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Review Article

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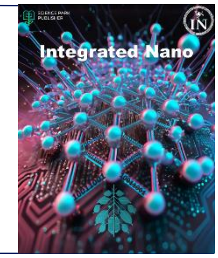

Integrated Nano

Recent advances in nanomaterials: Synthesis, properties, and applications

Khushbu Sharma[1,*], Yogita Dahiya[2], Takayuki Ichikawa[1]

[1] Graduate School of Advanced Science and Engineering, Hiroshima University, Higashi-Hiroshima-739-8527, Japan

[2] Institute for Plasma Research, Gandhinagar, 382428, India

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Abstract

Nanomaterials, defined by at least one dimension below 100 nanometres, have emerged as a transformative class of materials due to their unique size-dependent properties. From medicine and energy to electronics and environmental remediation, nanomaterials are enabling breakthroughs across disciplines. This review highlights recent developments in nanomaterial synthesis, examines their distinctive properties, and explores diverse applications. Challenges related to toxicity, scalability, and regulatory frameworks are also discussed, with a forward-looking view on future directions.

Keywords: Nanotechnology; Nanomaterials; Structure-property relationship; Quantum confinement; Synthesis methods

1. Introduction

Nanomaterials, defined by their structures with dimensions in the range of 1 to 100 nanometers, form the foundation of nanotechnology a rapidly advancing field that has witnessed remarkable growth since the early 2000s [1, 2]. At this scale, materials exhibit distinct properties that differ significantly from their bulk counterparts, primarily due to quantum confinement effects and a substantial increase in surface area relative to volume. These unique phenomena result in altered chemical reactivity, optical behaviour, mechanical strength, electrical conductivity, and magnetic properties, opening new avenues for scientific exploration and technological innovation [3-5].

The unique characteristics of nanomaterials have driven transformative applications across diverse domains. In electronics, nanomaterials have enabled the miniaturization of devices and the development of high-performance sensors and memory storage units [6]. In energy systems, nanostructured materials are integral to improving the efficiency of batteries, supercapacitors, and photovoltaic cells. In medicine, nanoscale carriers have revolutionized drug delivery by enabling targeted therapy with controlled release mechanisms. Environmental science has also benefited through the use of nanomaterials in water purification, pollutant detection, and sustainable energy generation [6, 7].

Despite the progress, the field of nanomaterials remains complex and rapidly evolving. Researchers continually strive to understand and control the synthesis, stability, toxicity, and long-term behavior of these materials. Addressing these challenges is critical for ensuring the safe, sustainable, and economically viable deployment of nanotechnology across industries [8-10]. This review aims to provide a concise yet comprehensive exploration of nanomaterials. It covers their classification based on dimensionality and composition, elaborates on various synthesis techniques, discusses key physical and chemical properties, surveys a range of current and emerging applications, and reflects on future prospects and challenges. By offering a holistic overview, this work intends to serve as a valuable resource for researchers, students, and industry professionals engaged in the exciting and rapidly growing field of nanomaterials.

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2. Classification of nanomaterials

Nanomaterials can be broadly categorized based on their shape, composition, and origin.

2.1. Based on dimensions

Nanotechnology revolves around the use and manipulation of nanomaterials, which are materials that possess at least one dimension in the nanoscale range typically less than 100 nanometers (nm). To put this into perspective, a nanometer is one-billionth of a meter (10^{-9} m), making these materials much smaller than those observed at the microscale. This reduction in size leads to remarkable differences in the physical and chemical behavior of materials compared to their bulk counterparts [10]. What makes nanomaterials particularly fascinating is their size- and shape-dependent properties. By merely altering their dimensions or morphology at the nanoscale, entirely new characteristics and functionalities can emerge. Depending on their geometrical configuration, nanomaterials can exist in a variety of shapes such as nanoparticles (spherical), nanorods (elongated), nanosheets (flat layers), and others [11-14], shown in Figure 1. These forms can be grouped based on the number of dimensions that fall within the nanoscale, leading to a standard classification system.

2.1.1. Zero-dimensional (0D) nanomaterials: These materials have all three dimensions (length, width, and height) within the nanoscale. Nanoparticles are a typical example, where the particle is essentially a point-like structure.

2.1.2. One-dimensional (1D) nanomaterials: In this class, only one dimension is within the nanoscale range, while the other two are larger. Nanorods, nanotubes, and nanowires fall into this category, offering unique directional properties due to their elongated form.

2.1.3. Two-dimensional (2D) nanomaterials: These materials have two dimensions in the nanoscale, while the third is significantly larger. Examples include nanofilms, nanolayers, and nanocoatings, which are often used for surface modifications and functional coatings.

2.1.4. Three-dimensional (3D) or Bulk nanomaterials: Here, the material extends beyond the nanoscale in all three dimensions. Despite being larger, these structures are composed of nanoscale units or interactions between nanostructures, such as nanocomposites, core-shell structures, or bundles of nanowires and nanotubes.

2.2. Based on composition

Nanomaterials can be categorized into various classes depending on their morphology, particle size, internal structure, and chemical composition. These classifications help tailor their applications across fields such as electronics, medicine, energy, and environmental science. The major types include carbon-based nanomaterials, metal-based nanoparticles, semiconductor nanomaterials, polymer-based nanomaterials, lipid-based nanomaterials, and nanocomposites.

2.2.1. Carbon-based nanomaterials

These materials are composed primarily of carbon atoms arranged in distinct nanoscale geometries. The most well-known forms include:

Carbon Nanotubes (CNTs): These are cylindrical structures formed by rolling a single layer of graphene into a tube. CNTs are categorized into single-walled (SWCNTs) and multi-walled (MWCNTs) types, shown in Figure 2(a), depending on the number of concentric graphene layers [15-17]. Carbon nanotubes: synthesis, properties and engineering applications. They are renowned for their exceptional mechanical strength, thermal conductivity, and electrical properties, often outperforming steel in strength-to-weight ratio. These features make them valuable for reinforcing composite materials and in nanoelectronics.

Fullerenes: These are closed, cage-like molecules composed entirely of carbon, typically consisting of 60 or more atoms (e.g., C_{60}), shown in Figure 2(b). Their structure resembles a soccer ball, with carbon atoms arranged in a combination of pentagons and hexagons [18, 19]. Fullerenes are allotropes of carbon and exhibit high electron affinity, electrical conductivity, and resilience, making them useful in drug delivery systems, photovoltaics, and superconductors.

2.2.2. Metal-based nanomaterials

Metal-based nanomaterials, composed of metal atoms or ions, are widely researched due to their unique physicochemical properties and broad range of applications. These materials are typically synthesized through chemical or photochemical reduction methods, where metal salts containing divalent or trivalent metal ions are reduced using

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agents such as sodium borohydride, hydrazine, or citrate. Common examples include silver (Ag), gold (Au), and platinum (Pt) nanoparticles, as well as those based on transition metals like copper (Cu) and rare earth elements such as cerium (Ce). For instance, gold nanoparticles synthesized via citrate reduction are frequently used in biomedical imaging and diagnostics due to their biocompatibility and strong surface plasmon resonance effects [21]. Similarly, silver nanoparticles, known for their antimicrobial activity, have been applied in wound dressings and water purification systems [22]. The high surface-area-to-volume ratio of these materials imparts enhanced catalytic performance, increased adsorption capacities, and improved chemical reactivity. These properties are especially valuable in applications such as catalytic converters, environmental remediation, and drug delivery systems [23]. Additionally, doping metal nanoparticles with other elements for example, incorporating palladium into platinum nanoparticles can significantly improve their catalytic efficiency and thermal stability, particularly in fuel cell and hydrogenation reactions [24]. The tunable properties and multifunctionality of metal-based nanomaterials continue to make them a focal point in nanotechnology research.

2.2.3. Semiconductor nanomaterials

Semiconductor nanomaterials, characterized by their tunable electronic band structures at the nanoscale, have emerged as pivotal components in various advanced technological applications. Recent developments have introduced novel materials and composites that enhance the performance and broaden the applicability of these semiconductors.

Among the notable advancements is the exploration of two-dimensional materials like $MoSi_2N_4$. This material exhibits exceptional piezoelectricity, high thermal conductivity, and promising photocatalytic properties, making it a strong candidate for applications in optoelectronics and energy conversion systems. First-principles studies have confirmed its stability and potential in these domains [25]. In the realm of hybrid nanocomposites, the integration of graphene with semiconductor materials has led to significant improvements in gas sensing technologies. Graphene-based composites, due to their large surface area and excellent electrical conductivity, have demonstrated enhanced sensitivity and selectivity in detecting various gases. These properties are particularly beneficial for developing efficient gas sensors operating at room temperature [26]. Furthermore, the incorporation of metal halide perovskites with metal oxides has shown promise in enhancing the stability and performance of optoelectronic devices. These composites leverage the superior photoluminescence and charge transport properties of perovskites, combined with the robustness of metal oxides, to create efficient and durable components for applications such as light-emitting diodes and solar cells [27].

These advancements underscore the dynamic nature of semiconductor nanomaterials research, highlighting the continuous efforts to develop materials with superior properties for next-generation technological applications.

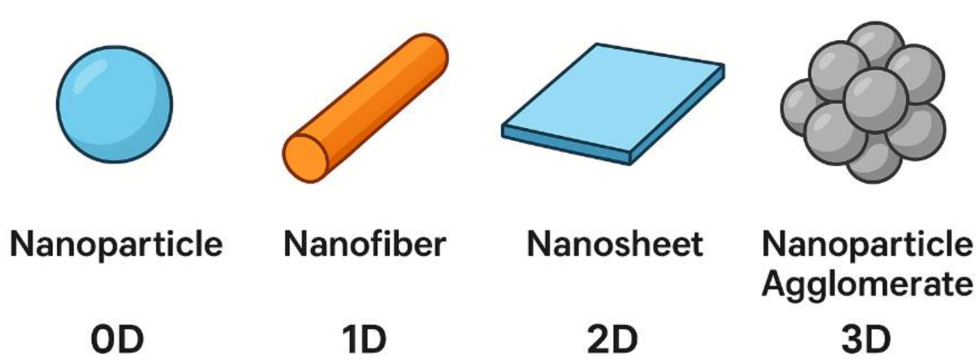

Figure 1. Dimensional classification of nanomaterials (0D, 1D, 2D, and 3D).

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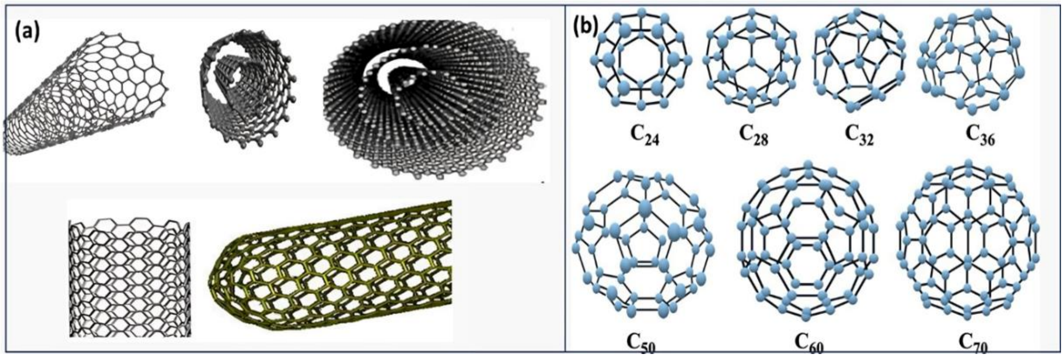

Figure 2. (a) Types of CNTs [17] Copyright (2019) Springer Nature (b) Various structures of fullerene [20] Copyright (2020) IOP Publishing.

2.2.4. Nanocomposites

Nanocomposites are multiphase materials where at least one phase possesses dimensions in the nanoscale range (less than 100 nm), leading to enhanced properties compared to their individual components. Recent advancements have expanded their applications across various fields, including structural materials, packaging, sensors, energy storage devices, and biomedical systems.

In structural applications, incorporating functionalized multi-walled carbon nanotubes (MWCNTs) into aluminum matrices has significantly improved mechanical properties and thermal stability, addressing challenges related to homogeneous dispersion. Similarly, the integration of graphene and silica nanoparticles into polypropylene matrices has enhanced mechanical strength and thermal stability, making them suitable for automotive and aerospace components [28]. For packaging applications, nanoclay-reinforced nanocomposites have been extensively studied due to their improved thermal resistance, flame retardancy, stiffness, and strength. These properties are particularly beneficial in food packaging, where barrier properties against gases and moisture are critical [29].

In the realm of sensors, polymeric nanocomposites incorporating carbon nanotubes and metal oxides have demonstrated enhanced electrical conductivity and sensitivity, making them ideal for developing advanced sensing devices. These materials are being explored for applications ranging from environmental monitoring to healthcare diagnostics [30]. Energy storage devices have benefited from nanocomposites through the incorporation of carbon nanotubes, which enhance electronic conductivity and structural integrity in battery electrodes. Such advancements contribute to the development of batteries with higher energy densities and longer lifespans [31]. In biomedical systems, polymer-based nanocomposites, particularly those incorporating magnetic nanoparticles, are actively utilized in diagnostics and cancer treatment applications. These materials offer targeted drug delivery and improved imaging capabilities, enhancing the efficacy of medical treatments [32]. Overall, the unique properties of nanocomposites, such as superior mechanical strength, thermal stability, and tunable electrical or magnetic behaviors, continue to drive their integration into diverse applications, underscoring their significance in advancing technology and industry.

3. Synthesis of nanomaterials

The synthesis of nanomaterials is a cornerstone in nanotechnology research and applications. The choice of synthesis technique influences the morphology, particle size, surface properties, crystallinity, and ultimately, the performance of nanomaterials in various applications, such as energy storage, catalysis, medicine, and electronics. Nanomaterial synthesis generally follows two main approaches: top-down and bottom-up. These methodologies are selected based on the desired structural and chemical properties of the final product.

3.1. Top-down approaches

Top-down approaches begin with bulk materials and systematically reduce their size to the nanoscale through physical or mechanical means. These methods are widely used for producing nanostructures where control over the shape is less critical than mass production or integration with existing microscale systems.

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3.1.1. Mechanical Milling

Mechanical milling or High-energy ball milling (HEBM) is a widely utilized top-down technique for producing nanomaterials, wherein bulk materials are subjected to repeated impact and friction within a rotating drum containing steel or ceramic balls. This method effectively reduces particle sizes to the nanoscale, making it cost-effective and scalable for large-scale production. Figure 3 illustrates the working principles of different types of ball mills used for mechanical grinding. Figure 3(a) shows the rotation mechanism where grinding media and material collide inside a rotating drum. Figure 3(b) compares three common mill types tumbler, vibratory, and planetary ball mills highlighting their distinct motion patterns used to achieve efficient size reduction [33].

Recent studies have demonstrated the versatility of HEBM in synthesizing various nanomaterials. For instance, a study achieved large-scale production of zinc oxide (ZnO) nanoparticles, reducing particle sizes from 416.60 nm to 33.27 nm through HEBM, highlighting its potential for mass production of nanomaterials. Similarly, nanocrystalline silver powders have been synthesized from micro-sized silver using HEBM, with detailed analyses of particle size and lattice strain conducted via X-ray diffraction techniques [34, 35]. HEBM has also been instrumental in producing nanocomposites. For example, Fe-doped ZnO nanoparticles prepared via HEBM exhibited enhanced sonophotocatalytic degradation efficiency, demonstrating the method's applicability in environmental remediation. Additionally, the synthesis of carbon nanotube-reinforced aluminum composites through HEBM has shown improved mechanical properties, indicating its usefulness in developing advanced structural materials [34, 36]. While HEBM is advantageous for its simplicity and scalability, it is essential to consider potential drawbacks, such as the introduction of defects and contamination during the milling process. Nonetheless, its ability to produce a wide range of nanomaterials, including alloys and composites, underscores its significance in nanotechnology and materials science.

3.1.2. Lithography

Lithography remains a cornerstone in nanofabrication, enabling the creation of intricate nanoscale patterns essential for various advanced applications. Traditional techniques like photolithography and electron beam lithography (EBL) offer high precision but are often complex and costly, limiting their scalability for bulk nanomaterial production. Figure 4 contrasts conventional photolithography and electron beam lithography both highly precise but limited by cost and scalability with modern bulk methods such as nanoimprint and soft lithography. These newer approaches use stamping-based processes that enable high-volume, versatile, and lower-cost pattern fabrication. Overall, the graphic highlights the technological shift toward scalable nanomanufacturing techniques.

Recent advancements have introduced alternative methods that address these limitations. Extreme ultraviolet (EUV) lithography, for instance, utilizes 13.5 nm wavelength light to achieve sub-10 nm resolution, facilitating the production of smaller, more powerful electronic devices. However, EUV systems are expensive and require complex infrastructure, which can be a barrier for widespread adoption [37]. Nanoimprint lithography (NIL) has emerged as a promising, cost-effective alternative. NIL involves mechanically pressing a patterned mold into a resist material to create nanoscale features.

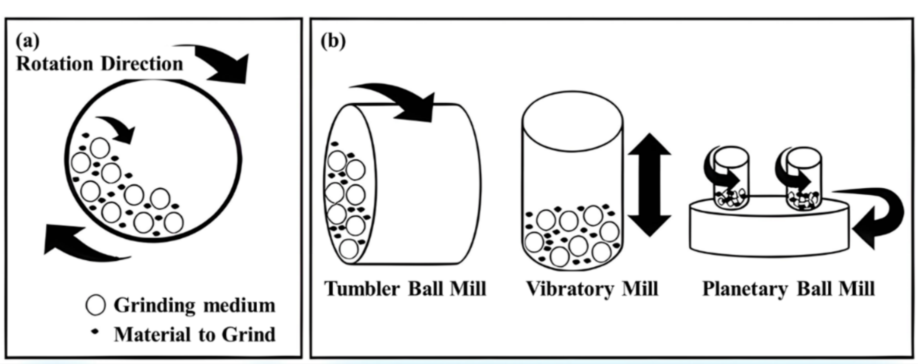

Figure 3. (a) Schematic of the grinding mechanism inside a rotating ball mill; (b) Comparison of tumbler, vibratory, and planetary ball mill configurations [33].

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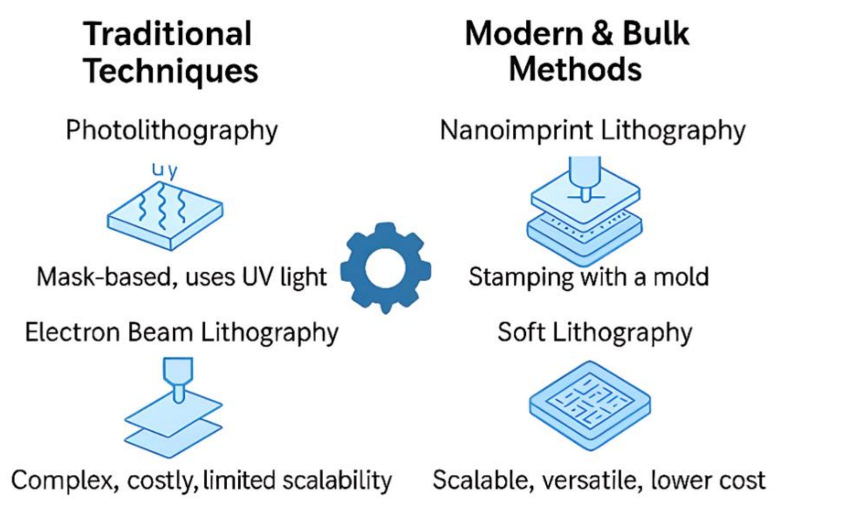

Figure 4. Comparison of traditional lithography techniques with modern, scalable nanofabrication methods.

This technique offers high resolution and throughput, making it suitable for applications in semiconductors, photovoltaics, and light-emitting devices. For example, NIL has been successfully employed in fabricating 3D carbon nanostructures for carbon nanotube electronic components, biosensors, and tissue scaffolds [38-40].

Furthermore, advancements in NIL have led to the development of roll-to-roll processes, enabling continuous, high-throughput production of nanostructured materials. This scalability positions NIL as a viable option for large-area applications, such as flexible electronics and wearable devices [41]. In summary, while traditional lithography techniques offer unparalleled precision, their complexity and cost hinder large-scale nanomaterial production. Emerging methods like EUV lithography and nanoimprint lithography provide alternative pathways, balancing resolution, cost, and scalability, thereby broadening the scope of nanofabrication applications [37].

3.1.3. Etching

Etching is a fundamental process in nanofabrication, involving the removal of material layers to sculpt desired nanostructures. Recent advancements have enhanced the precision and applicability of both plasma and ion beam etching techniques. Figure 5 contrasts plasma etching based on chemical reactions with reactive ionized gases with ion beam etching, which removes material through energetic ion bombardment. Plasma etching offers high selectivity and vertical profiles suited for integrated circuits, while ion beam etching provides highly directional, precise sculpting ideal for nanowire and fine-structure fabrication.

Plasma etching, particularly reactive ion etching (RIE), has seen significant progress in processing silicon-based materials. Innovations have enabled the fabrication of complex structures such as micropillar arrays and nanowires, which are crucial for applications in micro-electro-mechanical systems (MEMS), sensors, and bioelectronics. Additionally, the development of atomic layer etching (ALE) techniques, utilizing sequential exposures to gases like SF_6 and argon plasma, has achieved sub-nanometer precision in etching silicon dioxide, offering greater control over etch rates and uniformity [42, 43]. Ion beam etching (IBE) has also advanced, providing high-resolution patterning capabilities. Recent studies have demonstrated the effective use of IBE in modifying anodic aluminum oxide (AAO) templates, achieving low porosity levels suitable for applications in nanorod fabrication [44]. These advancements in etching technologies underscore the ongoing efforts to achieve higher precision and complexity in nanostructure fabrication, paving the way for innovations in various fields such as electronics, photonics, and biomedical engineering.

3.2. Bottom-up approaches

Bottom-up approaches assemble nanomaterials atom-by-atom or molecule-by-molecule, often providing superior control over structure, composition, and surface properties. These methods are ideal for synthesizing uniform nanoparticles and complex nanostructures.

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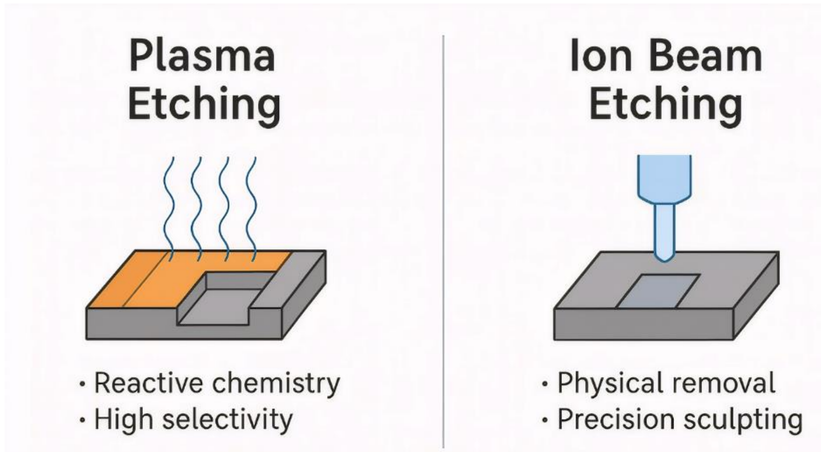

Figure 5. Plasma vs. Ion beam etching techniques.

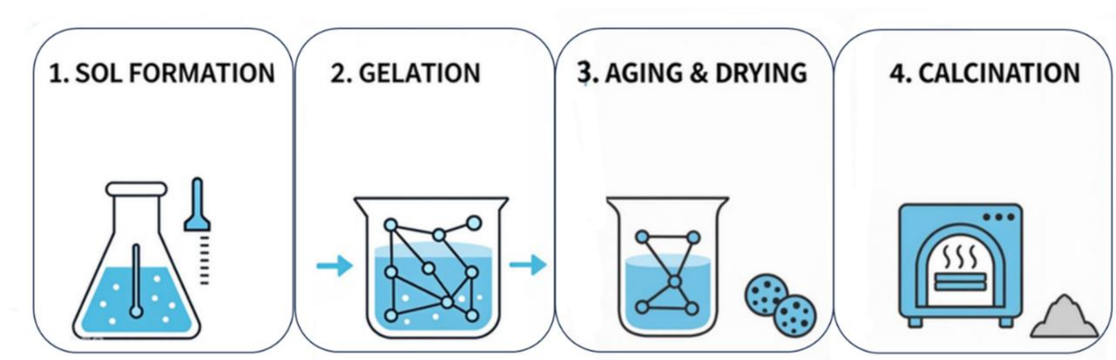

Figure 6. Sol-Gel process: From solution to nanomaterial.

3.2.1. Sol-Gel method process

The Sol-Gel method is a versatile and widely utilized method for synthesizing oxide-based nanomaterials, involving the transition from a colloidal "sol" to a solid "gel" phase through hydrolysis and condensation reactions of metal alkoxides or salts. Figure 6 illustrates the four key stages of the sol-gel method, beginning with sol formation and progressing through gelation, aging/drying, and final calcination. Together, these steps transform a liquid precursor into a solid nanostructured material.

This technique offers fine control over porosity, homogeneity, and nanostructure morphology, making it particularly effective for fabricating materials such as silica, titania, and alumina. Recent advancements have expanded the applications and capabilities of the sol-gel method. For instance, a study demonstrated the synthesis of silicon oxide (SiO_2) nanoparticles via the sol-gel process, revealing their potential in gas sensing applications due to their specific surface properties [45, 46]. Similarly, titanium dioxide (TiO_2) nanomaterials produced through sol-gel techniques have been explored for their photocatalytic properties, which are beneficial in environmental purification systems [47]. Additionally, the sol-gel synthesis of alumina nanoparticles has been investigated for their structural and thermal stability, making them suitable for various industrial applications [48-50]. Moreover, the sol-gel method has been employed to create complex nanostructures, such as mesoporous manganese oxide (Mn_3O_4), copper oxide (CuO), and magnesium hydroxide ($Mg(OH)_2$), with controlled sizes and shapes, enhancing their applicability in catalysis and energy storage. The adaptability of the sol-gel process also extends to the fabrication of hybrid materials, such as silica-alumina coatings containing cerium oxide nanofibers, which have shown promise in corrosion resistance and protective coatings [50, 51]. These developments underscore the sol-gel process's significance in nanomaterial synthesis, offering a low-cost, energy-efficient, and controllable approach to producing a

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wide range of functional oxide nanomaterials for diverse applications.

3.2.2. Hydrothermal and solvothermal synthesis method

Hydrothermal and solvothermal synthesis methods are pivotal in fabricating nanomaterials with controlled morphologies and properties. These techniques involve chemical reactions in sealed vessels under elevated temperatures and pressures, using water in hydrothermal processes and organic solvents in solvothermal ones (Figure 7). Such controlled environments facilitate the crystallization of materials with uniform particle sizes and specific structures. Recent advancements have showcased the versatility of these methods. For instance, the hydrothermal synthesis of high-entropy amorphous metal oxides has been achieved at low temperatures, resulting in materials with cauliflower-type morphology suitable for oxygen evolution reactions in water electrolysis applications. Similarly, solvothermal synthesis has been employed to produce ultra-small copper ferrite ($CuFe_2O_4$) nanoparticles with controlled diameters and aggregation states, enhancing their catalytic activity for hydrogen peroxide decomposition [52]. Moreover, the hydrothermal method has been utilized to synthesize antimony tungstate (Sb_2WO_6) nanoparticles, which exhibit excellent photocatalytic efficiency in degrading dyes under LED light irradiation. These examples underscore the importance of parameters such as temperature, reaction time, pH, and precursor concentration in tailoring the properties of nanomaterials [53]. In summary, hydrothermal and solvothermal synthesis techniques offer robust platforms for producing a wide range of nanomaterials, including metal oxides, sulfides, and zeolites, with applications spanning energy storage, catalysis, and environmental remediation.

3.2.3. Chemical vapor deposition (CVD)

CVD is a widely utilized technique for producing high-quality thin films and nanomaterials. In this process, volatile precursors are transported in the gas phase to a heated substrate, where they decompose or react to form a solid material layer. Figure 8 shows the steps of CVD, where volatile precursors are introduced into a chamber and transported to a heated substrate. The precursors then decompose or react on the hot surface, forming a solid, high-quality material layer on the substrate.

CVD is particularly effective for synthesizing materials such as carbon nanotubes, graphene, and various semiconductor nanomaterials. Recent advancements have expanded the capabilities of CVD. For instance, low-pressure CVD (LPCVD), atmospheric pressure CVD (APCVD), thermal CVD (TCVD), and plasma-enhanced CVD (PECVD) have been developed to produce high-quality and large-scale monolayer graphene, which is crucial for applications in electronics and optoelectronics. Additionally, CVD has been employed to fabricate three-dimensional architectures of two-dimensional materials like graphene and transition metal dichalcogenides (TMDCs), enhancing their performance in energy storage and catalysis applications [54, 55]. Advanced forms of CVD, such as Plasma-Enhanced CVD (PECVD) and Atomic Layer Deposition (ALD), offer further control over film properties. PECVD utilizes plasma to enhance chemical reactions at lower temperatures, making it suitable for depositing materials on temperature-sensitive substrates.

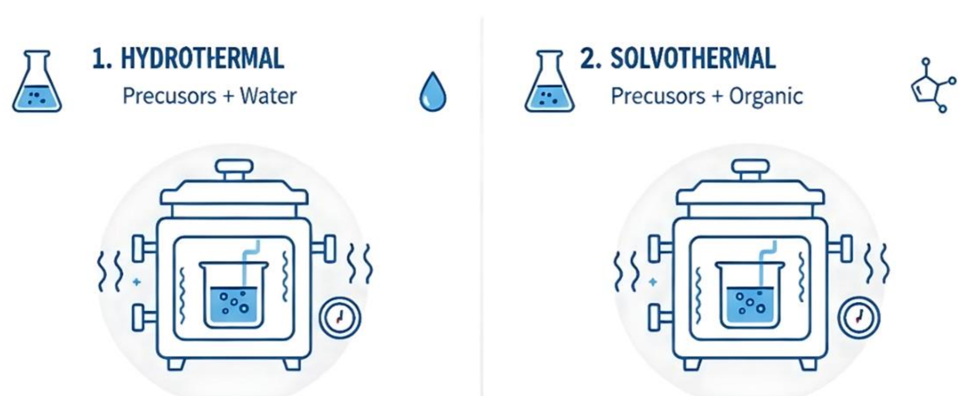

Figure 7. Hydrothermal and solvothermal synthesis for nanomaterial production.

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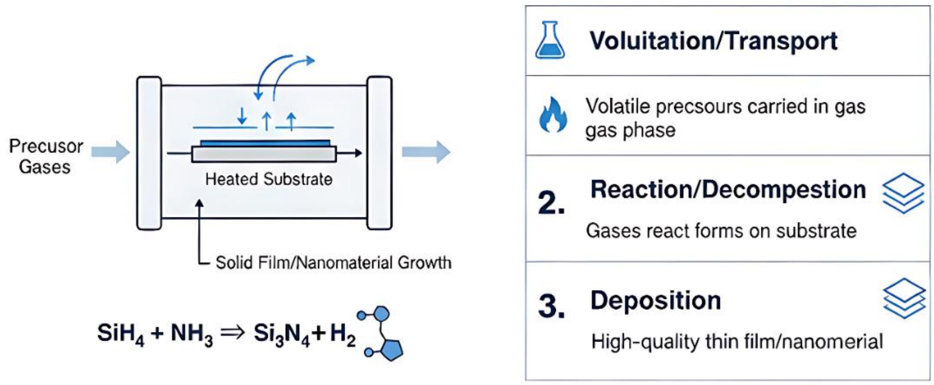

Figure 8. Schematic illustration of the Chemical vapor deposition (CVD) process for synthesizing thin films and nanomaterials.

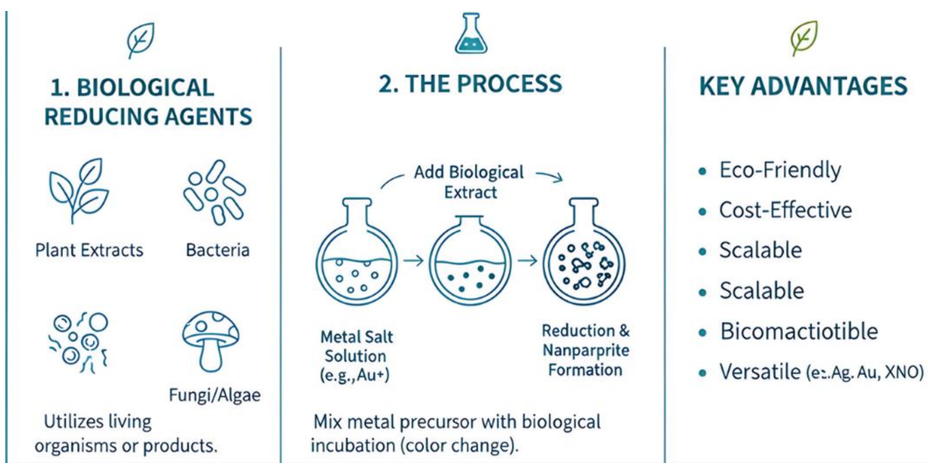

Figure 9. Green synthesis of nanomaterials.

ALD, on the other hand, allows for atomic-scale precision in film thickness and composition, which is essential for applications requiring ultra-thin and conformal coatings. Recent developments in atmospheric-pressure spatial ALD have achieved deposition rates up to 1.5 nm/min, significantly faster than traditional temporal ALD processes, thereby expanding the potential for high-throughput manufacturing [56]. These advancements in CVD and its variants underscore the technique's versatility and importance in the fabrication of nanomaterials for a wide range of applications, including electronics, energy storage, and catalysis.

3.2.4. Green synthesis methods

Green synthesis methods utilize biological entities such as plant extracts, bacteria, fungi, and algae to reduce metal ions into nanoparticles, offering an eco-friendly alternative to conventional chemical and physical synthesis techniques (Figure 9).

These biogenic approaches are gaining attention due to their low toxicity, minimal environmental impact, and biocompatibility, making them particularly suitable for biomedical and environmental applications [57]. Recent studies have demonstrated the successful synthesis of various nanoparticles using green methods. For instance, silver nanoparticles have been synthesized using plant extracts, with the size and shape of the nanoparticles being influenced by parameters such as pH, temperature, and extract concentration. Similarly, the green synthesis of platinum nanoparticles using plant extracts has been shown to produce nanoparticles with controlled size and morphology, which are crucial for their catalytic and biomedical applications [58]. The control over nanoparticle characteristics through green synthesis is further

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enhanced by understanding the role of various factors. For example, the pH of the reaction medium significantly affects the size and stability of the synthesized nanoparticles. A study highlighted that precise pH control is essential for obtaining silver nanoparticles with desirable characteristics, as pH influences the reduction rate of metal ions and the stabilization of the formed nanoparticles [59]. Moreover, the use of different biological sources, such as various plant parts or microbial strains, can lead to the synthesis of nanoparticles with distinct properties. This diversity in biological reducing agents allows for the tailoring of nanoparticle features to suit specific applications, ranging from drug delivery systems to environmental remediation technologies. Figure 10 illustrates the synthesis of nanomaterials through Top-Down and Bottom-Up approaches:

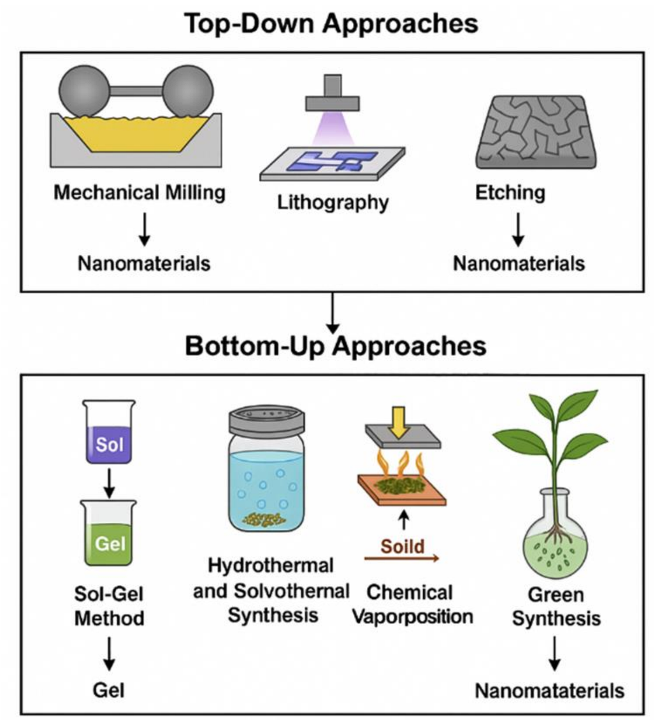

Figure 10. Schematic illustration of the synthesis of nanomaterials through Top-Down approaches such as Mechanical Milling, Lithography, and Etching, and Bottom-Up approaches including the Sol-gel method, Hydrothermal and Solvothermal synthesis, Chemical Vapor Deposition (CVD), and Green synthesis, with correspondings [1-4].

4. Properties of nanomaterials

Nanomaterials possess unique physical and chemical properties that markedly differ from those of their bulk counterparts. These distinct characteristics arise due to their extremely small size, large surface area-to-volume ratio, and quantum mechanical effects. As a result, nanomaterials often demonstrate enhanced optical, electrical, mechanical, magnetic, and thermal properties, which are of tremendous importance in advanced technological applications.

4.1. Optical properties

Nanomaterials exhibit unique optical properties due to quantum confinement and surface plasmon resonance (SPR), enabling applications in sensing, imaging, and catalysis. For instance, gold nanoparticles demonstrate SPR, leading to strong absorption and scattering of light, which is utilized in biosensing and photothermal therapies. Semiconductor quantum dots, such as CdSe, exhibit size-dependent fluorescence, making them suitable for biological labeling and display technologies. Additionally, nanostructured materials like TiO_2 and ZnO show enhanced photocatalytic activity due to their high surface area and efficient charge separation, beneficial for environmental remediation and solar fuel generation [60].

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4.2. Electrical properties

Nanomaterials exhibit exceptional electrical properties due to their nanoscale dimensions and unique surface characteristics. Carbon-based nanomaterials like carbon nanotubes (CNTs) and graphene demonstrate remarkable electrical conductivity, making them suitable for nanoelectronic devices and flexible circuits. At the nanoscale, quantum tunneling and quantized conductance become significant, enabling the development of single-electron transistors and molecular electronics. Additionally, incorporating nanoparticles into polymer matrices enhances dielectric constants and breakdown strengths, leading to high-performance capacitors and energy storage devices.

4.3. Mechanical properties

Nanomaterials exhibit exceptional mechanical properties due to their nanoscale dimensions and unique surface characteristics. Carbon nanotube (CNT)–reinforced nanocomposites demonstrate superior strength-to-weight ratios, making them ideal for applications in aerospace, automotive, and sports equipment. Nanocrystalline metals, such as nickel, show enhanced hardness and tensile strength owing to grain boundary strengthening mechanisms. Additionally, two-dimensional materials like MXenes offer remarkable flexibility and mechanical durability, enabling their integration into wearable and foldable electronic devices.

4.4. Magnetic properties

Nanomaterials exhibit unique magnetic properties distinct from their bulk counterparts, primarily due to size and surface effects. Superparamagnetic iron oxide nanoparticles (SPIONs), such as Fe_3O_4 and γ-Fe_2O_3, display magnetism only under an external magnetic field, making them ideal for biomedical applications like MRI contrast agents, targeted drug delivery, and magnetic hyperthermia for cancer treatment. Furthermore, by controlling parameters like size, shape, and surface coatings, the magnetic anisotropy and coercivity of nanoparticles can be finely tuned, facilitating their use in high-density data storage and spintronic devices [61].

4.5. Thermal properties

Nanomaterials exhibit remarkable thermal properties, making them highly suitable for advanced heat transfer and thermal management applications. Nanofluids suspensions of nanoparticles in base fluids like water or ethylene glycol demonstrate significantly enhanced thermal conductivity compared to conventional fluids, improving cooling efficiency in electronic devices and industrial heat exchangers. Incorporating nanoclays, such as montmorillonite or halloysite, into polymer matrices enhances thermal stability and flame retardancy by forming efficient char layers and acting as barriers to heat and mass transfer during combustion. Furthermore, nanostructured thermoelectric materials benefit from increased phonon scattering, which reduces thermal conductivity while maintaining electrical performance, thereby improving the thermoelectric figure of merit (ZT) [62].

5. Applications of nanomaterials

Nanomaterials have become extremely useful in a wide array of applications in the past few decades, driven by their unique and tunable chemical, physical, optical and mechanical features at the nanoscale as discussed in previous sections. Nanostructured materials offer a large surface to volume ratio, desired physical properties, efficient transport pathways, and confinement effects resulting from their nanoscale dimensions. This section comprises a complete discussion on employment of advanced nanomaterials across a broad spectrum of high-impact technologies related to energy storage and conversion, biomedicine, electronics, photonics and quantum computing.

5.1. Energy storage and conversion

Nanomaterials have been thoroughly researched and exploited in the energy field technologies, including solar cells, catalysts, thermoelectric, batteries, supercapacitors and hydrogen storage systems [63, 64]. These applications require chemical reaction or physical interactions at the interfaces or the surface, eventually depending upon specific surface area, surface chemistry, i.e., redox active sites. These surface features not only impact the thermodynamics of interfacial reactions, but also affect the nucleation and growth phenomenon during phase transitions [65].

5.1.1. Batteries

Batteries comprise two electrodes of opposite polarity and an electrolyte. In these devices, Faradaic reactions occurring in the bulk of active electrode materials and the interfaces convert the chemical energy of bonds into usable electrical

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energy [66]. Lithium-ion batteries (LIBs) are the most advanced energy storage option available in the market, given their long cycle life, high energy and power density, and negligible memory effects. Beyond LIBs, Li-O_2, Li-S, and Li-Se batteries have been in focus of research because of their potential to provide exceptional energy density. All these advancements are not possible without the development of nanomaterials of suitable physicochemical properties for electrode materials. A lot of advanced nanostructured electrode materials have been explored as anode/cathode materials and documented in the past decades. Nanomaterials such as carbon-coated silicon nanowires, layered oxides (V_2O_5, MnO_2, etc.), lithium alloy, graphene composites, and lithium-ion cathode materials ($LiFePO_4$, $LiMn_2O_4$, $LiCo_2O_4$ nanoparticles) allow for better energy density than typical metal or graphite electrodes [67, 68]. The anode materials in LIBs are grouped in three categories: (a) Intercalation/de-intercalation based materials, including graphite, layered 2D materials, (b) alloying/dealloying materials such as Si and Sn alloys, (c) conversion based anodes such as metal chalcogenides, metal fluorides and metal phosphides [69-71]. Nanomaterials are critical in the performance of battery systems and can be utilized in numerous ways to tackle the existing challenges. Nanocoating of graphite using metal and their oxides, polymers or amorphous carbon to minimize the side reactions at interfaces with electrolyte, improving the overall cell performance [72]. In other instances, spinal nanostructured lithium titanate (LTO, $Li_4Ti_5O_{12}$) or its composites have reduced Li-ion diffusion pathways and higher surface area than the bulk LTO [73]. Addressal of volume alteration issue linked with silicon is sought by pursuing hierarchical nanocomposite structure of silicon with carbon-based materials such as carbon nanoparticles, carbon shells, or carbon nanotubes [74]. Even in state of the art all-solid-state batteries, the role of nanomaterials extends beyond electrode materials to include nanoscale solid electrolyte design and optimization. Better interfacial contact with electrodes, increased dendritic suppression, and improved lithium-ion transport paths are all made possible by nanostructured solid electrolytes. Crucial issued to enhance ionic conductivity and electrochemical stability can be tackled by adjusting phase distribution, crystallinity, and grain boundary chemistry at the nanoscale.

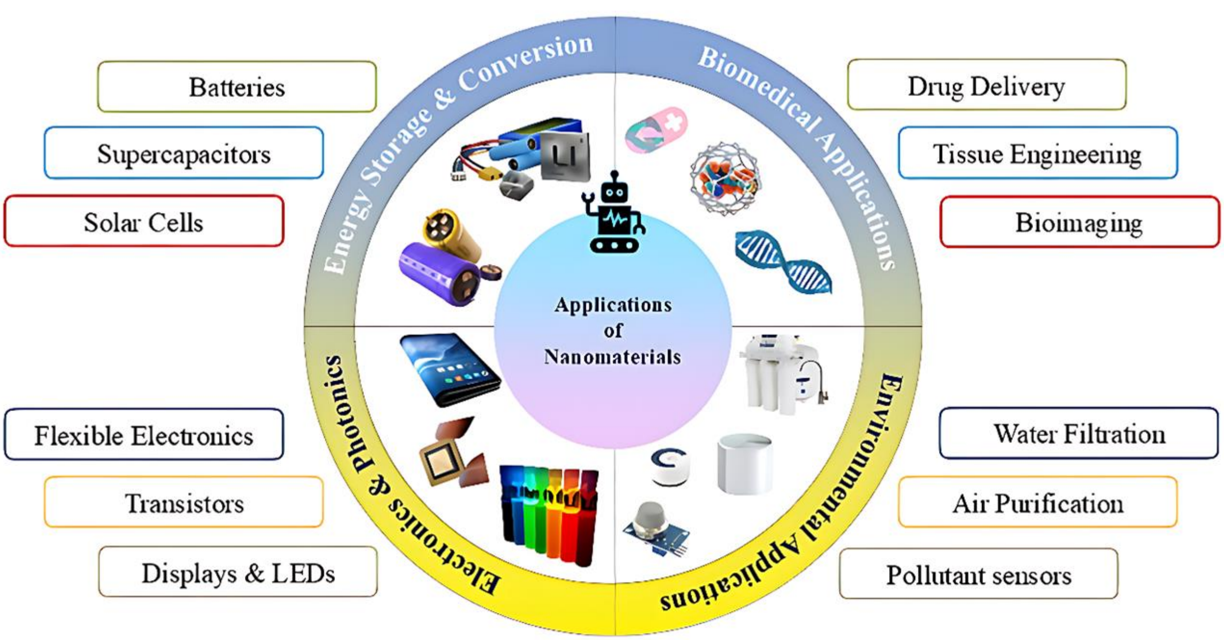

Figure 11. Schematics exemplifying diverse applications of nanomaterials across energy, environment, medicine, and electronics fields.

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5.1.2. Supercapacitors

Supercapacitors have become attractive for energy storage solutions due to their exceptional cycle life, greater power density, safety, economic and environmental benign nature. Typical supercapacitor utilizes electrodes, a separator, and an electrolyte, whereby their performance is dominated by the performance of the electrode that depends on its specific surface area, redox activity, pore-size distribution, ionic and electrical conductivity. Thus, nanomaterials are the key materials in these devices, as they can be manipulated to deliver desirable physical and chemical properties. Supercapacitors are classified in two major categories as follows: (1) electrical double layer capacitors (EDLCs): EDLCs store charge purely electrostatically via adsorption of electrolytic ions at the surface of active materials. Carbon-based nanomaterials with any dimensions can be exploited for EDLCs to deliver good performance, provided that the active materials have a high specific surface area, and pores in the meso and micro ranges. Reduction of materials to the nanoscale reduces the diffusion pathways, enhancing the surface area, providing higher value of specific capacitance. (2) Pseudo-capacitors: they store charge using adsorption, intercalation and redox reactions in the near surface/surface regions. Transition metal oxides (TMOs), including RuO_2 and MnO_2, are the earliest materials suggested for pseudocapacitive charge storage [75]. Despite their potential for greater energy density, their use in commercial applications has been restricted by glitches such as low capacitance and insufficient electronic conductivity- issues that can only be addressed through the intentional design of sophisticated nanostructures [76]. State of the art materials used in supercapacitors are conducting polymers, transition metal dichalcogenides (TMDs), MXenes, perovskite oxides, metal organic framework (MOF) derivatives, and heteroatom-doped carbon materials.

5.1.3. Solar cells

Nanostructures offer unique blend of optical and/or electrical properties, resulting in enhanced optical absorption and efficient electron transfer in solar cells. While selecting materials for solar cells construction, one must consider these principles: (1) optical absorption should be maximized, and to do so, materials having narrow and direct band gaps are chosen; (2) materials should have well-matched energy levels to ensure favorable energy gradient, facilitating efficient charge transfer within the solar cell device. Due to provisions of high electron mobility, wide bandgap, and chemical stability, metal oxides, including tin oxide (SnO_2), zinc oxide (ZnO), and titanium oxide (TiO_2), have been vastly exploited in solar cells. By nanoengineering of active materials, better surface area, enhanced light absorption, and interfacial contacts can be ensured [64]. These materials have been engineered to be explored in electron transport layers in different classes of solar cells, such as dye-sensitized, perovskite and organic solar cells [77]. For instance, incorporating carbon nanomaterial components with working photoanodes has been proven effective to enhance the overall device performance. Lately, 2D nanomaterials such as graphene, TMDs, and MXenes with thin structures, large surface area and improved light-harvesting capabilities have been preferred over traditional materials [78]. 2D nanomaterials have higher surface to volume ratio, unique electronic features and better absorption in the visible and near-infrared (IR) region. Incorporation of graphene offers flexibility to devices, and owing to higher charge carrier mobility (15000 cm^2/Vs) in graphene than traditional Si-based solar cells (~1500 cm^2/Vs), results in efficacious charge transport [79, 80]. Other advantageous feature of TMDs is their tunable band gap (1-2 eV), unlike the fixed band gap of Si-based solar cells, allowing for optimization of spectrum regions [81].

5.2. Biomedical applications

5.2.1. Drug delivery

Nanomaterials have revolutionised biomedical science by facilitating precise influence over biological interactions at the molecular and cellular levels. In drug delivery, therapeutic compounds can now be administered in a targeted and regulated way through the use of nanocarriers such as liposomes, layered double hydroxides, polymeric nanoparticles, and inorganic nanostructures like mesoporous silicon dioxide and gold nanoparticles [82]. These systems take advantage of size, surface charge, and surface functionalization (e.g., PEGylation, ligand conjugation) to enhance bioavailability, extended circulation time, and especially accumulate at pathological locations through passive (e.g., enhanced permeability and retention effect) or active targeting mechanisms [83]. Stimuli-responsive

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nanocarriers further enhance therapeutic specificity and lessen systemic toxicity by releasing cargo in response to changes in pH, redox potential, enzymes, or temperature gradients in sick tissues.

5.2.2. Tissue engineering

Nanomaterials are essential in replicating the nanoscale features of the extracellular matrix (ECM), which encourages cellular adhesion, growth, and division. Nanofibrous scaffolds generated using electrospinning methods, 3D bioprinting, or via self-assembly synthesis can mimic the fibrous structure of natural ECM, helping the regeneration of skin, bone, cartilage, and neural tissues [84]. Bioactive nanoparticles, like graphene oxide for nerve regeneration or hydroxyapatite for bone tissue, improve mechanical integrity and offer biochemical signals that control cell fate [83]. Furthermore, smart nanomaterials capable of enhancing growth factors or exhibiting mechanical adaptability are being developed to dynamically interact with evolving tissue environments.

5.2.3. Bioimaging

Nanomaterials facilitate multimodal imaging on manifold platforms while enhancing contrast. For multiplexed labelling and long-term cellular imaging, quantum dots enable stable, controllable fluorescence with broad excitation frequencies and narrow emission spectra. While gold (Au) and bismuth (Bi)-based nanoparticles are under investigation for computed tomography (CT) due to their high X-ray attenuation, superparamagnetic iron oxide nanoparticles (SPIONs) serve as efficient contrast agents in magnetic resonance imaging (MRI) [85]. Furthermore, hybrid nanomaterials are being developed for combination imaging modalities, such as PET/CT or MRI/optical, which enable real-time monitoring of therapy and disease progression. Surface modification methods make it possible to focus these imaging agents to particular tissues or molecular markers, greatly improving the accuracy of diagnosis.

5.2.4. Biotechnology

Protein purification, genetic modification, and high-throughput, ultrasensitive biomolecular detection are all rendered feasible with nanomaterials in biotechnology. Magnetic nanoparticles functionalized with specific ligands enable the selective isolation of nucleic acids, proteins, and cells, offering rapid processing and high purity of entities. In gene editing, nanoparticle-based delivery systems are being developed to deliver CRISPR-Cas enzymes with high efficiency and little off-target effects, overpowering limitations linked with viral vectors [86]. Additionally, biosensors and lab-on-a-chip platforms with enhanced sensitivity and specificity are engineered using nanoporous membranes and nanostructured surfaces, enabling quick molecular analysis and diagnostics.

All these potential applications highlight how groundbreaking nanomaterials could prove in solving challenging biomedical issues. Their multifunctionality, versatility, and biocompatibility make them excellent choices for integrated therapeutic and diagnostic systems in modern precision medicine.

5.3. Environmental applications

Environmental remediation technologies are becoming more and more dependent on nanomaterials. A fundamental change towards smarter, compact, and cost-effective environmental solutions appears in their adaptability across pollutant tracking, air purification, and water treatment systems. The incorporation of nanotechnology into environmental applications holds great promise for accomplishing sustainable development goals and protecting human and ecological health, as long as research continues to solve existing constraints and regulatory frameworks change.

5.3.1. Water purification

Application of nanomaterials across water filtration, air purification, and pollutant sensing echoes a transformative shift in the strategies employed to manage ecological pollutants with greater efficacy, precision, and sustainability. Various nanomaterials, such as metal oxides (such as TiO_2, ZnO, and Fe_2O_3) [87, 88], carbon nanostructures (such as graphene oxide and carbon nanotubes (CNTs) [89], and zero-valent metals (particularly nanoscale Fe) [90], have demonstrated exceptional proficiency in the removal of contaminants such as lead, arsenic, and mercury; organic micropollutants like pesticides and pharmaceuticals; and microbial pathogens in the water treatment process. The creation of multifunctional filtering systems that combine adsorption, photocatalysis, and disinfection is made possible by the strong reactivity and specific binding capabilities of nanomaterials. Silver (Ag) nanoparticles, for instance, exhibit antibacterial activity because of their capacity to produce

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reactive oxygen species and damage microbial membranes, which qualifies them for use in water disinfection technologies. Furthermore, in comparison to traditional filtration technologies, hybrid nanocomposite membranes that include nanoparticles into polymer matrices show promise for improved permeability and mechanical resilience.

5.3.2. Air filtration

For air purification, nanomaterials remove pollutants via adsorption, catalytic degradation, and photoactivation mechanisms. TiO_2 is well-known photocatalyst, and decomposes airborne pollutants such as nitrogen oxides, Sulphur oxides, and volatile organic compounds (VOCs) when activated under ultraviolet or visible light. Non-metal doped TiO_2 or linking it with other semiconductor materials increases its photo-response, improving its overall efficiency under solar irradiation [91]. Additionally, nanostructured activated carbon and MOFs materials exhibit are particularly advantageous for adsorbing low-concentration gaseous pollutants and toxic industrial emissions due to their high surface area. Using functionalized CNTs and graphene-based materials in air filtration systems improves the physical trapping of fine particulate matter (PM2.5 and PM10) and catalytically oxidizes hurtful gases [92]. Moreover, catalytic converters having platinum group metal NPs facilitate the conversion of carbon monoxide, hydrocarbons, and nitrogen oxide into less harmful substances, thus contributing to vehicular emission control and indoor air quality management.

5.3.3. Sensors

In real time, nano sensors can detect levels of pollutants in the environment by using the sensitivity and selectivity of nanomaterials. Nanoparticles can interact selectively with target analytes to produce observable electrical, optical, or electrochemical signals because of their large surface area and tunable surface chemistry. For example, localized surface plasmon resonance is shown by gold and silver nanoparticles, which can be used to optically detect organic contaminants, insecticides, and heavy metals. Because of their size-tunable fluorescence and photostability, semiconductor quantum dots provide excellent optical probes for sensor arrays and environmental imaging. Furthermore, because of their high conductivity and faster electron transfer kinetics, graphene and carbon nanotubes (CNTs) are widely utilized in electrochemical sensors to identify pollutants such as lead, bisphenol A, and polycyclic aromatic hydrocarbons in soil and water samples [93]. Incorporation of these sensors into wireless and portable devices has improved environmental monitoring responsiveness and accessibility, enabled early warning systems and aided in the making of well-informed choices about pollution control and legal compliance. Figure 11 shows the applications of nanomaterials.

5.4. Electronics and photonics

5.4.1. Flexible electronics

The fields of electronics and photonics have been revolutionized by nanomaterials because they offer unparalleled control over mechanical, optical, and electrical properties at the nanoscale. Combining them into gadget designs has improved multifunctionality, performance, and compactness. Materials including metal oxide, Ag nanowires, graphene, and carbon nanotubes have emerged as key elements for flexible electronics systems [94]. Their beneficial qualities, which include strong electrical conductivity, mechanical durability, and transparency, enable the creation of thin, light films. For new technologies like foldable smartphones, wearable fitness trackers, and electronic skin (e-skin), these characteristics are essential. Elastomeric/polymeric substrates and nanomaterial hybrid composites further increase mechanical robustness without sacrificing charge mobility, allowing circuits and sensors to operate dependably under dynamic and recurrent strain scenarios.

5.4.2. Transistors

Field-effect transistors (FETs) in post-CMOS logic and memory applications depend on intrinsic advantages such as high carrier mobility, tunable bandgaps, and excellent electrostatic control at the nanoscale that are provided by semiconducting carbon nanotubes and atomically thin materials like transition metal dichalcogenides (e.g., MoS_2, WS_2) [95]. These materials enable the creation of ultra-scaled transistors with high switching speeds and low power consumption by supporting channel lengths smaller than 10 nm. Nanomaterial integration has also helped new device topologies, such as vertical transistors, tunnelling FETs, and neuromorphic devices, by utilizing their electrical diversity to improve performance above and beyond what bulk semiconductors can do. Furthermore, recent efforts to pattern nanomaterials with sub-10 nm resolution with bottom-up approaches or advanced lithography have aided accurate control over device geometry and placement, which is vital for scalability and reproducibility in large-area electronics.

5.4.3. Displays and lighting

Nanomaterials have made significant advancements in colour quality, resolution, and energy efficiency possible in the realm of display technology. Quantum dots (QDs), especially those made of perovskite nanocrystals, indium phosphide, or cadmium selenide, provide narrow bandwidth photoluminescence with high quantum yields by providing tunable emission wavelengths that are dependent on particle size [96]. Superior contrast and brightness control can be achieved by integrating QDs into backlight units or emissive layers in quantum dot light-emitting diode (QLEDs) displays; new formulations now provide cadmium-free and ecologically friendly substitutes. Apart from QDs, brittle indium tin oxide (ITO) electrodes in flexible displays have been replaced by nanostructured transparent conductive films based on silver nanowires or doped graphene, which improve mechanical durability without compromising optical transparency [97]. These advancements are pivotal in the commercialization of foldable smartphones and tablets, and other next-generation display formats.

The development of transparent and stretchable LEDs, which are essential for applications in augmented and mixed reality systems, conformal biomedical sensors, and human–machine interfaces, has been made possible by the flexibility and functionality of nanomaterials, which go beyond conventional display and lighting functions. For example, light can be generated by embedded nano emitters in polymeric matrices when they are stretched or flexed, allowing for direct integration into smart fabrics and wearable technology. Furthermore, the potential of nanophotonic structures made of plasmonic or dielectric nanomaterials, such as metasurfaces and photonic crystals, to control light at subwavelength scales is being studied. These structures offer new capabilities in holographic displays, beam shaping, and polarization control.

6. Conclusion

Nanomaterials hold immense promise across a spectrum of applications due to their unique size-dependent properties. From energy storage to medicine and environmental protection, they are key enablers of next-generation technologies. However, to fully realize their potential, future work must address toxicity, scalability, and environmental concerns. With advances in synthesis and computational tools, the future of nanomaterials looks exceptionally bright.

Author contributions

Khushbu Sharma was responsible for conceiving the idea and structure of the review article. She prepared the overall outline, conducted an in-depth analysis of the fundamental concepts, and authored the sections covering the introduction, classification of nanomaterials, and various synthesis techniques. She also contributed to the coordination of the manuscript development and ensured thematic consistency throughout the article.

Yogita Dahiya performed a comprehensive literature survey related to the applications of nanomaterials in advanced technologies. She compiled and critically analyzed recent advancements in the field and authored the application-focused sections of the manuscript, including environmental, energy, and biomedical applications. She also contributed to the refinement of content and language.

Takayuki Ichikawa served as the supervising author and provided expert guidance throughout the development of the manuscript.

All authors contributed to the final revision and approved the submitted version of the manuscript.

Conflict of interest statement

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Author information

Corresponding author: Khushbu Sharma*

E-mail: khushbu@hiroshima-u.ac.jp

ORCID iD: 0009-0004-4733-3870

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