Ilam University of Medical Sciences

Plant Biotechnology Persa

Online ISSN: 2676-7414

Homepage: https://pbp.medilam.ac.ir

Recent Advancement of Nanomaterials: Properties, Fabrication, and Applications

Mustapha Isah [1]✉

[1]Department of Biosciences, Faculty of Science, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia

Article Info

Article type:
Review Article

Article History:
Received: Mar. 02, 2025
Revised: May. 20, 2025
Accepted: May. 22, 2025
Published Online: July. 27, 2025

✉ ***Correspondence to:***
Mustapha Isah

Email:
imustapha@graduate.utm.my

ABSTRACT

Nanotechnology has revolutionized materials science, enabling the development of nanoparticles, nanocomposites and nanomaterials with superior mechanical, electrical, optical and thermal properties for applications in medicine, electronics, energy and environmental sustainability. The data were taken from recent publications available via Scopus, Web of Science and Google Scholar. This review examines their classification, synthesis methods, key properties and applications and highlights the role of metal, metal oxide, carbon-based, polymeric and quantum dot nanoparticles in biomedicine, catalysis and nanoelectronics. Synthesis techniques are categorized into top-down (ball milling, lithography, laser ablation) and bottom-up approaches (sol-gel, chemical vapor deposition, biological synthesis), each offering unique advantages in terms of scalability and precision. Nanocomposites, including polymer-based, metal-based and ceramic-based types, incorporate nanofillers to improve mechanical strength, thermal stability and electrical conductivity, using fabrication methods such as in-situ polymerization. Functionalization further expands their applications in drug delivery, flexible electronics, and advanced coatings. However, challenges related to toxicity, environmental impact, scalability, and regulations persist, necessitating sustainable synthesis, AI-driven material design, and stringent ethical standards. Addressing these issues is key to unlocking nanotechnology's full potential for next-generation industrial and scientific advancements.

Keywords: Nanoparticles, Nanocomposites, Nanomaterials, Fabrication Methods, Applications

➢ **How to cite this paper**

Mustapha Isah. Recent Advancement of Nanomaterials: Properties, Fabrication, and Applications. Plant Biotechnology Persa 2025; 7(3): 148-163.

[DOI: 10.61186/pbp.7.3.148]

DOI: 10.61186/pbp.7.3.148

Publisher: Ilam University of Medical Sciences

Introduction

Nanotechnology, defined as the scientific discipline focused on the manipulation of matter at the atomic and molecular scale, has emerged as a transformative domain possessing significant ramifications across diverse sectors. Through the precise alteration of materials at the nanoscale (1-100 nm), scholars have identified distinctive physical, chemical, and mechanical characteristics that are not present in their bulk counterparts [1]. These advancements have precipitated ground-breaking innovations in the realms of medicine, electronics, energy, and environmental science, thereby facilitating the creation of highly effective sensors, targeted drug delivery mechanisms, and advanced energy storage systems [2]. The capacity to customize material attributes at such a diminutive scale has rendered nanotechnology a pivotal catalyst for innovation in the 21st century [3].

At the heart of nanotechnology are nanoparticles, nanocomposites and nanomaterials, all of which play a crucial role in the advancement of materials science. Nanoparticles are ultrafine materials with at least one dimension less than 100 nm that exhibit remarkable optical, electrical and catalytic properties due to their large surface-to-volume ratio and quantum effects [4]. Nanocomposites contain nanoparticles in a main matrix, such as polymers, metals or ceramics, and improve mechanical strength, thermal stability and conductivity [5]. Meanwhile, nanomaterials comprising zero-dimensional (0D), one-dimensional (1D) and two-dimensional (2D) structures have enabled breakthrough applications in biomedical engineering, nanoelectronics and environmental remediation [6, 7].

Given the increasing importance of these materials, this review aims to provide a comprehensive analysis of their classification, synthesis methods and functional properties. The discussion covers their diverse applications in areas such as health, energy, electronics and industry, and shows how nanotechnology is reshaping modern science and technology. It also highlights existing challenges in the field, including concerns about toxicity, scalability and regulatory hurdles that need to be addressed for widespread commercialization [8, 9].

The review article is structured to provide a comprehensive understanding of the nanoengineered materials by describing the classification and properties of nanoparticles, nanocomposites and nanomaterials, followed by an overview of their manufacturing techniques. Moreover, discusses their diverse applications in various industries, highlighting their advantages over conventional materials. Finally, the article discusses the challenges that stand in the way of large-scale implementation and the future directions of nanotechnology research, providing insights into its enormous potential for shaping the future of materials science.

Nanoparticles: Types, Synthesis, and Properties

Types of Nanoparticles

Metal and Metal Oxide Nanoparticles

Metal and metal oxide nanoparticles exhibit distinct optical, electrical, and catalytic characteristics that render them exceedingly valuable in the domains of medicine, electronics, and environmental science. The utilization of gold and silver nanoparticles is prevalent in applications such as drug delivery, imaging [10], and the formulation of antimicrobial coatings [11], while iron oxide nanoparticles facilitate advancements in magnetic resonance imaging (MRI) and targeted therapeutic drug administration [12]. Metal oxides, including titanium dioxide (TiO_2) and zinc oxide (ZnO), are integral to processes such as photocatalysis, the development of UV-blocking sunscreens [13], and the degradation of pollutants [14], thereby enhancing energy efficiency and promoting environmental sustainability [15].

Carbon-Based Nanoparticles (Fullerenes, Graphene, CNTs)

Carbon-based nanoparticles, encompassing fullerenes, graphene, and carbon nanotubes (CNTs), exhibit remarkable mechanical robustness, exceptional electrical conductivity, and significant thermal stability, which render them highly suitable for applications in nanoelectronics, energy storage, and biomedicine. Graphene, characterized as a monolayer of carbon atoms, is extensively

[DOI: 10.61186/pbp.7.3.148]

employed in flexible electronic devices, sensing technologies, and high-performance composites owing to its expansive surface area and unparalleled conductivity [16, 17]. CNTs, recognized for their superior tensile strength and conductivity, find applications in structural materials, transistors, and drug delivery mechanisms, thereby substantially enhancing performance across diverse industrial sectors [18].

Polymeric Nanoparticles

Polymeric nanoparticles composed of biodegradable polymers, including polylactic acid (PLA), polycaprolactone (PCL), and chitosan, are extensively employed in the fields of biomedicine, drug delivery, and tissue engineering. These nanoparticles facilitate the controlled release of therapeutics, enhance biocompatibility, and enable targeted delivery [19], thereby mitigating adverse effects and augmenting therapeutic efficacy [20]. Their applicability is further diversified to encompass gene therapy, vaccine delivery systems, and cosmetic formulations, providing safer and more effective alternatives to traditional drug carriers [21].

Quantum Dots

Quantum dots (QDs) are semiconductor nanoparticles that exhibit size-dependent optical and electronic properties, making them invaluable for bioimaging, optoelectronics and quantum computing [22]. Their high fluorescence efficiency and tuneable emission spectra improve the performance of LEDs, solar cells and medical diagnostics [23]. QDs are particularly important for cancer detection and biosensors as they offer highly sensitive and precise imaging capabilities [24]. However, concerns over toxicity and environmental impact, particularly with cadmium-based QDs, have driven research towards biodegradable and less toxic alternatives [25].

Synthesis Methods of Nanoparticles

The synthesis of nanoparticles can be roughly divided into top-down and bottom-up approaches. In top-down methods, bulk materials are broken down into nano-sized particles by mechanical or lithographic techniques, while bottom-up approaches focus on the assembly of nanoparticles from atomic or molecular starting materials by chemical reactions or deposition processes [1, 26]. The choice of synthesis method has a significant impact on the size, shape and surface properties of the nanoparticles, which in turn determine their applications [27].

Top-Down Approaches

In top-down methodologies, bulk materials are meticulously diminished to the nanoscale through the application of various physical techniques, including mechanical milling, thermal ablation, or lithographic structuring. Mechanical techniques, exemplified by ball milling, entail a series of repetitive collisions that fragment bulk materials into nanoparticles; however, excessive mechanical stress may induce surface imperfections, irregular morphologies, and a wide distribution of particle sizes [28]. Thermal methodologies, encompassing laser ablation and sputtering, employ high-energy beams to vaporize and subsequently condense materials into nanoscale architectures [29]. These techniques provide a high degree of compositional control but frequently necessitate substantial energy input. Lithographic techniques, such as electron beam lithography and photolithography, facilitate the fabrication of precisely defined nanostructures with regulated patterns; nevertheless, they are often constrained by scalability [30] and associated high costs [31]. Notwithstanding their capacity to yield well-defined structures, top-down approaches frequently result in surface defects, structural inconsistencies, and uncontrolled variations in size, which may adversely affect the properties and performance of nanoparticles in various applications [28].

Ball Milling

In this mechanical technique, known as ball milling, the grinding balls repeatedly impact the bulk material with high energy and gradually crush it into nanoscale particles. The process is usually carried out in a rotating cylindrical chamber in which metal

[DOI: 10.61186/pbp.7.3.148]

or ceramic balls impact the material with sufficient force to cause breakage, resulting in the formation of nanoparticles. Ball milling is widely used for the synthesis of metal and ceramic nanoparticles due to its cost-effectiveness, scalability and simplicity, making it suitable for large-scale production [32]. In addition, this method can be adapted for both wet and dry milling and allows the addition of solvents or surfactants to modify the morphology of the particles and reduce agglomeration [33]. However, despite its advantages, ball milling offers only limited control over particle size distribution, as the nanoparticles produced often exhibit large size differences and irregular shapes. In addition, the intense mechanical stress may introduce structural defects, contamination from the milling, and unwanted oxidation of reactive metals, which can alter the structural properties of the synthesized nanoparticles [28].

Lithography

Lithographic patterning is an important technique in semiconductor manufacturing and the production of nanodevices, in which high-precision structures are created on a nanoscale by etching patterns [34]. A designed pattern is transferred to a substrate using electron beam lithography (EBL) or photolithography, followed by etching or deposition processes. EBL uses a focussed electron beam to create patterns with a resolution of less than 10 nm. It offers exceptional precision but is slow and costly, making it unsuitable for mass production [35]. Photolithography, which exposes UV light through a patterned mask, is widely used in integrated circuit manufacturing and offers higher throughput, but is limited by light diffraction, which restricts the minimum size of patterns [36]. Although these methods allow precise and reproducible nanostructuring, they are still expensive and time consuming and require sophisticated equipment [37]. To overcome these limitations, new techniques such as nanoimprint lithography (NIL) and soft lithography are currently being developed for the cost-effective production of high-throughput nanostructures [38].

Laser Ablation

Laser ablation represents a highly effective top-down methodology for the generation of nanoparticles, wherein a high-energy laser beam is utilized to irradiate and vaporize a bulk material within a controlled environment, such as a vacuum or a liquid medium. The application of intense laser pulses induces localized thermal effects that result in the rapid vaporization or plasma generation of the target material, subsequently leading to the condensation of nanoparticles. This method is particularly beneficial for the fabrication of high-purity metal and metal oxide nanoparticles, as it obviates the need for chemical precursors, thereby diminishing the likelihood of contamination [39]. Furthermore, laser ablation facilitates precise manipulation of the size and composition of the nanoparticles by varying laser parameters, including wavelength, pulse duration, and energy intensity [39]. Owing to the superior quality of the nanoparticles produced through this technique, it is frequently employed in fields such as catalysis, biomedicine, and advanced coatings [[40]. However, this method requires specialized laser systems, precise control of experimental conditions and significant energy input, making it costly and complex compared to conventional chemical synthesis techniques [41]. Despite these challenges, ongoing research in pulse shaping, laser fluence optimization, and multi-pulse ablation strategies continues to improve the scalability and efficiency of this method for large-scale nanoparticle production [42].

Bottom-Up Approaches

In bottom-up approaches, nanoparticles are synthesized by assembling atoms or molecules through chemical, biological or physical processes, allowing precise control over size, shape and composition. These methods, including sol-gel synthesis, chemical vapor deposition (CVD) [43] and biological synthesis [44], enable the production of highly uniform nanoparticles with tailored properties that are ideal for high-performance applications in medicine, electronics and catalysis. Chemical methods such as precipitation and hydrothermal synthesis enable fine-tuned nanoparticle engineering, while biological

[DOI: 10.61186/pbp.7.3.148]

approaches using microorganisms or plant extracts offer environmentally friendly alternatives [45]. Physical techniques such as vapor deposition ensure high purity and structural integrity. The ability to precisely design nanoparticles at the atomic level makes bottom-up synthesis particularly valuable for drug delivery, nanoelectronics and energy storage, where uniformity and functionality are essential [46].

Sol-Gel Process

The sol-gel technique represents a prevalent wet-chemical synthesis methodology in which metallic precursors, commonly metal alkoxides or metal salts, undergo hydrolysis and subsequent condensation reactions to establish a three-dimensional gel network within a liquid medium. This gel is characterized by a porous architecture that encompasses solvent molecules. Following this, the gel undergoes drying and calcination processes to eliminate residual solvent and organic constituents, culminating in the formation of nanoparticles with meticulously controlled composition, morphology, and exceptional purity. The sol-gel technique is particularly beneficial for the synthesis of metal oxide nanoparticles as it facilitates precise regulation of particle dimensions, geometrical configurations, and surface characteristics by modulating reaction parameters such as pH, temperature, and precursor concentration. Owing to its adaptability, this methodology is extensively employed in coatings, catalysis, and biomedical applications where the demand for high purity and uniform nanoparticles is critical for enhanced performance. In addition, nanomaterials derived from sol-gel are often used for optical coatings, drug delivery systems and large surface area catalysts due to their adjustable porosity and flexible composition [47].

Chemical Vapor Deposition (CVD)

Chemical vapor deposition (CVD) represents a vapor-phase synthesis methodology wherein gaseous reactants (precursors) engage in chemical reactions upon a thermally activated substrate, leading to the generation of nanoparticles, thin films, or nanostructures with meticulous regulation of thickness, composition, and crystallinity. This technique is frequently employed in the production of carbon-based nanomaterials, including carbon nanotubes (CNTs), graphene, and diamond-like coatings, in addition to semiconductor nanomaterials such as silicon and gallium nitride, which are pivotal for applications in nanoelectronics, photovoltaics, and sensor technology. CVD is characterized by its high purity, remarkable uniformity, and scalability, rendering it particularly suitable for industrial applications [48]. Nevertheless, it necessitates stringent control over reaction parameters including temperature, pressure, and gas flow to ensure the reliable formation of nanostructures while minimizing defects and undesired by-products [49]. Variants such as plasma-enhanced CVD (PECVD) and metal-organic CVD (MOCVD) further enhance process efficiency and facilitate the synthesis of composite materials [50].

Biological Synthesis

Biological synthesis, often referred to as green synthesis, uses microorganisms, plant extracts or enzymes to produce nanoparticles in a sustainable and environmentally friendly way. In this method, biological agents act as reducing and stabilising units that convert metal precursors into nanoparticles under mild conditions, eliminating the need for hazardous chemicals [51]. The process of microbial synthesis involves the participation of bacteria, fungi or algae, which can facilitate the formation of nanoparticles via enzymatic or metabolic pathways [52], while plant synthesis uses phytochemicals such as flavonoids and polyphenols for the reduction and stabilization of nanoparticles [53]. This innovative method is attracting considerable attention in the fields of biomedicine, the environment and catalysis due to its biocompatibility, cost-effectiveness and low environmental impact [54]. In addition, biologically synthesised nanoparticles have special surface properties that make them particularly suitable for applications such as drug delivery, antibacterial agents, biosensors and water purification systems [55]. Despite these advantages, obstacles such as

[DOI: 10.61186/pbp.7.3.148]

scalability, consistent yield and process optimization need to be overcome to drive large-scale applications [56].

Key Properties of Nanoparticles

Optical, Electrical, Mechanical, and Magnetic Properties

Nanoparticles display distinctive optical, electrical, mechanical, and magnetic characteristics attributable to their quantum phenomena and elevated surface-to-volume ratios. Their optical characteristics are contingent upon size, facilitating applications in bioimaging, sensor technology, and display systems [57]. The electrical attributes of materials such as graphene and carbon nanotubes are significantly enhanced, rendering them indispensable for nanoelectronics, transistors, and conductive coatings [58]. Mechanical characteristics such as exceptional strength and elasticity are evident in nanocomposites, fostering advancements in lightweight structural materials and abrasion-resistant coatings [59]. Magnetic nanoparticles, including iron oxide, demonstrate superparamagnetic behaviour, rendering them optimal for use as MRI contrast agents, in targeted drug delivery, and in magnetic data storage [60].

Surface Chemistry and Functionalization

The high surface energy of nanoparticles makes their surface chemistry and functionalization crucial for stability, dispersion and reactivity in various applications [61]. Functionalization involves modifying the surface of nanoparticles with polymers, ligands or biomolecules to improve biocompatibility, solubility and targeting [62]. For example, functionalized gold nanoparticles improve targeted drug delivery and biosensing, while silica-coated nanoparticles increase stability in aqueous solutions [63]. In addition, surface modifications play a crucial role in preventing agglomeration, tuning optical properties and improving catalytic efficiency [64], enabling their integration into nanomedicine [65], energy storage and environmental remediation [18].

Table 1: An Overview of Recent Advancements in Nanoparticle Researches and Applications

Name of Nanoparticle	Type of Nanoparticle	Method of Synthesis	Application	Reference
Gold Nanoparticles (AuNPs	Metal-based	Biological	Cancer imaging and therapy	[66]
Bismuth-based Nanoparticles	Metal-based	Chemical	Diverse applications in materials science	[67]
Selenium Nanoparticles	Metal-based	Biological	Sustainable development applications	[54]
Bimetallic Nanoparticles	Metal-based	Biological	Sustainable development applications	[68]
Organic Nanoparticles	Carbon-based	Chemical	Optoelectronic devices	[69]

[DOI: 10.61186/pbp.7.3.148]

Nanocomposites: Classification, Fabrication, and Properties

Nanocomposites are multiphase materials that incorporate nanoscale reinforcements (nanoparticles, nanotubes or nanofibers) into a matrix material, resulting in improved mechanical, thermal, electrical and barrier properties compared to conventional composites [70]. These materials take advantage of the unique properties of nanofillers to develop lightweight, high-performance materials for various applications, such as automotive, aerospace [71], electronics, biomedical devices and structural materials [72].

Classification of Nanocomposites

Nanocomposites are classified according to their matrix material into polymer-based, metal-based and ceramic-based nanocomposites. Polymer-based nanocomposites reinforced with carbon nanotubes, graphene or nanosheets improve mechanical strength, thermal stability and barrier properties [73], making them suitable for packaging, coatings and electronics [74]. Metal nanocomposites, which consist of metal matrices interspersed with nanoparticles such as ceramics or carbon nanostructures, exhibit improved conductivity, strength and wear resistance [75] and are widely used in aerospace, automotive and structural applications [76]. Ceramic nanocomposites containing metal or oxide nanoparticles offer high temperature stability, corrosion resistance and improved toughness [77], making them ideal for energy storage, catalysis and biomedical implants [78].

Fabrication Techniques

Nanocomposites are produced using techniques that ensure uniform dispersion of the nanoparticles and strong interfacial bonding. In situ polymerization, nanoparticles are integrated into a polymer matrix during polymerization, resulting in improved adhesion and mechanical properties[79]. The sol-gel process, commonly used for ceramic and metallic nanocomposites, involves solution phase reactions that form a gel and provides precise control over the distribution of nanoparticles [80]. Melt blending, a scalable and cost-effective method, disperses nanofillers into molten polymers by shear blending, making it widely used in industrial plastic and composite manufacturing [81].

Key Properties and Enhancements

Nanocomposites exhibit higher mechanical strength, thermal stability, electrical conductivity and barrier properties [82] due to the strong interactions between nanoparticles and matrix [83]. Tensile strength, impact strength and wear resistance are significantly improved by the incorporation of nanofillers, making them suitable for high-performance structural applications [84]. Their thermal stability improves fire resistance and heat dissipation, which is essential for applications in the automotive and aerospace industries [85]. In addition, electrically conductive nanocomposites, such as graphene-polymer hybrids, are crucial for flexible electronics, energy storage and EMI shielding [86]. These improved properties make nanocomposites next-generation materials for advanced technological applications. The Table 2 below, highlight some fabricated nanoparticles and their relative applications.

[DOI: 10.61186/pbp.7.3.148]

Table 2: An Overview of Various Nanocomposites, Their Classifications, Fabrication Methods, and Applications

Name of Nanocomposite	Fabrication Method	Application	Reference
Polymer–Metal Nanocomposite Films	Various advanced fabrication techniques	Energy and electronic applications	[87]
High-Performance Polymer Nanocomposites	Incorporation of nanomaterials into polymers	Automotive, aerospace, marine, and construction industries	[88]
High-Performance Polymer Nanocomposites	Incorporation of nanomaterials into polymers	Automotive, aerospace, marine, and construction industries	[89]
Polyimide–Nickel Nanocomposites	Various fabrication techniques	Nanoelectronics, catalysis, hydrogen storage	[90]
Silica/Polymer Nanocomposites	Surface modification and functionalization	Automotive, aerospace, marine, and construction industries	[91]

Nanomaterials: Advances and Functionalization

Classification of Nanomaterials

Nanomaterials are systematically classified according to their dimensional characteristics, which profoundly affect their inherent properties and potential applications. Zero-dimensional (0D) nanomaterials encompass nanoparticles and quantum dots, wherein all spatial dimensions are restricted to the nanoscale, thereby demonstrating distinctive optical and electronic characteristics attributable to quantum confinement phenomena [92]. One-dimensional (1D) nanomaterials, including nanotubes, nanorods, and nanowires, possess a significant aspect ratio, rendering them particularly suitable for applications in nanoelectronics, energy storage, and biomedicine [93]. Two-dimensional (2D) nanomaterials, such as graphene, MXenes, and transition metal dichalcogenides (TMDs), manifest extraordinary electronic, thermal, and mechanical properties that have facilitated advancements in flexible electronics, sensing technologies, and catalytic processes [94]. These classifications establish a foundation for the innovation of novel nanomaterials possessing customized functionalities for a diverse array of technological applications.

Functionalization and Surface Modifications

The functionalization of nanomaterials is of paramount importance in enhancing their stability, dispersibility, and biocompatibility, thereby facilitating their effective application in targeted domains. The modification of surfaces can be accomplished through chemical functionalization, which may involve covalent or non-covalent interactions, the application of polymer coatings, or ligand exchange methodologies, thereby optimizing the interactions of nanomaterials with biological or environmental systems [95]. For instance, the process of PEGylation, which involves the attachment of polyethylene glycol to nanoparticles,

[DOI: 10.61186/pbp.7.3.148]

significantly enhances their biocompatibility and prolongs their circulation time in drug delivery applications, whereas the modification of metal oxide nanoparticle surfaces with silane or thiol groups markedly improves their catalytic and sensory functionalities [96, 97]. Furthermore, techniques such as doping, the creation of heterostructures, and hybridization serve to expand the functional capabilities of nanomaterials, thereby opening avenues for advancements in the fields of medicine, energy storage, and environmental remediation [98].

Challenges in Large-Scale Production and Stability

Despite remarkable progress in the synthesis and functionalization of nanomaterials, large-scale production remains a major challenge due to high manufacturing costs, reproducibility issues and environmental concerns [99]. Bottom-up approaches such as chemical vapour deposition (CVD) and sol-gel synthesis often require precise control of reaction conditions, making scalability difficult [80]. Top-down methods such as ball milling and lithography reach their limits in producing uniform nanomaterials with controlled properties [100]. In addition, the long-term stability of nanomaterials is an issue, as aggregation, oxidation and degradation can lead to loss of functionality over time [101]. Overcoming these challenges requires environmentally friendly synthesis methods, advanced manufacturing techniques and improved stabilization strategies to ensure safe and cost-effective commercialization of nanomaterials for various industries.

Applications of Nanoparticles, Nanocomposites, and Nanomaterials

Applications of Nanoparticles

Nanoparticles have revolutionized various industries due to their unique optical, electrical, catalytic and antimicrobial properties. In biomedicine, gold and silver nanoparticles are used for drug delivery, imaging and cancer therapy, while iron oxide nanoparticles enable targeted drug delivery and contrast enhancement in magnetic resonance imaging (MRI) [102]. In electronics, semiconductor nanoparticles improve the performance of solar cells, transistors and quantum dot displays [103]. Catalysis and environmental remediation also benefit from metal oxide nanoparticles, which improve pollutant degradation, water purification and hydrogen production [104]. In addition, nanoparticles are widely used in food packaging, coatings and antibacterial textiles, utilizing their antimicrobial and barrier-enhancing properties to improve product durability and safety [105].

Applications of Nanocomposites

Nanocomposites offer improved mechanical strength, thermal stability and conductivity, making them invaluable in various industries. In aerospace and automotive applications, polymer-based nanocomposites reinforced with carbon nanotubes (CNTs) and nanotubes reduce weight while improving structural integrity and fuel efficiency [106]. Electronics and energy storage benefit from supercapacitors, batteries and nanocomposite-based flexible circuits where graphene and metal oxide nanofillers improve charge storage and thermal management [5]. Biomedical applications include bone scaffolds, prostheses and antibacterial coatings, where hydroxyapatite-based nanocomposites are used for bone regeneration and implant durability [107]. In addition, nanocomposites improve packaging materials, fireproof coatings and electromagnetic interference (EMI) shielding, offering multifunctionality in various industries [108].

Applications of Nanomaterials

Nanomaterials have transformed electronics, medicine, energy and environmental sustainability due to their tuneable properties and high surface-to-volume ratio. In nanoelectronics, 2D materials such as graphene and transition metal dichalcogenides (TMDs) are being integrated into flexible transistors, sensors and next-generation

[DOI: 10.61186/pbp.7.3.148]

semiconductors [109]. In the field of renewable energy, nanomaterials enhance solar cells, hydrogen storage and thermoelectric devices, improving energy efficiency and sustainability [110]. Breakthroughs in biomedicine include nanomaterial-based biosensors, cancer diagnostics and tissue engineering, where biocompatible nanostructures facilitate cell growth and targeted therapies [111]. In addition, nanomaterials play a crucial role in water purification, carbon capture and pollution control, offering advanced solutions to global environmental problems [112]. The Figure 1 below indicates how the publications in the field of nanotechnology specifically nanomaterial and their applications are progressing annually.

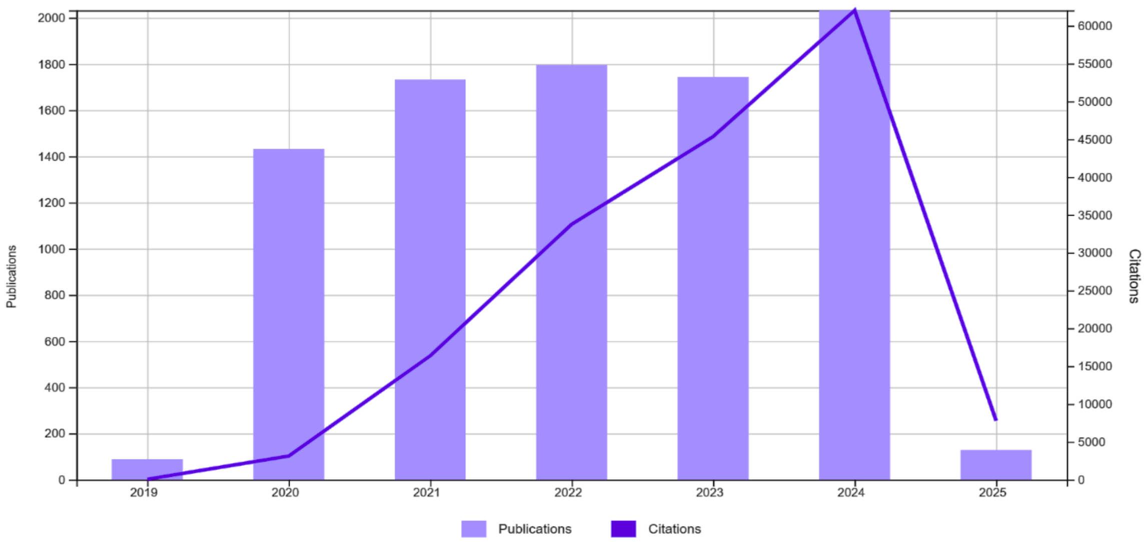

Figure 1. Chart showing the published articles on nanomaterial applications in the past few years from 01-01-2020 to 01-02-2025 with their corresponding citations as obtained from web of science (WOS).

Challenges and Future Perspectives

Toxicity and Environmental Concerns

Despite the remarkable benefits of nanotechnology, concerns about toxicity and environmental impact remain a major challenge. Due to their small size and high reactivity, nanoparticles can accumulate in biological systems, penetrate cell membranes and potentially cause cytotoxic effects, oxidative stress and DNA damage [113]. The long-term effects of exposure to nanoparticles on human health and ecosystems are still not fully understood, requiring extensive research in the field of nanotoxicology and bioaccumulation [114]. In addition, the release of engineered nanomaterials into air, water and soil raises concerns about environmental pollution and unintended ecological consequences [115]. To address these risks, scientists are required to develop biodegradable, environmentally friendly nanomaterials and exploring safer synthesis methods that minimize hazardous by-products.

Scalability and Cost-Effectiveness

One of the greatest challenges in nanotechnology is the scalability and economic feasibility of large-scale production. While lab-scale synthesis methods offer high precision and control, many bottom-up approaches (e.g., sol-gel, chemical vapor deposition) and top-down methods (e.g., lithography, ball milling) are either costly, time-consuming or require sophisticated infrastructure [116]. The lack of uniformity and reproducibility in the synthesis of nanoparticles further complicates commercialization [117]. To overcome these hurdles, researchers are urged in developing scalable, high-throughput manufacturing techniques, such as green synthesis, roll-to-roll processing and 3D printing, that reduce production costs while ensuring consistent quality and efficiency.

[DOI: 10.61186/pbp.7.3.148]

Ethical and Regulatory Aspects of Nanotechnology

As nanotechnology continues to advance, ethical, social and regulatory considerations must be made to ensure responsible development and use. The potential risks of nanomaterials in consumer products, healthcare and environmental applications necessitate rigorous safety assessments, labelling requirements and standardized testing protocols [118, 119]. The lack of globally harmonized regulations poses challenges for the industry seeking regulatory approval for nanoproducts and leads to uncertainties in marketing and public perception [120]. Ethical concerns also arise in areas such as the protection of privacy (e.g., nanosensors in surveillance), the enhancement of human performance (e.g., nano-biointerfaces) and unintended socio-economic inequalities [121]. This underlines the need for transparent policy and public involvement to build trust in nanotechnology.

Future Research Directions and Emerging Trends

The future of nanotechnology lies in multifunctional, intelligent and sustainable nanomaterials that address urgent global challenges. Advances in artificial intelligence (AI) and machine learning are accelerating the design and discovery of nanomaterials and enabling predictive modelling for novel nanostructures with tailored properties [122]. The integration of nanotechnology into personalized medicine, nanorobotics and bioengineered tissues promises a revolution in healthcare [123]. In addition, the development of self-healing nanocomposites, nanoelectronics for quantum computing and nanoscale energy storage systems will drive innovation in next-generation materials and devices [124]. A strong focus on green nanotechnology, circular economy and sustainable production methods will ensure that future advances are both technologically transformative and environmentally sustainable.

Conclusion

Nanotechnology has revolutionized numerous industries by harnessing the unique properties of nanoparticles, nanocomposites and nanomaterials, enabling breakthroughs in medicine, electronics, energy and environmental sustainability. Advances in synthesis methods, functionalization and surface modifications have improved their performance, stability and applicability, but challenges such as toxicity, scalability and regulatory hurdles remain. Despite these concerns, nanotechnology continues to drive innovation in drug delivery, renewable energy, environmental protection and next-generation electronics, offering transformative solutions to global challenges. Future advances will depend on sustainable production, AI-driven material design and responsible action to ensure the safe and ethical development of nanotechnology for broad societal and industrial impact.

Conflict of Interest

Authors have no any conflict

References

1. Kumar S, Kaur A, Gaur J, Singh P, Kaur H, Kaushal S, et al. State-of-the-Art in Co_3O_4 Nanoparticle Synthesis and Applications: Toward a Sustainable Future. ChemistrySelect. 2025;10(6):e202405147.
2. Das HS, Basak A, Maity S. Materials Science and Nanotechnology. In: Innovations in Energy Efficient Construction Through Sustainable Materials. IGI Global; 2025. p. 175–206.
3. Khaleel MM, Alsharif A. Nanotechnology in Materials Engineering Innovations in Construction and Manufacturing. Open Eur J Appl Sci. 2025;:51–64.
4. Kalita M, Baruah S, Deka R, Dutta GK, Barua S. Nanoparticles and Nanofillers. In: Handbook of Nanofillers. Springer; 2025. p. 1–43.
5. Zizhe L, Rauf S, Xu Z, Sagar RUR, Faisal F, Tayyab Z, et al. Advanced Fabrication Techniques for Polymer-Metal Nanocomposite Films: State-of-the-Art Innovations in Energy and Electronic Applications. Chem Sci. 2025;.
6. Dakal TC, Bhushan R, Dhakar R, Kumar A. Classification and Applications of Bio-

[DOI: 10.61186/pbp.7.3.148]

nanomaterials. Bio-Nanomaterials in Environmental Remediation: Industrial Applications. 2025;p. 47–73.
7. Hughes KJ, Ganesan M, Tenchov R, Iyer KA, Ralhan K, Diaz LL, et al. Nanoscience in Action: Unveiling Emerging Trends in Materials and Applications. ACS Omega. 2025;.
8. Kardani SL. Nanocarrier-based formulations: Regulatory Challenges, Ethical and Safety Considerations in Pharmaceuticals. Asian J Pharm. 2024;18(02).
9. Souto EB, Blanco-Llamero C, Krambeck K, Kiran NS, Yashaswini C, Postwala H, et al. Regulatory insights into nanomedicine and gene vaccine innovation: Safety assessment, challenges, and regulatory perspectives. Acta Biomater. 2024;.
10. Asl FD, Mousazadeh M, Taji S, Bahmani A, Khashayar P, Azimzadeh M, et al. Nano drug-delivery systems for management of AIDS: liposomes, dendrimers, gold and silver nanoparticles. Nanomedicine. 2023;18(3):279–302.
11. Balestri A, Cardellini J, Berti D. Gold and silver nanoparticles as tools to combat multidrug-resistant pathogens. Curr Opin Colloid Interface Sci. 2023;66:101710.
12. Qiao R, Fu C, Forgham H, Javed I, Huang X, Zhu J, et al. Magnetic iron oxide nanoparticles for brain imaging and drug delivery. Adv Drug Deliv Rev. 2023;197:114822.
13. Al-Attafi K, Al-Keisy A, Alsherbiny MA, Kim JH. Zn2SnO4 ternary metal oxide for ultraviolet radiation filter application: a comparative study with TiO2 and ZnO. Sci Technol Adv Mater. 2023;24(1):2277678.
14. Gatou M-A, Syrrakou A, Lagopati N, Pavlatou EA. Photocatalytic TiO2-based nanostructures as a promising material for diverse environmental applications: a review. Reactions. 2024;5(1):135–94.
15. Abdullah R, Jalil A, Asmadi M, Hassan N, Bahari M, Alhassan M, et al. Recent advances in zinc oxide-based photoanodes for photoelectrochemical water splitting. Int J Hydrogen Energy. 2024;.
16. Ahmad F, Zahid M, Jamil H, Khan MA, Atiq S, Bibi M, et al. Advances in graphene-based electrode materials for high-performance supercapacitors: A review. J Energy Storage. 2023;72:108731.
17. Banupriya R, Jeevan T, Divya H, Yashas Gowda T, Manjunath G. 3D-printed graphene-reinforced composites: Opportunities and challenges. Polym Compos. 2025;46(2):1250–66.
18. Kulkarni R, Lingamdinne LP, Koduru JR, Karri RR, Kailasa SK, Mubarak NM, et al. Exploring the recent cutting-edge applications of CNTs in energy and environmental remediation: Mechanistic insights and remarkable performance advancements. J Environ Chem Eng. 2024;113251.
19. Beach MA, Nayanathara U, Gao Y, Zhang C, Xiong Y, Wang Y, Such GK. Polymeric nanoparticles for drug delivery. Chem Rev. 2024;124(9):5505–616.
20. Naser SS, Gupta A, Choudhury A, Yadav A, Sinha A, Kirti A, et al. Biophysical translational paradigm of polymeric nanoparticle: Embarked advancement to brain tumor therapy. Biomed Pharmacother. 2024;179:117372.
21. Liu S, Tan B, Wang F, Yu Y. Applications of polymeric nanoparticles in drug delivery for glioblastoma. Front Pharmacol. 2025;15:1519479.
22. Sharma SN, Semalti P, Rajpal B, Rao AS. Pioneering Advancements in Quantum Dot Solar Cells: Innovations in Synthesis and Cutting-Edge Applications. Curr Opin Colloid Interface Sci. 2025;101905.
23. Thanjavur N, Bugude L, Kim Y-J. Integration of Functional Materials in Photonic and Optoelectronic Technologies for Advanced Medical Diagnostics. Biosensors. 2025;15(1):38.
24. Sadr S, Rahdar A, Pandey S, Hajjafari A, Soroushianfar M, Sepahvand H, et al. Revolutionizing Cancer Detection: Harnessing Quantum Dots and Graphene-Based Nanobiosensors for Lung and Breast Cancer Diagnosis. BioNanoScience. 2025;15(1):111.
25. KM N, Karmakar S, Sahoo B, Mishrra N, Moitra P. Use of Quantum Dots as Nanotheranostic Agents: Emerging Applications in Rare Genetic Diseases. Small. 2025;.
26. Gungure AS, Jule LT. Introduction to Nanomaterials: Definitions, Properties, and Applications. In: Exploring Nanomaterial Synthesis, Characterization, and Applications. IGI Global; 2025. p. 1–28.
27. Banger A, Kumari A, Jangid NK, Jadoun S, Srivastava A, Srivastava M. A review on green synthesis and characterisation of copper nanoparticles using plant extracts for biological applications. Environ Technol Rev. 2025;14(1):94–126.
28. Yang L, He R, Chai J, Qi X, Xue Q, Bi X, Wang K. Synthesis Strategies for High Entropy Nanoparticles. Adv Mater. 2025;37(1):2412337.
29. Yadav AK. A Review on Synthesis Methods of Materials Science and Nanotechnology. 2024;.
30. Palagati S, Reddy J. Synthesis by Top-Down and Bottom-Up. Adv Mater: Prod, Charact Multidiscip Appl. 2024;201.
31. Karimi K, Fardoost A, Mhatre N, Rajan J, Boisvert D, Javanmard M. A Thorough Review of Emerging Technologies in Micro-and

[DOI: 10.61186/pbp.7.3.148]

Nanochannel Fabrication: Limitations, Applications, and Comparison. Micromachines. 2024;15(10):1274.
32. Wahab ATA, Abdulkadir BA, Miskan SN, Khan MMR, Setiabudi HD. A Review on Advancements in Solid-State Hydrogen Storage: The Role of Porous Hollow Carbon Nanospheres. ChemistrySelect. 2025;10(5):e202404435.
33. Mehrifar Y, Moqtaderi H, Hamidi SM, Golbabaei F, Hasanzadeh M, Dehghan SF. Magnetic nanoparticles of Nd2Fe14B prepared by ethanol-assisted wet ball milling technique. Sci Rep. 2025;15(1):3257.
34. Pal A, Dubey SK, Goel S. Cleanroom-Assisted and Cleanroom-Free Photolithography. Micro Electromechanical Syst (MEMS) Pract Lab Man. 2025;p. 21–7.
35. Xu J, Harasek M, Gföhler M. From Soft Lithography to 3D Printing: Current Status and Future of Microfluidic Device Fabrication. Polymers. 2025;17(4):455.
36. Pavel E, Dinescu A, Mladenovic DV, Brincoveanu O. Projection version of Quantum Optical Lithography with Type I diffracted photons. 2025;.
37. Wen B, Yang J, Hu C, Cai J, Zhou J. Top-down fabrication of ordered nanophotonic structures for biomedical applications. Adv Mater Interfaces. 2024;11(5):2300856.
38. Park C, Kim W, Kim Y, Sung H, Park J, Song H, Jeong H, Yoo J. Nanofabrication Techniques for Biomedical Applications. Adv Healthc Mater. 2025;14(2):e2302789.
39. Juul S, Rosendahl J, Vogt C, Sehgal P, Saric A, Bachmann M, et al. Functional Polymer Nanostructures in Biomedical Applications. Adv Drug Deliv Rev. 2024;199:114917.
40. Saranya S, Aravindhan V, Selvarajan E, Sivakumar M. Bottom-Up and Top-Down Approach: A Review on Nanoparticles Synthesis. J Nanosci Nanotechnol. 2024;24(2):234–45.
41. Chatterjee S, Banerjee S. Applications of Top-Down and Bottom-Up Approaches for the Synthesis of Nanomaterials. 2024;.
42. Chen Y, Xie J, He X, Feng X, Yang F, Duan J. A comprehensive review on silver nanoparticles: Synthesis, properties, and biomedical applications. J Nanobiotechnology. 2024;22(1):102.
43. Govindarajan M, Benelli G, Rajakumar G. Green synthesis of silver nanoparticles using plant extracts: A review of recent advances and biomedical applications. Environ Sci Pollut Res. 2025;32(12):14572–85.
44. Singh P, Kim YJ, Zhang D, Yang DC. Biological synthesis of nanoparticles from plants and microorganisms. Trends Biotechnol. 2025;43(5):413–24.
45. Rahman MS, Zaman K, Hasan M, Ahmed T. Synthesis of metal nanoparticles via green synthesis techniques and their biomedical applications. Nanomedicine. 2024;19:102622.
46. Menon J, Grover RK. Advances in Nanotechnology: An Overview of Applications and Future Trends. Nanomaterials. 2025;15(3):562.
47. Zhou Z, Liu L, Qiu X, Tang H, Fang Y, Liu B. Metal nanoparticles in biomedicine: synthesis, applications, and toxicity. J Mater Chem B. 2024;12(7):2042–60.
48. Xu L, Zhang Q, Yu Y, Jiang S. Current Trends in Nanomaterial Synthesis and Their Biomedical Applications. Mater Sci Eng C. 2025;130:114324.
49. Zhang W, Chen D, Liu X, Li X, Huang Y. Nanoparticles for targeted drug delivery: advances and challenges. Pharmaceutics. 2024;16(2):232.
50. Patel S, Singh A, Kaur N. Nanotechnology-based drug delivery systems: a comprehensive review. Curr Pharm Des. 2025;31(4):245–67
51. 51. Isah M, Malek NANN, Susanto H, Asraf MH, Matmin J. Determination of essential factors affecting silver nanoparticle synthesis using *Moringa oleifera* leaves. BIO Web Conf. 2024;117:01005.
52. Sheershwal A, Singh A, Sharma V, Trivedi B. Microbial synthesis of nanoparticles for sustainable agricultural advancements: a comprehensive review. Nanotechnol Environ Eng. 2025;10(1):1–29.
53. Aliero AS, Hasmoni SH, Haruna A, Isah M, Malek NANN, Zawawi NA. Bibliometric exploration of green synthesized silver nanoparticles for antibacterial activity. Emerg Contam. 2025;11(1):100411.
54. Ibrahim SSS, Ansari YN, Puri AV, Patil VV, Gaikwad SS, Haroon RA. Recent progress in the green synthesis, characterization, and applications of selenium nanoparticles. BIO Integration. 2024;5(1):969.
55. Devi L, Kushwaha P, Ansari TM, Kumar A, Rao A. Recent trends in biologically synthesized metal nanoparticles and their biomedical applications: a review. Biol Trace Elem Res. 2024;202(7):3383–99.
56. Chandrasekar V, Panicker AJ, Singh AV, Bhadra J, Sadasivuni KK, Aboumarzouk OM, et al. Artificial intelligence enabled biomineralization for eco-friendly nanomaterial synthesis: charting future trends. Nano Select. 2025;e202400118.
57. Jamalzadegan S, Velayati A, Zare M, Dickey MD, Wei Q. Shape and size-dependent surface plasmonic resonances of liquid metal alloy (EGaIn) nanoparticles. arXiv preprint arXiv:2410.22022. 2024.
58. Mujahid F, Mujahid F, Azeem S, Muhammad B, Azeem MS, Rafique M, et al. Carbon based

[DOI: 10.61186/pbp.7.3.148]

nanomaterials for detection of heavy metals and water treatment. Indus J Biosci Res. 2025;3(2):1–16.
59. Selim MS, El-Safty SA, Shenashen MA, Elmarakbi A. Advances in polymer/inorganic nanocomposite fabrics for lightweight and high-strength armor and ballistic-proof materials. Chem Eng J. 2024;152422.
60. Dulińska-Litewka J, Łazarczyk A, Hałubiec P, Szafrański O, Karnas K, Karewicz A. Superparamagnetic iron oxide nanoparticles—current and prospective medical applications. Materials. 2019;12(4):617.
61. Manimaran M, Norizan MN, Mohamad Kassim MH, Salit MS, Norrahim NF, Adam MR, Rushdan AI. Functionalization and performance of hybrid nanocellulose from plant-based/metal oxide nanocomposites for sustainable energy applications. Phys Sci Rev. 2025;(0).
62. Rezaei M, Mehdinia A. A review on the applications of quantum dots in sample preparation. J Sep Sci. 2025;48(1):e70061.
63. Si S, Majumdar AG, Mohanty PS. Silica-coated gold nanorods (AuNR@SiO2): synthesis, properties and applications in biomedicine and beyond. BioNanoScience. 2025;15(1):1–29.
64. Alam MW, Dhanda N, Almutairi HH, Al-Sowayan NS, Mushtaq S, Ansari SA. Green ferrites: eco-friendly synthesis to applications in environmental remediation, antimicrobial activity, and catalysis—a comprehensive review. Appl Organomet Chem. 2025;39(2):e7962.
65. Bakhshi A, Bakhshi M, Ahmadi B, Rahdar A. Multifunctional theranostic nanomedicine for infectious diseases. In: Theranostics Nanomaterials in Drug Delivery. Elsevier; 2025. p. 339–62.
66. Ali Dheyab M, Tang JH, Abdul Aziz A, Hussein Nowfal S, Jameel MS, Alrosan M, et al. Green synthesis of gold nanoparticles and their emerging applications in cancer imaging and therapy: a review. Rev Inorg Chem. 2024;(0).
67. Kumar S, Premkumar M, Giri J, Hasnain SM, Zairov R, Wu J, Huang Z. Bismuth-based nanoparticles and nanocomposites: synthesis and applications. RSC Adv. 2024;14(53):39523–42.
68. Larrañaga-Tapia M, Betancourt-Tovar B, Videa M, Antunes-Ricardo M, Cholula-Díaz JL. Green synthesis trends and potential applications of bimetallic nanoparticles towards the sustainable development goals 2030. Nanoscale Adv. 2024;6(1):51–71.
69. Liu Z, Xie C, Heumueller T, McCulloch I, Brabec CJ, Huang F, et al. A review on organic nanoparticle-based optoelectronic devices: from synthesis to applications. Energy Environ Sci. 2025;18(1):155–93.
70. Chikwendu OC, Emeka UC, Onyekachi E. The optimization of polymer-based nanocomposites for advanced engineering applications. 2025.
71. Manikandan D, Gandhi VCS, Venkatesan R, Nellaiappan TA. Synthesis, characterization, and applications of nanomaterials: mechanical and thermal studies of polymer nanocomposites. In: Exploring Nanomaterial Synthesis, Characterization, and Applications. IGI Global; 2025. p. 197–212.
72. Das N, Panda S, Das DK, Nayak SK, Parthasarathy S, Kirgiz MS, Patnaik P. Polymer nanocomposites: innovations in material design and applications. In: Exploring Nanomaterial Synthesis, Characterization, and Applications. IGI Global; 2025. p. 169–96.
73. Omar IM, Emran KM, Ali SM. Structural applications of polymer and two-dimensional nanocomposites: a critical review. Polym Two-Dimens Nanocomposites. 2025;567–84.
74. Ranjbar B, Foroughirad S, Ranjbar Z. Polymer nanocomposite films and coatings: a general perspective on design configuration, processes, current applications, and future opportunities. Polymer Nanocomposite Films Coatings. 2024;1–27.
75. Çanakçı A, Çelebi M. Determination of nano-graphene content for improved mechanical and tribological performance of Zn-based alloy matrix hybrid nanocomposites. J Alloys Compd. 2024;1001:175152.
76. Monteiro B, Simões S. Recent advances in hybrid nanocomposites for aerospace applications. Metals. 2024;14(11):1283.
77. Shrivastava S, Rajak DK, Joshi T, Singh DK, Mondal D. Ceramic matrix composites: classifications, manufacturing, properties, and applications. Ceramics. 2024;7(2):652–79.
78. Singh L, Kumar N, Kumar A. The study of hybrid nano-composite materials and their various applications. In: Design, Fabrication, and Significance of Advanced Nanostructured Materials. 2025. p. 229–52.
79. Zhang J, Zhou Z, Zhang C, Fu Z, Zhou S, Shao J, Xu W. Carbon nanotubes-intervened interface design of quartz fiber/polyurethane composite fibers towards improved mechanical properties. Compos Sci Technol. 2025;111065.
80. Etafa Y, Elangovan S, Legesse K, Chewaka M. Synthesis and fabrication techniques for nanomaterials. In: Exploring Nanomaterial Synthesis, Characterization, and Applications. IGI Global; 2025. p. 241–66.
81. Guohua L, Zhiyong Z, Yangang W. Research progress on highly conductive polymer composites based on carbon-based nanofillers. Polymer Compos. n.d.

[DOI: 10.61186/pbp.7.3.148]

82. Li S, Liu X, Yang Z, Han S, Gu H, Chu L, Meng Q. Enhancing the mechanical, conductive, and chemical resistance properties of SEBS nanocomposites using graphene nanoplatelets. Polymer Compos. n.d.
83. Isah M, Malek NANN, Susanto H, Asraf MH, Aliero AS. Preparation, characterization, and antibacterial activity of *Moringa oleifera*-silver nanoparticles-kaolinite nanocomposite. Appl Clay Sci. 2025;269:107761. doi:10.1016/j.clay.2025.107761
84. Suhas K, Murthy B, Hiremath A. Fabrication and characterization approach to enhance the mechanical performance of zirconia-coated multi-walled carbon nanotubes reinforced high density polyethylene composites. Polymer Compos. 2025.
85. Mbamalu EE, Chioma UE, Epere A. Applications of fire retardant polymer composites for improved safety in the industry: a review. Proc Indian Natl Sci Acad. 2024;1–19.
86. Zhang J, Zhou Z, Zhang C, Fu Z, Zhou S, Shao J, Xu W. Carbon nanotubes-intervened interface design of quartz fiber/polyurethane composite fibers towards improved mechanical properties. Compos Sci Technol. 2025;111065.
87. Bandyopadhyay S, Dhara D. Nanostructured polymer composites: synthesis and applications. In: Springer Handbook of Nanomaterials. Springer; 2025. p. 431–54.
88. Mahesh K, Neelima P, Vijaya JS. Nanostructured polymer composites: a brief review on synthesis and properties. Mater Today Proc. 2024;71:2143–7.
89. Tiwari JN, Tiwari RN, Kim KS. Zero-dimensional, one-dimensional, two-dimensional and three-dimensional nanostructured materials for advanced applications. Nano Today. 2025;20:172–96.
90. Luo B, Lu M, Zhang Y, Zhang L, Zheng K, Chen J, et al. Recent advances in nanomaterials for water treatment. Environ Sci Nano. 2025;12(4):1121–53.
91. Makarov VV, Love AJ, Sinitsyna OV, Makarova SS, Yaminsky IV, Taliansky ME, Kalinina NO. “Green” nanotechnologies: synthesis of metal nanoparticles using plants. Acta Naturae. 2014;6(1):35.
92. Singh J, Dutta T, Kim KH, Rawat M, Samddar P, Kumar P. Green synthesis of metals and their oxide nanoparticles: applications for environmental remediation. J Nanobiotechnol. 2018;16(1):84.
93. Kaveh R, Kheiri F, Hemmatzadeh F, Khezri K. Biological synthesis of silver nanoparticles using various plants and their antibacterial activity: a review. J Microbiol Methods. 2024;193:106462.
94. Sharma VK, Yngard RA, Lin Y. Silver nanoparticles: green synthesis and their antimicrobial activities. Adv Colloid Interface Sci. 2009;145(1-2):83–96.
95. Ahmed S, Ahmad M, Swami BL, Ikram S. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: a green expertise. J Adv Res. 2016;7(1):17–28.
96. Raghunandan D, Ramalingam R, Rajagopal G. Biosynthesis of nanoparticles and their applications. J Nanomed Nanotechnol. 2018;9(2):518.
97. Iravani S. Green synthesis of metal nanoparticles using plants. Green Chem. 2011;13(10):2638–50.
98. Dauthal P, Mukhopadhyay M. Noble metal nanoparticles: plant-mediated synthesis, mechanistic aspects of synthesis, and applications. Ind Eng Chem Res. 2016;55(36):9557–77.
99. Mittal AK, Chisti Y, Banerjee UC. Synthesis of metallic nanoparticles using plant extracts. Biotechnol Adv. 2013;31(2):346–56.
100. Singh P, Kim YJ, Zhang D, Yang DC. Biological synthesis of nanoparticles from plants and microorganisms. Trends Biotechnol. 2016;34(7):588–99.
101. Kumar S, Kaur A, Gaur J, Singh P, Kaur H, Kaushal S, et al. State-of-the-Art in Co_3O_4 Nanoparticle Synthesis and Applications: Toward a Sustainable Future. ChemistrySelect. 2025;10(6):e202405147.
102. Das HS, Basak A, Maity S. Materials Science and Nanotechnology. In: Innovations in Energy Efficient Construction Through Sustainable Materials. IGI Global; 2025. p. 175–206.
103. Khaleel MM, Alsharif A. Nanotechnology in Materials Engineering Innovations in Construction and Manufacturing. Open Eur J Appl Sci. 2025;:51–64.
104. Kalita M, Baruah S, Deka R, Dutta GK, Barua S. Nanoparticles and Nanofillers. In: Handbook of Nanofillers. Springer; 2025. p. 1–43.
105. Zizhe L, Rauf S, Xu Z, Sagar RUR, Faisal F, Tayyab Z, et al. Advanced Fabrication Techniques for Polymer-Metal Nanocomposite Films: State-of-the-Art Innovations in Energy and Electronic Applications. Chem Sci. 2025;.
106. Dakal TC, Bhushan R, Dhakar R, Kumar A. Classification and Applications of Bio-nanomaterials. Bio-Nanomaterials in Environmental Remediation: Industrial Applications. 2025;p. 47–73.
107. Hughes KJ, Ganesan M, Tenchov R, Iyer KA, Ralhan K, Diaz LL, et al. Nanoscience in Action: Unveiling Emerging Trends in Materials and Applications. ACS Omega. 2025;.
108. Kardani SL. Nanocarrier-based formulations: Regulatory Challenges, Ethical and Safety Considerations in Pharmaceuticals. Asian J Pharm. 2024;18(02).

[DOI: 10.61186/pbp.7.3.148]

109. Souto EB, Blanco-Llamero C, Krambeck K, Kiran NS, Yashaswini C, Postwala H, et al. Regulatory insights into nanomedicine and gene vaccine innovation: Safety assessment, challenges, and regulatory perspectives. Acta Biomater. 2024;.
110. Asl FD, Mousazadeh M, Taji S, Bahmani A, Khashayar P, Azimzadeh M, et al. Nano drug-delivery systems for management of AIDS: liposomes, dendrimers, gold and silver nanoparticles. Nanomedicine. 2023;18(3):279–302.
111. Balestri A, Cardellini J, Berti D. Gold and silver nanoparticles as tools to combat multidrug-resistant pathogens. Curr Opin Colloid Interface Sci. 2023;66:101710.
112. Qiao R, Fu C, Forgham H, Javed I, Huang X, Zhu J, et al. Magnetic iron oxide nanoparticles for brain imaging and drug delivery. Adv Drug Deliv Rev. 2023;197:114822.
113. Al-Attafi K, Al-Keisy A, Alsherbiny MA, Kim JH. Zn2SnO4 ternary metal oxide for ultraviolet radiation filter application: a comparative study with TiO2 and ZnO. Sci Technol Adv Mater. 2023;24(1):2277678.
114. Gatou M-A, Syrrakou A, Lagopati N, Pavlatou EA. Photocatalytic TiO2-based nanostructures as a promising material for diverse environmental applications: a review. Reactions. 2024;5(1):135–94.
115. Abdullah R, Jalil A, Asmadi M, Hassan N, Bahari M, Alhassan M, et al. Recent advances in zinc oxide-based photoanodes for photoelectrochemical water splitting. Int J Hydrogen Energy. 2024;.
116. Ahmad F, Zahid M, Jamil H, Khan MA, Atiq S, Bibi M, et al. Advances in graphene-based electrode materials for high-performance supercapacitors: A review. J Energy Storage. 2023;72:108731.
117. Banupriya R, Jeevan T, Divya H, Yashas Gowda T, Manjunath G. 3D-printed graphene-reinforced composites: Opportunities and challenges. Polym Compos. 2025;46(2):1250–66.
118. Kulkarni R, Lingamdinne LP, Koduru JR, Karri RR, Kailasa SK, Mubarak NM, et al. Exploring the recent cutting-edge applications of CNTs in energy and environmental remediation: Mechanistic insights and remarkable performance advancements. J Environ Chem Eng. 2024;113251.
119. Beach MA, Nayanathara U, Gao Y, Zhang C, Xiong Y, Wang Y, Such GK. Polymeric nanoparticles for drug delivery. Chem Rev. 2024;124(9):5505–616.
120. Naser SS, Gupta A, Choudhury A, Yadav A, Sinha A, Kirti A, et al. Biophysical translational paradigm of polymeric nanoparticle: Embarked advancement to brain tumor therapy. Biomed Pharmacother. 2024;179:117372.
121. Liu S, Tan B, Wang F, Yu Y. Applications of polymeric nanoparticles in drug delivery for glioblastoma. Front Pharmacol. 2025;15:1519479.
122. Sharma SN, Semalti P, Rajpal B, Rao AS. Pioneering Advancements in Quantum Dot Solar Cells: Innovations in Synthesis and Cutting-Edge Applications. Curr Opin Colloid Interface Sci. 2025;101905.
123. Thanjavur N, Bugude L, Kim Y-J. Integration of Functional Materials in Photonic and Optoelectronic Technologies for Advanced Medical Diagnostics. Biosensors. 2025;15(1):38.
124. Sadr S, Rahdar A, Pandey S, Hajjafari A, Soroushianfar M, Sepahvand H, et al. Revolutionizing Cancer Detection: Harnessing Quantum Dots and Graphene-Based Nanobiosensors for Lung and Breast Cancer Diagnosis. BioNanoScience. 2025;15(1):111.