

Chapter 8

Emerging Trends in Nanotechnology

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1. Introduction

Nanotechnology has emerged as a foundational enabling technology of the 21st century, driving transformative advances across medicine, energy, electronics, environmental sustainability, agriculture, and advanced manufacturing. By manipulating matter at dimensions typically ranging from 1 to 100 nm, nanotechnology exploits unique physicochemical phenomena including quantum confinement effects, enhanced surface reactivity, tunable optical properties, and exceptional mechanical performance that are not observed in bulk materials. Recent scientific progress has shifted the field beyond conventional nanoparticle synthesis toward the development of intelligent, multifunctional, and application-specific nano-systems capable of responding dynamically to biological, environmental, and technological stimuli. These advancements have accelerated the emergence of next-generation innovations such as precision nanomedicine, targeted drug delivery platforms, nano-enabled diagnostics, smart nano-sensors, nanoelectronics, quantum nanodevices, green nanomaterials, nanorobotics, and advanced nanomaterials for energy storage and conversion. A particularly significant trend is the convergence of nanotechnology with artificial intelligence, machine learning, biotechnology, and data-driven materials science, enabling the rapid discovery, optimization, and deployment of high-performance nanomaterials with unprecedented efficiency. Simultaneously, sustainable and environmentally responsible approaches, including green nanoparticle synthesis, circular nanotechnology, and eco-friendly nanomanufacturing, are reshaping the future direction of the field. These developments position nanotechnology as a critical driver of global efforts to address pressing societal challenges, including disease burden, energy security, environmental pollution, resource scarcity, climate change, and sustainable industrial development.

Nanotechnology has emerged as a transformative paradigm in modern science and engineering, redefining the fundamental boundaries of material design, functional performance, and technological innovation. Operating at dimensions typically between 1 and 100 nanometers, nanotechnology exploits unique physicochemical phenomena that arise when matter is engineered at the atomic and molecular scales (Mallikarjun *et al.*, 2025). At these dimensions, materials exhibit extraordinary properties including quantum confinement effects, enhanced catalytic activity, tunable electronic structures, exceptional mechanical strength, superior optical responsiveness, and dramatically increased surface-area-to-volume ratios—that differ substantially from those observed in their bulk counterparts. These distinctive characteristics have enabled the development of advanced materials and devices with unprecedented precision, efficiency, and multifunctionality, positioning nanotechnology as one of the most disruptive and strategically important technologies of the Fourth Industrial Revolution. The global importance of nanotechnology has expanded rapidly over the last two decades, driven by increasing demands for innovative solutions to complex challenges in healthcare, energy security, environmental sustainability, food production, digital transformation, and industrial competitiveness. What

began as a field primarily focused on nanoparticle synthesis and nanoscale characterization has evolved into a highly interdisciplinary domain integrating materials science, chemistry, physics, biology, medicine, engineering, data science, and artificial intelligence. This convergence has accelerated the transition from passive nanomaterials to intelligent, adaptive, and multifunctional nano-systems capable of sensing, responding, and self-regulating within complex biological and environmental environments (Lu *et al.*, 2025).

Nanotechnology is no longer viewed merely as a materials platform but rather as a foundational enabling technology with the capacity to reshape entire industrial sectors and redefine future scientific capabilities. Recent breakthroughs have demonstrated that the next generation of nanotechnology is characterized by the development of smart and programmable nano-systems capable of performing highly specialized functions with exceptional precision. In biomedicine, nanotechnology has revolutionized targeted drug delivery, molecular imaging, precision diagnostics, tissue engineering, regenerative medicine, gene editing, and cancer therapeutics (Bolidi *et al.*, 2025). The unprecedented success of lipid nanoparticle-based mRNA vaccine delivery systems has provided compelling evidence of the translational potential of nanotechnology in addressing global health emergencies and accelerating personalized medicine. Similarly, stimuli-responsive nanocarriers capable of releasing therapeutic agents in response to pH, temperature, enzymes, magnetic fields, or biological signals are transforming conventional treatment strategies by improving efficacy while minimizing systemic toxicity. These advancements underscore the growing role of nanotechnology in the transition toward precision healthcare and patient-specific therapeutic interventions.

Beyond healthcare, nanotechnology is becoming increasingly indispensable for achieving sustainable energy transitions and environmental resilience. Nanostructured materials such as graphene, MXenes, carbon nanotubes, quantum dots, metal–organic frameworks, and advanced nanocomposites are driving significant improvements in batteries, supercapacitors, fuel cells, hydrogen production technologies, and next-generation photovoltaic systems. Their exceptional electrical conductivity, tunable surface chemistry, and enhanced charge-transfer properties have enabled substantial gains in energy conversion efficiency, storage capacity, and device durability. Simultaneously, engineered nanomaterials are being deployed for environmental remediation applications, including water purification, heavy metal adsorption, carbon capture, pollutant degradation, antimicrobial treatment, and air-quality management. These developments position nanotechnology as a critical technological pillar for addressing climate change, resource scarcity, and global environmental degradation.

A defining feature of contemporary nanotechnology is its convergence with artificial intelligence (AI), machine learning (ML), robotics, and advanced computational modeling. The integration of AI-driven methodologies has fundamentally transformed the discovery and optimization of nanomaterials by enabling predictive design, automated experimentation, high-throughput screening, and data-driven performance evaluation. Machine learning algorithms can now identify complex structure–property relationships, predict nanomaterial behavior, optimize synthesis parameters, and accelerate the development of novel nanoscale systems with

unprecedented efficiency (Diao *et al.*, 2025). This convergence is facilitating the emergence of autonomous research platforms and digital laboratories, significantly reducing development costs and shortening the time required to translate scientific discoveries into practical technologies. As a result, AI-assisted nanotechnology is rapidly becoming one of the most influential research frontiers in materials science and engineering. Traditional nanoparticle synthesis methods often involve toxic reagents, high energy consumption, and environmentally burdensome processes. In response, researchers are increasingly adopting green nanotechnology approaches based on renewable resources, plant-derived extracts, microbial synthesis, biodegradable materials, and circular manufacturing principles. These environmentally responsible strategies seek to maximize technological benefits while minimizing ecological risks, thereby aligning nanotechnology development with global sustainability objectives. Such efforts are particularly important given increasing concerns regarding nanoparticle toxicity, environmental persistence, bioaccumulation, and long-term ecological impacts.

Nano-enabled innovations are playing a pivotal role in advancing good health and well-being (SDG 3), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), industry, innovation and infrastructure (SDG 9), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13). Consequently, governments, research institutions, and industrial stakeholders worldwide are investing heavily in nanotechnology research and development as a strategic pathway toward sustainable economic growth, technological leadership, and societal advancement. Despite these remarkable achievements, the rapid expansion of nanotechnology has also introduced significant scientific, regulatory, ethical, and socioeconomic challenges. Issues related to nanotoxicity, human exposure, environmental safety, lifecycle assessment, regulatory standardization, manufacturing scalability, public acceptance, and responsible innovation remain critical barriers to widespread commercialization and societal adoption (Chand *et al.*, 2025). Addressing these challenges requires a comprehensive and multidisciplinary framework that integrates scientific excellence with safety-by-design principles, robust governance mechanisms, and sustainable development strategies. This study provides a comprehensive and critical examination of the most influential developments transforming the field, including smart nanomaterials, nanomedicine, AI-driven nanotechnology, Nano sensors, nanoelectronics, quantum nanotechnology, nanorobotics, sustainable nanomanufacturing, advanced energy nanomaterials, and environmental nanotechnology. By synthesizing recent findings from high-impact peer-reviewed literature, this study aims to identify key technological breakthroughs, emerging opportunities, existing limitations, and future research priorities. By consolidating contemporary scientific evidence into a unified analytical framework, the study provides a comprehensive understanding of how emerging nanotechnologies are reshaping scientific innovation, industrial transformation, and socioeconomic development.

Furthermore, this study highlights the growing convergence of nanotechnology with other disruptive technologies, particularly artificial intelligence, machine learning, biotechnology, quantum technologies, and advanced materials engineering. Such technological integration is accelerating the development of intelligent, multifunctional, and highly efficient nano systems

capable of addressing complex global challenges that conventional technologies cannot adequately solve. The study therefore serves as a valuable resource for identifying future research directions, technological opportunities, innovation pathways, and commercialization prospects that are likely to define the next generation of nanotechnology-enabled solutions. From a societal and environmental perspective, the importance of this study lies in its examination of how nanotechnology contributes to addressing some of the most pressing global challenges of the twenty-first century, including disease burden, environmental pollution, climate change, food insecurity, resource depletion, and energy sustainability (Prabhakar *et al.*, 2025).

By evaluating both the opportunities and challenges associated with nano-enabled technologies—including issues related to nanotoxicity, biosafety, environmental impacts, ethical considerations, and regulatory governance—this study promotes a balanced and responsible approach to technological advancement. Consequently, the insights presented herein can support evidence-based policymaking, foster sustainable innovation, and guide strategic investments in nanotechnology research, development, and industrial deployment. The significance of this study lies in its ability to bridge knowledge across multiple scientific disciplines while offering a forward-looking perspective on the transformative role of nanotechnology in shaping the future of science, technology, industry, and society. By identifying critical research gaps, emerging trends, technological priorities, and future opportunities, this study contributes to a deeper understanding of how nanotechnology can be leveraged to facilitate sustainable development, enhance global competitiveness, improve human well-being, and support the transition toward a more resilient, technologically advanced, and environmentally sustainable future.

2. Nanomedicine and Precision Healthcare: Transforming the Future of Disease Diagnosis and Therapy

Nanomedicine has emerged as one of the most influential and rapidly evolving frontiers in contemporary nanotechnology, fundamentally transforming the landscape of disease diagnosis, therapeutic intervention, and personalized healthcare. The convergence of nanoscale engineering, molecular biology, materials science, and clinical medicine has enabled the development of highly sophisticated nano-systems capable of interacting with biological structures at cellular and subcellular levels. Unlike conventional therapeutic approaches, which often suffer from poor bioavailability, nonspecific distribution, limited therapeutic efficacy, and systemic toxicity, nanomedicine offers unprecedented opportunities to enhance treatment precision through the rational design of multifunctional nanoplateforms. As healthcare systems worldwide increasingly transition toward precision and personalized medicine, nanotechnology has become a critical enabling technology for addressing complex biomedical challenges that remain inadequately managed by traditional therapeutic strategies. The growing prominence of nanomedicine is largely driven by the unique physicochemical properties exhibited by nanomaterials at the nanoscale. Their exceptionally high surface-area-to-volume ratio, tunable surface chemistry, controlled morphology, and ability to cross biological barriers enable the development of highly

efficient therapeutic and diagnostic systems. These characteristics facilitate improved drug encapsulation, prolonged circulation times, enhanced cellular uptake, controlled release kinetics, and selective accumulation at disease sites (Luo *et al.*, 2025).

A broad range of nanoscale platforms including lipid nanoparticles, polymeric nanoparticles, dendrimers, nanogels, metallic nanoparticles, mesoporous silica nanoparticles, extracellular vesicles, and biomimetic nanocarriers have been developed to improve the pharmacological performance of therapeutic agents while minimizing undesirable side effects. Such advances have significantly expanded the therapeutic window of many drugs and have opened new possibilities for treating diseases that were previously difficult to target effectively. Among all biomedical applications, oncology has witnessed perhaps the most profound impact of nanotechnology. Cancer remains one of the leading causes of mortality worldwide, and despite remarkable advances in surgery, chemotherapy, immunotherapy, and radiotherapy, treatment outcomes are frequently compromised by tumor heterogeneity, multidrug resistance, off-target toxicity, and limited drug penetration into tumor tissues.

Nanotechnology offers innovative solutions to these challenges through the development of targeted and multifunctional therapeutic systems capable of selectively delivering therapeutic payloads to malignant cells while sparing healthy tissues. Recent advances in surface engineering have enabled nanoparticles to be functionalized with antibodies, peptides, aptamers, and receptor-specific ligands that recognize tumor-associated biomarkers with high specificity (Yadav *et al.*, 2025). Such targeting strategies not only improve therapeutic efficacy but also reduce systemic toxicity, thereby enhancing patient safety and treatment tolerability. As illustrated in (Figure 1), nanomedicine provides an integrated framework for precision healthcare by linking nano-sensor-based diagnosis, biomarker detection, molecular imaging, AI-assisted clinical decision-making, targeted drug delivery, and monitoring.

Beyond targeted drug delivery, nanotechnology has facilitated the emergence of entirely new therapeutic paradigms. Photothermal therapy, photodynamic therapy, sonodynamic therapy, chemo dynamic therapy, magnetic hyperthermia, and nanoparticle-assisted immunotherapy have gained considerable attention as promising alternatives or complements to conventional cancer treatments. These approaches exploit the unique optical, magnetic, and catalytic properties of nanomaterials to induce highly localized therapeutic effects within tumor microenvironments. Particularly noteworthy is the growing development of nanoplatforms, which integrate diagnostic and therapeutic functionalities within a single nano-system. Such platforms enable simultaneous disease detection, treatment monitoring, image-guided therapy, and real-time assessment of therapeutic responses, representing a major step toward truly personalized oncology. The influence of nanomedicine extends far beyond cancer therapy and is increasingly evident in infectious disease management, regenerative medicine, neurological disorders, cardiovascular diseases, and genetic therapies. The global COVID-19 pandemic highlighted the transformative potential of nanotechnology through the unprecedented success of lipid nanoparticle-based mRNA vaccines.

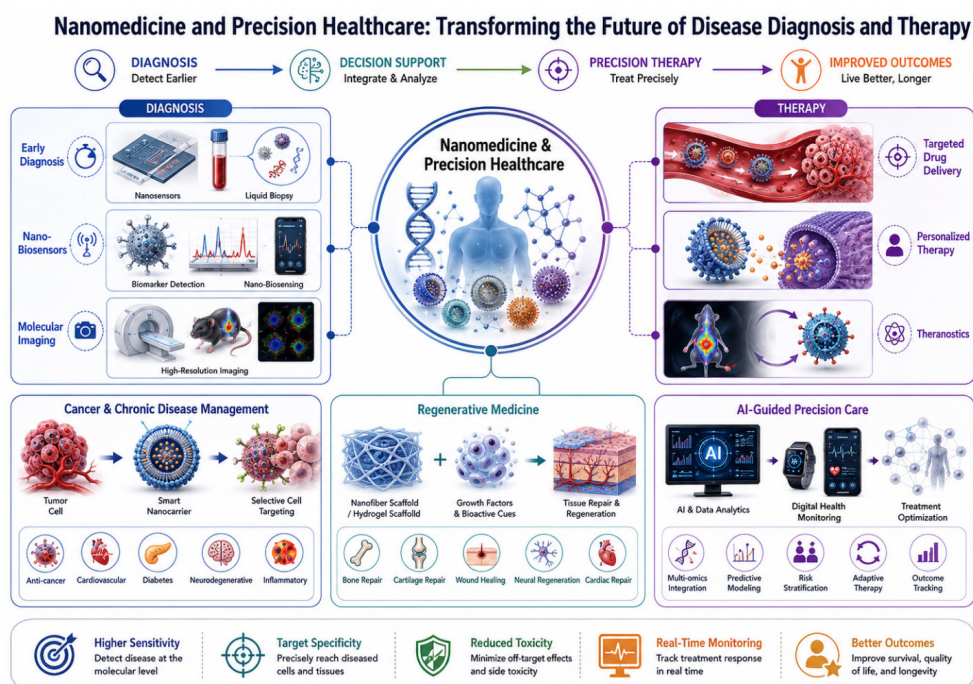


Figure 1. Schematic overview of nanomedicine-integrated precision healthcare, highlighting nanoscale diagnostics, AI-guided decision support, targeted therapy, and real-time monitoring.

These nanocarriers provided efficient protection and intracellular delivery of fragile nucleic acid cargo, demonstrating how nanotechnology can accelerate vaccine development and deployment on a global scale. This achievement has stimulated extensive research into nanoparticle-mediated delivery systems for gene editing technologies, including CRISPR-Cas platforms, RNA therapeutics, and next-generation vaccines. Consequently, nanomedicine is now regarded as a central component of future precision medicine strategies aimed at treating diseases at their molecular origins rather than merely managing clinical symptoms. Simultaneously, nanotechnology is revolutionizing diagnostic medicine through the development of ultra-sensitive biosensors, nanoscale imaging agents, wearable diagnostic devices, and point-of-care testing platforms. Conventional diagnostic techniques often face limitations in sensitivity, specificity, and detection speed, particularly during the early stages of disease progression. Nano-enabled diagnostic systems address these challenges by exploiting the unique electrical, optical, plasmonic, and magnetic properties of engineered nanomaterials.

Advanced nano-sensors can detect disease biomarkers at extremely low concentrations, facilitating earlier diagnosis and enabling timely clinical intervention. The integration of nanotechnology with artificial intelligence and digital health technologies further enhances diagnostic accuracy by enabling real-time data acquisition, automated interpretation, and predictive disease monitoring. Despite remarkable progress, several scientific and translational challenges continue to impede the widespread clinical adoption of nanomedicine. Concerns regarding nanoparticle toxicity, long-term biodistribution, immune responses, manufacturing

reproducibility, large-scale production, regulatory approval pathways, and economic feasibility remain significant barriers to commercialization. Furthermore, the complex interactions between nanomaterials and biological systems are not yet fully understood, necessitating comprehensive investigations into their long-term safety and environmental impacts. Addressing these challenges will require interdisciplinary collaboration among material scientists, biomedical researchers, clinicians, regulatory agencies, and industry stakeholders to establish standardized frameworks for the safe and effective translation of nanotechnologies into clinical practice. The future of nanomedicine is expected to be shaped by the convergence of nanotechnology with artificial intelligence, systems biology, synthetic biology, advanced biomaterials, and precision healthcare frameworks. Intelligent nano systems capable of autonomous disease recognition, real-time therapeutic adaptation, and personalized treatment delivery are increasingly becoming realistic possibilities. Such developments have the potential to redefine healthcare by shifting the focus from reactive disease treatment to predictive, preventive, and precision medicine (De la Torre *et al.*, 2025).

Nanomedicine is not merely an emerging application of nanotechnology; rather, it represents a paradigm shift in modern healthcare, offering transformative solutions for some of the most challenging medical problems of the twenty-first century while establishing the foundation for the next generation of patient-centered therapeutic and diagnostic technologies.

3. AI-Driven Nanotechnology: Revolutionizing Nanoscale Discovery and Design

The convergence of artificial intelligence (AI) and nanotechnology represents one of the most transformative developments in contemporary science and engineering, fundamentally redefining how nanomaterials are discovered, designed, optimized, and deployed across a wide range of applications. Traditionally, nanomaterial development has relied heavily on iterative trial-and-error experimentation, requiring substantial investments of time, labor, and financial resources to identify optimal material compositions, structures, and functional properties. However, the increasing complexity of nanoscale systems, coupled with the exponential growth of experimental and computational data, has created unprecedented opportunities for the application of artificial intelligence, machine learning (ML), deep learning (DL), and data-driven modeling approaches (Mim *et al.*, 2025). These technologies are enabling researchers to move beyond conventional empirical methodologies toward predictive, autonomous, and intelligent frameworks capable of accelerating scientific discovery and technological innovation at an unprecedented pace.

Artificial intelligence has emerged as a powerful tool for addressing one of the most fundamental challenges in nanoscience: understanding and predicting the complex relationships between nanomaterial structure, composition, processing conditions, and functional performance. Nanomaterials often exhibit highly nonlinear and multidimensional behaviors that are difficult to model using traditional theoretical approaches. Machine learning algorithms can analyze vast datasets generated from experiments, simulations, and high-throughput screening

platforms to identify hidden patterns, establish structure–property relationships, and predict material behavior with remarkable accuracy. Consequently, AI-driven approaches are increasingly being used to forecast nanoparticle size, morphology, surface chemistry, optical characteristics, catalytic activity, electrical conductivity, mechanical properties, and biological interactions before laboratory synthesis is performed. This predictive capability significantly reduces experimental uncertainty, shortens development cycles, and minimizes research costs.

One of the most significant contributions of AI to nanotechnology lies in the rational design and optimization of nanomaterials. Advanced machine learning models can evaluate thousands of potential material combinations within a fraction of the time required for conventional experimental screening. By leveraging predictive analytics, researchers can identify promising nanomaterial candidates with desired properties and optimize synthesis parameters such as temperature, pressure, precursor concentration, reaction time, and surface functionalization strategies. This capability is particularly valuable in the development of next-generation nanomaterials for biomedical applications, energy systems, catalysis, environmental remediation, and nanoelectronics, where even minor modifications in nanoscale architecture can substantially influence overall performance.

In nanomedicine, AI-assisted nanotechnology is driving a paradigm shift toward precision therapeutics and personalized healthcare. Machine learning algorithms are increasingly employed to predict nanoparticle biodistribution, cellular uptake, drug-loading efficiency, pharmacokinetic behavior, immunogenicity, and toxicity profiles (Wang *et al.*, 2025). Such predictive models facilitate the design of safer and more effective nanocarriers for targeted drug delivery, gene therapy, vaccine development, and cancer treatment. Moreover, AI-driven platforms can integrate genomic, proteomic, and clinical data with nanomaterial characteristics to develop patient-specific therapeutic systems tailored to individual biological conditions. This convergence of artificial intelligence and nanomedicine is accelerating the transition from generalized treatment strategies toward precision healthcare solutions capable of improving therapeutic outcomes while reducing adverse effects. Another rapidly expanding application of AI in nanotechnology involves advanced imaging and characterization. Modern nanoscience generates enormous quantities of complex imaging data through techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), atomic force microscopy (AFM), cryo-electron microscopy, and hyperspectral imaging.

Manual interpretation of these datasets is often time-consuming, subjective, and prone to variability. Deep learning and computer vision algorithms can automatically process, classify, and analyze nanoscale images with exceptional speed and accuracy, enabling real-time identification of structural defects, particle morphology, crystallographic features, and surface characteristics. Such capabilities are significantly enhancing the efficiency and reproducibility of nanoscale characterization while facilitating the discovery of previously unrecognized material phenomena.

Beyond healthcare, AI-driven nanotechnology is playing a pivotal role in addressing global challenges related to sustainable energy and environmental protection. In energy

Emerging Trends in Nanotechnology

research, machine learning models are being utilized to accelerate the discovery of advanced nanomaterials for batteries, supercapacitors, hydrogen production systems, fuel cells, and photovoltaic devices. By predicting electrochemical performance, charge transport behavior, and stability characteristics, AI can rapidly identify high-performance materials capable of improving energy storage and conversion efficiency. Similarly, in environmental nanotechnology, artificial intelligence is supporting the design of nanomaterials for water purification, pollutant degradation, carbon capture, heavy metal remediation, and environmental monitoring. Predictive algorithms can optimize nanomaterial functionality while simultaneously evaluating environmental risks and sustainability metrics, thereby promoting more responsible technological development. AI-driven nanotechnology integrates multimodal nanoscale data, predictive modelling, generative design, and autonomous optimization to accelerate nanomaterial discovery, rational nanoengineering, and translational healthcare applications (Figure 2).

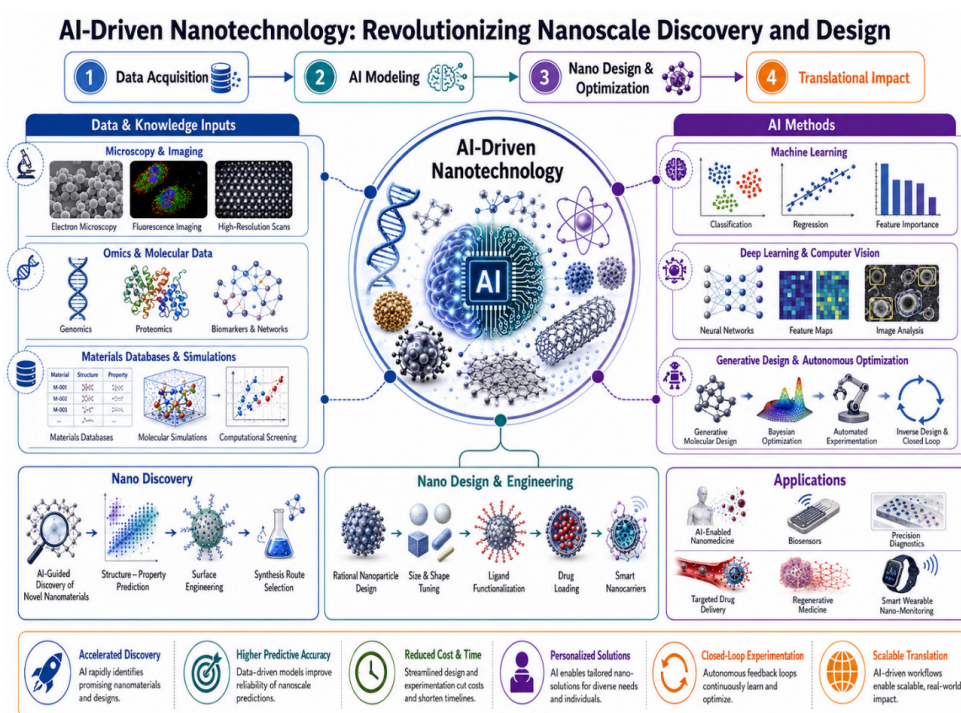


Figure 2. Schematic overview of AI-driven nanotechnology integrating data acquisition, machine learning, deep learning, generative design, and autonomous optimization for nanoscale discovery and engineering.

The integration of AI with robotics, automation, and high-throughput experimentation is further giving rise to autonomous nanotechnology laboratories capable of conducting experiments, analyzing results, generating hypotheses, and optimizing research pathways with minimal human intervention. These self-driving laboratories represent a significant shift in scientific methodology, enabling continuous and data-driven experimentation that dramatically accelerates the pace of innovation. Such systems are expected to play an increasingly important role in future nanomaterial discovery, particularly as the complexity of nanoscale systems continues to increase. Despite its immense potential, the integration of artificial intelligence into

nanotechnology also presents important challenges. The accuracy and reliability of AI models depend heavily on the quality, diversity, and availability of training datasets. Issues related to data standardization, reproducibility, algorithm transparency, interpretability, and model bias remain significant concerns within the scientific community. Furthermore, the development of universally accessible nanomaterial databases and robust validation frameworks is essential to ensure the reliability and transferability of AI-generated predictions (Madika *et al.*, 2025).

AI-driven nanotechnology is expected to become a cornerstone of next-generation scientific innovation. The continued convergence of artificial intelligence, quantum computing, digital twins, autonomous experimentation, and nanoscale engineering has the potential to revolutionize the entire lifecycle of nanomaterial development from initial discovery and design to manufacturing, deployment, and performance optimization. Rather than serving merely as a computational support tool, artificial intelligence is increasingly becoming an active partner in scientific discovery, enabling the creation of intelligent, adaptive, and multifunctional nanosystems that were previously beyond the reach of conventional research methodologies. Consequently, AI-driven nanotechnology is poised to redefine the future of materials science, healthcare, sustainable energy, environmental management, and advanced manufacturing, establishing a new paradigm for innovation in the twenty-first century.

4. Nanotechnology for Energy Storage and Conversion: Driving the Transition toward Sustainable Energy Systems

The global transition toward sustainable and low-carbon energy systems has intensified the search for advanced materials capable of overcoming the limitations of conventional energy generation, storage, and conversion technologies. In this context, nanotechnology has emerged as a transformative force in energy research, offering innovative solutions to some of the most pressing challenges associated with energy efficiency, storage capacity, resource utilization, and environmental sustainability. The unique physicochemical properties exhibited by nanomaterials including large specific surface areas, enhanced charge-transfer kinetics, tunable electronic structures, short ion-diffusion pathways, controllable porosity, and superior catalytic activity have positioned nanotechnology at the forefront of next-generation energy innovation. As global energy demand continues to rise alongside increasing concerns regarding climate change and fossil fuel dependence, nanotechnology is playing a pivotal role in accelerating the development of cleaner, more efficient, and more sustainable energy systems.

One of the most significant contributions of nanotechnology has been in the advancement of electrochemical energy storage technologies, particularly rechargeable batteries and supercapacitors. Conventional battery systems often face limitations related to energy density, charging speed, cycling stability, thermal management, and material degradation. Nanostructured materials have demonstrated remarkable potential for addressing these challenges by improving ion transport dynamics and enhancing electrochemical reaction kinetics. Materials such as graphene, carbon nanotubes, MXenes, transition metal oxides, metal sulfides, silicon

nanostructures, and hybrid nanocomposites have attracted substantial attention as electrode materials for lithium-ion, sodium-ion, potassium-ion, lithium-sulfur, and solid-state batteries. Their nanoscale architectures provide increased active surface areas and shorter diffusion distances, enabling faster charge-discharge rates, higher energy storage capacities, and improved long-term cycling performance. Consequently, nanotechnology is widely recognized for the development of high-performance energy storage systems required for electric vehicles, portable electronics, smart grids, and renewable energy integration (Sakthimurugan *et al.*, 2026). Beyond batteries, nanotechnology has significantly transformed the field of supercapacitors, which are increasingly regarded as complementary energy storage devices due to their exceptional power density, rapid charging capability, and long operational lifetimes. The incorporation of nanostructured carbon materials, conductive polymers, metal-organic frameworks (MOFs), and two-dimensional materials has substantially improved the electrochemical performance of supercapacitors by enhancing electrical conductivity, charge accumulation efficiency, and surface accessibility. Recent advances in hierarchical nanostructures and hybrid electrode architectures have further contributed to overcoming the traditional trade-off between energy density and power density, bringing supercapacitor technologies closer to practical large-scale applications.

Nanotechnology is also revolutionizing renewable energy generation, particularly in the fields of solar energy conversion and hydrogen production. Photovoltaic technologies have experienced substantial improvements through the incorporation of nanostructured materials capable of enhancing light harvesting, charge separation, and carrier transport processes. Semiconductor quantum dots, plasmonic nanoparticles, perovskite nanomaterials, graphene derivatives, and nanostructured metal oxides have demonstrated exceptional potential for increasing solar cell efficiency while reducing manufacturing costs. Among these technologies, perovskite solar cells have attracted considerable scientific interest due to their remarkable power conversion efficiencies and relatively simple fabrication processes. Nanoscale engineering strategies have played a crucial role in improving the stability, efficiency, and scalability of these emerging photovoltaic systems, positioning them as promising candidates for next-generation solar energy technologies. Figure 3 illustrates the pivotal role of nanostructured materials in enhancing energy storage and conversion technologies, highlighting their contributions to advanced batteries, supercapacitors, hydrogen storage systems, solar energy harvesting, electrocatalysis, and fuel cells, thereby accelerating the transition toward sustainable and low-carbon energy infrastructures.

Hydrogen energy is increasingly recognized as a cornerstone of future carbon-neutral economies, and nanotechnology is playing a critical role in overcoming existing barriers to hydrogen production, storage, and utilization. Nanostructured catalysts have significantly enhanced the efficiency of water-splitting reactions, enabling more effective hydrogen generation through photocatalytic, photoelectrochemical, and electrocatalytic processes. Materials such as metal nanoparticles, transition metal dichalcogenides, MXenes, carbon-based nanostructures, and single-atom catalysts exhibit superior catalytic performance due to their high surface reactivity and abundant active sites. These characteristics facilitate improved reaction kinetics and reduced energy requirements, thereby advancing the feasibility of large-scale green hydrogen production.

Furthermore, nanoscale materials are being explored for hydrogen storage applications, where their unique structural properties offer promising solutions to challenges associated with storage capacity, safety, and transport efficiency.

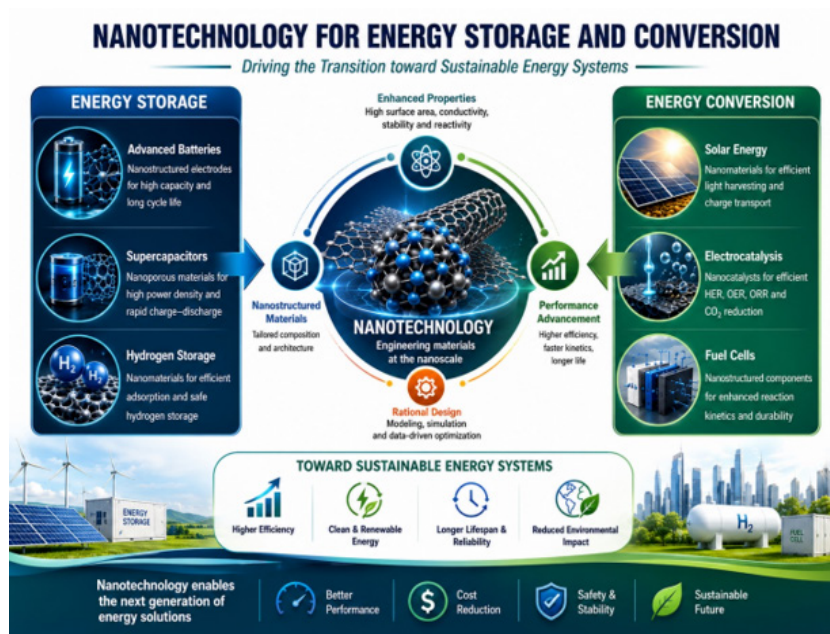


Figure 3: Nanotechnology-enabled energy storage and conversion systems illustrating the role of nanostructured materials in advanced batteries, supercapacitors, hydrogen storage, solar cells, electrocatalysis, and fuel cells to achieve higher efficiency, longer lifespan, reduced environmental impact, and sustainable energy solutions.

Fuel cell technology represents another area where nanotechnology has generated substantial advances. Fuel cells are considered highly efficient energy conversion devices capable of producing electricity with minimal environmental impact. However, their widespread adoption has historically been hindered by high costs, catalyst degradation, and limited durability. Nanotechnology has enabled the development of highly active and cost-effective electrocatalysts with enhanced catalytic efficiency and stability. Nanostructured platinum-based catalysts, alloy nanoparticles, transition metal nanomaterials, and carbon-supported catalyst systems have demonstrated significant improvements in fuel cell performance while reducing the reliance on expensive noble metals. These innovations are contributing to the commercialization of fuel cell technologies for transportation, portable power systems, and stationary energy applications.

Another rapidly expanding area of research involves the application of nanotechnology in photocatalytic energy conversion and environmental sustainability. Nanostructured photocatalysts are capable of harnessing solar energy to drive chemical reactions such as hydrogen evolution, carbon dioxide reduction, nitrogen fixation, and pollutant degradation. Semiconductor nanomaterials including titanium dioxide, zinc oxide, graphitic carbon nitride, metal sulfides, and heterojunction nanocomposites have demonstrated remarkable photocatalytic capabilities. Through nanoscale engineering, researchers have significantly improved light

absorption efficiency, charge carrier separation, and catalytic activity, thereby enhancing the overall performance of photocatalytic systems. Such technologies offer promising pathways for simultaneously addressing energy production and environmental remediation challenges.

Recent years have also witnessed the emergence of intelligent energy nanomaterials integrated with artificial intelligence, machine learning, and computational materials design. AI-assisted approaches are increasingly employed to accelerate the discovery of novel energy materials by predicting electrochemical properties, optimizing nanostructures, and identifying high-performance catalyst candidates. This integration of nanotechnology and artificial intelligence is substantially reducing development timelines and enabling the rapid advancement of next-generation energy technologies. The resulting synergy is expected to play a crucial role in achieving global energy sustainability goals while supporting the transition toward smart, decentralized, and carbon-neutral energy infrastructures. Despite remarkable progress, several challenges remain before nano-enabled energy technologies can achieve widespread commercial deployment. Issues related to material scalability, long-term stability, manufacturing costs, environmental impacts, resource availability, and lifecycle sustainability require further investigation. Additionally, concerns regarding the environmental and health implications of large-scale nanomaterial production necessitate the development of comprehensive regulatory frameworks and sustainable manufacturing practices. Addressing these challenges will be essential for ensuring the responsible integration of nanotechnology into future energy systems.

Nanotechnology is expected to remain a central driver of innovation in energy storage and conversion technologies. Continued advances in nanomaterial engineering, computational modeling, artificial intelligence, and sustainable manufacturing are likely to accelerate the development of highly efficient, cost-effective, and environmentally responsible energy solutions. As nations worldwide pursue ambitious decarbonization and renewable energy targets, nano-enabled technologies will play an increasingly vital role in enhancing energy security, reducing greenhouse gas emissions, and supporting the global transition toward a sustainable energy future. Consequently, nanotechnology is not merely improving existing energy systems; it is fundamentally redefining the scientific and technological foundations of future energy generation, storage, and utilization.

5. Environmental Nanotechnology: Advancing Sustainable Solutions for Global Environmental Challenges

Environmental degradation, climate change, freshwater scarcity, industrial pollution, and ecosystem contamination have emerged as some of the most pressing challenges confronting humanity in the twenty-first century. Rapid industrialization, urbanization, agricultural intensification, and unsustainable resource consumption have significantly increased the release of hazardous pollutants into air, water, and soil systems, posing serious threats to environmental sustainability and public health. Conventional remediation technologies, while effective in certain contexts, often suffer from limitations such as high operational costs, low treatment efficiency,

secondary pollution, excessive energy requirements, and limited applicability to emerging contaminants. Against this backdrop, environmental nanotechnology has emerged as one of the most promising and rapidly expanding branches of nanoscience, offering innovative and highly efficient approaches for environmental monitoring, pollution control, resource recovery, and ecosystem restoration. By exploiting the unique physicochemical properties of nanomaterials, environmental nanotechnology is transforming traditional environmental management strategies and creating new opportunities for achieving sustainable development objectives.

The exceptional performance of nanomaterials in environmental applications is primarily attributed to their large specific surface area, high surface reactivity, tunable porosity, controllable morphology, unique electronic properties, and enhanced catalytic capabilities. These characteristics enable nanomaterials to interact more effectively with contaminants than conventional materials, thereby improving adsorption capacity, reaction kinetics, selectivity, and treatment efficiency. As a result, a diverse range of engineered nanomaterials—including metal and metal oxide nanoparticles, carbon-based nanomaterials, quantum dots, nanocomposites, magnetic nanostructures, biochar-supported nanoparticles, and metal-organic frameworks (MOFs)—have been extensively investigated for environmental remediation applications. These advanced materials are increasingly being utilized to address complex environmental challenges associated with water pollution, air contamination, soil degradation, hazardous waste management, and emerging contaminants.

Among the various applications of environmental nanotechnology, water treatment and purification have received particular attention due to the growing global demand for clean and safe water resources. According to international estimates, billions of people continue to face challenges related to access to safe drinking water, while industrial effluents, agricultural runoff, pharmaceutical residues, heavy metals, dyes, pesticides, and pathogenic microorganisms increasingly threaten aquatic ecosystems. Nanotechnology offers powerful solutions through the development of highly efficient adsorbents, catalysts, membranes, and disinfection systems capable of removing contaminants at exceptionally low concentrations. Nanomaterials such as titanium dioxide (TiO_2), zinc oxide (ZnO), iron oxide nanoparticles, graphene derivatives, carbon nanotubes, biochar-based nanocomposites, and magnetic nanoparticles have demonstrated remarkable effectiveness in removing heavy metals, organic pollutants, pharmaceutical compounds, and microbial pathogens from contaminated water. Their ability to combine adsorption, photocatalysis, oxidation, and antimicrobial activity within a single platform significantly enhances treatment performance while reducing operational complexity.

Photocatalytic nanomaterials represent one of the most significant breakthroughs in environmental remediation. Semiconductor nanomaterials such as TiO_2 , ZnO , graphitic carbon nitride, metal sulfides, and heterostructured nanocomposites can utilize solar energy to generate highly reactive oxygen species capable of degrading a wide range of organic pollutants. Through advanced nanoscale engineering, researchers have successfully enhanced light absorption efficiency, charge carrier separation, and photocatalytic activity, enabling the effective degradation of dyes, pesticides, pharmaceutical residues, endocrine-disrupting compounds, and other

persistent pollutants. These technologies are particularly attractive because they simultaneously address pollution control and renewable energy utilization, making them highly relevant for sustainable environmental management.

Environmental nanotechnology is also playing an increasingly important role in air pollution control and atmospheric remediation (Srivastava *et al.*, 2022). Air pollution remains one of the leading environmental health risks worldwide, contributing to respiratory diseases, cardiovascular disorders, and premature mortality. Nanomaterials have demonstrated significant potential for capturing particulate matter, adsorbing toxic gases, degrading volatile organic compounds (VOCs), and improving air filtration systems. Nanostructured catalysts and photocatalytic coatings can effectively decompose harmful airborne pollutants under ambient conditions, while advanced nanofiber membranes provide highly efficient filtration performance with minimal energy consumption. Such innovations are contributing to the development of cleaner urban environments and more sustainable industrial emission control strategies. Similarly, soil contamination resulting from industrial activities, mining operations, excessive pesticide use, petroleum spills, and heavy metal accumulation has become a major environmental concern. Nanotechnology offers novel remediation approaches capable of addressing pollutants that are difficult to remove using conventional techniques. Engineered nanoparticles can immobilize toxic metals, catalyze degradation reactions, enhance microbial remediation processes, and facilitate the restoration of contaminated ecosystems. Magnetic nanocomposites, nano-zero-valent iron (nZVI), carbon-based nanomaterials, and biochar-supported nanoparticles have demonstrated particular promise for soil remediation due to their high reactivity, mobility, and contaminant removal efficiency. These technologies provide opportunities for restoring degraded land while minimizing environmental disturbance and remediation costs. Figure 4 presents an integrated framework of environmental nanotechnology, highlighting how engineered nanomaterials, Nano sensors, nano-bio interfaces, and AI-assisted monitoring systems collectively contribute to pollution remediation, environmental risk management, and the advancement of sustainable and resilient ecosystems.

The important emerging trend in environmental nanotechnology is the shift toward green and sustainable nanomaterial synthesis. Traditional nanoparticle production methods frequently involve hazardous chemicals, energy-intensive processes, and environmentally burdensome manufacturing pathways. In response to growing concerns regarding the environmental footprint of nanomaterial production, researchers are increasingly exploring eco-friendly synthesis approaches based on renewable biological resources. Green nanotechnology utilizes plant extracts, microorganisms, algae, fungi, agricultural residues, biopolymers, and environmentally benign solvents as reducing, stabilizing, and capping agents during nanoparticle synthesis. These biologically derived approaches not only reduce the use of toxic chemicals but also enhance biocompatibility, improve environmental safety, and lower production costs. Consequently, green nanotechnology has emerged as a critical component of sustainable nanomaterial development and circular economy strategies.



Figure 4: Environmental nanotechnology for sustainable remediation and monitoring, integrating tailored nanomaterials, advanced remediation, smart sensing, and AI-driven management to protect water, air, soil, and ecosystems.

Despite its considerable promise, environmental nanotechnology faces several scientific, regulatory, and societal challenges that must be addressed before widespread implementation can be achieved. Concerns regarding nanoparticle toxicity, environmental persistence, bioaccumulation, ecological impacts, and unintended interactions with living organisms remain important areas of investigation. While nanomaterials can facilitate environmental remediation, their uncontrolled release into ecosystems may generate new environmental risks if appropriate safety assessments are not conducted. Therefore, comprehensive life-cycle analyses, environmental risk evaluations, standardized toxicity testing protocols, and responsible governance frameworks are essential for ensuring the safe and sustainable deployment of nano-enabled environmental technologies. Environmental nanotechnology is expected to play an increasingly central role in achieving global sustainability objectives and supporting the transition toward a cleaner and more resilient society. Emerging developments involving smart nanomaterials, AI-assisted environmental monitoring, self-regenerating catalysts, multifunctional remediation platforms, and circular nanotechnology systems are expanding the scope and effectiveness of environmental applications. The integration of nanotechnology with artificial intelligence, biotechnology, renewable energy systems, and advanced environmental engineering is likely to accelerate the development of next-generation solutions capable of simultaneously addressing pollution control, resource recovery, environmental monitoring, and climate resilience. Consequently, environmental nanotechnology is not merely a technological tool for pollution remediation; rather, it represents a transformative scientific framework for advancing sustainable

environmental stewardship and safeguarding ecological and human health in an increasingly complex and resource-constrained world.

6. Nano sensors and Wearable Nanotechnologies: Bridging the Physical, Biological, and Digital Worlds

The emergence of Nano sensors represents one of the most significant technological developments within modern nanotechnology, fundamentally transforming the acquisition, interpretation, and utilization of information across biological, environmental, industrial, and agricultural systems. In an era increasingly characterized by data-driven decision-making, precision healthcare, smart manufacturing, environmental sustainability, and interconnected digital infrastructures, the ability to detect and quantify molecular, chemical, and physical signals with exceptional sensitivity has become critically important. Conventional sensing technologies, although widely used, often suffer from limitations related to detection thresholds, response times, miniaturization, selectivity, and real-time monitoring capabilities. As scientific and industrial challenges become increasingly complex, there is a growing demand for next-generation sensing platforms capable of providing rapid, continuous, and highly accurate information under dynamic operating conditions. Nanotechnology has emerged as a powerful solution to these challenges by enabling the development of Nano sensors that exploit unique nanoscale phenomena to achieve levels of performance that were previously unattainable using conventional sensing architectures.

The transformative potential of Nano sensors originates from the extraordinary properties exhibited by nanomaterials at dimensions approaching molecular and atomic scales. At these scales, even minor interactions between target analytes and sensing surfaces can generate measurable electrical, optical, electrochemical, magnetic, or mechanical signals. The exceptionally high surface-area-to-volume ratio of nanomaterials dramatically increases the density of active sensing sites, while quantum confinement effects and tunable electronic structures enable enhanced signal transduction mechanisms. Consequently, nanomaterials such as graphene, carbon nanotubes, quantum dots, plasmonic nanoparticles, semiconductor nanowires, two-dimensional transition metal dichalcogenides, MXenes, and metal–organic frameworks have become central to the development of highly sensitive sensing platforms capable of detecting analytes at ultralow concentrations (Fatma *et al.*, 2024). In many cases, nano-sensors can identify biomarkers, pathogens, toxins, pollutants, and chemical compounds at concentrations several orders of magnitude lower than those detectable by conventional analytical techniques. Perhaps the most transformative impact of nano sensor technology is being observed within the healthcare sector, where the global shift toward predictive, preventive, personalized, and participatory medicine is creating unprecedented demand for continuous physiological monitoring and early disease detection. Traditional diagnostic systems are largely episodic, relying on laboratory testing performed after the onset of symptoms. Such approaches often fail to capture dynamic physiological changes associated with disease initiation and progression.

Nano-sensors are fundamentally changing this paradigm by enabling real-time monitoring of biological processes at molecular resolutions. Advanced nano-enabled biosensors can detect circulating biomarkers, nucleic acids, proteins, metabolites, inflammatory mediators, and pathogenic organisms long before clinical symptoms become apparent. This capability has profound implications for diseases such as cancer, cardiovascular disorders, diabetes, neurodegenerative diseases, and infectious illnesses, where early intervention is often the most important determinant of clinical outcomes. These technologies are redefining the relationship between healthcare systems and patients by transforming health monitoring from an occasional clinical activity into a continuous and personalized process. Flexible and stretchable sensor platforms incorporating nanostructured materials can continuously monitor glucose levels, electrolyte concentrations, hydration status, stress hormones, inflammatory biomarkers, respiratory patterns, cardiovascular activity, and body temperature without disrupting daily activities. The significance of these technologies extends beyond convenience; they enable the generation of longitudinal physiological datasets that provide unprecedented insights into individual health trajectories. Such capabilities are increasingly viewed as foundational components of precision healthcare ecosystems, where treatment decisions are informed by continuous biological data rather than isolated clinical measurements.

The growing integration of Nano sensors with artificial intelligence, wireless communication technologies, and the Internet of Things (IoT) is further amplifying their transformative potential. Modern Nano sensors are no longer isolated analytical devices; rather, they are becoming integral components of interconnected digital ecosystems capable of autonomous data acquisition, transmission, interpretation, and response. AI-powered analytical frameworks can process massive streams of sensor-generated information, identify subtle physiological or environmental anomalies, predict emerging risks, and support real-time decision-making. This convergence is giving rise to intelligent healthcare systems capable of proactive disease management, smart environmental monitoring networks capable of detecting pollution events before ecological damage occurs, and industrial platforms capable of predicting equipment failures before catastrophic breakdowns take place. Consequently, Nano sensors are increasingly functioning as critical interfaces between the physical world and digital intelligence systems. Beyond healthcare, Nano sensors are becoming indispensable tools for addressing global environmental and sustainability challenges. Climate change, water scarcity, ecosystem degradation, food insecurity, and increasing levels of environmental pollution require monitoring systems capable of detecting threats at their earliest stages. Nano-enabled environmental sensors possess the sensitivity necessary to identify trace concentrations of heavy metals, pesticide residues, airborne toxins, greenhouse gases, pharmaceutical contaminants, pathogenic microorganisms, and emerging pollutants. Their deployment within distributed monitoring networks provides opportunities for real-time environmental surveillance, supporting evidence-based environmental governance and sustainable resource management. Similarly, in agriculture, Nano sensors are facilitating the transition toward precision farming systems by continuously monitoring soil chemistry, nutrient availability, plant health, moisture dynamics, and disease outbreaks, thereby optimizing resource utilization while minimizing environmental impacts. The

convergence of Nano sensors, wearable electronics, and digital health technologies, highlighting their role in real-time physiological monitoring, biomarker detection, continuous health tracking, and personalized healthcare interventions within next-generation intelligent healthcare systems is illustrated in Figure 5.

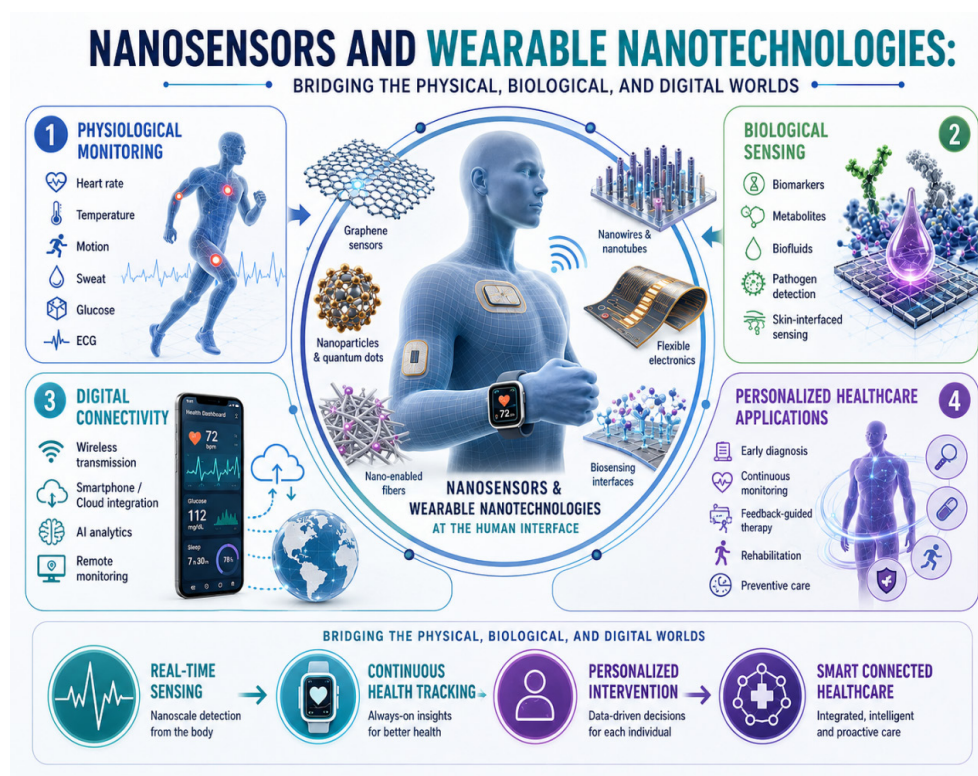


Figure 5. Nano sensors and wearable nanotechnologies enabling real-time physiological monitoring, biomolecular sensing, digital connectivity, and personalized healthcare through the integration of advanced nanomaterials, flexible electronics, and intelligent health analytics.

Despite their remarkable promise, Nano sensor technologies continue to face several significant scientific and translational challenges. Sensor fouling, signal drift, long-term stability, calibration complexity, manufacturing scalability, power management, data security, and regulatory compliance remain major obstacles to widespread commercialization. Furthermore, the increasing integration of Nano sensors into healthcare and digital infrastructure raises important ethical and societal concerns regarding data ownership, privacy protection, algorithmic bias, and equitable access to emerging technologies. Addressing these challenges will require multidisciplinary collaboration involving nanotechnologists, biomedical researchers, materials scientists, data scientists, clinicians, policymakers, and regulatory authorities. Nano-sensors are expected to evolve beyond passive monitoring devices into intelligent, self-powered, adaptive systems capable of autonomous decision-making and therapeutic intervention. Emerging concepts such as self-healing sensors, implantable nano sensor networks, digital twins, biohybrid sensing platforms, and AI-enabled closed-loop healthcare systems are already redefining the boundaries of what sensing technologies can achieve. As advances in nanomaterials, flexible electronics, artificial intelligence, synthetic biology, and wireless communication continue to

converge, Nano sensors are poised to become fundamental enabling technologies of the next digital revolution. Their significance extends far beyond improved detection capabilities; they represent a transformative platform for creating interconnected, responsive, and intelligent systems capable of continuously monitoring and optimizing human health, environmental sustainability, industrial productivity, and societal well-being.

7. Nanoelectronics and Quantum Nanotechnology: Redefining the Future of Information Processing and Intelligent Computing

The exponential growth of digital technologies, artificial intelligence, cloud computing, autonomous systems, and the Internet of Things has created unprecedented demand for electronic devices that are faster, smaller, more energy-efficient, and capable of processing increasingly complex volumes of information. For several decades, the remarkable progress of the semiconductor industry was largely sustained through the continuous miniaturization of silicon-based transistors, a phenomenon commonly described by Moore's Law. However, as device dimensions approach atomic scales, conventional semiconductor architectures are encountering fundamental physical limitations associated with power dissipation, quantum tunneling, interconnect bottlenecks, heat generation, and fabrication complexity. These challenges have prompted an intensive search for alternative materials and device architectures capable of sustaining technological progress beyond the limits of traditional microelectronics. In this context, nanoelectronics has emerged as one of the most strategically important frontiers of nanotechnology, offering revolutionary approaches for designing next-generation electronic systems with unprecedented functionality and performance.

Nanoelectronics exploits the unique electronic, optical, magnetic, and quantum properties that emerge when materials are engineered at nanometer dimensions. Unlike conventional electronic devices, which rely primarily on bulk material properties, nano electronic systems are fundamentally governed by nanoscale phenomena such as quantum confinement, ballistic electron transport, tunneling effects, spin interactions, and discrete energy states. These characteristics enable the development of devices that are not only smaller but also significantly more efficient, multifunctional, and computationally powerful. As a result, nanoelectronics is increasingly viewed as a critical enabling technology for future information processing, sensing, communication, and intelligent computing infrastructures.

A major driving force behind contemporary nanoelectronics is the rapid emergence of advanced low-dimensional materials that exhibit extraordinary electrical and optoelectronic characteristics. Among these, graphene has attracted exceptional scientific interest owing to its remarkable electron mobility, mechanical flexibility, thermal conductivity, and atomic-scale thickness. Since its discovery, graphene has stimulated extensive research into two-dimensional materials as potential successors to conventional silicon technologies. However, the absence of an intrinsic bandgap in graphene has motivated the exploration of alternative materials such as transition metal dichalcogenides (TMDs), black phosphorus, boron nitride, MXenes, and

other atomically thin semiconductors. These materials exhibit tunable electronic properties that make them highly attractive for applications in field-effect transistors, flexible electronics, photodetectors, optoelectronic devices, memory architectures, and integrated nanoscale circuits.

Carbon nanotubes, semiconductor nanowires, and quantum-confined nanostructures have similarly emerged as key building blocks for next-generation electronic systems. Their exceptional charge transport characteristics, nanoscale dimensions, and structural versatility enable the fabrication of ultrafast transistors, highly sensitive sensors, and energy-efficient electronic components (Alam *et al.*, 2026). Recent advances have demonstrated that nanoscale devices based on these materials can outperform conventional silicon-based technologies in specific applications while consuming significantly less power. Such developments are particularly important in the context of modern computing systems, where energy consumption has become one of the most significant technological and environmental concerns. Consequently, nanoelectronics is playing a crucial role in the development of sustainable computing architectures capable of supporting future digital infrastructures without proportional increases in energy demand.

Beyond conventional electronics, nanoelectronics is driving the emergence of flexible, wearable, and stretchable electronic systems that can seamlessly integrate with biological tissues, textiles, and complex surfaces. Traditional rigid electronic devices are often unsuitable for applications requiring mechanical adaptability and continuous interaction with dynamic environments. Nanostructured electronic materials enable the fabrication of flexible sensors, electronic skin, implantable medical devices, wearable healthcare systems, and next-generation human–machine interfaces. These technologies are increasingly influencing fields such as personalized healthcare, robotics, augmented reality, and smart manufacturing, demonstrating the broad societal impact of nano-electronic innovation.

Nanoelectronics seeks to extend and enhance conventional electronic technologies, quantum nanotechnology represents an even more profound shift in scientific and technological paradigms. At nanometer dimensions, matter begins to exhibit quantum mechanical behaviors that differ fundamentally from classical physical principles. Phenomena such as quantum superposition, quantum entanglement, quantum coherence, tunneling effects, and discrete energy quantization become increasingly significant, creating opportunities for entirely new forms of information processing and communication. Rather than viewing these effects as limitations, researchers are increasingly exploiting them as valuable resources for developing revolutionary technologies with capabilities far beyond those achievable using classical systems. One of the most important manifestations of quantum nanotechnology is the development of quantum dots, often referred to as “artificial atoms” due to their discrete energy levels and highly controllable optical properties (Deshmukh *et al.*, 2023).

Quantum dots have become central components in advanced display technologies, biomedical imaging systems, photonic devices, and quantum information platforms. Their ability to emit highly tunable and stable light makes them particularly attractive for quantum

communication systems, where precise control of photon generation is essential. Similarly, nanoscale single-photon emitters are emerging as foundational technologies for secure quantum communication networks and future quantum internet architectures. Quantum sensing represents another rapidly advancing area where nanotechnology is enabling extraordinary improvements in measurement precision and sensitivity. Quantum sensors based on nanoscale materials can detect magnetic fields, electric fields, temperature variations, gravitational effects, and molecular interactions with unprecedented accuracy. Such technologies have important implications for medical diagnostics, navigation systems, environmental monitoring, materials characterization, and national security applications. By leveraging quantum mechanical phenomena, these sensors can achieve performance levels that significantly exceed those of conventional sensing technologies. Figure 6 illustrates the integration of nanoelectronics, quantum nanotechnology, and intelligent computing, demonstrating their role in advancing high-performance, energy-efficient electronic devices, quantum information processing, and AI-assisted computational systems.

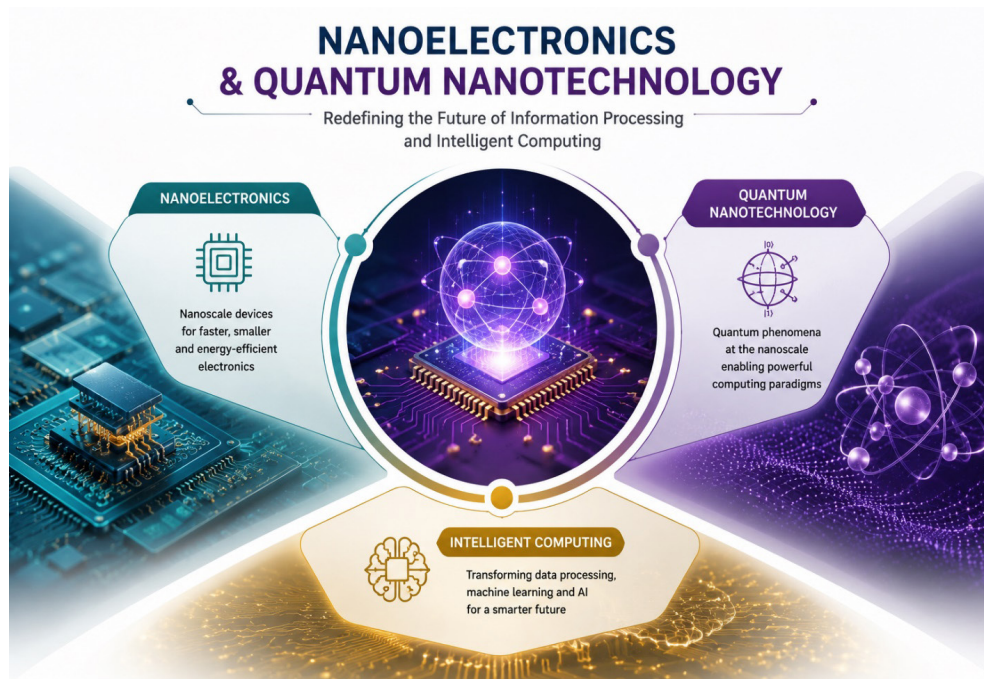


Figure 6. Nanoelectronics and quantum nanotechnology enabling next-generation intelligent computing, highlighting nanoscale electronic devices, quantum phenomena, and AI-driven data processing for faster, energy-efficient, and transformative information technologies.

Perhaps the most transformative application of quantum nanotechnology lies in quantum computing. Unlike classical computers, which process information using binary bits that exist in either a 0 or 1 state, quantum computers utilize quantum bits (qubits) capable of existing in multiple states simultaneously through quantum superposition. This capability enables quantum systems to perform certain computational tasks exponentially faster than even the most advanced classical supercomputers. Nanotechnology plays a critical role in the realization of quantum computing platforms through the fabrication of quantum dots, superconducting nanocircuits, spintronic devices, trapped-ion systems, photonic nanostructures, and topological quantum

materials. Although large-scale fault-tolerant quantum computing remains an ongoing scientific challenge, recent advances suggest that quantum technologies may fundamentally transform fields such as cryptography, drug discovery, materials design, financial modeling, artificial intelligence, and complex systems optimization.

The extraordinary promise of nanoelectronics and quantum nanotechnology, several critical challenges remain. Device reliability, quantum decoherence, fabrication precision, scalability, thermal management, integration with existing technologies, and manufacturing costs continue to limit widespread commercialization. Furthermore, the transition from laboratory-scale demonstrations to industrial-scale production requires substantial advances in materials engineering, device architecture, and fabrication methodologies. Addressing these challenges will require coordinated efforts across physics, materials science, computer engineering, nanotechnology, and information science. The convergence of nanoelectronics, quantum technologies, artificial intelligence, photonics, and advanced materials science is expected to redefine the foundations of information processing and communication systems. As traditional computing architectures approach their physical limits, nanoelectronics and quantum nanotechnology are emerging as key drivers of the next technological revolution. Their impact extends beyond faster devices and smaller circuits; they represent a fundamental reimagining of how information is generated, transmitted, processed, and secured. Consequently, these technologies are poised to play a central role in shaping future digital societies, enabling unprecedented computational capabilities, intelligent systems, and secure communication infrastructures that will define the technological landscape of the twenty-first century.

8. Agricultural and Food Nanotechnology: Transforming Sustainable Food Production and Global Food Security

The growing global population, climate change, declining agricultural productivity, depletion of natural resources, and increasing pressure on food supply systems have created unprecedented challenges for modern agriculture and food production. According to projections, the global population is expected to exceed 9 billion by the middle of the century, requiring substantial increases in agricultural output while simultaneously reducing environmental impacts and ensuring long-term sustainability. Conventional agricultural practices, heavily dependent on chemical fertilizers, pesticides, herbicides, and intensive resource utilization, have contributed significantly to soil degradation, water contamination, biodiversity loss, greenhouse gas emissions, and declining ecosystem resilience. Consequently, the development of innovative technologies capable of enhancing agricultural productivity while minimizing environmental consequences has become a critical global priority. In this context, agricultural nanotechnology has emerged as one of the most promising technological frontiers, offering transformative solutions for sustainable crop production, precision farming, food quality management, and global food security.

Agricultural nanotechnology represents the application of nanoscale materials, devices, and systems to improve the efficiency, sustainability, and resilience of agricultural production

systems. Unlike conventional agricultural inputs, nano-enabled technologies are designed to provide greater precision, enhanced delivery efficiency, controlled release characteristics, and improved interactions with biological systems. By exploiting the unique physicochemical properties of nanomaterials, researchers are developing innovative approaches to optimize nutrient management, crop protection, disease detection, environmental monitoring, and post-harvest preservation. These advancements are facilitating a gradual transition from traditional input-intensive farming toward intelligent, data-driven, and resource-efficient agricultural systems capable of meeting future food demands under increasingly challenging environmental conditions. One of the most significant applications of nanotechnology in agriculture is the development of nano fertilizers designed to enhance nutrient-use efficiency and reduce nutrient losses (Pudhuvai *et al.*, 2024).

Conventional fertilizers often suffer from low utilization rates, with substantial proportions of applied nutrients being lost through leaching, volatilization, runoff, and soil fixation processes. These inefficiencies not only increase production costs but also contribute to serious environmental problems such as eutrophication, groundwater contamination, and greenhouse gas emissions. Nano fertilizers address these limitations by enabling controlled and targeted nutrient delivery through nanoscale carriers capable of releasing nutrients in response to specific environmental or physiological conditions. Such systems improve nutrient availability, enhance plant uptake efficiency, and reduce fertilizer wastage while simultaneously minimizing environmental contamination. Consequently, Nano fertilizers are increasingly viewed as a key component of sustainable nutrient management strategies aimed at improving agricultural productivity without proportionally increasing resource consumption.

Crop protection represents another area where nanotechnology is generating substantial innovation. Pests, pathogens, and weeds continue to cause significant agricultural losses worldwide, often necessitating extensive use of chemical pesticides and herbicides. However, excessive reliance on conventional agrochemicals has raised concerns regarding environmental pollution, pesticide resistance, ecosystem disruption, and potential human health risks. Nano-enabled crop protection systems offer promising alternatives through the development of Nano pesticides and nanocarrier-based delivery platforms capable of enhancing pesticide efficacy while reducing application rates. Encapsulation technologies allow active compounds to be protected from premature degradation and released in a controlled manner at target sites, thereby increasing effectiveness and minimizing off-target effects. Such precision delivery systems contribute to more sustainable pest management practices while reducing the ecological footprint associated with conventional chemical applications.

The emergence of Nano sensors and smart agricultural monitoring systems is further transforming modern farming practices. Precision agriculture increasingly relies on real-time information regarding soil conditions, crop health, nutrient status, moisture availability, disease outbreaks, and environmental parameters. Nanotechnology enables the development of highly sensitive sensing platforms capable of detecting biological, chemical, and physical signals at extremely low concentrations. Nano-enabled sensors can monitor soil nutrient levels, identify

plant stress responses, detect pathogen infections, measure pesticide residues, and evaluate environmental conditions with exceptional accuracy. When integrated with artificial intelligence, remote sensing technologies, wireless communication networks, and Internet of Things (IoT) infrastructures, these Nano sensors provide valuable decision-support tools that enable farmers to optimize resource allocation, improve crop management strategies, and enhance agricultural productivity while reducing waste. Figure 7 demonstrates the integration of nano-enabled formulations, sensors, and smart delivery systems in agriculture and food technologies, highlighting their contributions to precision crop management, environmental sustainability, and improved food safety and nutrition.

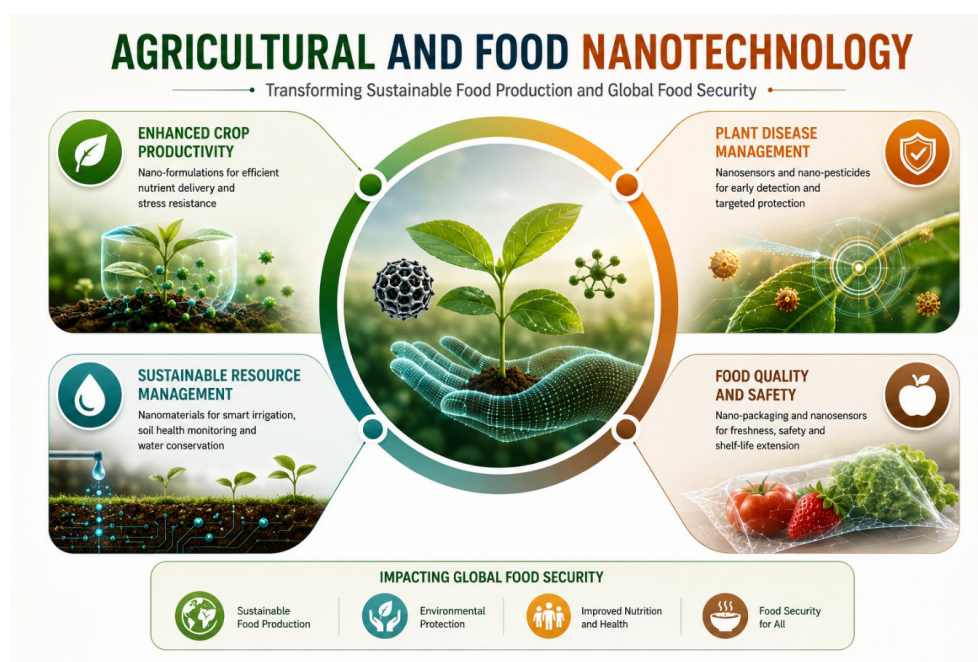


Figure 7. Agricultural and food nanotechnology applications enhancing crop productivity, plant disease management, resource efficiency, and food quality, illustrating the role of nanomaterials, nano sensors, and nano-enabled systems in promoting sustainable food production and global food security.

Beyond primary agricultural production, nanotechnology is increasingly influencing food processing, preservation, packaging, and safety monitoring systems. Food loss and waste remain major global concerns, with substantial proportions of agricultural products deteriorating before reaching consumers. Nano-enabled food packaging technologies are being developed to improve shelf life, maintain product quality, and enhance food safety. Nanocomposite packaging materials exhibit superior barrier properties against oxygen, moisture, ultraviolet radiation, and microbial contamination compared with conventional packaging systems. Additionally, antimicrobial nanocoatings incorporating silver nanoparticles, zinc oxide nanoparticles, and other bioactive nanomaterials can inhibit microbial growth and reduce food spoilage. Intelligent packaging systems equipped with nanosensors are also capable of monitoring freshness indicators,

temperature fluctuations, gas composition changes, and microbial contamination in real time, thereby providing valuable information throughout the food supply chain.

The integration of nanotechnology with biotechnology, artificial intelligence, genomics, and digital agriculture is creating new opportunities for developing highly sophisticated agricultural systems capable of responding to future food security challenges. Advanced nanocarriers are increasingly being explored for the delivery of biomolecules, genetic materials, plant growth regulators, and gene-editing components. Such technologies have the potential to accelerate crop improvement programs, enhance stress tolerance, improve nutrient utilization, and increase resistance to diseases and environmental stresses. As agriculture becomes increasingly data-driven and technologically integrated, nanotechnology is expected to play a central role in enabling climate-smart and precision-based farming systems that maximize productivity while minimizing environmental impacts.

Agricultural nanotechnology also raises important scientific, environmental, and regulatory concerns. The interactions of engineered nanomaterials with soil ecosystems, plant physiology, microorganisms, insects, and food chains remain incompletely understood. Questions regarding nanoparticle persistence, bioaccumulation, trophic transfer, ecological toxicity, and long-term environmental fate continue to generate significant scientific interest. Furthermore, the uptake and translocation of nanomaterials within plants may have implications for food safety and human health that require comprehensive investigation. The responsible development of agricultural nanotechnology therefore necessitates rigorous risk assessment frameworks, standardized regulatory guidelines, lifecycle analyses, and long-term environmental monitoring to ensure that technological benefits do not generate unintended ecological consequences.

The agricultural and food nanotechnology is expected to become a cornerstone of sustainable food production systems. Emerging developments in smart nanomaterials, responsive delivery systems, autonomous Nano sensors, nano-enabled precision agriculture, and AI-driven farm management platforms are expanding the possibilities for resource-efficient and environmentally sustainable agricultural practices. As global pressures on food systems continue to intensify, nanotechnology offers a powerful scientific and technological framework for enhancing productivity, strengthening food security, improving nutritional quality, and reducing environmental impacts. Consequently, agricultural nanotechnology is not merely an incremental improvement in farming practices; it represents a transformative approach to reimagining how food is produced, monitored, protected, and distributed in an increasingly resource-constrained and environmentally challenged world.

9. Safety, Toxicological, Regulatory, and Ethical Challenges of Nanotechnology

Nanotechnology has emerged as one of the most transformative scientific and technological innovations of the twenty-first century, its rapid expansion across healthcare, energy, agriculture,

electronics, environmental remediation, and consumer products has raised important questions regarding safety, sustainability, and societal responsibility. The same nanoscale properties that make engineered nanomaterials highly attractive for technological applications—including their extremely small size, high surface reactivity, tunable physicochemical characteristics, and enhanced biological interactions—also introduce unique risks that are often not encountered with conventional bulk materials. Consequently, understanding and managing the potential health, environmental, ethical, and regulatory implications of nanotechnology has become a critical prerequisite for its responsible development and long-term societal acceptance. As nanotechnology continues to move from laboratory research to large-scale commercialization, the ability to balance technological innovation with safety and sustainability considerations has emerged as one of the most important challenges facing researchers, policymakers, regulatory agencies, and industrial stakeholders. A fundamental concern surrounding nanotechnology relates to the interaction of engineered nanomaterials with biological systems (Tawade et al., 2023).

Due to nanoscale dimensions, nanoparticles can behave differently from larger particles of identical chemical composition. Their small size allows them to penetrate biological membranes, cross physiological barriers, and access cellular and subcellular structures that would otherwise be inaccessible to conventional materials. Human exposure to nanoparticles may occur through multiple pathways, including inhalation, ingestion, dermal absorption, medical administration, occupational exposure, and environmental contact. Once inside the body, nanoparticles can interact with proteins, lipids, DNA, cellular membranes, and intracellular organelles, potentially triggering a range of biological responses. Although many nanomaterials have demonstrated favorable biocompatibility profiles, increasing evidence suggests that certain engineered nanoparticles may induce oxidative stress, inflammation, genotoxicity, immunological responses, mitochondrial dysfunction, and cellular damage under specific conditions. These findings have highlighted the importance of nanotoxicology as a distinct scientific discipline dedicated to understanding the biological consequences of nanoscale materials and identifying potential risks associated with their use.

The most challenging aspects of nanotoxicological assessment is the extraordinary diversity of nanomaterials currently under development. Toxicological behavior is often influenced not only by chemical composition but also by particle size, shape, surface charge, crystallinity, coating materials, aggregation state, and environmental conditions. As a result, nanomaterials that appear chemically similar may exhibit substantially different biological effects. This complexity complicates traditional risk assessment approaches and underscores the need for comprehensive characterization strategies capable of evaluating Nano specific hazards. Furthermore, long-term exposure studies remain relatively limited, and significant knowledge gaps persist regarding chronic toxicity, biodistribution, bioaccumulation, transgenerational effects, and long-term interactions between nanomaterials and living organisms. Addressing these uncertainties is essential for ensuring that nano-enabled technologies can be safely integrated into healthcare, consumer products, industrial processes, and environmental applications.

Environmental safety represents another critical dimension of responsible nanotechnology development. As the production and use of engineered nanomaterials continue to increase, concerns have emerged regarding their potential release into air, water, soil, and ecological systems throughout their life cycle. Nanomaterials may enter the environment during manufacturing, transportation, product utilization, disposal, recycling, or accidental release events. Once introduced into natural ecosystems, nanoparticles can interact with microorganisms, plants, invertebrates, aquatic organisms, and higher trophic levels in ways that remain incompletely understood. Potential ecological consequences include altered microbial community structures, disruption of nutrient cycling processes, bioaccumulation within food webs, and impacts on biodiversity and ecosystem functioning. Consequently, environmental risk assessment has become an essential component of nanotechnology governance, requiring comprehensive investigations into nanoparticle fate, transport, transformation, persistence, and ecological interactions under realistic environmental conditions.

In response to challenges, researchers have increasingly embraced the concept of “safe-by-design” nanotechnology, which seeks to integrate safety considerations into the earliest stages of material development. Rather than evaluating risks only after commercialization, safe-by-design approaches emphasize the proactive engineering of nanomaterials to minimize toxicity while preserving desired functionality. This strategy involves optimizing physicochemical properties, selecting biocompatible materials, reducing environmental persistence, and designing nanomaterials that degrade into harmless byproducts after use. Such approaches represent a significant shift toward preventative risk management and are increasingly viewed as essential for the sustainable advancement of nanotechnology. The rapid expansion of nanotechnology has also exposed important regulatory challenges. Existing regulatory frameworks were largely developed for conventional chemicals and materials and may not adequately address the unique characteristics of nanoscale systems. Questions regarding material classification, exposure assessment, toxicity testing, labeling requirements, risk communication, and international regulatory harmonization remain subjects of ongoing debate. Furthermore, inconsistencies in testing methodologies and reporting standards often complicate comparisons among studies and hinder evidence-based regulatory decision-making. The development of internationally recognized standards for nanomaterial characterization, safety evaluation, and lifecycle assessment therefore remains a critical priority for the global nanotechnology community.

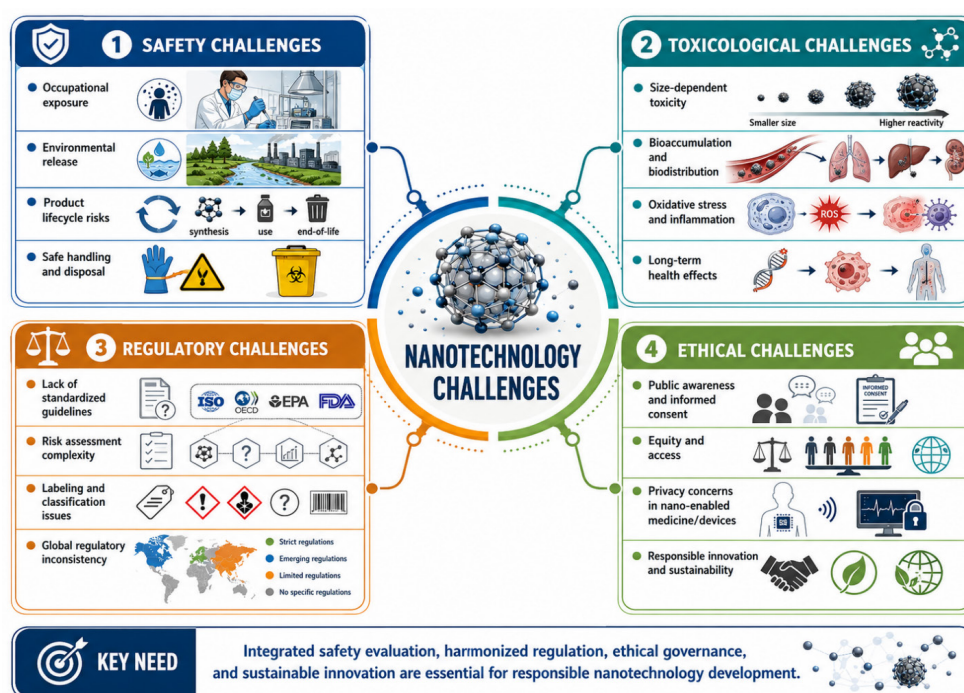


Figure 8. Key challenges in nanotechnology, encompassing safety, toxicology, regulatory, and ethical considerations, highlighting the need for integrated risk assessment, responsible innovation, and sustainable governance for safe and effective nano-enabled applications.

Beyond scientific and regulatory considerations, nanotechnology raises a number of complex ethical and societal questions. The increasing integration of nanotechnology into healthcare, digital systems, consumer products, surveillance technologies, and military applications has generated concerns regarding privacy, equity, transparency, and social justice. Nano-enabled biosensors and wearable monitoring devices, for example, can continuously collect highly sensitive physiological and behavioral data, raising important questions about data ownership, informed consent, cybersecurity, and individual privacy. Similarly, advances in nanomedicine may significantly improve healthcare outcomes, yet unequal access to expensive nano-enabled therapies could exacerbate existing healthcare disparities between developed and developing regions. Ensuring equitable distribution of technological benefits therefore represents an important ethical responsibility for policymakers and healthcare systems. Figure 8 illustrates the major safety, toxicological, regulatory, and ethical challenges associated with nanotechnology, emphasizing the importance of harmonized evaluation, ethical governance, and sustainable design to ensure responsible development and societal acceptance of nano-enabled technologies.

Another important ethical consideration involves the dual-use nature of many nanotechnologies. Scientific innovations developed for beneficial purposes may also possess the potential for misuse in surveillance systems, military technologies, cyber-physical infrastructures, or other applications that could raise security concerns. As nanotechnology becomes increasingly integrated with artificial intelligence, biotechnology, quantum technologies, and advanced

manufacturing systems, the importance of responsible innovation frameworks becomes even more pronounced (Amutha *et al.*, 2024). Such frameworks must ensure that technological development remains aligned with societal values, human rights, environmental sustainability, and long-term public welfare.

The advancement of nanotechnology will require a holistic and multidisciplinary approach that integrates scientific innovation with environmental stewardship, ethical reflection, regulatory oversight, and public engagement. Emerging concepts such as sustainable nanotechnology, green nanomanufacturing, lifecycle governance, responsible research and innovation (RRI), and circular nanotechnology are increasingly being recognized as essential pillars of future development strategies. The ultimate success of nanotechnology will therefore depend not only on its ability to generate scientific breakthroughs and economic value but also on its capacity to earn public trust through transparency, accountability, safety, and sustainability.

Consequently, the future trajectory of nanotechnology must be guided by a balanced framework that simultaneously promotes innovation and safeguards human and environmental well-being. By integrating robust nanotoxicological research, adaptive regulatory systems, ethical governance mechanisms, and sustainable design principles, the scientific community can ensure that nanotechnology continues to deliver transformative benefits while minimizing unintended risks. In this context, safety and ethics should not be viewed as barriers to innovation; rather, they should be regarded as fundamental enablers of responsible and sustainable technological progress in the nanoscale era.

10. Future Perspectives: Toward Intelligent, Autonomous, and Sustainable Nanotechnology

Nanotechnology is approaching a critical inflection point in its scientific and technological evolution. During the past three decades, the field has largely focused on understanding nanoscale phenomena, developing advanced nanomaterials, and demonstrating proof-of-concept applications across healthcare, energy, electronics, agriculture, and environmental systems. However, the next era of nanotechnology is expected to be fundamentally different. Rather than concentrating solely on material miniaturization or performance enhancement, future research will increasingly focus on the development of intelligent, adaptive, autonomous, and multifunctional Nano systems capable of sensing, learning, responding, and interacting with complex biological, environmental, and technological environments. This transition represents a paradigm shift from passive nanomaterials toward dynamic nanoscale systems that can actively participate in decision-making processes and functional optimization.

One of the most transformative developments expected to shape the future of nanotechnology is the emergence of artificial intelligence-driven nanoscience. Historically, the discovery of new nanomaterials has relied heavily on empirical experimentation and iterative optimization, often requiring years of laboratory work before commercially viable

solutions emerge. The integration of artificial intelligence, machine learning, and autonomous experimentation is rapidly changing this paradigm. Future nanomaterial development is expected to occur within self-driving laboratories where robotic platforms, advanced characterization systems, and AI algorithms operate as integrated discovery engines capable of designing, synthesizing, testing, and optimizing materials with minimal human intervention. Such systems may reduce material discovery timelines from decades to months, fundamentally transforming the innovation cycle of nanotechnology and accelerating the commercialization of advanced nanoscale solutions.

Another major transformation will be the evolution of nanomedicine from targeted therapy toward truly intelligent therapeutic systems. Current nanomedicine primarily focuses on improving drug delivery efficiency and diagnostic sensitivity. Future Nano systems, however, are expected to possess the ability to continuously monitor physiological conditions, identify disease-specific molecular signatures, make autonomous therapeutic decisions, and dynamically adjust treatment strategies in real time. Smart nanorobots, programmable biomolecular nanomachines, and AI-integrated therapeutic nanoparticles may eventually enable disease detection and intervention at the earliest stages of pathological development, long before clinical symptoms become apparent. Such technologies have the potential to shift healthcare from treatment-oriented medicine to predictive and preventive medicine, fundamentally redefining disease management and significantly extending healthy human lifespan.

Quantum nanotechnology is also expected to become a dominant force in future technological innovation. As conventional semiconductor technologies approach fundamental physical limits, quantum-enabled Nano systems are emerging as promising alternatives capable of overcoming the computational constraints of classical architectures. Future advances in quantum dots, spintronic nanodevices, topological materials, single-photon emitters, and quantum sensors may lead to entirely new computing paradigms characterized by unprecedented processing power, secure communication capabilities, and ultra-sensitive measurement technologies. The convergence of nanotechnology and quantum engineering could ultimately establish the technological foundations of the post-silicon computing era and redefine the global digital economy.

Sustainability will become an equally important determinant of future nanotechnology development. Although nanotechnology has demonstrated remarkable potential for addressing environmental challenges, increasing attention is being directed toward the environmental footprint of nanomaterial production and disposal. Future research will likely prioritize the development of biodegradable nanomaterials, circular nanomanufacturing systems, renewable feedstock utilization, and zero-waste synthesis approaches. Green nanotechnology is expected to evolve from a specialized research area into a central design principle governing the entire lifecycle of nano-enabled products. The future success of nanotechnology will therefore depend not only on technological performance but also on its ability to align with global sustainability objectives and environmental stewardship frameworks.

The future energy landscape will also be profoundly influenced by advances in nanotechnology. Achieving global carbon neutrality requires transformative innovations in energy generation, storage, conversion, and distribution. Nanomaterials are expected to play pivotal roles in next-generation batteries, solid-state energy storage systems, hydrogen technologies, photocatalytic fuel production, carbon capture platforms, and high-efficiency photovoltaic devices. Future research will increasingly focus on multifunctional energy nanomaterials capable of simultaneously addressing efficiency, durability, cost, and sustainability challenges. The integration of nanotechnology with artificial intelligence and digital energy systems may further accelerate the transition toward decentralized, intelligent, and carbon-neutral energy infrastructures.

Perhaps the most profound long-term impact of nanotechnology will arise from its convergence with other disruptive technologies, including synthetic biology, biotechnology, artificial intelligence, robotics, advanced manufacturing, and quantum computing. The boundaries that currently separate these disciplines are rapidly dissolving, creating opportunities for the development of hybrid technologies with capabilities far exceeding those of individual fields. Future innovations may include living nanomaterials capable of self-repair, biohybrid electronic systems, autonomous environmental remediation platforms, self-assembling manufacturing systems, and nanoscale computational architectures integrated directly with biological networks. Such developments suggest that the future of nanotechnology will not be defined by isolated material innovations but rather by its role as a foundational platform connecting multiple technological revolutions.

Despite these opportunities, several fundamental barriers remain unresolved. Challenges related to large-scale manufacturing, reproducibility, standardization, lifecycle sustainability, regulatory harmonization, public acceptance, and long-term safety continue to limit the translation of laboratory discoveries into commercial technologies. Furthermore, the increasing complexity of multifunctional Nano systems introduces new scientific questions regarding system reliability, biological interactions, environmental fate, and ethical governance. Addressing these challenges will require a transition from discipline-specific research toward integrated innovation ecosystems involving scientists, engineers, clinicians, policymakers, industrial stakeholders, and social scientists.

The ultimate success of nanotechnology will depend on its ability to move beyond proof-of-concept demonstrations and establish itself as a mature technological infrastructure capable of delivering scalable, safe, affordable, and globally accessible solutions. The future of the field will not be measured solely by the creation of smaller materials or faster devices but by its capacity to solve grand societal challenges related to human health, climate change, food security, clean energy, environmental sustainability, and digital transformation. As nanotechnology continues to converge with artificial intelligence, biotechnology, and quantum science, it is increasingly positioned to become one of the defining technological foundations of the twenty-first century. The coming decades may therefore witness the emergence of a new technological era in which intelligent Nano systems operate seamlessly across biological, physical, and digital domains,

fundamentally reshaping the way humanity interacts with matter, information, and the natural world.

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