conversion nanophosphors provide enhanced tissue penetration depths, reduced auto fluorescence, and enhanced signal-to-noise ratios compared to conventional organic fluorophores and quantum dots. This chapter is in honour of and optical properties for biomedical imaging. Special emphasis is placed on process-structure-property relationships in the control of luminescence efficiency, quantum yield, and biocompatibility. Core-shell nanostructure design, defect passivation, and surface ligand engineering are discussed to enhance emission brightness and physiological stability. Moreover, targeted bio functionalization strategies are introduced to enable selective cellular and tissue imaging. In conclusion, rare-earth-ion-doped nanophosphors are a highly versatile and scalable platform for next-generation precision bioimaging applications.

Keywords: Nanophosphors, Bioimaging, Rare earth ions, NIR-region, Applications

Introduction

Rare earth elements are a set of lanthanide ions in the 6th row of the periodic table (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu), as well as two other elements that are very similar to the lanthanides, namely yttrium (Y) and scandium (Sc). Due to the incomplete 4f shell and the spin-orbit interaction of the 4f free ions, they have very complex optical properties. One of the most intriguing properties of these ions is their photoluminescence. The luminescence of trivalent lanthanide ions originates from f-f transitions of the 4f shell and f-d transitions of the 4f-5d shell. The f-f transitions also cause the lanthanide elements to have their complex energy level structures in the UV, VIS, and NIR regions. Because they can be tailored from the UV to the NIR region, most nanomaterials of rare earth elements can be generally classified into two groups: Upconversion nanoparticles (UCNPs) and downconversion. It is worth noting that the unique spectroscopic properties of RENPs are not caused by quantum size effects but by a number of factors, such as particle size, doping composition, site symmetry, dopant-ligand distance, phase purity.

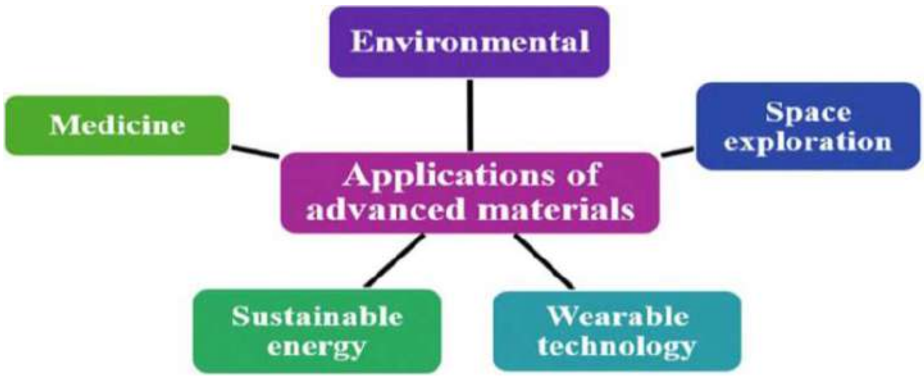

Fig.1.Application for different field

Based on the excellent advanced materials different field fig.1 and characteristics of rare-earth ions, such as their low photobleaching, various absorption and emission wavelengths, and low energy losses, NIR light mediated RENPs have been widely used in in vitro and in vivo imaging of biomolecules. Commonly, this kind of downconverting nanoparticle combines rare-earth ions and an inorganic crystalline host lattice (e.g., NaYF4, NaLuF4, and CaF2). The host can also provide an environment for energy transfer from a sensitizer to a rare-earth dopant resulting in NIR-II fluorescence [1].

One of the most important breakthroughs in this area is the emergence of upconversion nanophosphors, which have the ability to upconvert low-energy near-infrared (NIR) excitation into higher-energy visible or ultraviolet emission [2]. NIR excitation is within the biological transparency window, thus having the ability to penetrate deeper into tissues and avoiding photodamage. This makes rare-earth-doped nanophosphors extremely valuable for in vivo imaging, targeted diagnostics, and theranostics. By choosing the host materials and dopants appropriately, it is possible to choose the emission color and intensity to satisfy particular biomedical needs. Recent breakthroughs in synthesis methods, including hydrothermal, sol-gel, co-precipitation, combustion, and microwave-assisted synthesis, have enabled precise control over particle size, shape, crystallinity, and surface properties. Surface modification with biocompatible polymers, silica coating, or targeting ligands has further enhanced colloidal stability, biocompatibility, and target specificity [3]. These breakthroughs have enabled applications in cellular imaging, tumor targeting, multimodal imaging, biosensing, and tracking drug delivery. Disadvantages, as well as advantages, include the requirements. These breakthroughs have enabled applications in cellular imaging, tumor targeting, multimodal imaging, biosensing, and drug delivery tracking. Advantages, challenges remain, including the need for enhanced quantum efficiency at the nanoscale, biocompatibility, scalable synthesis methods, and toxicity studies [4].

In bioimaging, carbon quantum dots (CQDs) can be used for both in vitro and in vivo imaging. For example, in in vitro imaging, CQDs have been used for cell staining and the imaging of subcellular structures with high accuracy. These quantum dots can easily enter cells through endocytosis, where they can be localized in different cellular compartments such as the cytoplasm or membrane, depending on the surface modification of the CQDs [5]. The ability to target specific organelles such as the mitochondria, lysosomes, and Golgi apparatus makes CQDs ideal for imaging cellular processes, including the imaging of early disease biomarkers in diseases such as cancer, diabetes, and neurodegenerative diseases. The localization of CQDs in the cytoplasm plays a crucial role in ensuring the clarity and resolution of the image, which is essential for the imaging of physiological changes at the cellular level. One of the significant applications of CQDs is in the imaging of cancer cells. In breast cancer, biomarkers such as estrogen receptor (ER), progesterone receptor (PR), and human epidermal growth factor receptor are usually targeted in the imaging process [6].

In this review, we will discuss the recent developments in Nanophosphors materials for advanced bioimaging. We will also discuss the bioimaging properties of nanomaterials and their applications in various bioimaging techniques such as fluorescence microscopy, super-resolution microscopy, and multiphoton microscopic imaging.

Bioimaging Applications

Ln-based sensing systems are also regarded as a new generation of fluorophores and have attracted much attention in the field of bioanalytical sensing]7]. As in the above applications, this potential is attributed to their unique properties, i.e. high quantum yield, narrow emission bands, large stoke shifts, upconversion emission capability, good chemical stability, and low toxicity. Which make them superior in some aspects in comparison to organic fluorophores and other fluorescent NPs [8]. Although the research on Ln-doped NPs is still in its infancy, very diverse types of these NPs have been reported as sensing probes, such as lanthanide doped nanoparticles (Ln doped NPs). Regarding the sensing applications involving functionalized [9]. Bioimaging is a crucial field of modern biomedical research that offers essential information on complex biological systems and biochemical processes. Optical nanomaterials have been recognized as an effective platform for bioimaging owing to their distinctive properties that encompass adjustable optical properties, high luminescence with high photostability, and biocompatibility. This review provides a comprehensive overview about optical nanomaterials for advanced bioimaging and highlights their potential applications in various biomedical disciplines show in Table.1

Table.1: Nanomaterial for Advanced bioimaging applications

Nanomaterial	Size, functionalization	Bioimaging application	Unique aspect utilized
AIE probe	100 nm, peptide	imaging of cell apoptosis	fluorescence "turn-on" in response to enzyme
CdSe-ZnS quantum dot	<10 nm, arginine terminated	rapid mitochondria targeting	nonendocytic cell uptake
carbon dot	~3 nm, triphenyl phosphonium	imaging hydroxyl radicals in mitochondria of live cells	imaging at subcellular length scale
upconversion nanoparticle	30−50 nm, triphenyl phosphonium	thermal dynamics of mitochondria in living cells	temperature-dependent fluorescence
carbon dot	2.5 nm, sulfonic group	cell nucleus imaging	imaging at subcellular length scale
carbon dot	~5 nm, −	lysosomal pH imaging	pH-dependent emission
carbon dot	2.7 nm	imaging of formaldehyde in living cells	intramolecular charge transfer-dependent fluorescence
carbon dot	5−10 nm, antibody	cell membrane receptor counting	fluorescence blinking
carbon dot	5 nm, −	imaging mitochondrial fission and fusion dynamic at 130 nm resolution	fluorescence blinking
polymer dot	5 nm, −	imaging of nucleic acids in living cells at 100 nm resolution	high fluorescence depletion rate
aluminosilicate nanoparticle	10 nm, antibody	imaging of cellular cytoskeleton (tubulin and actin) and nucleus at 100 nm resolution	fluorescence blinking
phenanthroimidazole self-assembly	20−30 nm, −	tracking lipid droplet (~100 nm) dynamics at millisecond time scale	distinct nature of fluorescence lifetime
AIEgen aggregates	−, triphenylamine	imaging migration of AIEgen from mitochondria to nucleus at ~170 nm resolution	high fluorescence depletion efficiency
oligothiophene aggregates	−, −	imaging amyloid fibril with 14 nm resolution	photo activation
gold nanocluster	~5 nm	imaging 60 nm lysosome	fluorescence blinking
gold nanoparticle	40−100 nm	imaging individual nanoparticle in tumor cell with ~100 nm resolution	localized surface plasmon resonance

Ln-doped NPs, it should be noted that Ln-doped NPs are much more abundant because playing with different functionalization and mechanisms allows for more possibilities [10]. Since Ln-doped NPs do not have an intrinsic or specific luminescence response to most of the analytes (such as pH, oxygen, metal ions, and biomolecules), the functionalization of the surface of the Ln-doped NP with appropriate indicator dyes or recognition elements gives the Ln-doped NP the selectivity or specific recognise necessary for most of the sensing applications, especially biosensing.

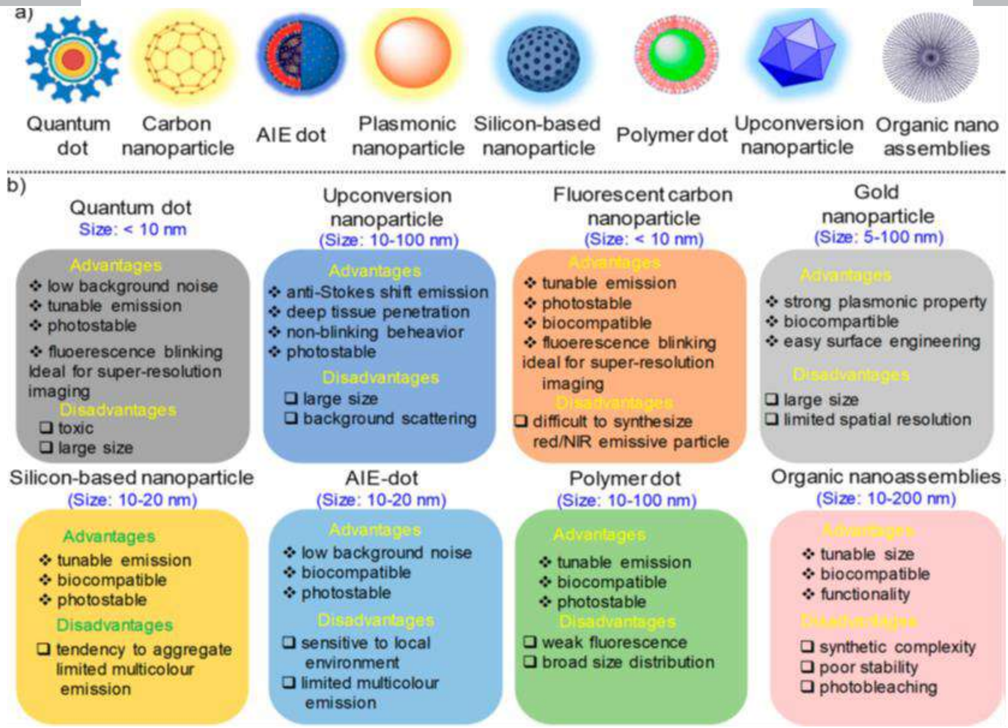

Fig.2: (a) Schematic illustration of various optical nanoparticles used for bioimaging. (b) Summary of their advantages and limitations bioimaging applications [11].

Up conversion Nanoparticles (UCNPs)

Upconversion nanoparticles possess the property of converting low-energy excitation light into higher-energy emission light through a process known as photon upconversion[12]. The commonly used upconversion nanoparticles are made up of erbium (Er), ytterbium (Yb), thulium (Tm), and holmium (Ho) ions doped in a matrix of yttrium oxide (Y2O3) or sodium yttrium fluoride (NaYF4). The size of UCNPs varies from 10 to 100 nm. UCNPs can absorb near-infrared light, which has good penetration depth in biological tissues, and emit visible or ultraviolet light [13]. This provides the ability to do deep tissue imaging with minimal background signals from biological samples [14]. The major advantage of UCNPs is their ability to penetrate deeper with less damage to tissue during imaging and lack of photobleaching without blinking of emission, unlike QDs. The application of UCNPs in imaging provides the advantage of minimum autofluorescence, which is universal for fluorescence imaging of biological samples. UCNPs also have the disadvantage of being toxic and having background scattering.

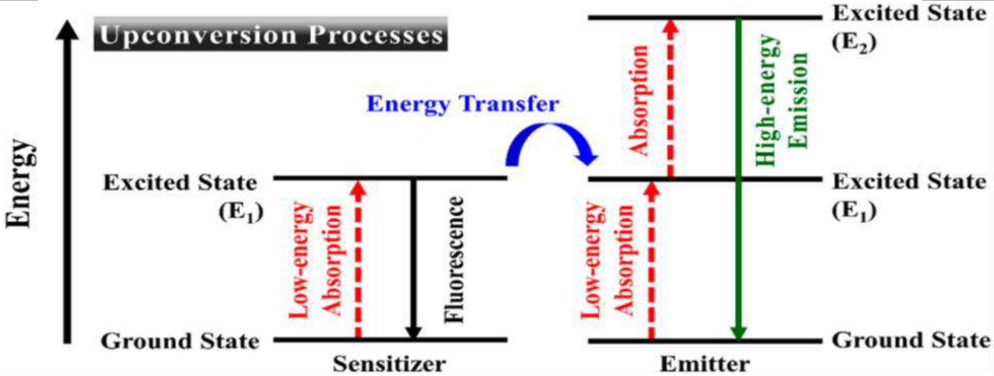

Fig .3: Up conversion processes involving low-energy photons absorption and energy transfer

RE elements, particularly trivalent lanthanide ions (Ln3+), have a number of energy levels of 4f configurations, which exhibit unique and interesting optical properties [15]. Due to the presence of intermediate energy levels, Ln3+ ions are capable of emitting several emissions through different possibilities of energy transfer [16]. Most photoluminescent emitters generally operate on the basis of Stokes' law, which can be simply explained as excited by photons of higher energy than the emitted ones or, in other words, that the energy of output photons is weaker than that of input photons [17].
The use of both of Nd3+ and Yb3+ as sensitizers allows the in vivo imaging with two different possible excitations [18-20] (Fig.4, For example, β-NaGdF4:Nd3+@ NaGdF4:Tm3+, Yb3+ NPs have been used for in vitro

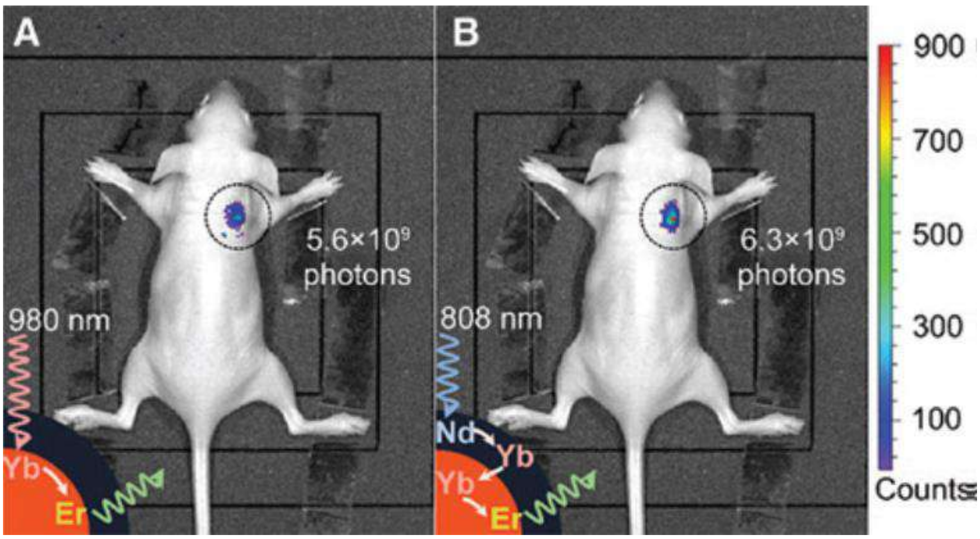

Fig.4: In vivo UC imaging of a nude mouse subcutaneously injected with NaGdF4: Yb, Er@NaGdF4: Nd, Yb NPs. The images were obtained with 980 nm laser (A) **and 808 nm laser(B) irradiation. Taken from Reproduced with permission of American Chemical Society. Copyright © 2013.**

Conclusion

Rare-earth-ion-doped nanophosphors have been identified as very promising luminescent nanomaterials for advanced bioimaging because of their special optical properties, such as long luminescence lifetimes, high photostability, low levels of photobleaching, and low cytotoxicity. The doping of rare-earth ions like Europium, Terbium, Erbium, Ytterbium, and Neodymium into a suitable host matrix makes it possible to achieve tunable emission from the visible to the near-infrared region, thus allowing deep tissue penetration and high-contrast imaging. up conversion nanophosphors have shown better results in suppressing background auto fluorescence and allowing real-time, non-invasive imaging of cells and tissues, this review offers a complete overview of optical nanomaterials for advanced bioimaging and their potential applications in various.

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Nanoscience: Core Principles, Historical Evolution, and Technological Impact

N. Amarabalan

M. Perumal

B. Srimanickam

S. Vinoth

Department of Electrical and Electronics Engineering, AMET University, Chennai-603112, India.

Email: vinothece@ametuniv.ac.in

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Abstract

Nanoscience explores the behavior, synthesis, characterization, and application of materials with at least one dimension between 1 nm and 100 nm. At this scale, matter displays size dependent physical, chemical, electrical, optical, and mechanical properties that differ fundamentally from bulk behavior due to quantum confinement, high surface-to-volume ratios, and interfacial effects. This chapter provides a concise overview of the field, from early colloidal observations to modern atomic-scale fabrication and characterization techniques. Core concepts including energy level discretization, quantum size effects, surface and interface dominance, and surface-energy-driven thermodynamics form the foundation for understanding nanosystems. Synthesis approaches such as top-down lithography and bottom-up self-assembly are discussed alongside enabling tools like scanning probe and electron microscopies and advanced spectroscopies. The influence of size, shape, composition, and defects on nanoparticles, nanowires, nanotubes, two-dimensional materials, and quantum dots is examined, with applications spanning electronics, biomedicine, catalysis, energy, and sensing. Ethical, environmental, and regulatory considerations, as well as emerging research frontiers, are also highlighted.

Keywords: nanomaterials, quantum confinement, surface-to-volume ratio, scanning probe microscopy, nanomanufacturing

Introduction

Nanoscience sits at the intersection of engineering, biology, chemistry, physics, and materials science, making it one of the most interdisciplinary fields in modern research. It focuses on understanding and manipulating matter at dimensions between 1 nm and 100 nm, where conventional bulk properties no longer apply. When materials are confined to length scales comparable to exciton radii, electron de Broglie wavelengths, or phonon mean free paths, they exhibit size-dependent optical, electrical, magnetic, mechanical, and chemical behaviors not observed at larger scales. These effects arise from quantum confinement and the dominance of surfaces and interfaces. As particle size decreases, surface area-to-volume ratios increase dramatically, enhancing reactivity and enabling tunable electronic and optical properties. Semiconductor nanoparticles, for instance, change color with size due to bandgap shifts. Such features enable advanced imaging, sensing, and electronic technologies. Built on quantum mechanics and solid-state physics, nanoscience has advanced through powerful tools such as scanning probe microscopy, electron microscopy, and spectroscopy, alongside synthesis methods including chemical vapor deposition, self-assembly, and lithography. Breakthrough instruments capable of atomic-scale imaging transformed the field from theory to experiment.

Today, nanomaterials nanoparticles, nanowires, nanotubes, thin films, quantum dots, and two-dimensional materials drive innovation in medicine, electronics, energy, and environmental technologies. However, challenges in scalability, reproducibility, safety, and regulation remain. Addressing them will determine how effectively nanoscience reshapes future materials and devices.

What is “nano”? Scale and significance

“Nano” refers to one billionth of a meter (10^{-9} m), but its significance lies in the physical changes that emerge at this scale. When material dimensions approach fundamental length scales, new phenomena appear. Figure 1, shows the schematic representation of major nanoscale phenomena, including quantum confinement, enhanced surface-to-volume ratio, and size-dependent behavior. At quantum scales, confinement comparable to electron wavelengths produces discrete energy levels, as seen in quantum dots and nanowires. In surface-dominated regimes, a larger fraction of atoms resides at interfaces, altering thermodynamics, reactivity, melting behavior, and strength. Thermal and electronic fluctuations also become more influential, limiting classical continuum descriptions. Additionally, strong interfacial coupling in nanoscale heterostructures can generate emergent properties absent in the individual materials.

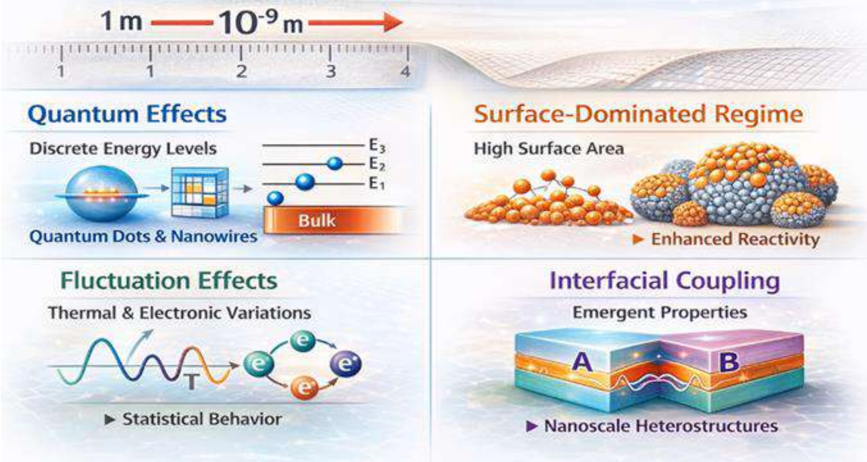

Figure: 1 Schematic showing major nanoscale phenomena, including quantum confinement, enhanced surface-to-volume ratio, and size-dependent behaviour

Core Physical and Chemical Principles

1. Quantum Confinement and Discrete States

When electrons are confined to dimensions comparable to their de Broglie wavelength, continuous energy bands break into discrete, quantized levels. Figure 2, shows the quantum confinement effect depicting discrete energy levels and size-dependent emission in nanoscale materials. This quantum confinement reshapes electronic structure, altering optical absorption, emission wavelengths, electrical conductivity, and carrier dynamics. Semiconductor quantum dots provide a classic example. As their diameter decreases, stronger carrier confinement increases the effective bandgap energy, producing a blueshift in photoluminescence. Smaller dots therefore emit light at shorter wavelengths. By controlling size and composition, quantum confinement enables tunable optoelectronic properties for displays, bioimaging, lasers, and quantum light sources.

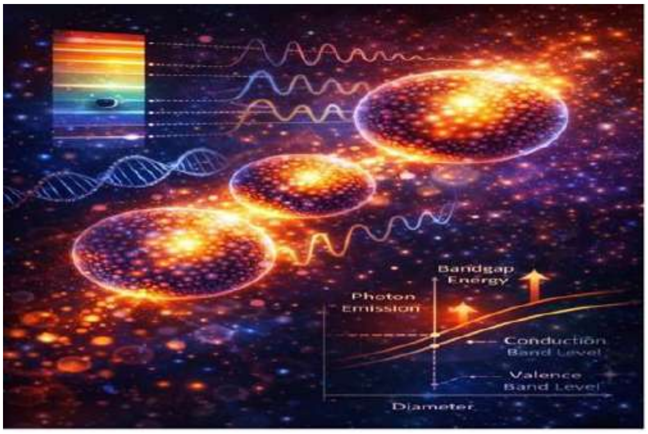

Figure: 2 Quantum confinement effect showing discrete energy levels and size-dependent emission in nanoscale materials.

2. Surface-To-Volume Ratio and Surface Energy

Surface atoms possess altered bonding environments compared to bulk atoms, resulting in distinct chemical and physical behaviour. As particle size decreases, the fraction of surface atoms rises dramatically, amplifying the influence of surface energy, adsorption processes, catalytic activity, and defect chemistry. Consequently, properties such as mechanical strength, melting temperature, phase stability, and reactivity become strongly size-dependent, distinguishing nanoscale materials from their bulk counterparts.

3. Electronic, Optical, and Plasmonic Resonances

Metal nanoparticles support localized surface plasmon resonances collective oscillations of conduction electrons excited by incident light. These resonances produce intense light absorption and scattering that can be precisely tuned by controlling particle size, shape, composition, and surrounding environment. The resulting field enhancement at the nanoparticle surface enables highly sensitive plasmonic sensors and amplifies spectroscopic signals, forming the basis of techniques such as surface-enhanced Raman spectroscopy and advanced optical detection platforms.

4. Phonons and Thermal Transport

At the nanoscale, phonon behaviour changes significantly as structural dimensions approach phonon mean free paths. Nanostructures can strongly scatter phonons, reducing thermal conductivity a key advantage in thermoelectric materials seeking improved energy conversion efficiency. Conversely, engineered interfaces and high-quality contacts can enhance heat dissipation in electronic devices. In this regime, heat transport may transition from diffusive to ballistic, fundamentally altering thermal management strategies and material performance.

5. Chemical Reactivity and Catalysis

The fraction of surface atoms increases dramatically with decreasing particle size, and many of these atoms are undercoordinated in comparison to their bulk counterparts. Because of their increased surface energy and unfulfilled bonds, undercoordinated atoms are more chemically active. This enhanced surface reactivity reduces activation barriers for surface reactions and improves reactant molecule adsorption. Bonding properties are further modified at the nanoscale by quantum size effects and changed electronic density of states. As a result, catalytic reaction routes and adsorption energies change, frequently increasing activity and selectivity or even opening up completely new catalytic processes.

Synthesis And Fabrication: Bottom-Up and Top-Down

1. Bottom-Up Approaches

Bottom-up strategies build nanostructures atom by atom or molecule by molecule with precise control. Colloidal chemistry enables wet-chemical synthesis of nanoparticles and quantum dots, where ligand coordination and reaction kinetics govern size and shape. Vapor-phase growth techniques, including chemical and physical vapor deposition, produce high-quality nanowires, nanotubes, and thin-film heterostructures. Self-assembly methods—using block copolymers, DNA origami, or surfactant templating—direct the formation of highly ordered and functional nanoscale architectures.

2. Top-Down Approaches

Top-down techniques sculpt nanoscale features from bulk materials with high precision and alignment control. Lithographic methods including electron-beam, photolithography, and nanoimprint lithography pattern structures at nanometer dimensions for integrated circuits and plasmonic devices. Focused ion or electron beams and advanced etching processes further enable subtractive fabrication of complex geometries.

While bottom-up approaches provide atomic-scale chemical control, top-down methods ensure deterministic patterning and system integration. Hybrid strategies that combine both are essential for scalable, high-performance device manufacturing.

Characterization and Instrumentation

Breakthroughs in instrumentation transformed nanoscience into a rigorous experimental discipline by enabling direct visualization and manipulation of matter at atomic resolution. Scanning Tunnelling Microscopy (STM) provided atomic-scale imaging of conductive surfaces and mapping of electronic states, while Atomic Force Microscopy (AFM) extended nanoscale characterization to insulating materials, revealing topography, mechanical properties, and chemical interactions. Transmission Electron Microscopy (TEM) and Scanning TEM (STEM) achieved sub-angstrom resolution for crystallography and spectroscopy (EELS, EDS), and Scanning Electron Microscopy (SEM) delivered detailed surface morphology. X-ray and synchrotron techniques enabled precise structural and in situ analysis. Complementary spectroscopies and single-molecule methods revealed electronic, optical, and dynamic processes, linking atomic structure to material function.

Representative Nanomaterials and Structure–Property Relationships

1. Nanoparticles and Nanoclusters

Nanoparticles and nanoclusters exhibit properties that are highly sensitive to size, composition, and ligand environment. By tailoring these parameters, researchers can precisely tune optical absorption, catalytic activity, and electronic structure. Noble metal nanoparticles are widely used in catalysis and chemical sensing due to their surface reactivity and plasmonic behaviour, while semiconductor nanocrystals enable size-controlled emission for advanced photonic and optoelectronic applications.

2. Nanowires and Nanotubes

Nanowires and nanotubes, characterized by their high aspect ratios and confined radial dimensions, enable highly directional charge and phonon transport. This anisotropic behaviour enhances electrical conductivity, thermal management, and mechanical sensitivity along the axial direction. Carbon nanotubes exhibit exceptional strength, flexibility, and carrier mobility, while semiconductor nanowires offer tunable bandgaps and efficient charge separation. These properties make them foundational components in nanoelectronics, high-performance photodetectors, energy harvesting devices, and ultrasensitive mechanical and electromechanical resonators.

3. Two-Dimensional Materials

Monolayer graphene, transition metal dichalcogenides such as MoS_2, and other van der Waals materials exhibit distinctive electronic band structures, valley-selective physics, and strong light–matter interactions. Their atomically thin nature enables extreme electrostatic control and mechanical flexibility. By stacking layers with controlled rotational alignment, a concept known as twistronics researchers can induce emergent phenomena, including correlated insulating phases and unconventional superconductivity, opening new pathways in quantum materials research and nanoelectronics.

4. Quantum Dots and Heterostructures

Quantum dots exhibit size-dependent electronic structures that enable precisely tunable light emission across a broad spectral range. By controlling particle dimensions and composition, researchers can tailor optical properties for specific applications. Engineered heterostructures, formed by combining materials with distinct band alignments, create controlled charge separation and recombination pathways. These capabilities support advanced light-emitting diodes, low-threshold lasers, and highly stable quantum emitters, playing a critical role in modern photonics, optoelectronics, and emerging quantum information technologies.

5. Nanocomposites and Hybrid Systems

Integrating nanomaterials with polymers, biomolecules, or bulk matrices creates multifunctional systems with enhanced and tunable properties. By embedding nanoparticles, nanotubes, or nanosheets into host materials, researchers can improve mechanical strength, electrical conductivity, thermal stability, and chemical responsiveness. Such nanocomposites enable applications ranging from flexible conductive inks and lightweight, high-strength structural composites to smart, stimuli-responsive surfaces. The synergistic interaction between nanoscale fillers and surrounding matrices allows performance levels unattainable with conventional materials alone.

Applications: Where Nanoscience Delivers Value

1. Electronics and Information Technology

Continued device scaling in modern electronics has relied on precise nanoscale engineering of transistors, interconnects, and advanced architectures such as FinFETs and gate-all-around devices. By controlling channel dimensions and interface quality at the nanometer level, engineers have sustained performance improvements while managing power consumption and leakage currents. Beyond classical computing, emerging quantum devices utilize nanostructured superconductors and semiconductors to create coherent qubits and highly sensitive components. These developments position nanoscale design at the heart of next-generation information processing technologies.

2. Energy Conversion and Storage

Nanostructuring electrode materials enhances battery performance by increasing active surface area and shortening ion diffusion distances, leading to higher specific capacity and faster charge discharge rates. At the nanoscale, improved electrical conductivity and reduced mechanical stress during repeated cycling contribute to longer operational lifetimes. In fuel cells and water electrolysis systems, nanoscale catalysts provide abundant active sites and optimized adsorption energies, accelerating reaction kinetics and lowering overpotentials. Additionally, plasmonic metals and quantum-confined semiconductors enable advanced photovoltaic architectures with improved light absorption, hot-carrier generation, and tunable bandgaps, ultimately boosting solar energy conversion efficiency.

3. Catalysis and Chemical Processing

Supported nanoparticles and single-atom catalysts offer exceptional catalytic activity and selectivity while significantly reducing precious metal usage. Their high surface-to-volume ratio maximizes the availability of active sites, enabling more efficient chemical transformations under milder conditions. Precise control over particle size, composition, and support interactions allows fine-tuning of reaction pathways, improving yield and minimizing by-products. These advances contribute to more sustainable industrial processes, lower energy consumption, and reduced environmental impact in chemical manufacturing and energy conversion.

4. Medicine and Biotechnology

Nanoparticles enable targeted drug delivery by improving solubility, stability, and controlled release while directing therapeutics to specific tissues or cells. In medical imaging, they enhance contrast in modalities such as MRI, CT, and fluorescence imaging, allowing earlier and more precise diagnosis. Nanomaterial-based biosensors also support rapid detection of disease biomarkers. However, interactions at the nano bio interface raise important safety considerations, including toxicity, immune response, and long-term biodistribution, requiring careful evaluation.

5. Sensing and Environmental Technologies

High surface area and tunable transduction mechanisms make nanomaterials exceptionally powerful platforms for ultrasensitive detection of gases, biomolecules, and physical stimuli. At the nanoscale, even minute changes in chemical composition, temperature, pressure, or electrical environment can produce measurable shifts in conductivity, optical response, or mechanical resonance. This sensitivity enables detection of trace pollutants, hazardous gases, pathogens, and disease biomarkers at extremely low concentrations, often in real time. Nanostructured sensors also offer rapid response times, miniaturization potential, and compatibility with portable or wearable devices. In environmental monitoring, they support continuous air and water quality assessment, while in healthcare, they enable early-stage diagnostics and personalized monitoring systems.

Safety, Ethics, and Regulation

The transition of nanotechnologies from laboratory research to commercial markets requires rigorous attention to safety, environmental stewardship, and social responsibility. Because nanoscale materials exhibit size-dependent properties distinct from bulk materials, traditional risk assessment frameworks are not always adequate. Thorough evaluation of toxicology, lifecycle impacts, and equitable deployment is essential for sustainable progress. Toxicology is a central concern. Particle size, shape, surface chemistry, charge, and aggregation state strongly influence biological interactions and biodistribution. Standardized testing protocols and clear dose metrics based on mass, surface area, or particle number are necessary to ensure reliable exposure assessments. Environmental fate must also be addressed. The persistence, mobility, bioaccumulation, and transformation of engineered nanomaterials require systematic study to protect ecosystems and food chains. Beyond safety, ethical considerations include equitable access to benefits, privacy implications of nanosensors, dual-use risks, and workforce impacts. Regulatory systems continue adapting existing laws, but clearer definitions and testing standards remain necessary for responsible innovation.

Historical Evolution: A Concise Timeline

The evolution of nanoscience spans centuries, progressing from early observations of unusual material behavior to a mature, engineering-driven discipline with global impact. Although formally established only in the late 20th century, its roots trace back much earlier. Before the term "nanotechnology" existed, artisans unknowingly exploited nanoscale effects. The 4th-century Lycurgus Cup, whose color changes due to embedded metal nanoparticles, and 19th-century colloidal science both hinted at size-dependent optical behavior. A conceptual turning point came in 1959 when Richard Feynman's lecture There's Plenty of Room at the Bottom envisioned atomic-scale manipulation. In 1974, Norio Taniguchi introduced the term "nano-technology" in the context of precision fabrication. The 1980s brought decisive experimental breakthroughs: the scanning tunneling microscope (Binnig and Rohrer) and atomic force microscopy enabled atomic-resolution imaging. The discovery of fullerenes, followed by carbon nanotubes in the 1990s and demonstrations of quantum confinement, accelerated research worldwide. In the 2000s, commercialization expanded, and graphene's isolation sparked the rise of two-dimensional materials. Today, nanoscience supports advanced electronics, medicine, and energy technologies, with increasing focus on safety, scalability, and responsible innovation.

Contemporary Frontiers and Research Challenges

As nanoscience advances from discovery to real-world deployment, several strategic frontiers are defining its next phase of innovation and impact.

Atomic Precision and Deterministic Assembly. A central ambition is to move beyond conventional self-assembly toward deterministic placement of individual atoms with near-perfect reproducibility. While self-assembly leverages thermodynamic forces efficiently, it lacks complete positional control. Emerging approaches in scanning probe manipulation, advanced lithography, and atomically precise synthesis seek to construct devices atom by atom. Such precision is critical for stable qubits, single-electron transistors, and defect-engineered materials whose performance depends sensitively on atomic arrangement.

Scalable and Green Nanomanufacturing. As nanomaterials enter industrial production, sustainability becomes essential. Future manufacturing must reduce energy use, eliminate hazardous reagents, and minimize waste without sacrificing performance. Green chemistry, solvent-free deposition, and low-temperature processing are increasingly integrated into scalable fabrication strategies.

Nano-Bio Interfaces. Interactions between nanomaterials and biological systems remain complex. Predictive models of nano–cell and tissue interactions are needed to accelerate safe biomedical translation, guiding the design of drug delivery systems and diagnostic platforms.

Quantum Materials, Modeling, and Standards. Engineered heterostructures are enabling qubits, topological states, and low-dissipation electronics. Meanwhile, multiscale modeling frameworks aim to connect quantum simulations with real-world performance. Robust standards and reproducible metrology remain indispensable for regulation, commercialization, and public trust.

Practical Guidance for Newcomers

Entering the field of nanoscience can feel overwhelming due to its interdisciplinary scope, but a structured approach can make the journey both manageable and rewarding. First, build a strong theoretical foundation. A solid understanding of solid-state physics, surface chemistry, and statistical thermodynamics is essential for interpreting nanoscale phenomena. These disciplines explain why materials behave differently at reduced dimensions and provide the language needed to engage with advanced research literature. Equally important is hands-on experience. Nanoscience is an experimentally driven field, and practical familiarity with at least one characterization technique such as atomic force microscopy (AFM), transmission electron microscopy (TEM), or spectroscopic methods will sharpen your intuition about nanoscale structure and measurement limitations. Complement this with experience in one synthesis or fabrication approach, whether colloidal chemistry, chemical vapor deposition (CVD), or lithographic patterning. Understanding how materials are made is just as important as knowing how they are measured. Focus consistently on structure property relationships. The ability to predict how variations in size, morphology, composition, or surface chemistry influence optical, electrical, mechanical, or catalytic properties is the hallmark of a skilled nanoscientist. When you can anticipate these connections, you move from observing phenomena to designing functional solutions.

Finally, integrate safety and environmental responsibility into your training from the outset. Safe laboratory practice, proper handling of nanomaterials, and awareness of potential environmental impacts are not secondary concerns they are fundamental professional competencies that ensure responsible and sustainable innovation.

Conclusion

Nanoscience uncovers and exploits behaviors absent in bulk materials, including quantized energy levels, surface-dominated reactivity, confined transport, and emergent collective effects. At the nanoscale, materials do not simply shrinkthey transform. Electrons occupy discrete states, phonons follow altered pathways, and surface interactions govern performance. Size becomes a defining parameter that dictates function. The field demands strong foundations in quantum mechanics and thermodynamics, expertise in synthesis and fabrication, advanced characterization skills, and responsible practice. It uniquely integrates theory, experiment, and application. Once limited to scientific curiosities such as color-changing glasses or unusual conductivity shifts, nanoscience now drives advances in electronics, medicine, energy, and catalysis. Nanoscale transistors power computation; engineered nanoparticles enable targeted therapies; tailored catalysts enhance sustainability. Despite progress, challenges remain in scalable manufacturing, safety evaluation, and predictive design. The nanoscale is exacting atomic imperfections matter but precise control converts understanding into transformative innovation.

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Nanomaterials In Renewable Energy Systems

[1]M. S. Dixit

[2]N. S. Dixit

[3]S. G. Khbragade

[3]A. S. Dixit

[1]Department of Physics, Jagadamba Mahavidyalaya, Achalpur, Amravati, Maharashtra, India 444806

[2]Department of Chemistry, G. S. Tompe college of Arts, Commerce and Science, Chandur Bazar, Amravati, Maharashtra, India 444704

[3]Department of Chemistry, Brijalal Biyani Science College, Amravati, Maharashtra, India 444605

Email: monikadixit83@gmail.com

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Abstract

The transition to sustainable energy globally is impeded by the performance limitations of traditional bulk materials. Nanotechnology, with its ability to control material architecture at the atomic and molecular level, presents unparalleled opportunities to break through these barriers. This chapter presents a comprehensive review of nanomaterials in renewable energy systems, covering solar energy harvesting, wind energy optimization, hydrogen production and storage, and electrochemical energy storage. We examine the underlying physical principles at the nanoscale, including quantum confinement, high surface-to-volume ratio, and improved charge transport, that underpin these breakthroughs. The chapter also describes advanced material synthesis techniques such as Chemical Vapor Deposition, electrospinning, and hydrothermal synthesis. Performance parameters for next-generation devices, such as perovskite solar cells and silicon-based lithium-ion anodes, are also presented. Finally, we examine the essential socio-economic and environmental challenges, including scalability, long-term material stability, and nanoparticle toxicity, to present a strategic plan for the commercialization of nanotechnology in the global sustainable energy infrastructure.

Keywords: Chemical Vapor Deposition, Organic Photovoltaics, Supercapacitors.

Introduction

The Nanotechnology Paradigm in Energy

The 21st century is characterized by a two-fold challenge: the provision of energy for a burgeoning global population and, at the same time, the mitigation of the disastrous consequences of climate change. The shift from fossil fuel-based economies to those based on renewable resources such as solar, wind, and hydrogen energy is no longer a choice but a survival necessity. Nevertheless, the efficiency, longevity, and cost-effectiveness of existing renewable energy technologies are inextricably bound to the material they are made of. Conventional bulk materials tend to approach their "theoretical limits" or "ceiling" values, such as the Shockley-Queisser limit for single-junction silicon solar cells (~33%) or the specific capacity of graphite anodes in lithium-ion batteries (~372 mAh/g).

Nanotechnology, the science of manipulating matter at a scale of 1-100 nanometers, is a paradigm shift in the field of energy. At this scale, the laws of classical physics are gradually replaced by quantum physics, and the material surface properties become dominant over their bulk properties. This gives rise to several revolutionary phenomena:

1. **Dominant Surface Effects:** In a nanoparticle of 10 nm, almost 20-30% of the atoms are on the surface. This leads to an enormous rise in the number of catalytic sites for the reaction, which is a critical factor in the production of hydrogen.
2. **Quantum Confinement:** If the size of a semiconductor nanocrystal is smaller than its Bohr exciton radius, the bandgap becomes a function of size. This "tunability" enables the development of solar cells that target specific regions of the solar spectrum, ranging from ultraviolet to infrared.
3. **Enhanced Mass and Charge Transport:** Nanostructured materials offer "highways" for ion and electron transport. For example, 1D nanomaterials such as nanowires and nanotubes provide "highways" for charge carriers, thus lowering recombination losses and internal resistance.
4. **Exceptional Mechanical and Thermal Properties:** Carbon nanotubes (CNTs) and graphene have mechanical properties and thermal conductivities that surpass any existing bulk material. These properties are leveraged to develop lightweight and robust wind turbine blades and advanced thermal management systems for electronics.

This chapter delves into the synthesis of these materials and their use in the development of the next generation of renewable energy technologies to fuel the global clean energy transition.

Advanced Synthesis and Characterization Methods

The applications of nanomaterials rely strictly on our ability to control their size, shape, crystallinity, and surface chemistry. Synthesis methods are broadly categorized into two approaches: "top-down" (physical reduction of bulk material) and "bottom-up" (assembly of atoms or molecules).

1. Chemical Vapor Deposition (CVD)

CVD is the most successful technique for the large-scale production of high-quality 1D and 2D carbon nanomaterials. In a conventional CVD process, carbon-containing precursor gases such as methane, ethylene, or acetylene are fed into a high-temperature reactor (700°C-1100°C) with a metallic catalyst like Cu, Ni, or Fe. The precursor gas decomposes on the surface of the catalyst, and carbon atoms assemble into graphene or carbon nanotube lattices. By carefully controlling the morphology of the catalyst and the growth temperature, it is possible to synthesize single-walled (SWCNTs) or multi-walled carbon nanotubes (MWCNTs) of desired chirality and length.

2. Hydrothermal and Sol-Gel Methods

Solution-based "bottom-up" processing is preferred for its ease of implementation, low cost, and scalability.

- **Sol-Gel:** A process that describes the transformation of a system from a liquid "sol" (a colloidal solution of nanoparticles) to a solid "gel" state. It is a popular technique for the large-scale production of high-purity metal oxide nanoparticles (TiO_2, ZnO, SnO_2) with controlled porosity, which are critical components of dye-sensitized solar cells and gas sensors.
- **Hydrothermal Synthesis:** Carried out in a pressurized water-based system (autoclave) at temperatures above the boiling point of water. This technique enables the fabrication of intricate 3D nanostructures like nanowire arrays, nanobelts, and nanoflowers directly on conductive substrates, making energy storage electrodes without binders.

3. Electrospinning: From Polymers to Energy Materials

Electrospinning is a flexible method for creating continuous nanofibers with diameters between tens and hundreds of nanometers. By applying a high-voltage electric field (usually 10-30 kV) to a polymer solution or melt, a "Taylor cone" is created, and a thin jet is extruded and stretched as the solvent evaporates. This leads to non-woven mats with very high porosity and surface area. These mats are finding applications as:

- **Battery Separators:** Offering much better thermal stability and electrolyte wettability than conventional polypropylene separators.
- **Catalyst Supports:** Offering maximum accessibility of noble metal nanoparticles (such as Pt on carbon nanofibers) for fuel cell reactions.

4. Comparison of Synthesis Methodologies

Method	Morphological Control	Scalability	Relative Cost	Primary Applications
CVD	Excellent	Moderate	High	Graphene, CNTs, thin films
Sol-Gel	Moderate	High	Low	Metal oxide nanoparticles/coatings
Hydrotherma	Good	High	Moderate	1D nanowire arrays for batteries
Electrospinning	Good	High	Low	Nanofiber mats, separators
Lithography	Superior	Low	Very High	Nanopatterned solar surfaces

Nanotechnology in Solar Energy Harvesting

- **Quantum Dot-Sensitized Solar Cells (QDSSCs):** Quantum dots (QDs) such as CdS, CdSe, and PbS are used as light-harvesting materials. By virtue of quantum confinement, their band gap can be varied by adjusting the size of the particles. This helps in the design of tandem or multi-junction solar cells that simultaneously utilize different parts of the solar spectrum. Moreover, QDs have the potential for "Multiple Exciton Generation" (MEG), in which a single photon of high energy generates two or more electron-hole pairs, potentially increasing efficiency above 40%.
- **Perovskite Solar Cells (PSCs):** Organometal halide perovskites (e.g., Methylammonium lead triiodide) have experienced an unprecedented boost in efficiency—from 3.8% in 2009 to over 25% in 2024. Nanoscale optimization of the perovskite layer's morphology and the addition of electron/hole transport layers (such as mesoporous TiO_2 or PCBM) play a pivotal role in minimizing charge recombination and maximizing the cell's life.

Organic Photovoltaics (OPVs) and Non-Fullerene Acceptors

OPVs employ conjugated polymers and small molecules to make flexible and thin solar cells. The basis of an OPV solar cell is the "Bulk Heterojunction" (BHJ), where the donor and acceptor materials are nano-scale mixtures. Recent breakthroughs in Non-Fullerene Acceptors (NFAs) have enabled OPV solar cells to achieve efficiencies above 18%. It is essential to achieve nano-scale phase separation between the donor and acceptor materials. If the domains are too large, the excitons (bound electron-hole pairs) will recombine before reaching the interface; if too small, the charge carriers will be trapped.

Plasmonic Enhancement and Light Management

Metal nanoparticles (Ag, Au) can be incorporated into the surface or absorber layer of a solar cell to create Localized Surface Plasmon Resonance (LSPR). This phenomenon offers:

- **Scattering Enhancement:** Increasing the optical path length of light in thin-film absorbers.
- **Near-Field Enhancement:** Focusing the electromagnetic field near the nanoparticle, which greatly increases photon absorption in the adjacent semiconductor.
- **Photonic Crystals:** Nanopatterning the surface of a silicon solar cell into a photonic crystal can suppress reflection to zero, ensuring that nearly 100% of the incident light is trapped.

Nanomaterials for Wind Energy Systems

Wind turbines are enormous mechanical systems that have to work for many decades in extreme conditions. Nanotechnology enhances their efficiency through structural reinforcement and functional coatings.

Reinforced Nanocomposites for Turbine Blades

With the increase in the length of turbine blades (over 100m) to maximize wind energy, the material's strength faces an exponential rise.

- **CNTs and Graphene Nanoplatelets:** These nanofillers are mixed into the epoxy resin matrix of glass or carbon fiber-reinforced polymers (GFRP/CFRP). Even at a very low concentration (0.5 wt%), CNTs can fill the distance between larger fibers, inhibiting the growth of micro-cracks and extending the lifespan of the blade by more than 50%.
- **Lightweighting:** Nanotechnology enhances the specific strength of the composite material, enabling the design of thinner and lighter blades that can turn at a lower wind speed, thus raising the capacity factor of the turbine.

Anti-Icing and Self-Cleaning Surfaces

Ice formation on the blades in cold regions changes the aerodynamic shape of the blades and increases their weight, resulting in power losses and mechanical failure.

- **Superhydrophobic Nanocoatings:** Nanocoatings with SiO_2 or PTFE nanoparticles produce a "lotus effect" surface with contact angles above 150°. Water droplets on the surface repel each other and bounce off before they freeze.
- **Active Joule Heating:** Conductive nanocoatings based on CNTs can be employed to pass an electric current through the surface of the blades, producing localized heating just sufficient to melt the ice-blade interface, allowing centrifugal force to remove the ice.

Nanoparticle-Enhanced Lubricants

The gearboxes and bearings of wind turbines are susceptible to wear and friction, which are major factors in turbine downtime.

- **Nano-Lubricants:** Mixing spherical nanoparticles such as molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), or nanodiamonds with conventional lubricants produces a "rolling-ball" effect at the nano level. This lowers the friction coefficient and prevents metal contact, increasing the maintenance cycles of offshore wind turbines.

Hydrogen: Production, Storage, and Fuel Cells

Hydrogen is the ultimate clean energy carrier, but its use is hindered by the expense of production and the challenge of high-density storage.

Electrocatalytic Hydrogen Production

The electrolysis of water to produce hydrogen and oxygen needs catalysts to reduce the activation energy barrier.

- **Non-Precious Metal Nanocatalysts:** Although Platinum (Pt) is the most active catalyst for the Hydrogen Evolution Reaction (HER), its high cost is a major drawback. Nanocatalysis of Transition Metal Dichalcogenides (TMDs) such as MoS_2 nanosheets or Transition Metal Phosphides (TMPs) offers a high number of catalytically active edge sites, which are comparable to Pt.
- **Photocatalytic Water Splitting:** Direct solar water splitting on the surface of a semiconductor nanoparticle (such as TiO_2 or g-C_3N_4). Nanostructuring maximizes the surface-to-volume ratio, ensuring that the photogenerated charges reach the surface before recombination.

Solid-State Hydrogen Storage

Conventional storage in compressed gas tanks is dangerous and weighs too much. Nanomaterials offer a safer "solid-state" solution.

- **Metal-Organic Frameworks (MOFs):** MOFs are crystalline materials with metal ions coordinated to organic molecules, creating highly porous materials. MOFs such as MOF-5 and Cr-MIL-101 have surface areas above 5,000 m^2/g and can adsorb hydrogen gas.
- **Metal Hydrides at the Nanoscale:** Bulk Magnesium hydride (MgH_2) can adsorb ~7.6 wt% hydrogen at temperatures above 300°C. However, nanoscale MgH_2 with 10 nm sizes and a Nb_2O_5 catalyst can lower the temperature requirement by several hundred degrees centigrade and accelerate hydrogen adsorption by a factor of ten.

Electrochemical Energy Storage: Batteries and Supercapacitors

The intermittent nature of solar and wind power requires an efficient storage system. Nanotechnology is the key to the "post-lithium" revolution and high-rate energy storage.

Next-Generation Lithium-Ion Batteries

- **Silicon Nanowire Anodes:** Silicon has a theoretical capacity of ~4200 mAh/g, but it expands by 300% during lithium absorption, causing mechanical pulverization. Silicon nanowires or "yolk-shell" nanostructures offer the required pore volume to host the expansion, enabling thousands of charge/discharge cycles.
- **Nanostructured Cathodes:** High-Ni NMC cathodes are susceptible to surface degradation. A thin (2-5 nm) Atomic Layer Deposition (ALD) layer of Al_2O_3 protects the cathode from the acidic electrolyte, significantly enhancing the battery cycle life.

Beyond Lithium: Sodium, Magnesium, and Zinc-ion Batteries

Lithium is a limited resource. Nanostructuring is opening the door for the utilization of more abundant ions such as Sodium (Na^+) or Magnesium (Mg^{2+}). These ions are larger or have higher charges than Li^+, making them much slower in bulk materials. Nanowires and 2D materials (such as MXenes) offer the required open channels and high surface area for fast intercalation of these ions.

Supercapacitors and MXenes

Supercapacitors provide high power for fast acceleration or grid support.

- **MXenes ($Ti_3C_2T_x$):** This emerging family of 2D transition metal carbides offers the high hydrophilic surface of graphene, along with high metallic conductivity. MXenes have the ability to store energy via "pseudocapacitance," a fast surface redox process, to achieve high volumetric capacitances above 1500 F/cm³.
- **Carbon Nanotubes and Graphene:** Applied for flexible wearable supercapacitors with record-breaking cycle counts (>100,000 cycles).

Integrated Systems and the "Nano-Grid"

The future of renewable energy is in nano-grid systems that integrate production, storage, and control within a single nano-optimized environment.

- **Self-Powered Systems:** A nano-scale solar cell directly integrated with a supercapacitor or battery (a "solar-rechargeable battery") enables a self-sustaining energy system for IoT sensors.
- **Thermoelectric Nanomaterials:** Harnessing the **Seebeck effect** to generate electricity from waste heat in turbines or industrial processes. Nanostructuring (Bi_2Te_3 nanowires) decreases thermal conductivity without

impairing electrical conductivity, a phenomenon described as "phonon glass, electron crystal," which enhances the efficiency of energy conversion.

Socio-Economic and Environmental Challenges

Although the technical successes are impressive, the route to commercialization is full of challenges.

Scalability and "The Valley of Death"

The current scale of nanomaterial innovation is typically in milligram quantities in university laboratories. However, to meet the global battery market demand of kilotons, enormous capital outlays are needed, and continuous processing methods (as opposed to batch processing) need to be developed. The current expense of precursors (such as certain organic ligands for MOFs) is still a challenge.

Stability and Degradation

Nanomaterials are metastable systems because of their high surface energy. They have a tendency to agglomerate or oxidize with time. The challenge of ensuring that a nano-improved solar cell or battery will last for 20 years in the environment, with exposure to UV radiation, heat, and humidity, is the main thrust of current industrial research.

Toxicity and Environmental Impact

- **Human Health:** Carbon nanotubes, because of their needle-like structure, have been found to induce lung inflammation like asbestos if inhaled. Strict safety measures (HEPA filtration and wet processing) are required during their production.
- **Circular Economy:** Recycling nanomaterials from discarded batteries or solar cells is not a straightforward process. We need to work on "Design for Recycling" approaches that can easily recycle and reuse nanomaterials to make the "clean energy" revolution sustainable.

Conclusion and Strategic Outlook

Nanotechnology has moved from being a laboratory phenomenon to the backbone of contemporary renewable energy technologies. The capability to "engineer" at the atomic level has enabled us to develop perovskite solar cells that compete with silicon, silicon anodes that can charge in minutes, and wind turbine blades that can detect their own damage.

The future is in Autonomous Discovery, where Artificial Intelligence and robotics are employed to search through millions of nanomaterials to identify the ultimate catalyst or electrode. As we continue to optimize the synthesis and mitigate the environmental concerns, nanotechnology will surely be the key enabler of the global transition to a carbon-neutral and sustainable future.

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ABOUT THE EDITORS

Mr. Amol Rajendrasing Pardeshi

Mr. Amol Rajendrasing Pardeshi is an accomplished Assistant Professor in Physics with over 6 years of teaching experience at Dada Patil Mahavidyalaya, Karjat. He holds an M.Sc. in Physics from Savitribai Phule Pune University and has qualified both NET (2019) and SET (2023). Currently, he is pursuing his Ph.D. in Physics. He has a strong academic and research background with multiple research publications in reputed journals and conference proceedings, particularly in nanomaterials, thin films, and super capacitor applications. His research interests include material science, nanotechnology, and energy-efficient systems. He has actively participated in national and international conferences, seminars, and faculty development programs, presenting research papers and posters. Additionally, he has contributed to book chapters in international publications.

Dr. Sandeep S. Kahandal

Dr. Sandeep S. Kahandal is currently working as an Assistant Professor in the Department of Chemistry at V.P.M.'s B.N. Bandodkar College of Science (Autonomous), Thane, affiliated to University of Mumbai. He has completed B.Sc. (Chemistry) in 2005 and obtained his M.Sc. in Analytical Chemistry (2007) from Pune University, securing the first rank. He earned his Ph.D. in Chemistry from the Institute of Chemical Technology (ICT), Mumbai, from the University of Mumbai in 2013. During his doctoral studies, he was awarded the prestigious UGC-CSIR fellowships (JRF and SRF). Dr. Kahandal has made significant contributions to scientific research, with more than 16 publications in reputed International Journals indexed in Scopus and Web of Science, as well as conference proceedings. He has also authored several book chapters related to nanomaterials, catalysis, environmental sustainability, and Chemical Sciences. His research interests primarily encompass heterogeneous catalysis, green and sustainable chemistry, nanomaterials, and multicomponent organic reactions. He is also a recognized research guide at the University of Mumbai for the Ph.D. (Chemistry) and M.Sc. by Research (Chemistry) programs.

Ms. Monika Shyamkumarji Dixit

She is an Assistant Professor in the Department of Physics at Jagadamba Mahavidyalaya, Achalpur. She has over 3 years of teaching experience and around 4 years of research experience in the fields of dye-sensitized solar cells, polymers, and nanomaterials. Her teaching expertise includes Quantum Mechanics, Thermodynamics, Statistical Mechanics, Classical Physics, and Solid State Physics.She has actively contributed to academics through a published textbook for B.Sc. students and several research publications in reputed journals. She also holds a patent in the field of solid-state lighting. Ms. Dixit is a lifetime member of professional bodies such as NUTA and the Indian Association of Physics Teachers.In addition to teaching and research, she plays an active role in college administration through various committees, including cultural, soft skills development, and women's empowerment. She has participated in multiple faculty development programs, workshops, and orientation courses to enhance her academic and professional skills.

Dr. S. Muthurajan

He is an Assistant Professor in the Department of Marine Engineering at the Academy of Maritime Education and Training (AMET) Deemed to be University, Chennai, India. He teaches Electrical and Electronics Engineering subjects to undergraduate engineering students and is actively involved in research related to advanced materials, energy systems, and emerging engineering technologies.His academic interests include nanomaterials, sustainable energy systems, smart technologies, and interdisciplinary engineering applications. He is actively engaged in academic publishing, research collaborations, and editorial activities in emerging areas of science and engineering. Dr. Muthurajan is committed to promoting innovative research and knowledge dissemination in the field of nanomaterials and their practical engineering applications.

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