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“Emerging Trends in Nanotechnology: Applications, Challenges and Future Directions”

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Abstract

Nanotechnology has become one of the fastest-growing areas of modern science and continues to reshape the way materials, devices, and technologies are developed. Its influence can be seen in healthcare, electronics, energy, agriculture, environmental protection, and many other fields. As research in this area continues to expand, new nanomaterials and fabrication techniques are creating opportunities to improve product performance, reduce resource consumption, and solve complex real-world problems. This review explores the latest trends in nanotechnology and examines how recent advances are driving innovation across different sectors. It discusses key applications such as targeted drug delivery, nanoelectronics, renewable energy, water purification, environmental remediation, and smart agricultural systems. The paper also considers the challenges that may affect the wider adoption of nanotechnology, including safety concerns, potential environmental risks, large-scale manufacturing, regulatory issues, and production costs. Finally, it highlights future research directions, with particular attention to the growing integration of nanotechnology with artificial intelligence, biotechnology, and sustainable technologies. By bringing together recent findings from the literature, this review provides a clear understanding of the current state of nanotechnology, the challenges that remain, and the opportunities that lie ahead for research, industry, and society.

Keywords: Nanotechnology; Nanomaterials; Healthcare; Renewable Energy; Environmental Remediation; Sustainable Development.

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1.Introduction

Nanotechnology has transformed the way scientists understand and manipulate matter

at the atomic and molecular levels. By working with materials that measure between

1 and 100 nanometres, researchers have been able to develop products with unique physical, chemical, and biological properties that are not observed in their bulk form. These distinctive characteristics have opened new possibilities for innovation across science, engineering, medicine, and industry. Over the past two decades, nanotechnology has moved from laboratory research to practical applications that influence everyday life. Nanomaterials are now used in medical diagnostics, drug delivery systems, electronic devices, renewable energy technologies, water treatment, food packaging, and advanced manufacturing. Their ability to improve efficiency, durability, and performance has made them an important part of many modern technologies. At the same time, growing investment from governments, research institutions, and private industries has accelerated the pace of innovation and expanded the scope of nanotechnology research.

Recent developments have further strengthened the role of nanotechnology in addressing global challenges. In healthcare, nanoparticles are improving targeted therapies and diagnostic techniques. In the energy sector, nanomaterials are contributing to more efficient solar cells, batteries, and hydrogen storage systems. Environmental applications such as water purification, pollution control, and waste treatment are

also receiving increasing attention. More recently, the integration of nanotechnology with artificial intelligence, biotechnology, and advanced manufacturing has created new opportunities for developing smarter and more sustainable solutions.

Despite these advances, several challenges continue to influence the future of nanotechnology. Questions related to the safety of nanomaterials, their long-term impact on human health and the environment, large-scale manufacturing, regulatory standards, and production costs remain important concerns. Addressing these issues is essential to ensure that nanotechnology develops in a responsible and sustainable manner. Continued collaboration among researchers, industries, and policymakers will play a key role in translating scientific discoveries into practical and socially beneficial applications.

Given the rapid pace of innovation, it is important to examine the current direction of nanotechnology and identify the opportunities and challenges that lie ahead. A comprehensive understanding of recent developments can support future research, encourage responsible innovation, and guide informed decision-making across scientific and industrial sectors.

This study examines recent developments in nanotechnology and offers a broad perspective on its evolving applications, key

challenges, and future directions. It explores how advances in nanomaterials and nanoscale technologies are driving innovation across diverse fields while also drawing attention to the scientific, technological, and regulatory issues that require further research. By bringing together findings from recent studies, the present study provides researchers, academics, industry professionals, and policymakers with a clear understanding of the current progress in nanotechnology and the opportunities that lie ahead.

2. Evolution of Nanotechnology

2.1 Origin and Historical Development

Nanotechnology has developed from a scientific concept into a multidisciplinary field that plays a central role in modern physics, materials science, and engineering. It deals with the study and manipulation of matter at dimensions ranging from approximately 1 to 100 nanometres, where materials often display physical and chemical properties that differ significantly from those observed in their bulk form. Changes in electronic structure, optical behaviour, magnetic characteristics, mechanical strength, and thermal transport at the nanoscale have created opportunities to design materials with properties that are difficult or impossible to achieve using conventional approaches (Bayda et al., 2019; Jeevanandam et al., 2018).

The origins of nanotechnology can be traced to the visionary lecture delivered by Richard Feynman in 1959, in which he proposed the possibility of manipulating matter at the atomic level. Although the experimental capabilities needed to realize this idea did not yet exist, his proposal stimulated scientific interest in controlling materials with atomic precision. The field acquired a clearer scientific identity when Norio Taniguchi introduced the term *nanotechnology* in 1974 to describe manufacturing processes involving nanometre-scale precision. This definition established a conceptual foundation that guided subsequent developments in nanoscale science and engineering (Feynman, 1960; Taniguchi, 1983).

A major turning point occurred during the 1980s with the development of high-resolution characterization techniques. The invention of the Scanning Tunneling Microscope (STM), followed by the Atomic Force Microscope (AFM), enabled researchers to visualize and investigate individual atoms and nanoscale surfaces with unprecedented accuracy. These instruments transformed nanotechnology from a largely theoretical concept into an experimentally accessible discipline, providing new opportunities to investigate atomic-scale phenomena in condensed matter physics, surface science, and advanced materials

research (Binnig & Rohrer, 1982; Binnig et al., 1986).

The discovery of new classes of nanomaterials further accelerated the growth of the field. Fullerenes, carbon nanotubes, and later graphene demonstrated that reducing materials to the nanoscale could produce entirely new physical properties arising from quantum confinement and large surface-area effects. Exceptional electrical conductivity, remarkable mechanical strength, high thermal conductivity, and distinctive optical characteristics made these materials attractive for a wide range of applications. Their discovery stimulated extensive research in nanoelectronics, photonics, energy technologies, biomedical engineering, and environmental science, considerably broadening the scope of nanotechnology (Kroto et al., 1985; Iijima, 1991; Novoselov et al., 2005).

Nanotechnology has since evolved into a highly interdisciplinary research area that integrates principles from physics, chemistry, biology, materials science, and computational modelling. Continuous advances in nanoscale characterization, precision synthesis, and device fabrication have strengthened both fundamental research and technological development. Today, the field supports innovations across diverse sectors, ranging from quantum technologies and advanced electronics to sustainable energy systems and

healthcare. This historical progression illustrates how nanotechnology has matured from a visionary scientific idea into a cornerstone of contemporary science and technology, with continuing influence on future research and industrial innovation (Bayda et al., 2019; Roco, 2003).

2.2 Evolution of Nanotechnology Research

Nanotechnology research has evolved significantly over the past few decades, moving from fundamental scientific investigations to a broad range of practical applications. In its early stages, research mainly focused on understanding how materials behave when their dimensions are reduced to the nanometre scale. Scientists observed that materials at this scale often exhibit properties that differ markedly from those of their bulk counterparts. Changes in electrical conductivity, optical behaviour, magnetic characteristics, and thermal transport demonstrated that nanoscale materials follow physical principles that are not always observed in conventional materials. These discoveries established the scientific foundation of modern nanotechnology and encouraged further investigation into nanoscale phenomena (Roco, 2003).

As research progressed, the emphasis shifted from simply observing these unique properties to controlling them through precise material design. Advances in synthesis and

fabrication techniques enabled researchers to produce nanostructures with well-defined sizes, shapes, and chemical compositions. Materials such as nanoparticles, nanowires, quantum dots, and ultrathin films could now be manufactured with much greater precision than before. This level of control allowed scientists to systematically examine how variations in nanoscale structure influence material performance. As a result, important advances were achieved in condensed matter physics, nanoscience, and materials engineering, providing a deeper understanding of the relationship between structure and physical properties (Malik et al., 2023).

The next stage in the evolution of nanotechnology was driven by the growing demand for materials with specific functional properties. Rather than studying nanomaterials only to understand their behaviour, researchers increasingly focused on developing materials for targeted technological applications. Carbon nanotubes, graphene, semiconductor nanostructures, and magnetic nanoparticles became some of the most extensively studied systems because of their exceptional electrical, optical, thermal, and mechanical characteristics. Their unique performance created new opportunities in fields such as nanoelectronics, photonics, spintronics, sensing, and energy conversion, where

traditional materials often faced performance limitations (Patel et al., 2024).

Another major development has been the integration of computational approaches into nanotechnology research. Modern studies no longer rely solely on experimental investigations. Computational modelling, first-principles calculations, molecular simulations, and machine learning techniques are now widely employed to predict the behaviour of nanomaterials before they are synthesized in the laboratory. These approaches help researchers identify promising material candidates, optimise their properties, and reduce the time and cost associated with experimental trial-and-error. The close interaction between theoretical modelling, computational analysis, and experimental validation has significantly accelerated the pace of materials discovery and has improved the design of nanomaterials for specific applications (Tripathy et al., 2024).

In recent years, nanotechnology research has become increasingly interdisciplinary and application-oriented. Scientists are now addressing complex scientific and engineering challenges by combining concepts from physics, chemistry, materials science, biology, electronics, and computer science. Current research is focused on emerging areas such as quantum materials, nanoscale energy storage and conversion

systems, nanoelectronic devices, flexible electronics, smart functional materials, and nanomedicine. At the same time, considerable effort is being devoted to overcoming practical challenges, including large-scale manufacturing, reproducibility of material properties, long-term stability, reliable characterization, environmental sustainability, and safety assessment. Addressing these issues is essential for translating laboratory discoveries into commercially viable technologies. As nanotechnology continues to advance, it is expected to play an increasingly important role in modern physics, advanced materials research, and the development of next-generation technologies across multiple scientific and industrial sectors (Roco, 2023).

2.3 Recent Scientific and Technological Advances

Recent progress in nanotechnology has been driven by major improvements in material synthesis, characterization techniques, and theoretical understanding of nanoscale phenomena. Researchers are now able to precisely tailor the size, morphology, composition, and surface chemistry of nanomaterials, allowing their physical properties to be engineered for specific applications. Such control has led to significant improvements in electrical conductivity, optical response, magnetic behaviour, thermal transport, and catalytic

activity, greatly expanding the range of functional nanomaterials available for scientific and industrial use (Ariga et al., 2024; Tripathy et al., 2024).

A notable breakthrough has been the rapid development of two-dimensional (2D) materials. Since the discovery of graphene, extensive research has focused on other atomically thin materials, including transition metal dichalcogenides (TMDs) and MXenes. These materials possess exceptional carrier mobility, mechanical flexibility, large surface-to-volume ratios, and tunable electronic band structures, making them attractive for advanced electronic devices, flexible sensors, photonic systems, and high-performance energy storage technologies. Their distinctive physical characteristics continue to inspire new approaches in nanoscale device engineering and condensed matter research (Andreeva et al., 2020).

Advances in nanofabrication have further accelerated the development of nanoscale technologies. Modern fabrication methods, including electron-beam lithography, atomic layer deposition, focused ion beam processing, and nanoscale patterning techniques, enable the production of highly complex structures with nanometre precision. These technologies have substantially improved the performance of transistors, integrated photonic circuits, quantum devices, and microelectromechanical systems

while supporting the continued miniaturization of electronic components (George, 2015; Schwartzman & Wind, 2009). Computational methods have become equally important in contemporary nanotechnology research. Artificial intelligence, machine learning, and high-throughput computational modelling are increasingly used to predict material properties, identify optimal material compositions, and accelerate the discovery of novel nanostructures. By analysing large experimental and computational datasets, these techniques reduce the reliance on trial-and-error experimentation, shorten development cycles, and improve the efficiency of materials design. The growing integration of data-driven methods with experimental research represents one of the most significant changes in modern nanoscience (Butler et al., 2018; Schmidt et al., 2024).

Quantum nanotechnology has emerged as another rapidly advancing research area. Significant progress has been achieved in the development of quantum dots, single-photon emitters, nanoscale superconducting structures, and other quantum devices capable of manipulating individual quantum states. These systems are being investigated for applications in quantum communication, quantum sensing, secure information processing, and quantum computing. Their development highlights the increasingly close

relationship between nanotechnology and quantum physics, with both fields contributing to the design of future information technologies (Awschalom et al., 2021; Montblanch et al., 2023).

Alongside technological innovation, increasing attention is being directed towards the environmental sustainability of nanotechnology. Researchers are exploring greener synthesis routes that minimize hazardous chemicals, reduce energy consumption, and employ renewable or biodegradable resources wherever possible. Equal emphasis is being placed on improving the stability, recyclability, and large-scale manufacturability of nanomaterials so that laboratory-scale discoveries can be translated into commercially viable and environmentally responsible technologies. These efforts reflect the growing recognition that long-term technological advancement must be accompanied by sustainable manufacturing practices and comprehensive environmental assessment (Hezekiah, 2021; Jain et al., 2024).

Collectively, these advances demonstrate how nanotechnology has evolved into a highly interdisciplinary field that combines materials science, physics, chemistry, engineering, and computational science. Continued developments in advanced materials, precision nanofabrication, artificial intelligence, and quantum technologies are

expected to further expand the capabilities of nanoscale systems, enabling innovative solutions to challenges in electronics, energy, healthcare, environmental protection, and next-generation manufacturing (Ariga et al., 2024; Awschalom et al., 2021).

3. Emerging Trends in Nanotechnology

Nanotechnology has entered a new phase of development in which research is increasingly focused on designing materials and systems with enhanced functionality rather than simply investigating nanoscale phenomena. Continuous progress in material synthesis, characterization techniques, and computational tools has broadened the scope of nanotechnology, allowing researchers to address challenges across physics, engineering, healthcare, energy, agriculture, and environmental science. As a result, the field has become highly interdisciplinary, bringing together knowledge from multiple scientific disciplines to develop innovative solutions for complex technological problems (Islam, 2014; Khan, 2021).

A defining feature of current nanotechnology research is the emphasis on application-oriented innovation. Researchers are developing nanomaterials with tailored structural, electronic, optical, and mechanical properties to meet the demands of advanced technologies. At the same time, improvements in fabrication techniques and nanoscale engineering have enabled greater

control over material performance, supporting the development of more efficient electronic devices, functional coatings, smart sensors, energy systems, and biomedical technologies (Dwivedi & Dwivedi, 2012; Khan, 2021).

Recent studies also reflect a growing shift towards intelligent and sustainable nanotechnology. Considerable attention is being given to environmentally responsible synthesis methods, resource-efficient manufacturing, and the safe use of nanomaterials throughout their life cycle. Alongside technological advancement, researchers are examining issues related to nanomaterial toxicity, environmental impact, and regulatory frameworks to ensure that future developments are both scientifically sound and socially responsible. These considerations have become increasingly important as nanotechnology moves from laboratory research to large-scale industrial applications (Das et al., 2009; Islam, 2014).

Another important trend is the integration of nanotechnology with other emerging scientific fields. Advances in nanobiotechnology have enabled the development of improved diagnostic systems, targeted drug delivery platforms, biosensors, and tissue engineering materials, demonstrating the expanding role of nanotechnology in modern healthcare. Similar interdisciplinary collaborations are

accelerating innovation in areas such as environmental monitoring, renewable energy, and advanced manufacturing, where nanoscale materials offer performance advantages that are difficult to achieve using conventional technologies (Sobha et al., 2010; Khan, 2021).

The continued evolution of nanotechnology reflects a shift from isolated material development to the design of multifunctional systems capable of addressing real-world scientific and industrial challenges. This transformation is expected to strengthen the role of nanotechnology in future technological innovation while supporting the development of safer, more efficient, and sustainable materials for a wide range of applications (Islam, 2014; Khan, 2021).

3.1 AI-Driven Nanotechnology

Artificial intelligence (AI) is transforming the way nanotechnology research is conducted by complementing traditional experimental methods with data-driven analysis and predictive modelling. Developing new nanomaterials has traditionally relied on extensive laboratory experimentation, which is often time-consuming and resource-intensive. The availability of large experimental datasets, combined with advances in machine learning, now allows researchers to predict material properties and identify promising candidates before laboratory synthesis. This has significantly

accelerated the discovery and optimization of nanomaterials while reducing the cost and time associated with conventional trial-and-error approaches (Butler et al., 2018; Schmidt et al., 2024).

Machine learning techniques are increasingly being applied to predict crystal structures, electronic behaviour, catalytic performance, and the stability of nanoscale materials. By identifying relationships within complex datasets, these models help researchers narrow down potential material combinations and prioritize the most promising candidates for experimental validation. AI is also improving the analysis of microscopy and spectroscopy data, enabling faster and more accurate characterization of complex nanostructures that would otherwise require extensive manual interpretation (Agrawal & Choudhary, 2019; Schleider et al., 2019).

Another emerging development is the use of AI in autonomous research laboratories, where automated systems integrate material synthesis, characterization, and data analysis into a continuous workflow. Experimental results are analysed in real time, allowing machine learning algorithms to refine subsequent experiments and optimize research strategies with minimal human intervention. This closed-loop approach is shortening development cycles, improving experimental efficiency, and enabling more rapid translation of laboratory discoveries

into practical technologies (Teng et al., 2023).

As computational methods continue to advance, AI is expected to play an increasingly important role in nanotechnology research. Its ability to combine predictive modelling with automated experimentation is reshaping materials discovery, supporting both fundamental scientific investigations and the development of high-performance nanomaterials for industrial and technological applications.

3.2 Smart and Responsive Nanomaterials

Smart and responsive nanomaterials have emerged as an important area of nanotechnology because of their ability to dynamically adjust their properties in response to changes in the surrounding environment. Unlike conventional materials, these nanosystems can respond to external stimuli such as temperature, light, magnetic or electric fields, mechanical stress, and variations in chemical conditions. This adaptive behaviour enables them to perform specific functions without continuous external control, making them valuable for a wide range of advanced technological applications (Stuart et al., 2013).

Current research is directed towards developing multifunctional nanomaterials that integrate sensing, actuation, and self-regulating capabilities within a single

platform. Shape-memory nanomaterials, self-healing coatings, magnetically responsive nanoparticles, and photoresponsive nanostructures have attracted considerable attention because they can modify their behaviour according to changing environmental conditions. These materials are being explored for applications in flexible electronics, intelligent sensing systems, wearable technologies, adaptive optical devices, and soft robotics, where responsiveness and reliability are essential for improved performance (Wei et al., 2024).

The rapid advancement of nanofabrication and surface engineering techniques has further enhanced the functionality of these materials. Improved control over particle size, morphology, surface chemistry, and interface design has increased their sensitivity, structural stability, and long-term operational reliability. Such improvements have expanded the practical use of responsive nanomaterials in increasingly demanding environments while supporting the development of more efficient and durable nanoscale devices (Roy et al., 2024).

Ongoing research continues to broaden the capabilities of smart nanomaterials through the integration of multiple responsive mechanisms within a single system. As fabrication techniques become more precise and material design strategies continue to evolve, these adaptive nanomaterials are

expected to play an increasingly significant role in next-generation technologies, particularly in advanced electronics, healthcare, energy systems, and intelligent manufacturing (Roy et al., 2024; Wei et al., 2024).

3.3 Green and Sustainable Nanotechnology

Sustainability has become a key consideration in the development of nanotechnology, with increasing emphasis on designing materials and manufacturing processes that minimize environmental impact while maintaining high performance. Growing awareness of resource conservation and environmental safety has encouraged the adoption of renewable raw materials, biodegradable precursors, and energy-efficient synthesis routes. Among these approaches, green synthesis using plant extracts, microorganisms, and other biological agents has attracted considerable interest because it reduces the dependence on hazardous chemicals, lowers energy consumption, and generates fewer toxic by-products compared with conventional chemical methods (Shukla et al., 2016; Cui et al., 2016).

Beyond environmentally friendly synthesis, nanotechnology is contributing directly to the development of sustainable technologies. Nanostructured catalysts improve reaction efficiency while reducing energy requirements, whereas advanced

nanomaterials have enhanced the performance of solar cells, rechargeable batteries, and hydrogen production systems. Likewise, nanoporous membranes and nanoadsorbents are being widely investigated for water purification, wastewater treatment, and pollutant removal owing to their high surface area, selective adsorption, and improved separation efficiency (Nasrollahzadeh et al., 2019; Ghosh et al., 2024).

The focus of sustainable nanotechnology now extends throughout the entire life cycle of nanomaterials. Increasing attention is being given to recyclability, environmental fate, long-term stability, and the safe disposal of nanomaterials after use. Life-cycle assessment and environmental risk evaluation are becoming integral components of nanomaterial development, ensuring that technological innovation is accompanied by responsible manufacturing practices and environmental stewardship. These efforts are supporting the transition towards nanotechnology that is not only efficient but also environmentally sustainable (Nowack & Bucheli, 2011; Kah et al., 2023).

3.4 Quantum Nanotechnology

Quantum nanotechnology has become one of the most dynamic areas of contemporary nanoscale research, driven by the unique behaviour of materials at dimensions where quantum mechanical effects dominate. When

the size of a material approaches only a few nanometres, quantum confinement significantly modifies its electronic structure and optical properties, resulting in characteristics that differ fundamentally from those of bulk materials. These phenomena provide the basis for developing devices with enhanced sensitivity, faster operation, and improved energy efficiency (Loss, 2009; Awschalom et al., 2021).

Among the various quantum nanostructures, quantum dots have received particular attention because their optical and electronic properties can be precisely tuned by controlling particle size. This size-dependent behaviour has enabled their application in quantum photonics, high-resolution displays, bioimaging, light-emitting devices, and advanced optoelectronic systems. At the same time, rapid progress in quantum sensors, single-photon emitters, and nanoscale qubits is expanding the possibilities for secure communication, precision sensing, and quantum information processing (Laucht et al., 2021).

Advances in crystal growth, nanoscale fabrication, and quantum state manipulation have accelerated the development of quantum nanodevices with improved stability and performance. Continued progress in these areas is expected to strengthen the integration of nanotechnology with quantum science, providing the material foundation for future

quantum computers, communication networks, and sensing technologies. As research continues to evolve, quantum nanotechnology is likely to play a central role in the next generation of information and electronic systems (Awschalom et al., 2021).

3.5 Digital Nanomanufacturing and Advanced Nanofabrication

The continued advancement of nanotechnology relies heavily on fabrication techniques capable of producing structures with exceptional precision and consistency. Recent developments in nanofabrication have combined high-resolution manufacturing methods with digital technologies, making it possible to construct increasingly complex nanoscale architectures while maintaining strict control over their dimensions and structural quality. Techniques such as electron-beam lithography, focused ion beam processing, nanoimprint lithography, and atomic layer deposition have become essential tools for fabricating nanostructures with high accuracy, excellent reproducibility, and well-defined material properties (George, 2015; Schwartzman & Wind, 2009).

The growing adoption of digital manufacturing technologies is further reshaping nanoscale fabrication processes. Automation, robotics, real-time process monitoring, and computational simulation are increasingly integrated into manufacturing workflows to improve production efficiency

and process reliability. These technologies enable continuous optimization of fabrication parameters, reduce material consumption, and minimize production errors. The emergence of digital twins and intelligent manufacturing platforms has added another level of capability by allowing fabrication processes to be simulated, analysed, and optimized before physical production begins, thereby reducing development time and improving manufacturing performance (Tao et al., 2019; Xu et al., 2022).

The integration of precision nanofabrication with digital manufacturing represents an important step towards large-scale and economically viable production of nanomaterials and nanoscale devices. Enhanced process control, greater manufacturing flexibility, and improved production efficiency are supporting the transition of nanotechnology from laboratory-scale research to industrial applications. These advances are particularly important for the fabrication of next-generation nanoelectronic components, photonic devices, sensors, and energy technologies, where consistent material quality and precise structural control are essential for achieving reliable device performance.

3.6 Data-Driven Materials Discovery

The discovery of advanced nanomaterials has been transformed by the growing availability

of computational resources, large-scale materials databases, and data-driven analytical methods. Traditional materials development often depended on extensive experimental screening, making the discovery process both time-consuming and resource-intensive. The integration of machine learning, high-performance computing, and materials informatics has introduced a more efficient strategy in which promising materials can be identified and evaluated computationally before laboratory synthesis. This approach has significantly shortened development cycles while improving the efficiency of materials design and optimization (Butler et al., 2018; Jain et al., 2024).

High-throughput computational screening now plays a central role in evaluating the structural, electronic, thermal, and mechanical properties of nanomaterials. Machine learning algorithms can rapidly analyse thousands of potential material compositions, uncover relationships within complex datasets, and identify candidates with properties suited to specific applications. These predictive capabilities allow researchers to prioritize the most promising materials for experimental validation, reducing unnecessary laboratory work and making more effective use of research resources (Schmidt et al., 2024).

Another important factor driving this progress is the increasing availability of open-access materials databases and advanced computational platforms. The combination of experimental data with computational modelling has strengthened collaboration between theoretical and experimental research, leading to more reliable predictions and faster validation of newly designed materials. As these digital resources continue to expand, data-driven materials discovery is expected to remain a key component of nanotechnology research, supporting the development of high-performance nanomaterials for applications in electronics, energy systems, healthcare, and advanced manufacturing (Kim et al., 2023).

4. Applications of Nanotechnology

Nanotechnology has emerged as one of the most transformative areas of modern science because materials exhibit unique physical and chemical characteristics when engineered at the nanoscale. Their large surface-area-to-volume ratio, improved mechanical strength, enhanced electrical conductivity, and tunable optical properties make them highly suitable for developing advanced technologies. These distinctive features have enabled researchers to design materials and devices with greater efficiency, precision, and functionality than many conventional alternatives. As a result, nanotechnology has moved beyond

laboratory research and is now contributing to practical solutions in healthcare, electronics, energy, environmental protection, agriculture, and industrial manufacturing. Its ability to improve existing technologies while supporting the development of sustainable and high-performance systems has made it a key driver of scientific and technological innovation (Nasrollahzadeh et al., 2019).

4.1 Healthcare and Nanomedicine

Healthcare is one of the most prominent application areas of nanotechnology, owing to the ability of nanoparticles to interact with biological systems at the cellular and molecular levels. This has enabled significant advances in targeted drug delivery, disease diagnosis, medical imaging, regenerative medicine, and vaccine development, offering improved therapeutic efficiency with fewer side effects than conventional treatment approaches (Surendiran et al., 2009).

Targeted drug delivery is among the most established applications of nanomedicine. Nanocarriers enhance drug bioavailability by delivering therapeutic agents directly to diseased tissues, thereby improving treatment outcomes while minimizing toxicity to healthy cells. These systems have shown considerable promise in the management of cancer, cardiovascular, infectious, and neurological diseases (Navalakhe & Nandedkar, 2007).

Nanotechnology has also strengthened medical diagnostics through highly sensitive biosensors and advanced imaging platforms that enable early disease detection and support precision medicine. Furthermore, nanostructured biomaterials have advanced regenerative medicine by promoting tissue repair and the development of next-generation biomedical implants. The growing use of nanoscale delivery platforms in vaccines and gene therapies further highlights the expanding role of nanotechnology in modern healthcare (Haleem et al., 2023).

Despite these advances, concerns regarding long-term toxicity, biocompatibility, large-scale manufacturing, regulatory approval, and production costs continue to limit broader clinical translation. Addressing these challenges through continued research and standardized regulatory frameworks will be essential for realizing the full potential of nanomedicine in future healthcare systems (Malik et al., 2023).

4.2 Nanoelectronics

Nanoelectronics has become a major application of nanotechnology as conventional semiconductor technologies approach their physical scaling limits. Nanomaterials such as graphene, carbon nanotubes, and semiconductor nanowires possess exceptional electrical conductivity, high carrier mobility, and excellent thermal stability, making them promising materials

for the development of smaller, faster, and more energy-efficient electronic devices (Nasrollahzadeh et al., 2019).

These materials have significantly improved the performance of transistors, integrated circuits, memory devices, and flexible electronic systems while enabling the continued miniaturization of semiconductor components. In addition, nanotechnology has facilitated the development of highly sensitive nanosensors that are widely used in healthcare diagnostics, environmental monitoring, industrial automation, and wearable devices. Their rapid response, high sensitivity, and compact size have expanded their applications across diverse technological sectors (Nasrollahzadeh et al., 2019).

The scope of nanoelectronics is now extending beyond conventional semiconductor applications to include flexible electronics, wearable devices, neuromorphic computing, and quantum technologies. Advances in nanomaterial synthesis and nanoscale fabrication are expected to further improve device performance, reduce energy consumption, and support the development of next-generation intelligent electronic systems.

4.3 Energy Storage and Conversion

The increasing demand for clean and sustainable energy has accelerated the application of nanotechnology in energy

storage and conversion. Owing to their large surface area, enhanced electrical conductivity, and short ion diffusion pathways, nanomaterials improve electrochemical performance and have significantly enhanced the efficiency of batteries, supercapacitors, fuel cells, and photovoltaic devices (Zhang et al., 2013).

Nanostructured electrode materials play a crucial role in rechargeable battery technologies by facilitating faster electron and ion transport. This improves energy density, charging rates, power output, and cycling stability, making advanced batteries more suitable for electric vehicles, portable electronics, and renewable energy storage systems. Continued improvements in nanomaterial design are further enhancing the performance and durability of next-generation energy storage technologies (Li et al., 2015).

Nanotechnology has also strengthened renewable energy conversion through its application in solar cells, fuel cells, hydrogen production, and photocatalytic systems. By improving light absorption, charge separation, and catalytic efficiency, nanomaterials contribute to higher energy conversion efficiencies while reducing energy losses. These advances support the transition towards cleaner and more sustainable energy solutions (Zhang et al., 2013).

Beyond improving the performance of existing technologies, advances in nanomaterial engineering are enabling the development of multifunctional materials with greater stability, lower production costs, and improved environmental compatibility. These developments are expected to further strengthen the role of nanotechnology in meeting future energy demands and supporting the global transition to sustainable energy systems (Li et al., 2015).

4.4 Environmental Protection

Nanotechnology has emerged as an effective approach for addressing environmental challenges, particularly in water treatment, air quality monitoring, soil remediation, and pollution control. Owing to their high surface area and enhanced reactivity, nanomaterials can efficiently adsorb, degrade, or transform a wide range of contaminants, making them valuable tools for environmental remediation (Taran et al., 2021).

Among these applications, water purification has received considerable attention. Nanomaterials such as metal oxide nanoparticles, carbon-based nanomaterials, and nanocomposites exhibit excellent adsorption and catalytic properties, enabling the efficient removal of heavy metals, organic pollutants, dyes, pesticides, and pathogenic microorganisms from contaminated water. These materials improve purification efficiency while reducing

treatment time and operational costs compared with many conventional treatment methods (Ali Mansoori et al., 2008).

Nanotechnology has also enhanced environmental monitoring through highly sensitive nanosensors capable of detecting pollutants at very low concentrations. Their rapid response and high detection accuracy enable continuous monitoring of air, water, and soil quality, supporting timely pollution control and more effective environmental management (Ibrahim et al., 2016).

Increasing emphasis is also being placed on the development of biodegradable nanomaterials, green synthesis methods, and sustainable remediation technologies to minimize ecological risks associated with engineered nanomaterials. These advances are expected to improve the long-term sustainability of nanotechnology-based environmental applications and contribute to cleaner and healthier ecosystems (Taran et al., 2021).

4.5 Agriculture

Nanotechnology is increasingly contributing to sustainable agriculture by improving crop productivity and the efficient use of agricultural inputs. Conventional farming often faces challenges such as low fertilizer efficiency, excessive pesticide use, soil degradation, and environmental pollution. Nano-enabled technologies address these issues by enhancing nutrient delivery,

reducing chemical losses, and supporting precision farming, thereby improving agricultural productivity while minimizing environmental impacts (Chhipa, 2019).

A major application is the development of nanofertilizers and nanopesticides, which provide controlled and sustained release of nutrients and active ingredients. This enhances nutrient-use efficiency, reduces losses through leaching and volatilization, and lowers the amount of fertilizer and pesticide required, resulting in improved crop performance and reduced environmental contamination (Pramanik et al., 2020).

Nanotechnology has also advanced precision agriculture through nanosensors that monitor soil moisture, nutrient status, crop health, and pathogen activity in real time. The information generated supports timely decisions on irrigation, fertilization, and pest management, leading to more efficient resource utilization, higher crop yields, and reduced production losses (Usman et al., 2020).

Growing attention is also being directed towards biodegradable nanomaterials and environmentally friendly nanoformulations that combine high agricultural efficiency with lower ecological risks. Continued advances in this area are expected to strengthen sustainable food production and support climate-resilient agricultural systems (Pramanik et al., 2020).

4.6 Industrial Manufacturing

Nanotechnology has transformed modern manufacturing by enabling the development of materials with superior mechanical, thermal, electrical, and chemical properties. The incorporation of nanomaterials has produced lighter, stronger, and more durable products with enhanced resistance to wear, corrosion, and heat. These improvements have expanded the use of nanotechnology across industries such as aerospace, automotive, electronics, construction, and biomedical engineering, where high-performance materials are essential (Ahmed & Jackson, 2014).

Nanocomposites and nanocoatings are among the most widely adopted industrial applications. Nanocomposites combine nanoscale fillers with conventional materials to improve strength, stiffness, and durability without significantly increasing weight. Likewise, nanocoatings enhance resistance to corrosion, abrasion, heat, and chemical degradation, extending the service life of industrial components while reducing maintenance requirements (Subhan et al., 2021).

Nanotechnology has also advanced precision manufacturing through nanofabrication techniques capable of producing semiconductor devices, sensors, optical components, and microelectromechanical systems with exceptional dimensional

accuracy. These technologies improve product reliability, minimize material waste, and enhance manufacturing efficiency, supporting more sustainable production processes (Ahmed & Jackson, 2014).

The integration of nanotechnology with digital manufacturing, automation, artificial intelligence, and smart production systems is further reshaping industrial practices. Continued advances in nanomaterials and fabrication technologies are expected to enhance productivity, optimize resource utilization, and accelerate the development of high-performance products, reinforcing the role of nanotechnology in the future of advanced manufacturing (Subhan et al., 2021).

5. Challenges

Despite the significant progress and diverse applications of nanotechnology, several challenges continue to limit its widespread commercialization and long-term sustainability. Although many nanomaterials demonstrate exceptional performance under laboratory conditions, translating these advances into commercially viable products remains difficult. Issues related to material safety, environmental impact, large-scale manufacturing, production cost, and regulatory oversight must be addressed to ensure the responsible development and adoption of nanotechnology (Nasrollahzadeh et al., 2019).

One of the primary concerns is the potential toxicity of engineered nanomaterials. Their extremely small size and high surface reactivity allow them to interact with biological systems in ways that differ from conventional materials. While these properties enhance their performance in medical and industrial applications, they may also pose risks to human health depending on factors such as particle size, morphology, surface chemistry, concentration, and exposure duration. Comprehensive toxicological evaluation and improved material design are therefore essential to minimize potential health risks while preserving the functional advantages of nanomaterials (Surendiran et al., 2009; Malik et al., 2023).

Environmental safety is another important consideration. During production, use, or disposal, engineered nanoparticles may be released into air, water, and soil, where they can interact with microorganisms, plants, and aquatic organisms. The long-term environmental behaviour and ecological consequences of these materials are not yet fully understood, highlighting the need for continuous environmental monitoring, life-cycle assessment, and the development of biodegradable and environmentally benign nanomaterials (Taran et al., 2021; Ibrahim et al., 2016).

Large-scale manufacturing also remains a major challenge. Although considerable progress has been made in nanomaterial synthesis, maintaining consistent particle size, morphology, purity, and functional properties during mass production is technically demanding. In addition, many fabrication processes require sophisticated equipment, controlled operating conditions, and substantial financial investment, increasing production costs and limiting industrial-scale implementation. Developing scalable, cost-effective, and energy-efficient manufacturing techniques will be essential for the broader commercialization of nanotechnology (Ahmed & Jackson, 2014; Subhan et al., 2021).

Another challenge lies in the development of appropriate regulatory and ethical frameworks. The rapid advancement of nanotechnology has outpaced regulatory policies in many regions, creating uncertainties regarding safety evaluation, product standardization, environmental risk assessment, and commercialization. Establishing harmonized regulatory guidelines, together with transparent risk communication and responsible innovation, will be critical for strengthening public confidence and supporting the safe and sustainable integration of nanotechnology into healthcare, industry, agriculture, and

environmental applications (Malik et al., 2023; Taran et al., 2021).

Overall, addressing these scientific, technological, environmental, and regulatory challenges will be essential for realizing the full potential of nanotechnology. Continued collaboration among researchers, industry, and policymakers can accelerate the development of safer, more sustainable, and commercially viable nanomaterials, enabling their broader contribution to future technological advancement.

6. Future Directions

Nanotechnology is expected to remain a key enabling technology for addressing future challenges in healthcare, energy, environmental sustainability, agriculture, and advanced manufacturing. Future progress will depend not only on the discovery of novel nanomaterials but also on improving their safety, scalability, functionality, and commercial viability. Increasing emphasis is being placed on designing multifunctional nanomaterials with enhanced stability, improved performance, and reduced environmental impact to meet the growing demand for sustainable technologies (Patel et al., 2024; Khan, 2021).

Artificial intelligence (AI) and machine learning (ML) are expected to transform nanotechnology research by accelerating material discovery, optimizing synthesis conditions, and predicting the properties of

nanomaterials with greater accuracy. Their integration with computational modelling and high-throughput experimentation can significantly reduce the time and cost associated with developing advanced functional materials, thereby facilitating faster translation from laboratory research to industrial applications (Butler et al., 2018; Schleder et al., 2019; Jain et al., 2024).

Quantum nanotechnology is another rapidly evolving area with considerable potential. Advances in quantum materials, nanoscale devices, and two-dimensional materials are expected to support breakthroughs in quantum computing, secure communication, high-precision sensing, and next-generation electronic systems. Continued progress in nanoscale fabrication will further enhance the performance and efficiency of quantum technologies (Awschalom et al., 2021; Laucht et al., 2021; Montblanch et al., 2023). Sustainability will continue to shape future developments in nanotechnology. Greater attention is being directed towards green synthesis methods, recyclable nanomaterials, and environmentally responsible manufacturing processes that minimize waste, energy consumption, and ecological risks. At the same time, advances in nanotechnology are expected to strengthen sustainable agriculture, environmental remediation, and clean energy technologies, contributing to global efforts towards

sustainable development (Shukla & Iravani, 2016; Cui et al., 2016; Tripathy et al., 2024). Future advances will also depend on the commercialization of nanotechnology through scalable manufacturing processes, robust quality control, and standardized production methods. The integration of nanotechnology with smart manufacturing and industrial automation is expected to improve production efficiency, product reliability, and cost-effectiveness, thereby accelerating its adoption across diverse industrial sectors (Hezekiah, 2021; Ahmed & Jackson, 2014; Subhan et al., 2021).

Overall, the future of nanotechnology will rely on interdisciplinary collaboration among materials scientists, chemists, engineers, biomedical researchers, industry, and policymakers. Such collaboration, supported by effective regulatory frameworks and responsible innovation, will be essential for translating scientific discoveries into safe, sustainable, and commercially viable technologies that address emerging global challenges (Roco, 2003; Jeevanandam et al., 2018).

7. Conclusion

Nanotechnology has transformed the way materials are designed and utilized by enabling precise control over matter at the nanoscale. The unique properties exhibited by nanomaterials have expanded their applications across diverse fields, including

healthcare, nanoelectronics, energy storage and conversion, environmental protection, agriculture, and industrial manufacturing. As advances in material synthesis, characterization techniques, and nanofabrication continue, nanotechnology is becoming an increasingly important driver of scientific innovation and technological progress.

The findings presented in this paper demonstrate that nanotechnology offers significant opportunities to improve the efficiency, functionality, and sustainability of existing technologies. Its ability to enhance targeted drug delivery, develop high-performance electronic devices, improve energy storage systems, support environmental remediation, promote precision agriculture, and strengthen advanced manufacturing highlights its broad interdisciplinary impact. However, realizing these benefits on a larger scale requires addressing challenges related to nanomaterial toxicity, environmental safety, scalable manufacturing, production costs, and appropriate regulatory frameworks.

The future of nanotechnology will depend on the development of safer, more efficient, and environmentally sustainable nanomaterials together with reliable large-scale manufacturing processes. At the same time, stronger collaboration among researchers, industry, and policymakers will be essential

for translating scientific discoveries into commercially viable and socially responsible technologies.

In conclusion, nanotechnology is expected to remain one of the most influential technologies of the twenty-first century. Continued scientific advances, responsible innovation, and sustainable development strategies will further expand its applications and strengthen its contribution to addressing global challenges while improving industrial performance and human well-being.

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