

## ADVANCED MATERIALS & NANOTECHNOLOGY: RECENT ADVANCES, APPLICATIONS AND FUTURE PERSPECTIVES

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**Article Info:** Received: 20 August 2026, Revised: 10 September 2026, Accepted: 30 September 2026

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**DOI:** <https://doi.org/10.5281/zenodo.23245634>



### Citation:

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### ABSTRACT

Advanced materials and nanotechnology have become important areas of pharmaceutical, biomedical and healthcare research. The development of materials with controlled size, composition, surface properties and functionality has created new opportunities for drug delivery, diagnosis, tissue engineering and therapeutic applications. This review discusses the fundamental concepts of advanced materials and nanotechnology, their classification, preparation methods, characterization techniques, pharmaceutical applications, advantages, limitations, safety considerations and future perspectives. Particular attention is given to polymeric nanoparticles, lipid nanoparticles, liposomes, metallic nanoparticles, magnetic nanoparticles, dendrimers, nanogels, smart biomaterials and biomimetic systems. Nanotechnology can improve drug solubility, stability, bioavailability, controlled release and targeted delivery, while also enabling applications in cancer therapy, gene delivery, vaccines, diagnostics, tissue engineering and theranostics. However, toxicity, reproducibility, scale-up, characterization, long-term stability and regulatory requirements remain important challenges. Future progress will depend on multidisciplinary research, standardized characterization, quality-by-design approaches and robust safety evaluation.

**KEYWORDS:** Advanced materials; Nanotechnology; Nanomaterials; Nanoparticles; Nanomedicine; Drug delivery; Polymeric nanoparticles; Lipid nanoparticles; Magnetic nanoparticles; Targeted drug delivery; Biomedical applications; Theranostics.

### INTRODUCTION

Advanced materials are materials engineered to possess improved or novel properties compared with conventional materials. Their properties can be modified through control of composition, structure, morphology, particle size, surface chemistry and processing conditions. Advanced materials include polymers, ceramics, metals, composites, biomaterials and smart or stimuli-responsive materials.<sup>[16-22]</sup>

Nanotechnology focuses on understanding and controlling matter at very small dimensions, commonly around the 1–100 nm scale, where materials can display physicochemical or biological properties that differ from their larger-scale counterparts.<sup>[1-5]</sup> In pharmaceutical science, nanotechnology has created new approaches for overcoming limitations of conventional dosage forms. Nanocarriers can protect active pharmaceutical ingredients from degradation, improve aqueous solubility, modify pharmacokinetics and facilitate controlled or targeted delivery.<sup>[23-31]</sup>

Different nanocarrier systems have been developed, including liposomes, polymeric nanoparticles, lipid nanoparticles, solid lipid nanoparticles, nanostructured lipid carriers, dendrimers, nanogels, metallic nanoparticles and magnetic nanoparticles.<sup>[32-42]</sup> The field has progressed from simple nanoparticle formulations toward multifunctional and intelligent systems capable of responding to biological or external stimuli.<sup>[43-50]</sup>

## MATERIAL AND METHODS

### objectives of the review

To explain the concept of advanced materials.

To describe the fundamental principles of nanotechnology.

To classify different types of nanomaterials.

To discuss important preparation techniques.

To describe characterization methods used for nanomaterials.

To evaluate pharmaceutical and biomedical applications.

To compare major nanocarrier systems.

To discuss safety, regulatory considerations and future perspectives.

## 3. ADVANCED MATERIALS

Advanced materials are designed to provide specific functional properties that may not be achieved with conventional materials. In pharmaceutical and biomedical applications, important characteristics include biocompatibility, biodegradability, mechanical strength, chemical stability, surface functionality and responsiveness to biological stimuli.<sup>[16-22]</sup>

### 3.1 Classification of Advanced Materials

## 4. NANOTECHNOLOGY AND NANOMATERIALS

Nanotechnology involves the design and application of materials and systems at the nanoscale. At this scale, changes in surface area, surface chemistry, optical behaviour, magnetic properties and interactions with biological systems may occur.<sup>[1-5]</sup> Nanomaterials can be classified according to their composition, dimensionality and structure.

Polymeric nanoparticles

Lipid nanoparticles

Liposomes

Solid lipid nanoparticles

Nanostructured lipid carriers

Metallic nanoparticles

Magnetic nanoparticles

Dendrimers

Nanogels

Polymeric micelles

Nanoemulsions

Nanocrystals

Carbon-based nanomaterials

Mesoporous silica nanoparticles

Biomimetic and cell-derived nanoparticles

## 5. TYPES OF PHARMACEUTICAL NANOCARRIERS

### 5.1 Polymeric Nanoparticles

Polymeric nanoparticles are nanosized carriers prepared using biodegradable or biocompatible polymers such as PLGA, PLA, PEG and chitosan. Their size, surface chemistry, architecture and drug-release properties can be modified according to therapeutic requirements.<sup>[16,23,24]</sup>

### 5.2 Liposomes

Liposomes are vesicular systems composed mainly of phospholipid bilayers. They can encapsulate hydrophilic drugs within the aqueous core and incorporate lipophilic drugs into the lipid bilayer.<sup>[32-34]</sup>

### 5.3 Lipid Nanoparticles

Lipid nanoparticles are important delivery systems for nucleic acids and other therapeutics. Their development has been strongly accelerated by the clinical success of mRNA vaccines.<sup>[35,36]</sup>

### 5.4 Solid Lipid Nanoparticles

Solid lipid nanoparticles consist of a solid lipid matrix stabilized by surfactants. They have been investigated for controlled drug delivery and improved stability.<sup>[38]</sup>

### 5.5 Nanostructured Lipid Carriers

Nanostructured lipid carriers combine solid and liquid lipids and can provide increased loading capacity for selected active ingredients.<sup>[39]</sup>

### 5.6 Metallic Nanoparticles

Gold, silver, iron oxide and other metallic nanoparticles have been investigated for drug delivery, imaging, antimicrobial applications and theranostics.<sup>[18,19,40]</sup>

### 5.7 Magnetic Nanoparticles

Magnetic nanoparticles, particularly iron oxide nanoparticles, can respond to external magnetic fields and have applications in targeted delivery, imaging and hyperthermia.<sup>[41,42]</sup>

### 5.8 Dendrimers

Dendrimers are highly branched nanoscale macromolecules with multiple surface functional groups that can be modified for drug attachment, targeting or solubility enhancement.<sup>[45]</sup>

### 5.9 Nanogels

Nanogels are nanosized cross-linked polymer networks capable of absorbing large quantities of water. Their soft and responsive structure supports delivery of drugs and biomolecules.<sup>[46]</sup>

## 6. PREPARATION OF NANOMATERIALS

Nanomaterials can be prepared by top-down or bottom-up approaches. Selection of method depends on material composition, target particle size, morphology, drug properties, desired scalability and final application.

## 7. CHARACTERIZATION OF NANOMATERIALS

Characterization is essential because changes in size, morphology, surface charge, composition and aggregation can influence the performance and safety of nanomaterials.<sup>[1–3,54]</sup>

## 8. PHARMACEUTICAL APPLICATIONS

### 8.1 Improvement of Solubility

Poor aqueous solubility is a major limitation for many active pharmaceutical ingredients. Nanocrystals, polymeric nanoparticles and lipid systems can increase effective surface area and improve dissolution behavior.<sup>[63,64]</sup>

### 8.2 Improvement of Bioavailability

Nanotechnology can improve bioavailability by modifying dissolution, protecting drugs from degradation and improving interaction with biological barriers.<sup>[23–31]</sup>

### 8.3 Controlled Drug Release

Nanocarriers can be designed to release drugs slowly or in response to specific environmental conditions, potentially reducing dosing frequency.

### 8.4 Targeted Drug Delivery

Nanocarriers can be modified with ligands, antibodies, peptides or other targeting molecules to improve interaction with selected cells or tissues.<sup>[65–67]</sup>

### 8.5 Cancer Therapy

Nanotechnology has been investigated for cancer drug delivery, imaging, photothermal therapy, photodynamic therapy and theranostics.<sup>[68–71]</sup>

### 8.6 Gene and Nucleic-Acid Delivery

Nanotechnology provides platforms for DNA, RNA, siRNA and mRNA delivery. Lipid nanoparticles can protect nucleic acids and facilitate cellular delivery.<sup>[35,36]</sup>

### 8.7 Vaccine Delivery

Nanoparticles can act as antigen carriers or adjuvant systems and are being investigated in infectious-disease and cancer vaccines.<sup>[72]</sup>

### 8.8 Brain Drug Delivery

Nanocarriers are being investigated to improve delivery across or around biological barriers to the central nervous system.<sup>[73]</sup>

### 8.9 Antimicrobial Applications

Silver nanoparticles and other functional nanomaterials have been studied for antimicrobial activity.<sup>[74]</sup>

### 8.10 Tissue Engineering

Advanced biomaterials and nanostructured scaffolds can provide environments supporting cell attachment, proliferation and tissue regeneration.<sup>[20,75]</sup>

## 9. BIOMEDICAL APPLICATIONS

Particle size and distribution Surface properties  
Chemical composition Aggregation Stability Distribution  
Cellular uptake Immunological effects Genotoxicity  
Organ accumulation Elimination.

## 10. SMART AND STIMULI-RESPONSIVE NANOMATERIALS

Smart nanomaterials are designed to respond to specific biological or external stimuli. These systems may release therapeutic cargo more selectively according to local pH, temperature, light, magnetic field, enzymes or redox conditions.<sup>[76]</sup>

## 11. BIOMIMETIC AND CELL-DERIVED NANOMATERIALS

Biomimetic nanomaterials attempt to reproduce selected functions of biological systems. Cell membranes can be used to modify nanoparticle surfaces and may provide biological recognition and targeting properties.<sup>[43,44]</sup> Cell-derived nanomaterials represent a growing area in which natural cellular structures are incorporated into nanoscale systems.

## 12. ADVANTAGES

Improved drug solubility  
Enhanced dissolution  
Improved bioavailability  
Controlled drug release  
Potential targeted delivery  
Protection of unstable drugs  
Delivery of biological molecules  
Improved intracellular delivery  
Potential reduction in systemic toxicity  
Combination of diagnosis and therapy  
Potential for personalized medicine  
Potential application in tissue engineering

## 13. LIMITATIONS AND CHALLENGES

Safety and toxicity: nanoparticle size, surface properties, dose and route may affect biological responses.  
Scale-up and reproducibility: laboratory processes may be difficult to transfer consistently to larger-scale manufacturing.  
Characterization and stability: multiple analytical methods and long-term stability evaluation may be required.  
Regulatory challenges: complex nanomedicines require product-specific quality, safety and efficacy assessment.

## 14. SAFETY AND TOXICOLOGICAL CONSIDERATIONS

The safety of nanomaterials depends on factors including size, shape, surface chemistry, composition, aggregation, dose and route of administration.<sup>[8,9,78]</sup> Product-specific scientific evaluation is required because the same chemical composition may show different biological behaviour when particle size or surface properties change.<sup>[1–3]</sup>

## 15. REGULATORY CONSIDERATIONS

Nanotechnology-based pharmaceutical products require careful evaluation of quality, safety and efficacy. Regulatory agencies consider the characteristics of individual products rather than treating all nanomaterials as a single category.<sup>[1-3]</sup> FDA guidance emphasizes characterization, critical quality attributes, manufacturing controls, testing and stability considerations for drug products containing nanomaterials.<sup>[1]</sup>

Identification of critical quality attributes  
Control of particle size and distribution  
Control of morphology and aggregation  
Evaluation of manufacturing changes  
Stability assessment  
Evaluation of drug loading and release  
Toxicological evaluation  
Reproducible manufacturing  
Appropriate analytical characterization  
Product-specific regulatory assessment

## 16. FUTURE PERSPECTIVES

The future of advanced materials and nanotechnology is moving toward multifunctional, personalized and biologically responsive systems. Future research is expected to focus on AI-assisted nanomaterial design, machine-learning-based formulation optimization, smart stimuli-responsive nanocarriers, cell-derived nanomaterials, biomimetic nanoparticles, personalized nanomedicine, improved brain drug delivery, advanced cancer theranostics, RNA and gene delivery, continuous manufacturing, microfluidic production, green synthesis, improved biodegradability and standardized characterization.<sup>[43,44,76,80]</sup>

## 17. SUMMARY

Advanced materials and nanotechnology have created new opportunities in pharmaceutical and biomedical sciences. Nanomaterials can be engineered with specific size, morphology, surface properties and functionality. Polymeric nanoparticles, lipid nanoparticles, liposomes,

metallic nanoparticles, magnetic nanoparticles, dendrimers and nanogels have been investigated for a wide range of applications. The major pharmaceutical advantages include improved solubility, enhanced bioavailability, controlled release, protection of active ingredients and targeted delivery. However, successful clinical translation requires reproducible manufacturing, standardized characterization, comprehensive safety assessment, appropriate regulatory strategies and long-term evaluation.

## 18. CONCLUSION

Advanced materials and nanotechnology represent important platforms for the future development of innovative pharmaceutical and biomedical products. Their ability to modify drug distribution, improve delivery and provide controlled or targeted therapeutic effects makes them highly attractive for modern drug-development strategies. Future development should combine materials science, pharmaceuticals, nanotechnology, pharmacology, toxicology, engineering and regulatory science to support safer, more effective and clinically translatable advanced nanomedicines.

## ACKNOWLEDGMENTS

The authors express their gratitude to the management and faculty members of the institution for their academic support, guidance and encouragement during the preparation of this review article.

## STATEMENTS AND DECLARATIONS

Funding

No specific external funding was received for the preparation of this review article.

Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

The authors contributed to the literature review, organization of information and preparation of the manuscript.

**Table 1: Classification of Advanced Materials.**

| Material class       | Examples                    | Important properties               | Application                        | Reference |
|----------------------|-----------------------------|------------------------------------|------------------------------------|-----------|
| Polymeric materials  | PLGA, PEG, chitosan         | Biodegradable, modifiable          | Drug delivery                      | [16,17]   |
| Metallic materials   | Gold, silver                | Optical, electrical, antimicrobial | Diagnostics, antimicrobial systems | [18,19]   |
| Ceramic materials    | Silica, hydroxyapatite      | Stable, biocompatible              | Tissue engineering                 | [20]      |
| Composite materials  | Polymer-ceramic composites  | Improved mechanical properties     | Implants, scaffolds                | [21]      |
| Smart materials      | Stimuli-responsive polymers | Response to environmental changes  | Controlled delivery                | [22]      |
| Biomimetic materials | Cell-membrane systems       | Biological recognition             | Targeted delivery                  | [43,44]   |

**Table 2: Major Pharmaceutical Nanocarriers.**

| Nanocarrier                   | Key feature                          | Major application                    | Reference  |
|-------------------------------|--------------------------------------|--------------------------------------|------------|
| Polymeric nanoparticles       | Biodegradable polymer-based carriers | Controlled drug delivery             | [16,23]    |
| Liposomes                     | Phospholipid bilayer vesicles        | Hydrophilic/lipophilic drug delivery | [32–34]    |
| Lipid nanoparticles           | Lipid-based nucleic-acid carriers    | Gene and mRNA delivery               | [35,36]    |
| Solid lipid nanoparticles     | Solid lipid matrix                   | Controlled delivery and stability    | [38]       |
| Nanostructured lipid carriers | Solid + liquid lipids                | Improved loading capacity            | [39]       |
| Metallic nanoparticles        | Gold/silver/iron oxide systems       | Imaging, antimicrobial, theranostics | [18,19,40] |
| Magnetic nanoparticles        | Magnetic responsiveness              | Targeting, imaging, hyperthermia     | [41,42]    |
| Dendrimers                    | Highly branched macromolecules       | Drug attachment/targeting            | [45]       |
| Nanogels                      | Cross-linked water-swollen networks  | Drug and biomolecule delivery        | [46]       |

**Table 3: Preparation Methods of Nanomaterials.**

| Method                             | Principle                                      | Major advantage         | Limitation                            | Reference |
|------------------------------------|------------------------------------------------|-------------------------|---------------------------------------|-----------|
| Nanoprecipitation                  | Polymer precipitates from solution             | Simple and reproducible | Solvent selection required            | [16,47]   |
| Emulsification–solvent evaporation | Formation and evaporation of emulsion droplets | Useful for many drugs   | Organic solvent may be required       | [47]      |
| High-pressure homogenization       | High-energy particle size reduction            | Suitable for scale-up   | Specialized equipment                 | [48]      |
| Ultrasonication                    | Acoustic energy reduces particle size          | Rapid processing        | Possible heating                      | [49]      |
| Ionic gelation                     | Electrostatic interaction between polymers     | Mild conditions         | Polymer dependent                     | [50]      |
| Thin-film hydration                | Lipid film hydrated to form vesicles           | Common for liposomes    | Additional size control may be needed | [32]      |
| Microfluidic mixing                | Controlled rapid mixing                        | Good reproducibility    | Equipment cost                        | [36,51]   |

**Table 4: Characterization Techniques for Nanomaterials.**

| Parameter                  | Technique      | Purpose                      | Reference |
|----------------------------|----------------|------------------------------|-----------|
| Particle size              | DLS            | Hydrodynamic diameter        | [54]      |
| Particle-size distribution | DLS/PDI        | Size uniformity              | [54]      |
| Morphology                 | TEM/SEM        | Shape and surface structure  | [54,55]   |
| Surface charge             | Zeta potential | Electrostatic stability      | [56]      |
| Chemical structure         | FTIR           | Functional groups            | [57]      |
| Crystallinity              | XRD            | Crystalline/amorphous nature | [58]      |
| Thermal behaviour          | DSC/TGA        | Thermal stability            | [59]      |
| Drug content               | HPLC/UV        | Drug concentration           | [60]      |
| Encapsulation efficiency   | HPLC/UV        | Amount encapsulated          | [60]      |

**Table 5: Pharmaceutical and Biomedical Applications.**

| Application           | Nanomaterial                  | Function                  | Reference |
|-----------------------|-------------------------------|---------------------------|-----------|
| Drug delivery         | Polymeric nanoparticles       | Controlled delivery       | [16,23]   |
| Gene delivery         | Lipid nanoparticles           | Nucleic-acid delivery     | [35,36]   |
| Cancer diagnosis      | Gold nanoparticles            | Imaging/sensing           | [69]      |
| MRI                   | Magnetic nanoparticles        | Contrast enhancement      | [41,42]   |
| Tissue engineering    | Nanocomposites                | Scaffolding               | [20,75]   |
| Antimicrobial therapy | Silver nanoparticles          | Antimicrobial activity    | [74]      |
| Brain delivery        | Nanocarriers                  | Brain-delivery strategies | [73]      |
| Theranostics          | Multifunctional nanoparticles | Diagnosis + therapy       | [68–71]   |

**Table 6: Smart and Stimuli-Responsive Nanomaterials.**

| Stimulus          | Example                  | Mechanism                      | Application            | Reference |
|-------------------|--------------------------|--------------------------------|------------------------|-----------|
| pH                | pH-sensitive polymer     | Ionization/swelling            | Tumour/GI delivery     | [22,76]   |
| Temperature       | Thermoresponsive polymer | Phase transition               | Controlled release     | [76]      |
| Light             | Photoresponsive material | Photochemical/thermal response | Cancer therapy         | [69,77]   |
| Magnetic field    | Magnetic nanoparticles   | Magnetic response              | Targeting/imaging      | [41,70]   |
| Enzymes           | Enzyme-sensitive carrier | Enzymatic degradation          | Site-specific delivery | [76]      |
| Redox environment | Redox-sensitive carrier  | Bond cleavage/reduction        | Intracellular delivery | [76]      |

**Table 7: Limitations and Challenges.**

| Challenge              | Description                                     | Possible approach                  | Reference |
|------------------------|-------------------------------------------------|------------------------------------|-----------|
| Toxicity               | Unwanted biological effects may occur           | Detailed toxicological evaluation  | [8,9,78]  |
| Aggregation            | Particles may change size during storage        | Stabilizer optimization            | [1,3]     |
| Scale-up               | Laboratory methods may be difficult to transfer | Continuous/microfluidic processing | [36,51]   |
| Reproducibility        | Small process changes can alter CQAs            | QbD and process control            | [1,3]     |
| Characterization       | Multiple techniques may be required             | Orthogonal characterization        | [54,55]   |
| Regulatory uncertainty | Complex products may need additional assessment | Early regulatory interaction       | [1–3]     |
| Long-term safety       | Biological fate may remain uncertain            | Extended preclinical studies       | [8,78]    |

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