



Harnessing Nanotechnology: Transforming Science, Medicine, and Industry

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Abstract: Nanotechnology, defined as the manipulation of matter at dimensions between 1 and 100 nanometers, has emerged as a transformative discipline with applications across science, engineering, and industry. The unique physicochemical properties of nanomaterials—including high surface-to-volume ratios, quantum effects, and tunable electrical and optical characteristics—have enabled breakthroughs in medicine, energy, environment, electronics, agriculture, and consumer products. In healthcare, nanocarriers and biosensors enhance targeted drug delivery, diagnostics, and regenerative medicine. In energy systems, nanostructures improve solar cells, batteries, and fuel cells while supporting environmental remediation through pollutant removal. Nanoelectronics and quantum dots have revolutionized information technology, while nanosensors and smart packaging contribute to agriculture and food security. Industrial applications range from textiles and cosmetics to advanced composites in aerospace and automotive sectors. Despite these advances, challenges persist, including toxicity, environmental accumulation, regulatory gaps, and ethical concerns. Future progress lies in sustainable, green nanotechnology and the integration of artificial intelligence to design scalable and efficient systems. This paper highlights both the promise and the challenges of nanotechnology, offering insights into its role in driving sustainable development and technological innovation.

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Introduction

Nanotechnology, defined as the science and engineering of materials at dimensions between roughly 1 and 100 nanometers, has emerged as one of the most dynamic frontiers of modern material science. At this scale, matter exhibits properties—mechanical, electrical, optical, and chemical—that differ fundamentally from bulk counterparts, opening pathways to design advanced materials with enhanced or entirely new functionalities. Over the past two decades, these nanoscale phenomena have transformed both fundamental research and industrial practices, offering innovations across healthcare, energy, environment, and advanced technologies.

Nanomaterials, engineered structures with at least one dimension in the nanoscale range, derive their remarkable behavior from two primary factors: quantum effects and a high proportion of atoms at surfaces or interfaces. These features enable unique electrical, catalytic, and mechanical properties, making them central to technological breakthroughs [1]. Depending on their dimensionality, nanomaterials can be classified into several categories. Zero-dimensional nanomaterials, such as nanoparticles, quantum dots, and fullerenes, display isotropic properties and size-dependent optical

behavior; for instance, quantum dots can be tuned to emit different colors by adjusting particle size [2]. One-dimensional forms, including nanowires and nanotubes, exhibit high aspect ratios, directional conductivity, and extraordinary mechanical strength, as exemplified by carbon nanotubes [3]. Two-dimensional nanomaterials, such as graphene, MXenes, and MoS_2 , combine exceptional electron mobility, mechanical flexibility, and thermal conductivity due to their layered atomic structures [4]. Three-dimensional assemblies, including aerogels, nanoporous materials, and nanocomposites, demonstrate synergistic properties arising from hierarchical architectures.

The exceptional performance of nanomaterials stems from several intrinsic characteristics. Quantum confinement, especially in semiconductors, leads to discrete energy levels and tunable electronic and optical properties. Their high surface-to-volume ratio provides abundant reactive sites, greatly enhancing their effectiveness in catalysis, adsorption, and sensing. Many nanomaterials also exhibit superior mechanical strength compared to bulk analogs, with carbon nanotubes and graphene surpassing conventional materials in tensile strength and elasticity, making them attractive for lightweight, high-performance composites. Furthermore, the surface chemistry of nanomaterials can be readily modified with ligands, polymers, or coatings to enhance stability, selectivity, and integration into complex systems [5]. Such functional tunability has proven vital in drug delivery, catalysis, and environmental remediation, where precise targeting and tailored reactivity are required.

Collectively, these attributes establish nanotechnology as a cornerstone of innovation in material science. Its ability to engineer matter at the smallest scales has unlocked applications that were once unimaginable, laying the foundation for continued advances in sustainable energy, next-generation electronics, advanced healthcare, and beyond.

Applications in Electronics and Optoelectronics

Nanotechnology has profoundly reshaped the landscape of electronics and optoelectronics by enabling the miniaturization of components, enhancing device performance, and introducing entirely new functionalities. At the nanoscale, quantum and surface phenomena dominate, allowing unprecedented control over charge transport, optical interactions, and material flexibility. These advances have pushed the boundaries of speed, efficiency, and integration in modern systems.

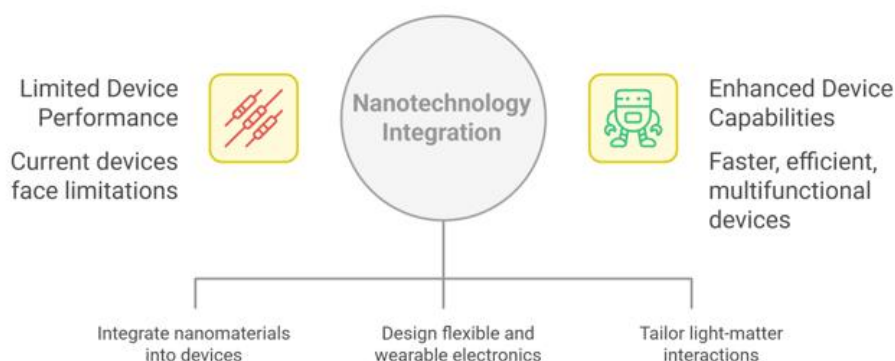
In electronic circuits, the scaling limits of silicon-based CMOS technology have driven the exploration of nanoscale alternatives. Carbon nanotubes, with their ballistic transport and high carrier mobility, show great promise in next-generation field-effect transistors [6], while semiconducting nanowires such as InAs or GaN provide excellent electrostatic control in gate-all-around architectures. Two-dimensional materials, including MoS_2 and WS_2 , combine direct bandgaps with mechanical flexibility, supporting low-power and flexible logic devices. Even graphene, despite its lack of a bandgap, contributes to high-speed interconnects and analog systems. Together, these nanomaterials not only extend Moore's law but also enable novel paradigms such as neuromorphic and quantum computing.

Beyond rigid circuits, nanotechnology is a cornerstone of flexible and wearable electronics. Nanostructured inks composed of silver nanowires, graphene flakes, or conductive polymers allow the printing of lightweight, deformable circuits and antennas. Alternatives to brittle indium tin oxide, such as silver nanowire networks and graphene films, serve as transparent, flexible electrodes in displays and solar panels [7]. Nanoscale sensors based on piezoelectric or piezoresistive effects enable electronic skins, health-monitoring patches, and prosthetic feedback systems, while nanogenerators and nanostructured supercapacitors provide integrated energy harvesting and storage. This synergy of nanomaterials with flexible substrates has led to stretchable, conformal, and even self-healing devices that can seamlessly integrate with the human body or irregular surfaces.

In optoelectronics, nanomaterials have opened new possibilities by tailoring light-matter interactions at the nanoscale. Quantum dots, with their tunable emission and sharp photoluminescence, are widely used in high-color-purity displays and light-emitting devices [8], while also finding roles in lasers, detectors, and photovoltaics. Plasmonic nanoparticles of gold and silver enhance light absorption and emission through localized surface plasmon resonances, driving advances in ultrafast photodetectors, surface-enhanced Raman spectroscopy, and bioimaging. Meanwhile, photonic crystals and metamaterials manipulate optical pathways by creating bandgaps or negative refractive indices, enabling low-threshold nanolasers, optical filters, and cloaking effects [9]. Two-dimensional semiconductors such as MoS_2 and black phosphorus, with strong light-matter coupling and mechanical flexibility, have further advanced ultrathin phototransistors, solar cells, and transparent optoelectronic devices.

Collectively, these innovations demonstrate how nanotechnology is redefining the future of electronics and optoelectronics. By integrating quantum materials, flexible architectures, and light-manipulating nanostructures, researchers are paving the way for faster computing, next-generation displays, on-chip photonic systems, and energy-efficient, multifunctional devices.

Nanotechnology Revolutionizes Electronics



Nanotechnology in Energy Applications

The urgent global demand for sustainable energy has propelled nanotechnology to the forefront of energy research, where its unique size-dependent properties—such as high surface area, tunable bandgaps, and superior electrical conductivity—are revolutionizing energy harvesting, storage, and conversion systems. By exploiting nanoscale phenomena, researchers are achieving significant gains in efficiency, stability, and versatility across solar energy devices, electrochemical storage systems, and hydrogen technologies.

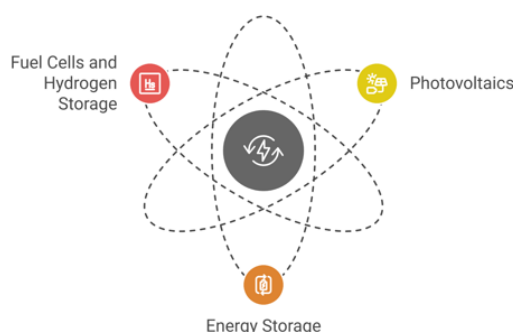
In photovoltaics, nanomaterials have driven remarkable advances in solar cell performance and adaptability. Metal halide perovskites, with their high absorption coefficients, long carrier diffusion lengths, and tunable bandgaps, have rapidly achieved conversion efficiencies above 25%, aided by nanostructured films and quantum dot perovskites. Semiconductor quantum dots such as PbS and CdSe introduce size-tunable bandgaps and multiple exciton generation, expanding light-harvesting potential beyond traditional limits [10]. Carbon nanotubes and graphene, with their exceptional conductivity and mechanical robustness, serve as transparent electrodes and charge-transport layers, replacing brittle indium tin oxide. Additionally, nanopatterned surfaces and plasmonic nanoparticles enhance light trapping, enabling thinner, more flexible, and even wearable solar devices.

For energy storage, nanostructuring enhances both battery and supercapacitor technologies. In lithium-ion batteries, silicon nanowires, graphene composites, and carbon nanotubes increase ion insertion sites and accommodate volumetric strain, improving capacity and cycle life [11]. Cathodes composed of nanosized oxides and phosphates benefit from enlarged surface areas, enabling faster kinetics. Supercapacitors also rely on nanomaterials—such as MnO_2 and graphene—that offer hierarchical porosity for rapid ion transport and high capacitance, balancing power and energy density. Beyond lithium, nanoscale electrodes and solid electrolytes are being developed for sodium-ion, magnesium-ion, and solid-state batteries, where interface stability and conductivity are critical.

Fuel cells and hydrogen storage systems likewise depend on nanoscale innovations. In proton exchange membrane fuel cells, platinum and alloy nanoparticles supported on nanostructured carbons maximize active surface area, reducing costly catalyst loadings. Alternative nanocatalysts based on transition metals, carbides, or nitrides offer more affordable pathways with competitive performance. Hydrogen storage benefits from nanostructured hydrides, porous frameworks, and carbon nanomaterials that confine hydrogen in pores or lattice defects, enhancing uptake and release under moderate conditions. Meanwhile, nanostructured catalysts for water splitting, including transition metal dichalcogenides, phosphides, and oxides, increase the efficiency of electrolyzers, enabling scalable green hydrogen production [12].

Collectively, these advances underscore the transformative role of nanotechnology in energy applications. By tailoring materials at the nanoscale, researchers are creating devices that are not only more efficient and durable but also adaptable to emerging demands for flexibility, portability, and sustainability. From next-generation photovoltaics to high-performance batteries and hydrogen systems, nanotechnology provides a powerful foundation for the transition toward a clean and resilient energy future.

Nanotechnology's Role in Energy Transformation



Nanotechnology in Medicine and Healthcare

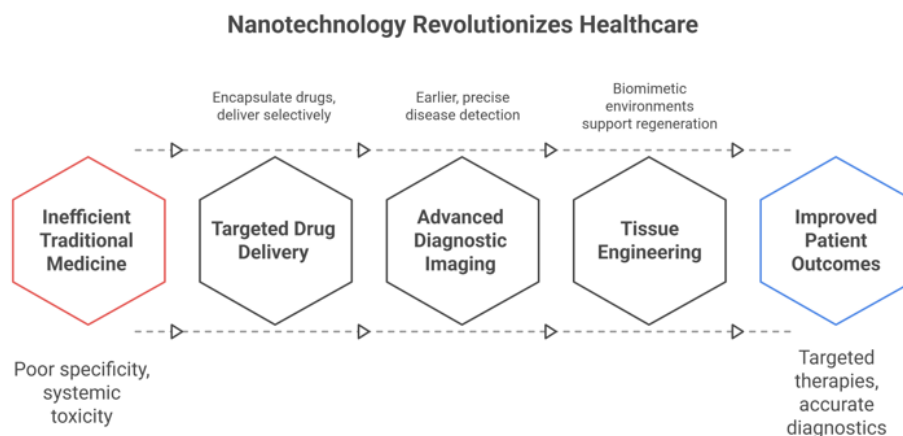
Nanotechnology has ushered in a new era of innovation in medicine and healthcare, transforming how diseases are diagnosed, treated, and managed. By harnessing the unique physicochemical properties of nanomaterials—including high surface area, tunable size, and multifunctionality—nanomedicine provides precision therapies, advanced diagnostic tools, and effective regenerative solutions that were previously unattainable.

One of the most impactful applications lies in targeted drug delivery [13]. Traditional approaches often struggle with poor specificity and systemic toxicity, whereas nanoscale carriers such as liposomes, solid lipid nanoparticles, and polymeric nanostructures can encapsulate therapeutic agents and deliver them selectively to diseased cells. By functionalizing their surfaces with ligands like antibodies or peptides, these carriers achieve active targeting of cancer cells, reducing side effects and enhancing efficacy. Liposomal formulations such as Doxil have already demonstrated clinical success, while multifunctional theranostic platforms integrate treatment with real-time monitoring. For instance, magnetic nanoparticles can be loaded with drugs, guided to tumors by external fields, and simultaneously visualized using MRI.

Nanotechnology has also revolutionized diagnostic imaging by enabling earlier and more precise disease detection. Semiconductor quantum dots provide bright, size-tunable fluorescence far superior to traditional dyes, allowing multiplexed biomarker detection [14]. Superparamagnetic iron oxide nanoparticles enhance MRI contrast with high specificity, while gold nanoshells and nanorods, leveraging plasmonic resonance, improve contrast in CT and photoacoustic imaging. Increasingly, multimodal nanoprobe combine multiple imaging capabilities into a single platform, offering complementary information that enhances surgical precision and treatment monitoring.

In tissue engineering, nanotechnology plays a crucial role in creating biomimetic environments that support cell growth and regeneration [15]. Nanofibrous scaffolds produced by electrospinning replicate the fibrous architecture of the extracellular matrix, facilitating nutrient diffusion and cellular integration. Incorporating bioactive nanoparticles, such as hydroxyapatite for bone regeneration or silver for antimicrobial activity, further enhances scaffold performance. Nanostructured surfaces also influence stem cell behavior, guiding their differentiation into specialized tissues such as bone, nerve, or muscle. The integration of nanomaterials into 3D bioprinting expands these capabilities, enabling the fabrication of complex tissue constructs with precise architectures tailored to patient-specific needs.

Together, these advances demonstrate how nanotechnology is redefining medicine by enabling therapies that are more targeted, diagnostics that are more accurate, and regenerative solutions that are more effective. From drug delivery systems that minimize toxicity to imaging platforms that allow real-time disease monitoring and scaffolds that guide tissue regeneration, nanotechnology has become an indispensable tool in advancing modern healthcare and improving patient outcomes.



Environmental Applications

Nanotechnology is increasingly recognized as a powerful tool for tackling global environmental challenges, offering innovative solutions for water purification, air quality management, and pollution monitoring. The exceptional properties of nanomaterials—including high surface area, catalytic reactivity, and selective adsorption—enable systems that are more efficient, durable, and sustainable than conventional approaches.

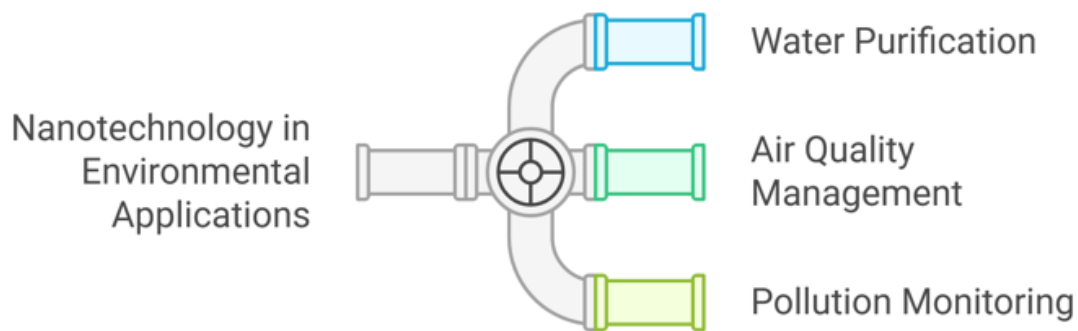
In water purification, nanomaterials have demonstrated superior contaminant removal and disinfection capabilities [16]. Carbon nanotube membranes, with their smooth, hydrophobic inner channels and nanoscale pores, allow rapid water flow while selectively filtering bacteria, viruses, heavy metals, and organic pollutants. Silver nanoparticles, valued for their strong antimicrobial action, are incorporated into filters to inhibit microbial growth and enhance pathogen removal. Zeolites and nanoclays, with their well-defined nanoporous structures and ion-exchange properties, effectively capture toxic metals and pesticides, while photocatalytic nanomaterials such as titanium dioxide use light-driven advanced oxidation to degrade organic contaminants without chemical additives. The integration of these materials into membranes, adsorbents, and catalytic systems has led to more efficient, longer-lasting, and lower-energy purification technologies.

Air pollution control has also benefited from nanoscale innovations. Nanostructured catalysts in automotive converters enhance the breakdown of harmful gases such as carbon monoxide, nitrogen oxides, and hydrocarbons into benign products at lower operating temperatures, reducing both emissions and fuel consumption [17]. Electrospun nanofiber filters, with their fine pores and high porosity, efficiently capture ultrafine particulate matter that conventional filters miss, making them essential in air purifiers, HVAC systems, and personal protective equipment. Meanwhile, photocatalysts like TiO_2 and ZnO are employed to oxidize volatile organic compounds from industrial and household sources, further improving indoor and outdoor air quality. Nanomaterials also enhance electrochemical scrubbers used to reduce sulfur dioxide and nitrogen oxides in industrial flue gases.

In parallel, nanotechnology has enabled the development of highly sensitive and miniaturized environmental sensors. Nanosensors fabricated from metal oxides, carbon nanotubes, or graphene detect trace concentrations of hazardous gases such as ammonia, methane, or nitrogen oxides with remarkable precision and speed [18]. Biosensors that combine functionalized nanoparticles with enzymes, antibodies, or DNA sequences allow selective identification of heavy metals, pesticides, and pathogens in water and soil. The miniaturization of these devices has facilitated portable and wireless monitoring systems, often integrated into IoT networks, enabling real-time data collection and pollution tracking in remote or urban environments.

Together, these applications highlight the transformative role of nanotechnology in promoting environmental sustainability. By combining purification, emission control, and real-time sensing, nanoscale solutions not only mitigate pollution but also provide critical tools for proactive environmental management and decision-making.

Nanotechnology's Multifaceted Environmental Impact



Structural and Construction Materials

Nanotechnology has emerged as a pivotal force in advancing structural and construction materials, enabling enhanced mechanical performance, improved durability, and the introduction of novel functionalities. By incorporating nanomaterials into conventional building materials, researchers and engineers are addressing long-standing challenges in infrastructure, such as limited lifespan, high maintenance demands, and environmental sustainability, while also creating new opportunities for multifunctional construction systems.

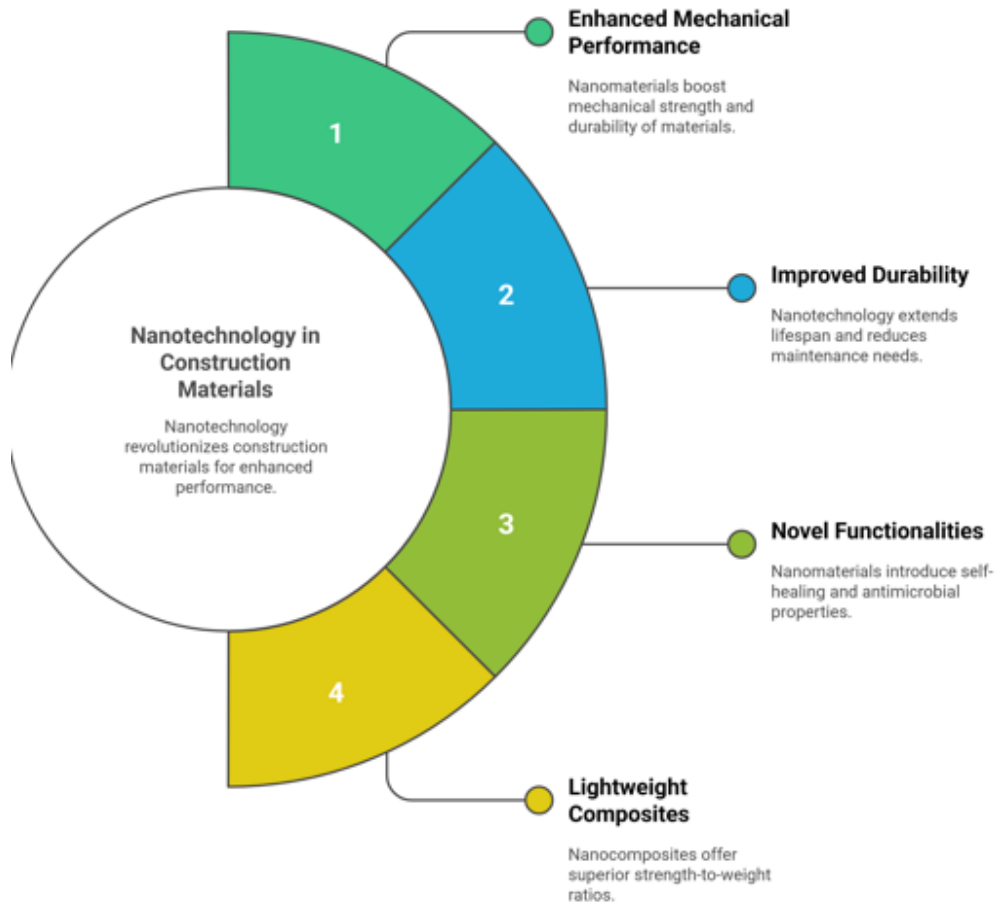
Concrete, the most widely used material in the built environment, has been significantly improved through nanoscale additives. Nanosilica particles refine cement microstructure by filling pores and accelerating hydration, leading to denser matrices with higher compressive strength, reduced porosity, and increased resistance to chemical attack [19]. Nanoclays enhance rheological properties and provide barriers against water penetration, freeze–thaw damage, and corrosive agents. Furthermore, the development of self-healing concrete, which incorporates nanoscale capsules or bacteria that autonomously repair cracks, holds promise for extending service life and reducing costly maintenance [20]. Together, these innovations contribute to more durable and sustainable infrastructure.

Surface treatments and nanocoatings also play a crucial role in improving material performance. Protective nanolayers containing zinc oxide, cerium oxide, or graphene oxide inhibit corrosion in steel reinforcements and other metal components, prolonging structural reliability [21]. Nanostructured titanium dioxide coatings provide self-cleaning and anti-fogging properties through photocatalytic activity and hydrophobicity, ensuring cleaner and safer surfaces. Additionally, antimicrobial nanocoatings based on silver or copper oxide prevent microbial colonization in high-traffic public spaces, hospitals, and water systems, thereby enhancing hygiene and safety standards [22].

Beyond traditional construction materials, nanotechnology has enabled the creation of lightweight composites with superior strength-to-weight ratios. Carbon nanotube-reinforced polymers exhibit remarkable tensile strength, stiffness, and impact resistance, making them suitable for aerospace, automotive, and civil engineering applications. Graphene-enhanced composites improve electrical conductivity, thermal stability, and mechanical integrity [23], enabling multifunctional structural components. Similarly, nanoclays and nanofibers incorporated into polymers enhance flame retardancy, dimensional stability, and barrier properties, producing materials that are both safe and high-performing.

By integrating these nanoscale strategies, the construction sector is advancing toward more resilient, sustainable, and multifunctional materials. From stronger and self-repairing concretes to protective nanocoatings and lightweight nanocomposites, nanotechnology is redefining how modern infrastructure is designed, built, and maintained.

Nanotechnology's Impact on Construction Materials



Emerging and Future Directions

As nanotechnology continues to mature, its scope is expanding far beyond established applications, converging with fields such as robotics, biotechnology, artificial intelligence, and quantum science to create transformative possibilities. These emerging directions not only extend the technological frontier but also raise important questions about safety, ethics, and sustainability, underscoring the need for balanced progress.

One of the most exciting prospects is nano-robotics, where miniature machines are being designed to operate at cellular or molecular levels. Though still in early stages, nano-robots could one day perform minimally invasive surgical procedures, deliver therapeutic agents directly to diseased cells, or even repair cellular components. Such targeted interventions would minimize systemic side effects and accelerate recovery, paving the way for highly personalized medicine.

Equally promising is the field of spintronics and quantum nanodevices, which harness the spin of electrons as well as their charge to develop faster, more efficient information technologies. Nanostructured magnetic materials have already enabled commercial devices such as magnetic random-access memory, while future quantum architectures based on spin qubits in quantum dots or 2D materials could revolutionize computing by achieving capabilities far beyond classical systems.

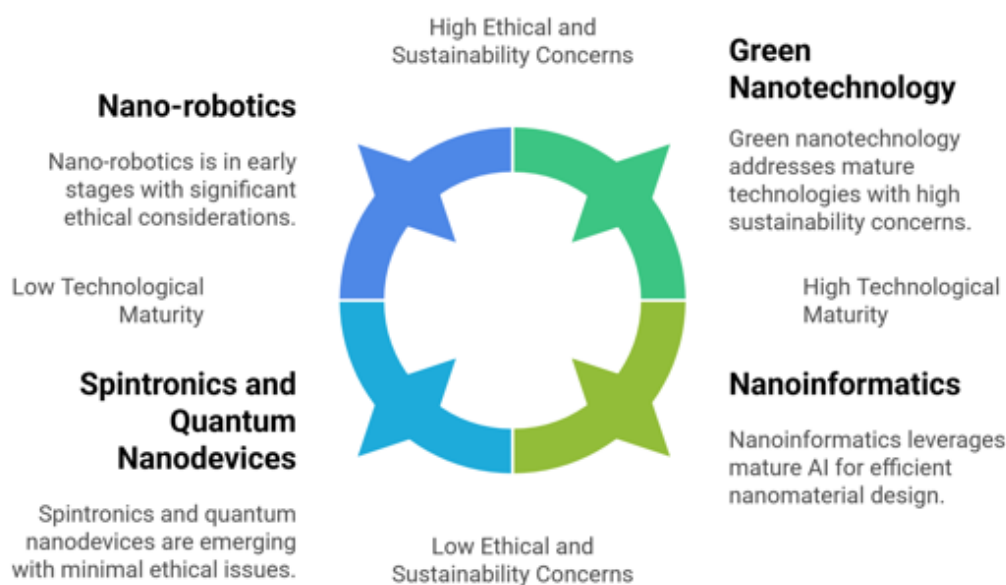
The complexity of designing such materials has given rise to nanoinformatics, a data-driven approach that applies artificial intelligence and machine learning to predict nanomaterial properties, optimize performance, and guide synthesis. By combining computational modeling with high-throughput experimentation, researchers can accelerate discovery and move away from traditional trial-and-error methods. This integration of AI with nanoscience signals a paradigm shift toward intelligent materials design.

At the same time, sustainability has become a central focus through green nanotechnology, which emphasizes environmentally friendly synthesis methods, biodegradable nanomaterials, and closed-loop recycling systems. Eco-conscious approaches aim to minimize energy use, reduce hazardous by-products, and ensure safe end-of-life disposal. Safer-by-design strategies also prioritize the development of nanomaterials that degrade in specific environments or exhibit reduced toxicity, aligning innovation with global sustainability goals.

Despite these advances, several challenges remain. Concerns over toxicity, bioaccumulation, and long-term health impacts demand comprehensive risk assessments and standardized testing protocols. Ethical considerations related to privacy, enhancement technologies, and environmental justice also require robust governance frameworks. Public awareness and transparent engagement are essential to counter misinformation and build trust in emerging nanotechnologies. Furthermore, many laboratory successes face hurdles in scalability and cost, highlighting the need for industrial processes that maintain performance while enabling affordable, large-scale production.

Together, these emerging directions underscore both the immense promise and the critical responsibility associated with nanotechnology's future. By combining innovation with sustainability, ethics, and public trust, nanotechnology can evolve into a cornerstone of transformative, responsible, and globally beneficial technologies.

Nanotechnology's Emerging Directions and Challenges



Conclusion

Nanotechnology has emerged as one of the most transformative disciplines in modern science and engineering, fundamentally redefining the way materials are designed, synthesized, and applied. By manipulating matter at the atomic and molecular scale, it enables the creation of materials with unprecedented properties—such as enhanced strength, improved conductivity, superior reactivity, and targeted functionality—that are unattainable through conventional approaches.

In the realm of electronics and optoelectronics, nanomaterials like carbon nanotubes, quantum dots, and two-dimensional materials are pushing the limits of device miniaturization, energy efficiency, and speed. They are integral to the evolution of next-generation transistors, displays, sensors, and flexible electronic systems. Energy technologies have been significantly enhanced by nanostructured materials that improve the efficiency and durability of solar cells, batteries, super-capacitors, and fuel cells, addressing the global imperative for cleaner and more sustainable energy solutions.

In medicine and healthcare, nanotechnology offers precision tools for targeted drug delivery, high-resolution diagnostics, and regenerative medicine. By improving therapeutic outcomes while minimizing side effects, it is revolutionizing personalized medicine and disease management. Likewise, environmental applications are benefitting from nanomaterials that can remove pollutants, detect contaminants at trace levels, and catalyze cleaner chemical processes.

In the construction and structural materials sector, nanotechnology enhances mechanical strength, durability, and multifunctionality, leading to more efficient and sustainable infrastructure. Whether it is in the form of high-performance concrete, corrosion-resistant coatings, or lightweight composites, nanomaterials are contributing to safer and longer-lasting built environments.

Looking ahead, the future of nanotechnology lies in its convergence with emerging fields such as artificial intelligence, robotics, quantum computing, and green chemistry. Innovations like nano-robots for targeted therapy, spintronic devices for quantum data storage, and AI-assisted nanomaterial design represent the next frontiers. However, these advancements also bring new challenges that must be met with rigorous attention—particularly concerning the safety, ethics, environmental impact, and regulatory oversight of nanomaterials.

In conclusion, nanotechnology is not merely an enabling technology but a foundational platform that is redefining the very principles of material science and engineering. Its multidisciplinary influence is reshaping industries, driving economic growth, and offering sustainable solutions to some of the world's most pressing challenges. To fully realize its potential, sustained investment in research, cross-sector collaboration, public engagement, and the development of robust ethical and regulatory frameworks are essential. By embracing these principles, nanotechnology can serve as a powerful catalyst for global progress and human well-being in the 21st century and beyond.

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