Chemical Process Design Vol.4 No.2 (2025) 79-88

University of Sistan
and Baluchestan

Chemical Process Design

Available online at http://cpd.usb.ac.ir/

Nanoparticles in Drilling Fluids and Environmental Applications: Fundamentals, Classification, and Characterization

Fardin Talebi Sarokolai[1], Yousof Shiri[2]✉

[1] Shahrood University of Technology, Faculty of Mining, Petroleum and Geophysics Engineering Shahrood, Iran.
E-mail: f.taleby.ama@shahroodut.ac.ir
[2] Corresponding author, Shahrood University of Technology, Faculty of Mining, Petroleum and Geophysics Engineering Shahrood, Iran.
E-mail: yousefshiri@shahroodut.ac.ir

ARTICLE INFO

Article type:
Research Article

Article history:
Received: 2025-07-01
Received in revised form: 2025-08-14
Accepted: 2025-08-24
Available online: 2025-08-24

Keywords: *Nanomaterials; Metal nanoparticles; Biogenic nanoparticles; Drilling fluid; Nano biotechnology; Characterization of nanomaterials*

ABSTRACT

Nanomaterials-particularly nanoparticles-have garnered significant attention across scientific and industrial domains owing to their distinct physicochemical attributes. Their exceptionally high surface area-to-volume ratio, controllable reactivity, and modifiable optical, electrical, and magnetic properties render them suitable for a wide range of applications, spanning from drug delivery and diagnostics to advanced drilling fluid engineering, where they can improve stability under harsh subsurface conditions. Such features have enabled innovative applications in diverse fields, including medicine, electronics, energy storage, environmental remediation, catalysis, agriculture, and the food industry. Among recent developments, the biological synthesis of nanoparticles using plant extracts and microorganisms has emerged as a sustainable and eco-friendly approach that reduces both production costs and environmental hazards associated with traditional methods. This review provides an in-depth discussion of nanoparticle classifications, physicochemical features, and general approaches to their evaluation. Furthermore, it outlines the key differences in behavior and functionality of materials at the nanoscale, offering useful insight into their performance. Several case studies involving biologically synthesized nanoparticles and their applications are presented to demonstrate their potential across various sectors, offering practical guidance for researchers aiming to adopt green synthesis strategies in their investigations.

Cite this article: Talebi Sarokolai, F., Shiri, Y., (2025), Nanoparticles in Drilling Fluids and Environmental Applications: Fundamentals, Classification, and Characterization, *Chemical Process Design*, 4(2), 79-88. http//doi.org/10.22111/cpd.2025.52493.1064

DOI: http//doi.org/10.22111/cpd.2025.52493.1064

Publisher: University of Sistan and Baluchestan.

1. Introduction

Nanotechnology, though considered a modern field, has been unknowingly utilized for centuries. Ancient Egyptians used nanosized lead sulfide (PbS) particles for hair dyeing, reacting with hair keratin to form stable pigments [1]. The Romans crafted the Lycurgus Cup, which changes color due to the presence of 50–100 nm gold and silver nanoparticles [2]. Other early civilizations, including those in Mesopotamia, India, and the Maya, also harnessed nanoscale processes [3]. Nanomaterials exhibit unique properties due to surface and quantum effects [4]. Their large surface area and high fraction of surface atoms enhance reactivity and catalytic behavior [5]. The reduced atomic neighbors lower binding energy, significantly affecting melting points, as seen in 2.5 nm gold nanoparticles, which melt 407°C lower than bulk gold. Quantum confinement at the nanoscale alters electronic properties, making non-magnetic materials like palladium and platinum magnetic [6]. These features enable applications in catalysis, medicine, and energy storage [7]. However, agglomeration can hinder performance, which can be controlled by modifying zeta potential, hydrophilicity, and pH conditions [8].

2. Material and method

This study was conducted using a structured methodology based on systematic collection, screening, and analysis of previously published data. Relevant literature from 2015 to 2024 was retrieved using academic databases such as Scopus, Web of Science, and PubMed. The search was guided by specific keywords, including “*nanoparticles*”, “*biogenic synthesis*”, “*characterization*”, “*drilling fluid enhancement*” and “*environmental nanotechnology*” Articles were selected based on their experimental outcomes, relevance to drilling fluid systems or environmental applications, and inclusion of specific nanoparticle types with defined properties. Studies focusing on synthesis methods, characterization techniques (e.g., XRD, SEM, zeta potential), and performance evaluation in drilling muds or remediation systems were prioritized. The collected data were categorized and analyzed to extract common trends, identify performance gaps, and compare nanoparticle behaviors across different systems. This structured analysis forms the basis of the comparative insights and performance synthesis presented in the following sections.

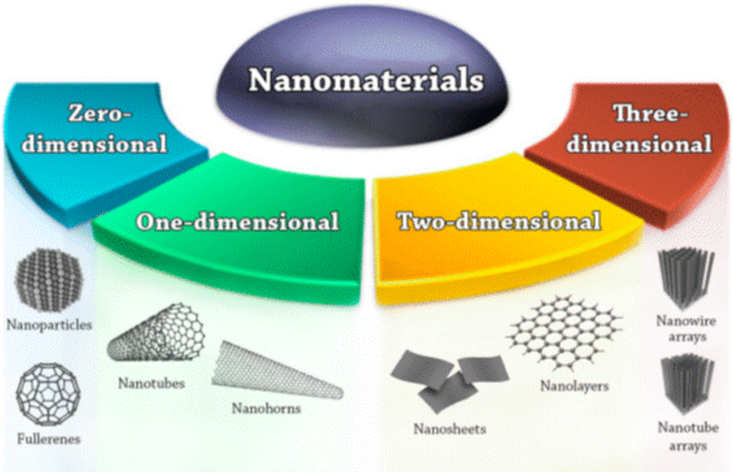

Fig. 1. Nanomaterials classification based on dimensionality [9]

2.1. Classification of nanomaterials

Nanomaterials are classified into four types based on dimensionality (Fig. 1) [9]

(1) 0-D: All dimensions <100 nm (e.g., quantum dots, nanoparticles). Nanomaterials in which all dimensions are less than 100 nm, such as quantum dots and nanoparticles, fall into the zero-dimensional category. These materials are essentially point-like structures with no dimension exceeding 100 nm.
(2) 1-D: One dimension >100 nm (e.g., nanotubes, nanowires). One-dimensional nanomaterials have one dimension larger than 100 nm while the other two dimensions remain below 100 nm. Examples include nanotubes and nanowires, which have a rod-like or tubular shape with nanoscale diameter but potentially much longer length.
(3) 2-D: Two dimensions >100 nm (e.g., nanosheets, nanofilms). Two-dimensional nanomaterials have two dimensions larger than 100 nm and one dimension confined to less than 100 nm. Examples include nanosheets and nanofilms, which have a large surface area but extremely thin thickness at the nanoscale.
(4) 3-D: No nanoscale confinement (e.g., nanoparticle dispersions, nanowire arrays). Three-dimensional nanomaterials have no specific nanoscale confinement in any dimension. This category includes structures like nanoparticle dispersions or nanowire arrays, which are bulk assemblies or collections of nanostructures without strict dimensional nanoscale limitations.

3. Organic nanoparticles (NPs)

These NPs are composed of organic molecules like proteins, lipids, carbohydrates, and polymer. Examples include dendrimers, liposomes, micelles, and ferritin (Fig. 2). They are biodegradable, non-toxic, and often used in drug delivery and cancer treatment due to their biocompatibility and ability to encapsulate substances [10]. For instance, liposomes have been widely used to deliver anticancer drugs due to their ability to evade the immune system and target tumor tissues via the enhanced permeability and retention (EPR) effect. Ferritin, a natural iron-storage protein, can be exploited for targeted delivery to cancer cells via transferrin receptor-mediated endocytosis. Beyond biomedical uses, organic nanoparticles have also found emerging roles in drilling fluid formulations due to their environmental safety and functional versatility. For example, polymeric micelles and liposome-like nanocarriers can encapsulate corrosion inhibitors, fluid-loss additives, or lubricants, allowing for controlled release under high conditions. Their biodegradability makes them attractive for eco-friendly drilling operations, particularly in offshore or environmentally sensitive zones. Furthermore, surface-modified dendrimers can enhance shale inhibition and reduce clay swelling by interacting with negatively charged clay surfaces.

3.1. Types of organic nanoparticles

Dendrimers are highly branched, tree-like structures with a well-defined molecular architecture. They are widely used in biomedical applications, particularly in targeted drug delivery, due to their ability to encapsulate therapeutic agents within their branched structure. Dendrimers can be functionalized with various surface groups to enhance their interaction with biological systems Liposomes are spherical vesicles composed of a lipid bilayer, which can encapsulate both hydrophilic and hydrophobic substances. They are extensively used in drug delivery systems because they can protect drugs from degradation and target specific tissues or cells. Liposomes are also biocompatible and can be engineered to release their payload in response to specific stimulate [11]. Micelles are spherical structures formed by the self-assembly of amphiphilic molecules in aqueous solutions. They have a hydrophobic core and a hydrophilic shell, making them ideal for solubilizing hydrophobic drugs and delivering them to target sites. Micelles are commonly used in cancer therapy and other biomedical applications due to their small size and ability to penetrate tissue. Ferritin is a protein complex that naturally stores iron in a non-toxic form. It has a hollow core, which can be used to encapsulate metal ions or other molecules. Ferritin-based NPs are biocompatible and have potential applications in drug delivery, imaging, and catalysis [10]. Liposomes are spherical vesicles composed of a lipid bilayer, capable of encapsulating both hydrophilic and hydrophobic substances. In biomedical contexts, they have shown efficiency in protecting therapeutic agents from enzymatic degradation and facilitating targeted drug delivery. Similarly, in drilling fluid systems, liposome-like nanocarriers have been explored for encapsulating corrosion inhibitors or fluid loss additives, enabling controlled release under high degree conditions. The biocompatibility and tunable surface chemistry of liposomes offer advantages in both domains; however, their thermal stability remains a limitation in deep-well drilling applications.

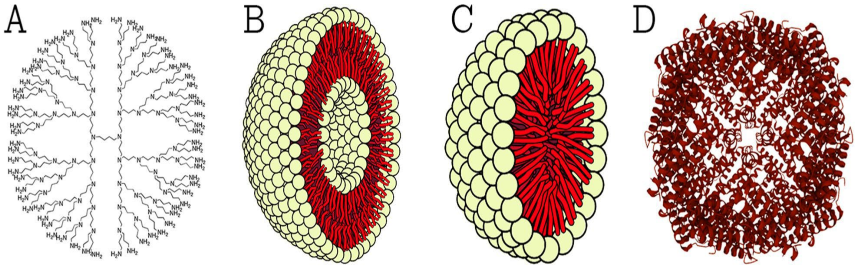

Fig. 2. Types of organic NPs: (A) dendrimers; (B) liposomes; (C) micelles; and (D) ferritin [11]

3.2. Carbon-based nanoparticles (NPs)

These NPs consist entirely of carbon atoms and include fullerenes, carbon black, and carbon quantum dots (Fig. 3) [10]. Fullerenes, such as C60, have cage-like structures, while carbon black forms aggregated clusters. Their high electrical conductivity, strength, and optical properties make them useful in various applications [12]. C60 fullerene, also known as Buckminsterfullerene, is a symmetrical, closed-cage carbon molecule composed of 60 carbon atoms arranged in a soccer ball-like structure. It is characterized by its high electron affinity, optical properties, and potential applications in electronics, photovoltaics, and biomedicine. Other types of fullerenes, such as C70 and C540, have also been described [13].

Carbon black NPs are aggregates of highly fused spherical carbon particles, resembling a grape-like structure. They are widely used in industrial applications, such as rubber reinforcement, conductive materials, and pigments. Carbon black NPs also have applications in environmental sensing and catalysis due to their large surface area and electrical conductivity [14]. Carbon quantum dots (CQDs) are small, quasi-spherical carbon nanoparticles with sizes below 10 nm. They exhibit unique optical properties, including photoluminescence, making them suitable for applications in bioimaging, drug delivery, and environmental monitoring. CQDs are also biocompatible and can be synthesized from various carbon source [15]. Carbon-based nanoparticles, due to their high mechanical strength, thermal stability, and electrical conductivity, are increasingly utilized in drilling fluid systems. Carbon black and graphene derivatives, for instance, improve the thermal conductivity and lubricity of drilling muds, helping to dissipate heat and reduce torque during deep-well drilling. Carbon quantum dots, with their tunable surface chemistry, have also been explored for shale stabilization and filtration control. Their nano-size allows them to penetrate into fine pore spaces in the formation, forming a thin but impermeable sealing layer that minimizes fluid invasion and formation damage.

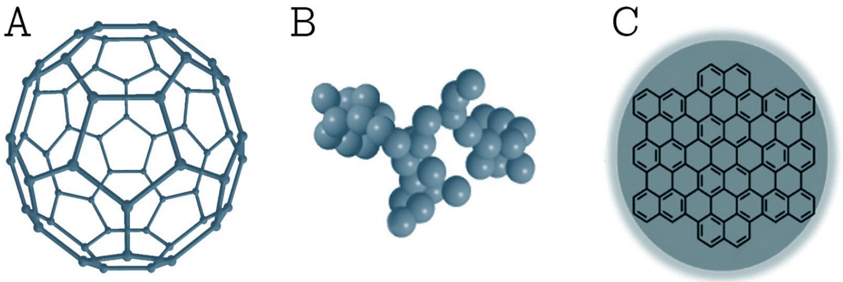

Fig. 3. Different types of carbon-based NPs: (A) C60 fullerene; (B) carbon black NPs; and (C) carbon quantum dots [15]

4. Inorganic nanoparticles (NPs)

These NPs are composed of non-carbon-based materials, including metals, ceramics, and semiconductors. Metallic NPs can be monometallic, bimetallic, or polymetallic, often in core–shell structures [16]. They exhibit unique optical, electrical, magnetic, and catalytic properties, making them valuable in nanodevices and biomedical applications [5]. In the biological domain, metallic nanoparticles such as silver (Ag), zinc oxide (ZnO), and cerium oxide (CeO_2) have shown potent antimicrobial activity and reactive oxygen species (ROS) modulation. These features make them suitable for wound healing, biosensing, and anticancer strategies. Additionally, their surface can be functionalized with antibodies or ligands to enhance cellular targeting.

5. Comparative analysis of characterization techniques and practical applications

X-ray diffraction (XRD) analysis confirmed the crystalline nature of nanoparticles (NPs), revealing characteristic peaks that correspond to well-defined crystal structures. For instance, Ag NPs exhibited peaks at $2\theta = 38°$, 44°, and 64°, indicating a face-centered cubic structure [17]. However, some biogenic Ag NPs showed impurity-related peaks, suggesting variations in synthesis conditions. Energy-dispersive X-ray spectroscopy (EDX) further verified the elemental composition of various NPs, including Au, Pd, and Te nanoparticles, confirming their successful synthesis [18]. X-ray photoelectron spectroscopy (XPS) provided insights into oxidation states, revealing the dominance of the zero-valence state in Ag and Pt NPs, with minor oxidation contributions [19]. Inorganic nanoparticles, particularly metal oxides such as SiO_2, ZnO, and MgO, have been widely applied in drilling fluids to improve their rheological behavior, thermal stability, and filtration properties. For instance, silica nanoparticles can significantly reduce fluid loss and enhance filter cake quality by forming a dense barrier on the wellbore wall. Metallic nanoparticles like iron oxide (Fe_3O_4) also offer magnetic responsiveness, allowing for potential real-time monitoring and recovery. Their tunable surface functionality enables better dispersion in water-based muds and compatibility with other additives, making them ideal candidates for smart and multifunctional drilling fluids.

5.1. Surface morphology and stability

Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) revealed the size and morphology of NPs, demonstrating variations in aggregation tendencies. For example, Ag NPs synthesized from *Arbutus unedo* leaf extract were found to be uniformly spherical (~30 nm), while others showed slight deviations in shape and aggregation behavior [20]. Zeta potential analysis indicated NP stability in colloidal suspensions. Generally, NPs with zeta potentials above ±30 mV were considered stable. For example, Ag NPs produced using *Ziziphus jujuba* leaf extract exhibited a zeta potential of -26.4 mV, indicating moderate stability [21].

5.2. Quantum and optical properties

The unique optical behavior of NPs was primarily attributed to localized surface plasmon resonance (LSPR). UV-Vis spectroscopy demonstrated a size-dependent extinction band in Ag NPs, shifting based on NP size and shape [22]. Additionally, Raman spectroscopy identified functional groups on NP surfaces, confirming organic capping agents in biogenic Ag, Te, and Se NPs [23]. Photoluminescence (PL) analysis revealed strong emission variations in Cu NPs synthesized from different biological sources, highlighting the impact of quantum confinement effects [24]. The optical properties of biogenic CeO_2 NPs were found to be superior to chemically synthesized counterparts, attributed to better crystallinity and smaller size [25].

5.3. Applications and stability considerations

NPs have demonstrated significant potential in biomedical and industrial applications. For instance, Ag and ZnO NPs have been integrated into food packaging to prevent microbial contamination and extend shelf life. However, concerns about NP toxicity remain, as certain studies suggest their potential to trigger inflammatory responses or disrupt cellular homeostasis [26].

Table 1. Nanoparticle type

Nanoparticle type	Biological application	Drilling fluid application	Advantages	Limitations
Liposomes	Drug delivery	Encapsulation of additives	Biocompatible, tunable	Thermally unstable
Carbon Quantum Dots	Bioimaging	Viscosity tuning agent	Photoluminescent, stable	Costly synthesis
Silver NPs	Antibacterial agents	Microbial control in mud	High reactivity	Potential toxicity
Silica NPs	Gene delivery	Rheology and filtration control	Surface modifiable	Aggregation in saline muds

6. Future perspectives and challenges of biogenic nanoparticles

Biogenic nanoparticles (NPs), synthesized through environmentally friendly routes using biological organisms or extracts, have attracted increasing attention due to their low toxicity, cost-effectiveness, and ecological sustainability. However, despite their potential, several challenges must be addressed before their widespread adoption in industrial and biomedical applications can be realized. One major challenge lies in the lack of reproducibility and control over size, shape, and surface functionality during green synthesis. The inherent variability of biological sources makes it difficult to achieve standardized production protocols. Additionally, the scale-up of biosynthesis processes remains technically and economically challenging, limiting the commercial viability of biogenic NPs.

Another key concern is the long-term stability and storage conditions of biogenic NPs, particularly when intended for use in high conditions environments such as drilling operations. While their biocompatibility is a strength in biomedical contexts, systematic toxicity studies are still needed to fully assess their impact on human health and ecosystems. Looking forward, integrating biogenic nanoparticles into smart delivery systems—for example, responsive carriers in drug delivery or encapsulated additives in drilling fluids—offers exciting prospects. Emerging trends also include the use of artificial intelligence (AI) and machine learning to optimize biosynthesis parameters and predict nanoparticle behavior. In conclusion, although biogenic NPs represent a sustainable alternative to chemically synthesized counterparts, interdisciplinary efforts are needed to overcome current limitations and translate laboratory-scale success into real-world applications.

7. Biological risks and toxicological considerations

Although nanoparticles offer significant functional benefits, concerns about their potential biological risks are growing. Inorganic nanoparticles, particularly silver (Ag) and zinc oxide (ZnO), have demonstrated strong antimicrobial properties but may also induce oxidative stress and DNA damage at higher concentrations. Carbon-based nanoparticles such as carbon nanotubes and carbon black have been associated with pulmonary inflammation and long-term retention in lung tissues.

In contrast, organic nanoparticles like liposomes and polymeric micelles generally exhibit higher biocompatibility, although their degradation products must also be evaluated for safety. Studies have shown that the size, surface charge, and functionalization of nanoparticles greatly influence their interaction with biological systems. For instance, smaller particles tend to penetrate cellular membranes more easily, potentially leading to bioaccumulation. Comparative toxicological data suggest that metallic nanoparticles tend to exhibit higher cytotoxicity compared to organic or carbon-based counterparts, especially when used in high concentrations or non-targeted delivery systems. To mitigate these risks, rigorous toxicological testing, environmental monitoring, and development of biodegradable nanomaterials are essential steps moving forward. Regulatory guidelines and standardized evaluation methods must also evolve to keep pace with the rapid development of nanotechnology.

8. Comparative evaluation of green synthesis methods

Green synthesis of nanoparticles is gaining significant attention due to its eco-friendliness, cost-effectiveness, and biocompatibility. Among the diverse approaches, plant-mediated, microbial, and algal synthesis methods are the most studied.

8.1. Plant-mediated synthesis

Its utilizes plant extracts rich in phytochemicals (e.g., flavonoids, alkaloids, phenolics) as reducing and capping agents. This method is fast, scalable, and typically results in well-dispersed nanoparticles. However, reproducibility may vary depending on plant species, extraction method, and environmental factors.

8.2. Microbial synthesis

Its involves bacteria, fungi, and yeast that reduce metal ions enzymatically. Although this method offers precise control over particle morphology and size, it is relatively slower and requires stringent sterile conditions, which may limit its industrial scalability.

8.3. Algal synthesis

Using macro- or microalgae, provides a sustainable route that combines the benefits of both plant and microbial methods. Algae produce extracellular metabolites that facilitate nanoparticle formation, though optimization protocols are still under development.

Table 2. Comparative evaluation of green synthesis methods

Method	Reducing agents	Time efficiency	Control over size	Scalability	Challenges
Plant-mediated	Phytochemicals	High	Moderate	High	Variability in plant extracts
Microbial	Enzymes	Low	High	Moderate	Sterility and culture maintenance
Algal-based	Algal metabolites	Moderate	Moderate	Moderate	Standardization of protocols

9. Results and discussion

9.1. Comparative functional performance

Organic nanoparticles, such as dendrimers, micelles, and liposomes, were found to offer exceptional biocompatibility and encapsulation capacity. In biomedical applications, they have shown promise in targeted drug delivery due to their ability to avoid immune detection and control release kinetics. Interestingly, similar capabilities are now being explored in drilling fluids, where liposome-like carriers encapsulate fluid loss additives or corrosion inhibitors. However, these organic structures often suffer from limited thermal stability, reducing their performance under high-temperature drilling conditions.

Carbon-based nanoparticles, especially carbon black and carbon quantum dots (CQDs), displayed high mechanical robustness, thermal conductivity, and tunable surface functionality. In drilling muds, these characteristics enable enhanced thermal management, reduced torque and drag, and improved wellbore stability. In contrast, CQDs are also promising for bioimaging and pollutant detection in environmental applications due to their intrinsic photoluminescence. Despite their versatility, synthesis costs and potential long-term environmental impact remain as limitations.

Inorganic nanoparticles, notably SiO_2, ZnO, and Fe_3O_4, were prominent in both domains. Their rigidity, surface reactivity, and magnetic properties make them suitable for improving rheology, filter cake quality, and smart mud performance in drilling systems. Concurrently, their antimicrobial behavior especially that of silver and zinc-based particles, offers considerable advantages in water treatment and biofilm control. However, concerns regarding cytotoxicity and bioaccumulation have been consistently raised, highlighting the need for safe design and environmental monitoring.

9.2. Cross-system challenges and opportunities

Stability in complex environments: Nanoparticles often aggregate or degrade under extreme conditions such as high salinity, temperature, or pH. Surface modification and dispersion control remain critical research priorities. Scalability of green synthesis: While biogenic methods are sustainable and low-cost, inconsistencies in nanoparticle size and morphology limit their industrial deployment. More standardized protocols are needed.

Toxicological uncertainty: Especially in environmental and drilling applications, long-term exposure risks to ecosystems and human operators are not fully understood. Comprehensive toxicity profiling and biodegradable alternatives are essential.

On the other hand, the convergence of fields such as nanobiotechnology and petroleum engineering opens up new interdisciplinary avenues. For instance, smart drilling fluids incorporating stimuli-responsive nanoparticles could enhance zonal isolation, reduce formation damage, and deliver real-time sensing capabilities. Similarly, nanomaterials engineered for selective pollutant capture in water remediation can benefit from drilling-derived stability technologies.

9.3. Summary of performance insights

To consolidate findings, Table 1 in the manuscript offers a comparative overview of nanoparticle types, highlighting their biological and drilling fluid applications, as well as key benefits and limitations. This table, along with Figs. 2 and 3, provides a visual synthesis of data and performance trends drawn from the reviewed literature.

10. Conclusion

Nanoscience and nanotechnology are inherently interdisciplinary fields of science. With the emergence of new bio-based approaches, there is a growing need for biologists to not only understand the fundamental principles of nanoscience but also become familiar with the technologies and methods traditionally used to characterize nanomaterials. This paper aims to inspire new interdisciplinary collaborations across various scientific fields by assisting biologists in identifying the most suitable technologies and partners to characterize their nanomaterials. At the same time, we emphasize the importance of considering the potential biological risks of these new materials during the planning phase of such experiments. Nanoparticles interact with biological systems through cellular uptake mechanisms such as endocytosis and phagocytosis, influenced by their size, shape, and surface chemistry. These properties make them suitable carriers for targeted drug delivery, improving bioavailability and reducing side effects. Additionally, functionalized nanoparticles are applied in diagnostics, including imaging and biosensing. Understanding these interactions not only enhances biomedical applications but also informs safer use in other fields like drilling fluids, where biocompatibility and environmental safety are essential.

References

[1] Madhavi, A., Srinivasulu, M., Shankar, P.C., Rangaswamy, V., 2023. Synthesis and applications of fungal-mediated nanoparticles. Microbial Processes for Synthesizing Nanomaterials, Springer, 113–131. https://doi.org/10.1007/978-981-99-2808-8_5

[2] Barber, D.J., Freestone, I.C., 1990. An investigation of the origin of the colour of the Lycurgus Cup by analytical transmission electron microscopy. Archaeometry, 32 (1), 33–45. https://doi.org/10.1111/j.1475-4754.1990.tb01079.x

[3] Brill, R.H., Cahill, N.D., 1988. A red opaque glass from Sardis and some thoughts on red opaques in general. Journal of Glass Studies, 30, 16–27.

[4] Roduner, E., 2006. Size matters: why nanomaterials are different. Chemical Society Reviews, 35 (7), 583–592. https://doi.org/10.1039/B502142C

[5] Lines, M.G., 2008. Nanomaterials for practical functional uses. Journal of Alloys and Compounds, 449 (1–2), 242–245. https://doi.org/10.1016/j.jallcom.2006.02.082

[6] Buzea, C., Pacheco, I.I., Robbie, K., 2007. Nanomaterials and nanoparticles: sources and toxicity. Biointerphases, 2 (4), MR17–MR71. https://doi.org/10.1116/1.2815690

[7] Bratovcic, A., 2019. Different applications of nanomaterials and their impact on the environment. International Journal of Materials Science and Engineering, 5 (1), 1–7. https://doi.org/10.14445/23948884/IJMSE-V5I1P101

[8] Ashraf, M.A., Peng, W., Zare, Y., Rhee, K.Y., 2018. Effects of size and aggregation/agglomeration of nanoparticles on the interfacial/interphase properties and tensile strength of polymer nanocomposites. Nanoscale Research Letters, 13, 1–7. https://doi.org/10.1186/s11671-018-2624-0

[9] Kolahalam, L.A., Viswanath, I.V.K., Diwakar, B.S., Govindh, B., Reddy, V., Murthy, Y.L.N., 2019. Review on nanomaterials: Synthesis and applications. Materials Today: Proceedings, 18, 2182–2190. https://doi.org/10.1016/j.matpr.2019.07.371

[10] Ealia, S.A.M., Saravanakumar, M.P., 2017. A review on the classification, characterisation, synthesis of nanoparticles and their application. IOP Conference Series: Materials Science and Engineering, 263, 032019. https://doi.org/10.1088/1757-899X/263/3/032019

[11] Pan, K., Zhong, Q., 2016. Organic nanoparticles in foods: fabrication, characterization, and utilization. Annual Review of Food Science and Technology, 7 (1), 245–266. https://doi.org/10.1146/annurev-food-041715-033215

[12] Khan, I., Saeed, K., Khan, I., 2019. Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry, 12 (7), 908–931. https://doi.org/10.1016/j.arabjc.2017.05.011

[13] Long, C.M., Nascarella, M.A., Valberg, P.A., 2013. Carbon black vs. black carbon and other airborne materials containing elemental carbon: Physical and chemical distinctions. Environmental Pollution, 181, 271–286. https://doi.org/10.1016/j.envpol.2013.06.009

[14] Yuan, X., Zhang, X., Sun, L., Wei, Y., Wei, X., 2019. Cellular toxicity and immunological effects of carbon-based nanomaterials. Particle and Fibre Toxicology, 16, 1–27. https://doi.org/10.1186/s12989-019-0299-z

[15] Lu, K.-Q., Quan, Q., Zhang, N., Xu, Y.-J., 2016. Multifarious roles of carbon quantum dots in heterogeneous photocatalysis. Journal of Energy Chemistry, 25 (6), 927–935. https://doi.org/10.1016/j.jechem.2016.09.015

[16] Toshima, N., Yonezawa, T., 1998. Bimetallic nanoparticles—novel materials for chemical and physical applications. New Journal of Chemistry, 22 (11), 1179–1201. https://doi.org/10.1039/A805753B

[17] Tripathi, R.M., Gupta, R.K., Shrivastav, A., Singh, M.P., Shrivastav, B.R., Singh, P., 2013. Trichoderma koningii assisted biogenic synthesis of silver nanoparticles and evaluation of their antibacterial activity. Advances in Natural Sciences: Nanoscience and Nanotechnology, 4 (3), 035005. https://doi.org/10.1088/2043-6262/4/3/035005

[18] Balasubramanian, S., Kala, S.M.J., Pushparaj, T.L., 2020. Biogenic synthesis of gold nanoparticles using Jasminum auriculatum leaf extract and their catalytic, antimicrobial and anticancer activities. Journal of Drug Delivery Science and Technology, 57, 101620. https://doi.org/10.1016/j.jddst.2020.101620

[19] Sneha, K., Sathishkumar, M., Lee, S.Y., Bae, M.A., Yun, Y.-S., 2011. Biosynthesis of Au nanoparticles using cumin seed powder extract. Journal of Nanoscience and Nanotechnology, 11 (2), 1811–1814. https://doi.org/10.1166/jnn.2011.3414

[20] Kouvaris, P., Delimitis, A., Zaspalis, V., Papadopoulos, D., Tsipas, S.A., Michailidis, N., 2012. Green synthesis and characterization of silver nanoparticles produced using Arbutus unedo leaf extract. Materials Letters, 76, 18–20. https://doi.org/10.1016/j.matlet.2012.02.025

[21] Gavade, N.L., Kadam, A.N., Suwarnkar, M.B., Ghodake, V.P., Garadkar, K.M., 2015. Biogenic synthesis of multi-applicative silver nanoparticles by using Ziziphus jujuba leaf extract. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 136, 953–960. https://doi.org/10.1016/j.saa.2014.09.118

[22] Kelly, K.L., Coronado, E., Zhao, L.L., Schatz, G.C., 2003. The optical properties of metal nanoparticles: the influence of size, shape, and dielectric environment. Journal of Physical Chemistry B, 107 (3), 668–677. https://doi.org/10.1021/jp026731y

[23] Barabadi, H., Kobarfard, F., Vahidi, H., 2018. Biosynthesis and characterization of biogenic tellurium nanoparticles by using Penicillium chrysogenum PTCC 5031: A novel approach in gold biotechnology. Iranian Journal of Pharmaceutical Research, 17 (Suppl 2), 87–95.

[24] Al-Hakkani, M.F., 2020. Biogenic copper nanoparticles and their applications: A review. SN Applied Sciences, 2 (3), 505. https://doi.org/10.1007/s42452-020-2279-1

[25] Rajan, A.R., Vilas, V., Rajan, A., John, A., Philip, D., 2020. Synthesis of nanostructured CeO_2 by chemical and biogenic methods: optical properties and bioactivity. Ceramics International, 46 (9), 14048–14055. https://doi.org/10.1016/j.ceramint.2020.02.204

[26] Khot, L.R., Sankaran, S., Maja, J.M., Ehsani, R., Schuster, E.W., 2012. Applications of nanomaterials in agricultural production and crop protection: a review. Crop Protection, 35, 64–70. https://doi.org/10.1016/j.cropro.2012.01.007