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Review

Biomedical applications of nanomaterials: A short review

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Abstract: Nanomaterials have emerged as transformative tools in the biomedical field due to their distinct physical and chemical properties. This review delves into the synthesis, classifications, and applications of nanomaterials, emphasizing advancements in drug delivery, bioimaging, and diagnostics. Unique aspects include a focused discussion on sol-gel synthesis methods and recent trends in nanomaterial applications for personalized medicine. The review concludes with a future perspective on overcoming challenges such as toxicity and regulatory issues, paving the way for sustainable biomedical innovations.

Keywords: nanomaterials; biomedical applications; drug delivery; biological imaging; carbon nanomaterials; metal nanoparticles; composite nanomaterials

1. Introduction

Nanomaterials are materials that exhibit unique properties due to their nanometer size, typically ranging from 1 nm to 100 nm [1]. These materials can be organic, inorganic or a combination of both and are known as organometallic materials. The importance of nanomaterials lies in their outstanding physical properties, such as plasmonic, magnetic, catalytic, mechanical and fluorescent properties, and their high electrical conductivity [2]. These distinctive properties have led to the development of high-performance biosensors with applications in various sensing platforms, including optical, electrical and electrochemical systems. According to their morphology, nanomaterials are classified into various types such as nanoparticles (NPs), nanofibers, nanotubes, nanowires, nanohelices, nanosheets, nanopillars, nanobelts, nanospheres, and nanopyramids [3]. Moreover, conductive nanomaterials for transparent conductors are categorized as carbon-based nanomaterials, metal-based nanomaterials and hybrid nanomaterials [4]. These classifications show the diverse nature of nanomaterials and their applications in different fields. In terms of size, nanomaterials can also be categorized into low-dimensional nanomaterials such as quantum dots (QDs), carbon nanotubes (CNTs), graphene, MXenes, semiconductor nanowires (NWs) and transition metal disulfides (TMDs) [5]. These low-dimensional nanomaterials play important roles in various applications, including human-machine interactions and biosensor technologies. Moreover, nanomaterials have been extensively investigated in this study for their applications in different sectors. For example, carbon-based nanomaterials have been used in fluorescence polarization-based biosensors showing various formats and structures such as graphene oxide, carbon nanotubes, fullerenes, and carbon/graphene quantum dots [6]. However, nanomaterials have been used in diverse fields such as liquid chromatography, gas sensors and biomedical applications, demonstrating their versatility and potential impact in different disciplines [7–9]. Nanomaterials represent a broad class of materials with unique properties attributed to their nanoscale dimensions. Their various classifications based on morphology, dimensionality and composition are characterized by their role in technological advances in many fields, from biosensors to energy storage and environmental improvement.

As a result, the types and properties of nanomaterials can be summarized as in **Table 1**, and the usage areas and applications of nanomaterials can be summarized as in **Table 2**.

Table1. Nanomaterial types and properties.

Nanomaterial Type	Morphology	Features
Nanoparticles (NPs)	Spherical	Plasmonic, magnetic, catalytic, mechanical, fluorescent properties, high electrical conductivity
Nanofibers	Fibrous	High surface area, mechanical durability
Nanotubes	Tubular	Electrical conductivity, mechanical durability, lightness
Nanowires	Wires	High aspect ratio, electronic features
Nanohelices	Helical	Unique optical and magnetic properties
Nanosheets	Layers	High surface area, mechanical durability
Nanopillars	Columns	Mechanical and optical properties
Nanobelts	Strips	Electrical conductivity, flexibility
Nanospheres	Spherical	High surface area, mechanical and optical properties
Nanopyramids	Pyramids	Unique optical and magnetic properties

Table 2. Nanomaterial usage areas and applications.

Nanomaterial Type	Area of Use	Example applications
Carbon Based Nanomaterials	Transparent conductors, biosensors	Graphene oxide, carbon nanotubes, fullerene, carbon/graphene quantum dots
Metal Based Nanomaterials	Electronics, catalysis, energy storage	Metal nanoparticles, metal oxide nanoparticles, gas sensors
Hybrid Nanomaterials	Multifunctional applications	Organic-inorganic compounds, metal-organic frameworks
Quantum Dots (QDs)	Optoelectronics, bioimaging	CdSe quantum dots, InP quantum dots
Carbon Nanotubes (CNTs)	Electronics, energy storage, composite materials	Electronics, supercapacitors, nanocomposite materials, gas sensors
Graphene	Electronics, energy storage, biosensors	Graphene sheets, graphene oxide, reduced graphene oxide
MXenes	Electronics, energy storage	Ti_3C_2 MXene, Nb_2C MXene
Semiconductor Nanowires (NWs)	Electronics, optoelectronics	Silicon nanowires, GaN nanowires
Transition Metal Disulfides (TMDs)	Electronics, photocatalysis	MoS_2, WS_2
Silica nanoparticles, polymer coated nanoparticles	Liquid chromatography	Analytical chemistry, biomedical applications

This review stands out for its comprehensive comparison of nanomaterial synthesis methods, with a particular emphasis on the sol-gel process and its unique advantages in biomedical applications. Additionally, it explores recent advancements in nanomaterials tailored for personalized medicine and diagnostics, addressing gaps in existing literature. The review provides a detailed examination of different nanomaterial types, their synthesis methods, and their biomedical applications, highlighting both their benefits and challenges. Finally, the paper discusses potential future applications and research directions, concluding with an overall evaluation of the field and its prospects.

2. Types of nanomaterials

Different types of nanomaterials exhibit unique optical, electronic and biological properties depending on their size and structural properties, with the potential for wide-ranging applications in various fields such as biomedical imaging, drug delivery, energy storage and electronics. When we consider these nanomaterials one by one, their properties and applications are as follows. Quantum dots are zero-dimensional nanomaterials with unique optical and electronic properties due to size-dependent quantum confinement effects. They are used in various fields such as biological imaging, solar cells, LEDs and quantum computing [10]. Nanorods and nanowires are one-dimensional nanomaterials that find applications in fields such as electronics, sensors, and catalysis due to their high aspect ratios and unique properties [11]. Nanosheets and nanocubes are two-dimensional nanomaterials whose properties are influenced by their shape, size and microstructure, which affect their chemical and physical properties [12,13]. Carbon nanomaterials encompass a variety of structures such as graphene, carbon nanotubes and fullerenes, each with different properties and applications in areas such as electronics, energy storage and composite materials [14]. Liposomal nanomaterials are lipid-based nanoparticles used for drug delivery due to their ability to encapsulate both hydrophilic and hydrophobic drugs, increase their bioavailability and target specific tissues [15]. Polymer-based nanomaterials are used for drug delivery, tissue engineering and coatings due to their biocompatibility, tunable properties and ability to encapsulate drugs or molecules for controlled release [16]. Metal-based nanomaterials such as nanocubes, nanorods and nanospheres are used in catalysis, sensing and biomedical applications due to their unique physical and chemical properties [17,18]. Fluorescent silicon-based nanomaterials are used in biological imaging, sensors and optoelectronics due to their tunable emission properties and biocompatibility [19]. Hydrogels are three-dimensional hydrophilic polymer networks used in drug delivery, wound healing and tissue engineering due to their high water content and biocompatibility [20]. Polymer dots are fluorescent polymer nanoparticles used in biological imaging and sensing applications due to their brightness, photostability and biocompatibility [21]. Magnetic nanoparticles exhibit magnetic properties and are used in applications such as magnetic resonance imaging, drug delivery and hyperthermia cancer therapy due to their magnetic response [22]. Micelles and dendrimers are nanostructures used in drug delivery and gene therapy due to their ability to encapsulate drugs or nucleic acids and target specific cells [23]. Lipid nanoparticles are lipid-based carriers used in drug delivery to improve drug solubility, stability and bioavailability [15]. Semiconductor quantum dots are nanocrystals with semiconducting properties used in displays, solar cells and biological imaging due to their size-tunable optical properties [10]. TiO_2 nanoparticles find applications in photocatalysis, sunscreen and environmental improvement due to their photocatalytic activity and stability [24]. Nanoclay is a type of nanomaterial used in composites, packaging and drug delivery due to its high surface area and barrier properties [23].

As a result, the types and properties of all mentioned nanomaterials can be summarized as in **Table 3**, and the types of nanomaterials and their application examples can be summarized as in **Table 4**.

Table 3. Nanomaterial types and properties.

Nanomaterial Type	**Size/Morphology**	**Features**
Quantum Dots	Zero dimensional	Optical and electronic properties, size-dependent quantum confinement effects
Nanorods and Nanowires	One dimensional	High aspect ratio, unique electronic and optical properties
Nanosheets and Nanocubes	Two dimensional	Chemical and physical properties influenced by shape, size and microstructure
Carbon Nanomaterials	Various structures	Different structures (graphene, carbon nanotubes, fullerenes) for electronics, energy storage, composite materials
Liposomal Nanomaterials	Nanoparticles	Ability to encapsulate both hydrophobic and hydrophilic drugs, increasing bioavailability
Polymer Based Nanomaterials	Nanoparticles	Biocompatible, tunable properties, ability to encapsulate drugs or molecules for controlled release
Metal Based Nanomaterials	Various structures	Physical and chemical properties, catalysis, sensors and biomedical applications
Fluorescent Silicon-Based Nanomaterials	Nanoparticles	Adjustable emission properties, biocompatible
Hydrogels	Three dimensional	High water content, biocompatible, drug release, wound healing, tissue engineering
Polymer Dots	Nanoparticles	Brightness, photostability, biocompatible
Magnetic Nanoparticles	Nanoparticles	Magnetic properties, magnetic resonance imaging, drug transport, hyperthermia cancer treatment
Micelles and Dendrimers	Nanostructures	Ability to encapsulate drugs or nucleic acids, targeting specific cells
Lipid Nanoparticles	Nanoparticles	Improving drug solubility, stability and bioavailability
Semiconductor Quantum Dots	Nanocrystals	Size tunable optics, displays, solar cells, biological imaging
TiO_2 Nanoparticles	Nanoparticles	Photocatalytic activity, stability, photocatalysis, sunscreen, environmental remediation
Nanoclay	Nanomaterials	High surface area, barrier properties, composites, packaging, drug release

Table 4. Nanomaterial types and application areas.

Nanomaterial Type	**Application area**	**Example applications**
Quantum Dots	Biological imaging, solar cells, LEDs, quantum computing	CdSe quantum dots, InP quantum dots
Nanorods and Nanowires	Electronics, sensors, catalysis	Silicon nanowires, GaN nanowires
Nanosheets and Nanocubes	Electronics, energy storage, biosensors	Graphene, MoS_2, WS_2
Carbon Nanomaterials	Electronics, energy storage, composite materials	Graphene oxide, carbon nanotubes, fullerenes
Liposomal Nanomaterials	Transporting medicine	Liposomal drug delivery systems
Polymer Based Nanomaterials	Drug delivery, tissue engineering, coatings	Polymer-coated nanoparticles, biomedical coatings
Metal Based Nanomaterials	Catalysis, sensors, biomedical applications	Gold nanoparticles, silver nanoparticles, metal oxide nanoparticles
Fluorescent Silicon-Based Nanomaterials	Biological imaging, sensors, optoelectronics	Fluorescent silicon nanoparticles
Hydrogels	Drug delivery, wound healing, tissue engineering	Biocompatible hydrogels

Table 4. (*Continued*).

Nanomaterial Type	Application area	Example applications
Polymer Dots	Biological imaging, sensor applications	Fluorescent polymer nanoparticles
Magnetic Nanoparticles	Magnetic resonance imaging, drug delivery, hyperthermia cancer treatment	Iron oxide nanoparticles
Micelles and Dendrimers	Drug delivery, gene therapy	Dendrimers, micellar structures
Lipid Nanoparticles	Transporting medicine	Lipid-based drug carriers
Semiconductor Quantum Dots	Displays, solar cells, bioimaging	CdSe quantum dots, InP quantum dots
TiO_2 Nanoparticles	Photocatalysis, sunscreen, environmental remediation	TiO_2 nanoparticles
Nanoclay	Composites, packaging, drug delivery	Nanoclay composites

The sol-gel method is highlighted due to its versatility in synthesizing nanostructured materials with enhanced properties for biomedical applications, such as improved corrosion resistance and thermal stability. Compared to other methods, the sol-gel process offers precise control over material composition and structure, although challenges such as scalability and cost remain.

3. Synthesizing nanomaterials

The synthesis of nanomaterials encompasses a variety of methods, each with unique properties and applications. One of the common methods is the sol-gel process, a wet chemical method used to synthesize nanostructures, particularly metal oxide nanoparticles [25]. Chemical vapor deposition (CVD) is another technique in which thin films are deposited from vapor phase precursors onto a substrate, allowing precise control over the composition and structure of the film [26]. Sol-gel processes have been widely used to produce nanostructured inorganic films that exhibit improved resistance to oxidation, corrosion, erosion and abrasion along with good thermal and electrical properties [27]. However, sol-gel methods have been used to produce coatings, porous glasses and optical components and to join porous materials [28]. Biological synthesis methods offer an innovative approach to nanomaterial synthesis. For example, encapsulation of cytochrome c in silica aerogel nanomachines without metal nanoparticles has been achieved while maintaining gas phase bioactivity [29]. Furthermore, the sol-gel process has been used to prepare highly porous, homogeneous and hybrid thin film materials for supercapacitor electrode applications, demonstrating the versatility of this method in electrochemical applications [30]. Innovative synthesis methods also include the use of sol-gel coatings to improve the corrosion resistance of materials such as magnesium alloys [31]. In addition, modification of silane-based sol-gel coatings has been investigated to improve the corrosion resistance of magnesium alloys through various approaches such as incorporating nanoparticles, corrosion inhibitors and composite coatings [31]. These developments reveal the importance of continuous research and development of new techniques to tailor nanomaterial properties for specific applications. Consequently, the synthesis of nanomaterials involves a wide variety of methods such as sol-gel processes, CVD, biological synthesis and other innovative techniques. Each method offers unique advantages and applications, contributing to the various processes of nanomaterial synthesis and opening new roads for tailored materials with improved properties [32].

As a result, all mentioned nanomaterial synthesis methods can be summarized as in **Table 5**, and the Sol-gel method and its applications can be summarized as in **Table 6**.

Table 5. Nanomaterial synthesis methods.

Synthesis Method	Definition	Features and Applications
Sol-Gel Method	Wet chemical method; production of metal oxide nanoparticles	Oxidation, high corrosion resistance, erosion and wear resistance, precise control over composition.
Chemical Vapor Deposition (CVD)	Thin film deposition; Film formation from vapor phase precursors	Composition and structure control, thin film coatings.
Biological Synthesis Methods	Nanomaterial production using biological materials	Silica airgel nanomachines, gas phase bioactivity.
Other Innovative Methods	Various innovative methods; Microwave-assisted synthesis, green synthesis methods [33]	Customized material properties. Rapid and precise nanomaterial synthesis. Eco-friendly approaches using plants or microorganisms.

Table 6. Sol-Gel method and applications.

Application area	Detail
Nanostructured Inorganic Films	Oxidation, corrosion, erosion and wear resistance, good thermal and electrical properties
Coatings, Porous Glass and Optical Components	Production of coatings, porous glasses and optical components
Gas Phase Bioactivity	Silica airgel nanomachines with gas-phase bioactivity without metal nanoparticles
Supercapacitor Electrode Applications	Highly porous, homogeneous and hybrid thin film materials
Corrosion Resistance Improvement	Sol-gel coatings to increase corrosion resistance of magnesium alloys
Nanoparticle, Corrosion Inhibitors and Composite Coatings	Various approaches to improve the corrosion resistance of magnesium alloys

4. Biomedical applications of nanomaterials

Nanomaterials play important roles in various biomedical applications due to their unique properties. In drug delivery systems, nanomaterials are used to improve the efficiency and specificity of drug delivery to target sites [34]. They can improve targeted drug delivery, solubility, bioavailability and drug retention time, thereby reducing side effects and drug toxicity risks [34]. Nanomaterials such as nanoparticles, nanogels and nanorods have revolutionized medicine, especially in the fields of drug delivery, bioimaging and theranostics [35]. These materials facilitate the delivery of anti-cancer drugs directly to tumor tissues, opening new opportunities in oncology [36]. For imaging and diagnostics, nanomaterials are used to develop contrast agents that enhance imaging techniques such as Magnetic Resonance Imaging (MRI), Computed Tomography (CT) scans and fluorescence imaging [37] [38]. Nanomaterials with unique biophotonic properties show promise in biomedical applications for imaging and diagnosis [39]. However, nanomaterials can be engineered to combine drug delivery with other therapeutic approaches such as photothermal therapy to enhance imaging and diagnostic capabilities [40]. Theranostics, combining therapy and diagnostics, is an emerging field in which nanomaterials play an important role. Nanomaterial-based drug delivery systems can respond to specific stimuli in the tumor microenvironment and enable targeted drug delivery and treatment monitoring through imaging techniques [41]. Nanomaterials have been successfully applied in theranostics by developing smart drug delivery systems that respond to temperature changes in the tumor microenvironment and improve cancer treatment outcomes [41]. In tissue engineering, nanomaterials are used to create scaffolds that mimic the extracellular matrix, promoting cell growth and tissue regeneration [42]. Nanomaterials have been used in tissue engineering to develop advanced drug delivery systems that can also support tissue regeneration [43]. Nanomaterials offer promising properties for medical applications in tissue engineering, providing superior platforms for drug delivery and tissue regeneration [40]. In antimicrobial applications, nanomaterials such as quaternary ammonium compounds (QACs) have been widely used due to their excellent antimicrobial activity [44]. These materials have shown potential in eliminating biofilms and combating infections [44]. Nanomaterials can be tailored to effectively target and eliminate microbial pathogens, making them valuable in antimicrobial applications [44]. In cancer therapy, nanomaterials are widely used in drug delivery systems to enhance the delivery of anti-cancer drugs to tumor tissues [45]. Furthermore, nanomaterials have been used to combine different cancer treatments such as radiotherapy, chemotherapy and immunotherapy to improve therapeutic outcomes. Nanomaterial-based drug delivery systems have shown promise in improving the efficacy of cancer treatment while minimizing side effects [45]. For gene therapy, nanoparticles are used as carriers to deliver genetic material to cells for therapeutic purposes. Nanoparticles have been functionalized to create drug delivery systems that can precisely target and deliver therapeutic agents for gene therapy, improving treatment efficacy. Nanoparticles play an important role in gene therapy by facilitating the delivery of genetic material to specific cells for therapeutic interventions.

As a result, biomedical applications of nanomaterials can be summarized as in **Table 7**, drug delivery systems and Theranostics in **Table 8**, imaging and diagnostic applications as in **Table 9**, and tissue engineering and antimicrobial applications as in **Table 10**.

Table 7. Biomedical applications of nanomaterials.

Application area	Nanomaterial Types	Features and Benefits
Drug Delivery Systems	Nanoparticles, nanogels, nanorods	Targeted drug delivery, increased solubility and bioavailability, reduced side effects
Imaging and Diagnostics	Nanomaterials (MRI, CT, fluorescence)	Contrast agents that improve imaging techniques, biophotonic properties
Therapeutics and Diagnostics (Theranostics)	Nanomaterial-based systems	Targeted drug delivery, smart drug systems that respond to the tumor microenvironment
Tissue Engineering	Nanomaterials	Scaffolds that promote cell growth and tissue regeneration
Antimicrobial Applications	Quaternary ammonium compounds (QACs)	Excellent antimicrobial activity, eliminating biofilms
Cancer Therapy	Nanoparticles	Targeted anti-cancer drug delivery, combined treatment methods (radiotherapy, chemotherapy)
Gene Therapy	Nanoparticles	Delivering genetic material to cells, increasing treatment effectiveness

Table 8. Drug delivery systems and theranostics.

Application area	Explanation
Drug Delivery Systems	Nanomaterials increase the targeted delivery, solubility, bioavailability and residence time of drugs.
Theranostics	In this field where treatment and diagnosis are combined, nanomaterials provide smart drug systems that respond to specific stimuli.

Table 9. Imaging and diagnostic applications.

Imaging Technique	Nanomaterial Types	Features and Benefits
MRI (Magnetic Resonance Imaging)	Nanoparticles	Contrast enhancing agents provide clear and detailed images.
CT (Computed Tomography)	Nanoparticles	Contrast agents highlight tissue differences.
Fluorescent Imaging	Nanomaterials with biophotonic properties	High precision imaging, monitoring of biological processes.

Table 10. Tissue engineering and antimicrobial applications.

Application area	Nanomaterial Types	Features and Benefits
Tissue Engineering	Nanomaterials	Scaffolds, advanced drug delivery systems that promote cell growth and tissue regeneration
Antimicrobial Applications	Quaternary ammonium compounds (QACs)	Excellent antimicrobial activity, eliminating biofilms, fighting infections

5. Advantages and challenges of nanomaterials

Nanomaterials offer various advantages in different fields. They have been shown to increase therapeutic efficacy, improve bioavailability, enable targeted delivery and reduce side effects in drug delivery systems [46]. In addition, nanomaterials provide superior efficacy, bioavailability, safety and personalization compared to conventional therapies [47]. Their modular tunability allows the addition of functionalities that assist in diagnostics, imaging, drug delivery, therapy and monitoring of patient response [48]. In agriculture, nano-fertilizers and nano-pesticides enable controlled release of agrochemicals, maximizing biological effectiveness without overdose [49]. Nanomaterials also play an important role in environmental applications such as removing pollutants from contaminated soils and water [50]. However, the use of nanomaterials comes with challenges. One major concern is their toxicity. Nanomaterials, especially carbon nanomaterials, have raised toxicity concerns due to their potential application as drug nanocarriers, especially in drug delivery systems [51]. Toxicity issues extend to various nanomaterials, including iron oxide nanoparticles, which are widely used in the biomedical field [52]. The toxicity of zero- and one-dimensional carbon nanomaterials has also been a topic of research, emphasizing the importance of understanding the possible adverse effects of these materials [53]. Moreover, the neurotoxicity of nanomaterials, especially those with dimensions smaller than 100 nm, is a major concern in terms of human health and environmental impacts [54]. Regulatory and ethical issues surround the use of nanomaterials. The increase in the application of engineering nanomaterials across industries raises safety concerns regarding human health and environmental impacts, necessitating safer design approaches [55]. Assessing the bioaccumulation, pharmacokinetics and potential toxicity of novel nanomaterials is crucial before mass production or clinical use [56]. However, assessment of nanomaterial toxicity is essential for regulatory agencies to evaluate environmental and health risks and guide the development of safer nanomaterials and products [57]. In conclusion, while nanomaterials offer a wide range of advantages in drug delivery, agriculture, environmental improvement and other fields, their use comes with challenges related to toxicity, regulatory oversight and ethical considerations. Addressing these challenges through rigorous toxicity assessments, safer design approaches and ethical considerations is critical to ensure human health and environmental safety while harnessing the full potential of nanomaterials.

As a result, the advantages of nanomaterials can be summarized as in **Table 11**, the difficulties of nanomaterials in **Table 12**, and the general summary of the advantages and difficulties of nanomaterials in **Table 13**.

Table 11. Advantages of nanomaterials.

Application area	Explanation
Drug Delivery Systems	Increasing therapeutic efficacy, improving bioavailability, targeted delivery, reducing side effects [43]
General Medical Applications	Superior efficacy, bioavailability, safety and personalization [44]
Diagnostics and Imaging	Diagnosis, imaging, drug delivery, treatment and patient response monitoring with modular adjustability [45]
Agriculture	Controlled agrochemical release with nano-fertilizers and nano-pesticides, maximizing biological efficiency [46]
Environmental Applications	Removal of pollutants from contaminated soil and water [47]

Table 12. Challenges of nanomaterials.

Challenges	Detail
Toxicity, Neurotoxicity and Toxicity Assessment	Toxicity concerns when nanomaterials, especially carbon nanomaterials, are used as drug carriers [48], human health and environmental effects of nanomaterials, especially smaller than 100 nm in size [51], assessment of environmental and health risks, guiding the development of safer nanomaterials and products [54]
Iron Oxide Nanoparticles	Despite their widespread use in the biomedical field, toxicity problems [49]
Zero- and One-Dimensional Carbon Nanomaterials	The importance of understanding possible adverse effects [50]
Regulatory and Ethical Issues	Safety concerns regarding human health and environmental impacts, the need for safer design approaches [52]
Bioaccumulation and Pharmacokinetics	Bioaccumulation and potential toxicity assessment of new nanomaterials before mass production or clinical use [53]

Table 13. Overview of advantages and challenges of nanomaterials.

Category	Advantages	challenges
Medical Applications	Therapeutic efficacy, bioavailability, targeted delivery, diagnostics, imaging, personalization [43–45]	Toxicity, neurotoxicity, regulatory and ethical issues [48–54]
Agriculture	Controlled agrochemical release, biological activity [46]	-
Environment	Removal of pollutants [47]	-

6. Future perspective for nanomaterials

Emerging trends in nanomaterials research encompass a wide range of exciting developments. Recent advances in the synthesis of micro- and nanoparticles have created opportunities in diverse fields such as catalysis, plasmonics, sensors, drug delivery and nanomedicine [58]. Nanomaterials are increasingly being explored for their potential in personalized medicine with applications in neurological diseases, cancer treatment, tissue regeneration and drug delivery systems [59]. The use of nanomaterials in energy, wastewater treatment and biomedical applications is increasing with a focus on environmentally friendly synthesis methods, long-term environmental impacts and physicochemical properties tailored for specific applications [60–62]. Innovations in the synthesis and application of nanomaterials are expected to continue to evolve. Scalable synthesis methods are crucial to provide significant amounts of high-quality nanomaterials with tunable properties [63]. Carbon-based hollow nanomaterials have attracted interest due to their unique structure and promising applications [64]. Strategies such as wet chemical synthesis and microwave-assisted synthesis increase control over the size, shape, and composition of nanomaterials, facilitating their incorporation into various applications [65]. Overcoming current challenges in nanomaterials research includes identifying compositions and structures, developing reliable synthesis methods, designing safer nanomaterials, and maximizing their benefits in products [66]. Nanomaterials are being explored for their role in green supply chains and environmental sustainability by utilizing their unique properties for sustainable solutions to environmental challenges [67]. The controlled synthesis of complex hollow nanostructures offers additional functionalities to be explored in various applications [68]. As a result, nanomaterials research is advancing rapidly with a focus on personalized medicine, energy applications, environmental improvement, and innovative synthesis methods. The future of nanomaterials has great potential to address current challenges and open new avenues for applications in various fields.

As a result, the future perspectives of nanomaterials can be summarized as in **Table 14**, innovative syntheses and methods in **Table 15**, future challenges and solutions in **Table 16**, and future application areas in **Table 17**.

Table 14. Future perspectives of nanomaterials.

Fields	Developments and Applications
Catalysis	Creating new opportunities with recent developments in microparticle and nanoparticle synthesis [58]
Plasmonic	More effective plasmonic applications with advanced nanomaterials [58]
Sensors	Development of high sensitivity sensors with innovative nanomaterials [58]
Drug Delivery and Nanomedicine	Potential for use in personalized medicine for cancer treatment, neurological diseases and tissue regeneration [59]
Energy and Wastewater Treatment	Energy and wastewater treatment applications considering environmentally friendly synthesis methods and long-term environmental impacts [60–62]
Green Supply Chains	Using nanomaterials for environmentally friendly solutions [67]
Environmental Sustainability	Nanomaterials offer sustainable solutions with their environmentally friendly properties [67]

Table 15. Innovative synthesis methods and applications.

Synthesis Methods	Apps and Features
Scalable Synthesis Methods	Significant production of high-quality nanomaterials with tunable properties [63]
Carbon-Based Hollow Nanomaterials	Attracting attention due to their unique structure and promising applications [64]
Wet Chemical Synthesis and Microwave Assisted Synthesis	Providing greater control over the size, shape and composition of nanomaterials [65]
Complex Hollow Nanostructures	Exploration in various applications by offering additional functionalities [68]

Table 16. Future challenges and solutions.

challenges	Answers
Determining Composition and Structure	Identifying and optimizing the composition and structure of nanomaterials [66]
Developing Reliable Synthesis Methods	Development of reliable and reproducible synthesis methods [66]
Designing Safer Nanomaterials	Designing safe and effective nanomaterials [66]
Maximizing Benefits in Products	Maximizing the benefits of nanomaterials in products [66]

Table 17. Future application areas.

Fields	Developments and Potential Applications
Personalized Medicine	Use of nanomaterials for cancer treatment, neurological diseases and tissue regeneration [59]
Energy	Energy applications with environmentally friendly synthesis methods [60]
Environmental Remediation	Nanomaterials offer sustainable solutions to environmental challenges [67]
Innovative Synthesis Methods	Development of scalable, reliable and controllable synthesis methods [63,65]

7. Discussion

Nanomaterials have become a valuable tool in biomedical applications due to their unique properties and versatility. Carbon-based nanomaterials such as graphene, graphene oxides and carbon nanotubes have attracted attention due to their potential in developing medical devices [69]. These materials show promise in various biomedical fields, including diagnostics, therapeutics, and tissue engineering [70]. Nanomaterials are being investigated for stem cell responses, drug delivery and regenerative medicine applications in concert with biological components in the body [71]. The future of nanomaterials research in biomedicine looks promising with continuous advances in multifunctional nanomaterials for various biomedical uses [72]. Nanomaterials are also being investigated for controlled drug delivery, bioimaging, biosensor and therapeutic applications [73]. However, research on nanomaterials for cancer treatment and other medical therapies is advancing and nanostructured materials have the potential to transform healthcare [74]. Moreover, the integration of nanomaterials with other technologies, such as photosensitive DNA nanomaterials and metallic nanomaterials, creates new opportunities for efficient biological imaging, drug delivery and tissue engineering [75,76]. Strategic design and functionalization of nanomaterials, including silver and gold nanomaterials, are enhancing diagnostic and therapeutic capabilities for biomedical applications [77]. In addition, the use of composite nanomaterials is expanding the scope of diagnostic and therapeutic procedures for various diseases [78]. Nanomaterials offer significant potential to revolutionize biomedical applications by providing tailored solutions for drug delivery, imaging, therapy and tissue engineering. The interdisciplinary nature of nanomaterials research, combined with ongoing innovations in materials design and functionalization, is paving the way for a new era of personalized and precision medicine.

As a result, the use of nanomaterials in biomedical applications can be summarized as in **Table 18**, the advantages of nanomaterials and their role in biomedical applications in **Table 19**, and future perspectives in **Table 20**.

Table 18. Use of nanomaterials in biomedical applications.

Application area	Nanomaterial Type	Usage and Potential Applications
Disease Diagnosis, Treatment and Imaging	Silver and Gold Nanomaterials, Composite Nanomaterials, Carbon Based Nanomaterials	Increasing diagnostic and treatment capabilities [77], Expanding diagnostic and treatment procedures of various diseases [78], Use in diagnosis, treatment and tissue engineering [69,70].
Biological Imaging	Photosensitive DNA Nanomaterials and Metallic Nanomaterials	New opportunities for bioimaging, drug delivery and tissue engineering [75,76].
Drug Distribution	Carbon Based Nanomaterials	Controlled drug delivery and regenerative medicine applications with biological components [71,73].
Regenerative Medicine	Carbon Based Nanomaterials	Investigation of stem cell responses and tissue engineering applications [71].
Cancer Treatment	Nanostructured Materials	Potential of nanomaterials in cancer treatment [74].

Table 19. Advantages of nanomaterials and their role in biomedical applications.

Advantages and Application Areas	Detail
Drug Distribution	Increasing drug effectiveness and reducing side effects in targeted areas [69].
Biological Imaging and Diagnostics	Improving image quality and accuracy [69,73].
Therapeutic Applications	Providing innovative solutions in cancer treatment and other disease management [74].
Biosensor Development	Developing biosensors that detect biomolecules with high sensitivity [69,77].
Bioscaffold Development	Creating bioscaffolds that promote cell growth [69,71].
Antimicrobial Properties	Preventing infections and accelerating wound healing [69,73].
Diagnostic Kits	Playing an important role in the development of rapid and accurate diagnostic kits [69,73].

Table 20. Future perspectives.

Future Trends and Innovations	Detail
Personalized Medicine	Use of nanomaterials in personalized and precision medicine [72,73].
Environmental Sustainability	Environmentally friendly synthesis methods and consideration of long-term environmental impacts [73].
Multifunctional Nanomaterials	Continuing development of multifunctional nanomaterials for biomedical use [72,73].
Strategic Design and Functionalization	Strategic design and functionalization of silver and gold nanomaterials for diagnosis and therapy [77].

In short, nanomaterials are attracting attention due to the various advantages they offer in biomedical applications. In drug delivery systems, these materials increase drug efficacy at targeted sites and reduce side effects. In biological imaging and diagnostics, nanomaterials improve image quality and accuracy. In therapeutic applications, they offer innovative solutions in cancer treatment and other disease management. Nanomaterials also develop biosensors that detect biomolecules with high sensitivity, create bioscaffolds that promote cell growth, and improve contrast and performance in medical imaging techniques. Thanks to their antimicrobial properties, they prevent infections and accelerate wound healing. They also play an important role in the development of fast and accurate diagnostic kits. In the future, advances in nanomaterials research could open the door to a new era in personalized medicine and precision medicine. Therefore, extensive research and application of nanomaterials in the biomedical field is going on full speed, and more innovations and discoveries are expected in this field.

8. Conclusion

Nanomaterials offer unparalleled opportunities in advancing biomedical applications. Their ability to enable targeted drug delivery, enhance imaging techniques, and support tissue regeneration underscores their potential. However, addressing challenges such as toxicity, regulatory compliance, and long-term sustainability remains critical. Future research directions should focus on designing safer and multifunctional nanomaterials that align with personalized medicine goals.

Conflict of interest: The author declares no conflict of interest.

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