



The Journal of Multidisciplinary Research (TJMDR)

Content Available at www.saap.org.in

ISSN: 2583-0317



NANOPARTICLES AND THEIR APPLICATIONS IN BIOLOGY

J. Ajani^{1,*}

Department of Biochemistry, Yogi Vemana University, Kadapa - 516 005, Andhra Pradesh, India

Received: 22 Oct 2023 Revised: 09 Nov 2023 Accepted: 15 Dec 2023

Abstract

Nanoparticles are materials with dimensions generally ranging from 1 to 100 nm and have attracted considerable attention because their physicochemical properties differ from those of bulk materials. Their small size, high surface-area-to-volume ratio, optical and magnetic properties, and modifiable surfaces make them valuable tools in biological research and medicine. Nanoparticles have been investigated for applications in drug delivery, gene delivery, bioimaging, biosensing, cancer therapy, antimicrobial treatment, tissue engineering, and regenerative medicine. Different types of nanoparticles, including metallic, magnetic, polymeric, lipid, silica, and semiconductor nanoparticles, possess distinct properties that can be tailored for specific biological applications. In particular, lipid nanoparticles have become important carriers for nucleic acids, while gold and magnetic nanoparticles have shown promise in imaging and cancer therapy. Despite their potential, issues related to toxicity, biodistribution, stability, immune responses, and large-scale manufacturing remain important challenges. This article reviews the major types of nanoparticles and their applications in biology, with emphasis on their therapeutic, diagnostic, and research uses.

Keywords: Nanoparticles; Nanobiotechnology; Nanomedicine; Drug Delivery; Bioimaging; Biosensing; Gene Delivery; Cancer Therapy; Antimicrobial Activity.

This article is licensed under a Creative Commons Attribution-Non Commercial 4.0 International License.

Copyright © 2023 Author(s) retains the copyright of this article.



*Corresponding Author

J. Ajani

Produced and Published by

South Asian Academic Publications

Nanoparticles can improve the solubility and stability of poorly soluble drugs, provide controlled release, protect nucleic acids from degradation, and facilitate delivery to particular tissues or cells [2,4]. They can also act as imaging probes and biosensing platforms because of their optical, magnetic, electrical, and catalytic properties.

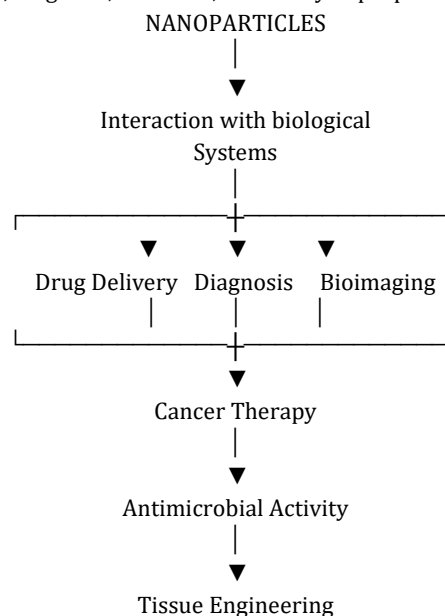


Figure 01: Short flow chart showing applications of nanoparticles in biology

Introduction

Nanotechnology is an interdisciplinary field involving the design and application of materials and structures at the nanometer scale. Nanoparticles are among the most widely studied nanomaterials because their small dimensions result in unique physical, chemical, optical, magnetic, and biological properties. Their high surface-area-to-volume ratio and ability to undergo surface modification make them particularly useful for interactions with biological molecules and cells [1,2].

Nanoparticles can be engineered with different sizes, shapes, compositions, surface charges, and functional groups to achieve specific biological functions. They may interact with proteins, nucleic acids, cell membranes, microorganisms, and tissues. These characteristics have led to their application in drug delivery, molecular imaging, diagnostics, gene delivery, antimicrobial therapy, cancer treatment, and tissue engineering [1,3].

The development of nanobiotechnology has provided new approaches for addressing limitations associated with conventional therapeutic and diagnostic technologies.

Types of Nanoparticles Used in Biology

Nanoparticles can be classified according to their composition, morphology, and physicochemical properties. The major types used in biological applications include metallic nanoparticles, magnetic nanoparticles, polymeric nanoparticles, lipid nanoparticles, quantum dots, silica nanoparticles, and dendrimers.

Table 01: Major types of nanoparticles and their biological applications

Type of nanoparticle	Major properties	Important biological applications
Gold nanoparticles	Optical properties, surface functionalization	Biosensing, imaging, drug delivery, cancer therapy [5]
Silver nanoparticles	Antimicrobial activity	Antimicrobial therapy, wound treatment, coatings [6]
Iron oxide nanoparticles	Magnetic properties	MRI, drug delivery, cell separation, hyperthermia [7]
Polymeric nanoparticles	Biodegradability, controlled release	Drug and gene delivery [8]
Lipid nanoparticles	Nucleic-acid encapsulation, biocompatibility	mRNA, siRNA and gene delivery [9]
Quantum dots	Strong and tunable fluorescence	Bioimaging, cell tracking, biosensing [10]
Silica nanoparticles	High surface area and tunable pores	Drug delivery, imaging, biosensing [11]
Dendrimers	Branched structure and multiple surface groups	Drug delivery, gene delivery, imaging [12]

Metallic Nanoparticles

Metallic nanoparticles, particularly gold and silver nanoparticles, have been extensively investigated in biological applications. Gold nanoparticles possess unique optical properties associated with surface plasmon resonance. Their surfaces can also be easily functionalized with antibodies, peptides, DNA, RNA, and other biomolecules [5].

These properties make gold nanoparticles useful in biosensing, molecular imaging, drug delivery, and cancer therapy. Gold nanoparticles have been investigated for

photothermal therapy, in which absorbed light energy is converted into heat that can damage tumor cells [5].

Silver nanoparticles are particularly well known for their antimicrobial activity. They can interact with microbial membranes and cellular components and may produce reactive oxygen species and release silver ions. These mechanisms can contribute to antibacterial and antifungal effects [6]. Consequently, silver nanoparticles have been studied for antimicrobial coatings, wound dressings, medical devices, and other applications.

Magnetic Nanoparticles

Magnetic nanoparticles, especially iron oxide nanoparticles, have important applications in biology and medicine. Their response to an external magnetic field allows them to be manipulated, separated, and localized. Iron oxide nanoparticles have been investigated as contrast agents for magnetic resonance imaging (MRI), carriers for targeted drug delivery, and agents for magnetic hyperthermia [7].

In magnetic hyperthermia, magnetic nanoparticles generate heat when exposed to an alternating magnetic field. This heat can potentially damage tumor cells and may be combined with other therapeutic approaches. Magnetic nanoparticles have also been used experimentally for cell separation and purification because specific cells or biological molecules can be attached to their surfaces and subsequently separated using a magnetic field [7].

Polymeric Nanoparticles

Polymeric nanoparticles are commonly prepared using biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA). They can encapsulate therapeutic compounds and provide controlled or sustained drug release. The polymer composition and particle characteristics can be modified to regulate degradation and drug-release rates [8].

One important advantage of polymeric nanoparticles is their ability to protect therapeutic molecules from degradation. They have therefore been investigated for delivery of anticancer drugs, antibiotics, proteins, peptides, and nucleic acids. Surface modification can further improve their stability and interaction with target cells [4,8].

Lipid Nanoparticles

Lipid nanoparticles have become particularly important for the delivery of nucleic acids. RNA molecules are susceptible to enzymatic degradation and have difficulty crossing cell membranes. Lipid nanoparticles can encapsulate RNA, protect it from degradation, and facilitate cellular uptake [9].

The development of lipid nanoparticle systems for mRNA delivery represented a major advance in nanomedicine. Before 2022, lipid nanoparticles had already been successfully developed as delivery systems for mRNA

vaccines, demonstrating their potential for clinical applications [9,13]. Lipid nanoparticles have also been investigated for the delivery of small interfering RNA (siRNA), messenger RNA, and other nucleic acids. Their ability to transport genetic material into cells makes them important tools for gene therapy, vaccination, and molecular medicine [9].

Quantum Dots

Quantum dots are semiconductor nanocrystals with unique optical properties. Their fluorescence depends on particle size and composition, allowing their emission characteristics to be adjusted. They are highly fluorescent and relatively resistant to photobleaching, making them useful biological labels [10]. Quantum dots have been used experimentally for cell labeling, molecular imaging, protein detection, and cellular tracking. Their ability to produce different fluorescence signals can also facilitate simultaneous detection of multiple biological targets. However, potential toxicity associated with certain quantum-dot compositions remains an important limitation for biomedical applications [10].

Silica Nanoparticles and Dendrimers

Silica nanoparticles possess high surface areas and tunable pore structures. These characteristics allow them to accommodate therapeutic molecules and other biological agents. Mesoporous silica nanoparticles have therefore been investigated for drug delivery and imaging applications [11].

Dendrimers are highly branched nanoscale polymers with numerous surface functional groups. These groups can be modified with drugs, targeting molecules, imaging agents, or nucleic acids. Their well-defined structure makes dendrimers attractive carriers for drug and gene delivery [12].

Applications in Drug Delivery

Drug delivery is one of the most important applications of nanoparticles. Conventional drug administration can result in poor solubility, rapid degradation, short circulation times, nonspecific distribution, and systemic toxicity. Nanoparticles can overcome some of these limitations by encapsulating drugs and modifying their distribution and release [2,4].

A drug may be incorporated inside a nanoparticle, attached to its surface, or chemically linked to the nanoparticle. The nanoparticle can protect the drug and provide controlled release. This approach may improve therapeutic effectiveness and reduce exposure of healthy tissues [4].

Nanoparticles can also be designed for targeted drug delivery. Passive targeting depends on physiological characteristics of diseased tissues, whereas active targeting involves attaching molecules such as antibodies, peptides, aptamers, or ligands to the nanoparticle surface

[14]. These targeting strategies have been extensively investigated in cancer therapy.

Applications in Gene and Nucleic Acid Delivery

Nucleic acids such as DNA, mRNA, and siRNA have significant therapeutic potential. However, their clinical use is limited by instability, degradation by nucleases, poor cellular uptake, and difficulty crossing biological membranes. Nanoparticles can provide protection and facilitate intracellular delivery [9].

Lipid nanoparticles are among the most successful systems for RNA delivery. They can encapsulate RNA and facilitate its entry into cells. This technology has been used in mRNA-based vaccines and has encouraged further research into RNA-based treatments for infectious diseases, cancer, and genetic disorders [9,13].

Polymeric nanoparticles, dendrimers, and other nanocarriers have also been investigated for DNA and siRNA delivery. Important challenges include efficient cellular uptake, endosomal escape, tissue-specific delivery, and minimizing unwanted immune responses.

Applications in Bioimaging

Nanoparticles have important applications in biological imaging because they can generate optical, magnetic, or other detectable signals. Quantum dots, for example, can provide bright and stable fluorescence and have been used to visualize cells and biomolecules [10].

Gold nanoparticles have optical properties that can be exploited for imaging and detection [5]. Magnetic nanoparticles are particularly useful in MRI because their magnetic properties can modify the relaxation characteristics of surrounding water molecules, thereby improving image contrast [7].

Multifunctional nanoparticles can combine imaging agents with therapeutic compounds. Such systems are referred to as **nanotheranostic platforms** because they integrate diagnostic and therapeutic functions [15].

Applications in Biosensing and Diagnostics

Nanoparticles are valuable components of biosensors because of their large surface area and unique optical, electrical, magnetic, and catalytic properties. Their surfaces can be functionalized with antibodies, enzymes, nucleic acids, aptamers, and other recognition molecules.

Gold nanoparticles have been used in colorimetric and optical biosensors because their optical properties change following particle aggregation or interaction with target molecules [5]. Nanoparticle-based biosensors have been investigated for detection of proteins, nucleic acids, pathogens, enzymes, and other biomarkers.

Aptamer-functionalized nanoparticles have also been studied for sensitive detection of biological targets. Aptamers are short nucleic acid molecules capable of selectively binding specific molecules and can be combined with nanoparticles to produce sensitive diagnostic systems [16].

Applications in Cancer Therapy

Cancer is one of the major areas of nanomedicine research. Nanoparticles can improve the delivery of anticancer drugs and may help reduce systemic toxicity. They can also be designed to carry multiple therapeutic agents or combine therapy with imaging [17,18].

Nanoparticles may deliver chemotherapeutic drugs directly or preferentially to tumors. Surface modification with targeting ligands can facilitate interaction with tumor-associated receptors. In addition, nanoparticles can be engineered to respond to characteristics of the tumor microenvironment, including pH, enzymes, temperature, and redox conditions [15,17].

Gold nanoparticles have been investigated for photothermal therapy, whereas magnetic nanoparticles can be used for magnetic hyperthermia [5,7]. Nanoparticles can also be used to deliver nucleic acids and immune-modulating molecules, creating opportunities for combination cancer therapies [17,18].

Antimicrobial Applications

The increasing prevalence of antimicrobial resistance has stimulated interest in alternative antimicrobial strategies. Nanoparticles possess several mechanisms of antimicrobial activity and have therefore been investigated against bacteria and fungi.

Silver nanoparticles are among the most extensively studied antimicrobial nanoparticles. Their activity may involve membrane damage, oxidative stress, interaction with proteins and nucleic acids, and release of silver ions [6].

Other nanoparticles, including zinc oxide, titanium dioxide, copper oxide, and gold nanoparticles, have also demonstrated antimicrobial properties. Potential applications include antimicrobial coatings, wound dressings, medical devices, and infection-control materials.

However, antimicrobial effectiveness must be balanced against toxicity toward human cells. Factors such as nanoparticle size, concentration, surface chemistry, and exposure time can influence both antimicrobial activity and biological safety.

Applications in Tissue Engineering and Regenerative Medicine

Nanoparticles have also been investigated in tissue engineering and regenerative medicine. They can be incorporated into scaffolds or used as carriers for growth factors, proteins, genes, and drugs.

Nanostructured materials may provide physical and biochemical characteristics that influence cell attachment, proliferation, migration, and differentiation. Nanoparticles can also provide additional functions such as antimicrobial activity or controlled release of bioactive molecules.

For example, polymeric nanoparticles can be incorporated into biomaterial scaffolds to provide sustained release of therapeutic molecules. Such systems may be useful in

bone, cartilage, skin, and other tissue-regeneration applications.

Applications in Molecular and Cellular Biology

Nanoparticles have become useful research tools for studying molecular and cellular processes. Fluorescent nanoparticles can label cells, proteins, and intracellular structures, while magnetic nanoparticles can facilitate separation and manipulation of cells and biomolecules [7,10].

Nanoparticles can also be functionalized with specific biological molecules, allowing selective interactions with cellular receptors. This makes them useful for studying cellular uptake, receptor expression, intracellular trafficking, and molecular interactions.

Their ability to transport biological molecules into cells has further expanded their use in experimental gene regulation and molecular biology.

Toxicity and Biosafety

Despite their considerable potential, nanoparticles may produce biological effects that depend on their physicochemical properties. Size, shape, surface charge, composition, aggregation, dose, route of administration, and exposure duration can all influence nanoparticle toxicity [2,19].

Following administration, nanoparticles interact with proteins and other biomolecules, producing a dynamic layer known as the protein corona. This protein layer can alter nanoparticle stability, cellular uptake, biodistribution, and biological activity [19].

Potential adverse effects include oxidative stress, inflammation, membrane damage, genotoxicity, and immune responses. Some nanoparticles may accumulate in organs such as the liver and spleen. Therefore, comprehensive evaluation of toxicity, metabolism, clearance, and long-term biological effects is essential before clinical application [2,19].

Challenges and Future Perspectives

Several challenges must be addressed before the full potential of nanoparticles can be realized. One major challenge is the difference between nanoparticle behavior in laboratory models and in humans. Biological barriers, immune responses, protein corona formation, and tissue heterogeneity can influence nanoparticle performance [19].

Another challenge is the reproducible large-scale manufacture of nanoparticles. Small variations in size, surface chemistry, composition, or drug loading may alter their biological behavior. Therefore, standardized manufacturing and characterization methods are essential. Targeted delivery also remains challenging. Although nanoparticles can be functionalized with targeting ligands, biological systems may prevent nanoparticles from reaching their intended targets efficiently. Nonspecific uptake by the mononuclear phagocyte system and

interactions with serum proteins can reduce targeting efficiency [14,19].

Future research is expected to focus on biodegradable nanoparticles, precision drug-delivery systems, stimuli-responsive nanoparticles, multifunctional nanotheranostics, and improved nucleic-acid delivery. Advances in computational modelling and artificial intelligence may also contribute to the design and optimization of nanoparticles.

Conclusion

Nanoparticles have become important tools in modern biology and medicine because their unique physicochemical properties can be tailored for specific biological applications. They have been investigated for drug delivery, gene delivery, bioimaging, biosensing, cancer therapy, antimicrobial treatment, tissue engineering, and molecular biology. Different nanoparticle systems provide different advantages. Metallic nanoparticles are particularly useful for optical, antimicrobial, and photothermal applications; magnetic nanoparticles are valuable for imaging and magnetic manipulation; polymeric nanoparticles provide controlled drug delivery; lipid nanoparticles are highly effective for nucleic-acid delivery; and quantum dots provide powerful fluorescent probes. Although nanoparticle-based technologies have demonstrated considerable potential, issues related to toxicity, biodistribution, immune responses, targeting, stability, and manufacturing remain important. Continued interdisciplinary research will be necessary to improve nanoparticle safety and efficacy and to translate promising laboratory technologies into reliable clinical and biological applications.

Funding

No Funding

Author Contribution

All authors are contributed equally.

Conflict of Interest

No Conflict of Interest

Ethical Considerations

Not Required

Acknowledgement

Nil

References

- Salata OV. Applications of nanoparticles in biology and medicine. *J Nanobiotechnology*. 2004;2:3.
- De Jong WH, Borm PJA. Drug delivery and nanoparticles: applications and hazards. *Int J Nanomedicine*. 2008;3(2):133-149.
- Jain KK. Nanotechnology in clinical laboratory diagnostics. *ClinChimActa*. 2005;358(1-2):37-54.
- Torchilin VP. Multifunctional nanocarriers. *Adv Drug Deliv Rev*. 2006;58(14):1532-1555.
- Dreaden EC, Alkilany AM, Huang X, Murphy CJ, El-Sayed MA. The golden age: gold nanoparticles for biomedicine. *ChemSoc Rev*. 2012;41(7):2740-2779.
- Rai M, Yadav A, Gade A. Silver nanoparticles as a new generation of antimicrobials. *Biotechnol Adv*. 2009;27(1):76-83.
- Pankhurst QA, Connolly J, Jones SK, Dobson J. Applications of magnetic nanoparticles in biomedicine. *J Phys D Appl Phys*. 2003;36(13).
- Kumari A, Yadav SK, Yadav SC. Biodegradable polymeric nanoparticles based drug delivery systems. *Colloids Surf B Biointerfaces*. 2010;75(1):1-18.
- Hou X, Zaks T, Langer R, Dong Y. Lipid nanoparticles for mRNA delivery. *Nat Rev Mater*. 2021;6:1078-1094.
- Bruchez M Jr, Moronne M, Gin P, Weiss S, Alivisatos AP. Semiconductor nanocrystals as fluorescent biological labels. *Science*. 1998;281(5385):2013-2016.
- Vallet-Regí M, Balas F, Arcos D. Mesoporous materials for drug delivery. *AngewChemInt Ed Engl*. 2007;46(40):7548-7558.
- Svenson S, Tomalia DA. Dendrimers in biomedical applications—reflections on the field. *Adv Drug Deliv Rev*. 2005;57(15):2106-2129.
- Schoenmaker L, Witzigmann D, Kulkarni JA, Verbeke R, Kersten G, Jiskoot W, et al. mRNA-lipid nanoparticle COVID-19 vaccines: structure and stability. *Int J Pharm*. 2021;601:120586.
- Nag OK, Delehanty JB. Active cellular and subcellular targeting of nanoparticles for drug delivery. *Pharmaceutics*. 2019;11(11):543.
- Lafuente-Gómez N, Latorre A, Milán-Rois P, Rodríguez Díaz C, Somoza Á. Stimuli-responsive nanomaterials for cancer treatment: boundaries, opportunities and applications. *ChemCommun*. 2021;57:13662-13677.
- Kaur H, Shorie M. Nanomaterial based aptasensors for clinical and environmental diagnostic applications. *Nanoscale Adv*. 2019;1:2123-2138.
- Cheng Z, Li M, Dey R, Chen Y. Nanomaterials for cancer therapy: current progress and perspectives. *J HematolOncol*. 2021;14:85.
- Kemp JA, Kwon YJ. Cancer nanotechnology: current status and perspectives. *Nano Converg*. 2021;8:34.
- Monopoli MP, Åberg C, Salvati A, Dawson KA. Biomolecular coronas provide the biological identity of nanosized materials. *Nat Nanotechnol*. 2012;7(12):779-786.
- Mitchell MJ, Billingsley MM, Haley RM, Wechsler ME, Peppas NA, Langer R. Engineering precision nanoparticles for drug delivery. *Nat Rev Drug Discov*. 2021;20:101-124.