NANOPARTICLES THE CORE COMPONENT OF NANOTECHNOLOGY

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ABSTRACT

Nanoparticles are the fundamental building blocks of nanotechnology, typically ranging in size from 1 to 100 nanometers. Due to their extremely small size, nanoparticles exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts. These properties include enhanced reactivity, increased surface area, and the ability to penetrate biological membranes, making them highly valuable in a wide range of applications such as drug delivery, diagnostics, electronics, and environmental remediation. In nanomedicine, for instance, nanoparticles are engineered to target specific cells, delivering drugs directly to diseased tissues while minimizing side effects. Their versatility and tunable characteristics make nanoparticles the core component driving innovation and development in the field of nanotechnology. Despite their promise, the use of nanoparticles also raises concerns related to toxicity, environmental impact, and long-term safety. Hence, research in nanotechnology emphasizes the development of biocompatible and eco-friendly nanoparticles. As science continues to uncover the vast potential of these nanoscale materials, nanoparticles remain at the forefront of transformative technologies shaping the future of healthcare, industry, and sustainable development.

KEY WORDS: characteristics, nanometers, Pharmacological response, metal

INTRODUCTION

Nanotechnology has evolved as one of the most prominent scientific topics among all technologies. It relies on the synthesis and manipulation of nanoparticles, necessitating significant alterations to the properties of the metals. Nanomaterials have been exploited unknowingly for millennia; gold serves as a prime example. The identical nanoparticles utilized for staining glass were also applied in the treatment of certain ailments. Researchers have progressively acquired the capability to observe the shape- and size-dependent properties by utilizing advanced techniques to analyze the physicochemical aspects of nanoparticles. Recent studies have investigated the many applications of metal nanoparticles in agricultural, environmental, physicochemical, and biological domains [1].

Plants, fungi, and bacteria are the primary biological systems involved. segments [2] Recently, the biosynthetic technique of using plant extracts for nanoparticle production has gained prominence. The synthesis and research on the applications of silver nanoparticles obtained from diverse plant sources A significant quantity of researchers [3,4,5]. The utilization of ethnobotanical data in medicinal plant study has lately escalated. Research has garnered significantly more interest in several domains of the scientific community. These medicinal herbs are considered rich sources of phytochemicals utilized in the production and development of medications. Bioresources encompass fundamental metabolites (amino acids, proteins, and carbohydrates) and secondary metabolites (phenolics, glycosides, terpenoids, tannins, saponins, flavonoids, and coumarins) that confer medicinal properties to plants. [6].

Nanotechnology is a field of science and technology that deals with manipulating matter on an extremely small scale, typically at the level of individual atoms and molecules. It involves working with materials and structures with dimensions in the range of 1 to 100 nanometres. At this scale, materials exhibit unique properties due to quantum effects that become more pronounced as the size of the material decreases. Nanotechnology explores and exploits these unique properties to create new materials, devices, and systems with novel and enhanced characteristics.[7]

Nanotechnology has led to the development of new materials with unique properties, such as carbon nanotubes, graphene, and nanoparticles. These materials may exhibit enhanced strength, conductivity, reactivity, and other characteristics compared to their bulk counterparts. Nanomedicine uses nanoscale materials for drug delivery, imaging, and diagnostics, while nanoparticles can be designed to target specific cells or tissues, improving the effectiveness of medical treatments while minimizing side effects.

The electronics industry benefits from nanotechnology through the development of smaller and more efficient components, such as nanoscale transistors, which enable faster and more powerful computers. The pursuit of quantum computing is closely tied to advancements in nanotechnology.[8]

Nanotechnology plays a role in improving energy storage, conversion, and efficiency, as well as offering solutions for environmental remediation, pollution control, and water purification. It also has implications for manufacturing processes and materials science, allowing for the creation of lightweight yet strong materials and more efficient and precise manufacturing techniques.

Application of Nanotechnology and Nanoparticle

Nanotechnology is a multidisciplinary field with significant implications for various industries, including medicine, electronics, energy, and materials science. It offers precise control over drug delivery systems, enabling targeted delivery to specific cells or tissues, enhancing therapeutic effects while minimizing side effects. Nanoparticles are being developed for targeted cancer therapy, improving treatment efficacy and reducing damage to healthy tissues. They are also used in the development of highly sensitive diagnostic tools for early disease detection, such as biosensors and imaging agents.

Nanomaterials are employed in developing antimicrobial and barrier coatings for food packaging, extending shelf life and ensuring food safety. Nanoencapsulation allows for the controlled release of nutrients in food, enhancing their absorption and bioavailability. Advanced water purification technologies use nanomaterials to remove pollutants and contaminants, providing clean and safe drinking water. Understanding the long-term health effects of exposure to nanomaterials is an ongoing challenge, and comprehensive studies are needed to assess potential risks and establish guidelines for occupational safety.[9]

The history of nanoparticles spans centuries, with significant advancements occurring in the 20th and 21st centuries. Nanoparticles are particles with dimensions on the nanometre scale, typically ranging from 1 to 100 nanometers. The use of nanoparticles dates back to ancient times, with artists and craftsmen unknowingly incorporating nanoparticles into their work by grinding down materials to create pigments with unique properties. In the 17th century, scientists like Robert Hooke and Antonie van Leeuwenhoek laid the groundwork for nanoscience by developing early microscopes.

In the early 20th century, the development of quantum mechanics revolutionized our understanding of matter at the atomic and subatomic levels. The work of scientists like Max Planck and Albert Einstein provided the theoretical foundation for the behavior of particles at the nanoscale. The 1950s and 1960s saw the emergence of novel materials with unique properties due to their nanoscale dimensions, such as carbon black nanoparticles, which found applications in tires, pigments, and inks.

In the late 20th century, the term "nanotechnology" was coined by Eric Drexler, who envisioned a future where nanoscale machines could assemble materials at the atomic level. Advancements in semiconductor technology led to the integration of nanoparticles in electronics, contributing to the miniaturization and improved performance of electronics. As the use of nanoparticles expanded, so did concerns about their potential environmental impact and health risks.[10]

In the 21st century, nanoparticles are integral to various fields, including medicine, electronics, energy, and materials science. They play a crucial role in the development of new technologies, such as targeted drug delivery, efficient solar cells, and advanced sensors. The history of nanoparticles reflects a continuous journey of discovery and innovation, with ongoing research promising even more breakthroughs in the future.

Advances in nanotechnology continue to unfold, with emerging technologies like DNA nanotechnology, nanorobotics, and nanoscale 3D printing promising novel applications and capabilities. The convergence of nanotechnology with other disciplines, such as artificial intelligence, materials science, and biology, holds great potential for innovative solutions to complex challenges. As nanotechnology becomes more prevalent, international collaboration and effective governance mechanisms are crucial to address challenges, share knowledge, and ensure responsible development.[11]

As nanoparticles continue to push the boundaries of what is possible, ethical considerations, environmental impacts, and regulatory frameworks must be carefully navigated to harness the full benefits of nanotechnology.

Metallic nanoparticle synthesis

Metallic nanoparticles are nanoscale particles of metallic elements or alloys with unique physical and chemical properties. They have applications in fields like medicine, electronics, catalysis, and materials science due to their versatility. Synthesis involves various methods to control particle size, shape, and composition. The ability to tune these nanoparticles' characteristics makes them valuable in developing innovative materials and technologies. Common methods include reduction of metal ions.

A- Chemical reduction Chemical reduction is a widely used method for synthesizing metal nanoparticles, offering a cost-effective and versatile approach to producing nanoscale materials with unique properties. This process begins with a metal precursor, usually in the form of a metal salt, and a chemical reducing agent is introduced into the solution. Commonly used reducing agents include sodium borohydride ($NaBH_4$), hydrazine, and citric acid. The reaction conditions, such as temperature, pH, and reaction time, play a significant role in determining the size, shape, and crystallinity of the resulting nanoparticle.[12]

The advantages of chemical reduction include its simplicity, accessibility to researchers with varying levels of expertise, and control over nanoparticle properties. However, limitations include the need for stabilizing agents to prevent nanoparticle agglomeration and ensure stability, and the introduction of impurities that require thorough purification steps to obtain high-purity nanoparticles.

Advanced variations of chemical reduction include the polyol method, seeded growth, and sequential reduction, which allow for the synthesis of uniform nanoparticles with controlled shapes and sizes. Metal nanoparticles synthesized through chemical reduction find extensive use in catalysis due to their high surface area and unique catalytic properties. They are also used in medicine, electronic devices, and sensors, and exhibit unique optical properties due to surface plasmon resonance.[13]

Despite its widespread use in the laboratory, scaling up production for industrial applications remains a challenge. Researchers are exploring the intricacies of nucleation, growth, and stabilization to gain better control over the properties of synthesized nanoparticles. Continued research aims to refine methods for tailoring the properties of metal nanoparticles, such as achieving precise control over shape, composition, and surface chemistry to meet specific application requirements.

B- Microemulsion method: The microemulsion method is a versatile and effective approach for synthesizing metal nanoparticles, offering precise control over particle size, shape, and composition. It creates nanoscale reaction environments by stabilizing water and oil phases with surfactants and co-surfactants, providing a confined space for the nucleation and growth of nanoparticles. This method is particularly advantageous for producing uniform and stable metal nanoparticles with unique properties.[14]

The process of microemulsion-based synthesis involves mixing water, oil, a surfactant, and a co-surfactant. The choice of surfactant and co-surfactant is crucial for stabilizing the microemulsion and controlling the size of the resulting nanoparticles. Metal precursors are dissolved in the water phase, and a chemical reducing agent is introduced into the oil phase to initiate the reduction of metal ions, leading to the formation of nanoparticles within the confined spaces of the microemulsion droplets.

The microemulsion method is versatile and can be scaled up for industrial production, making it suitable for large-scale synthesis of metal nanoparticles. Applications of microemulsion-synthesized metal nanoparticles include drug delivery, imaging, diagnostics in medicine, electronics, sensors, and nanoelectronics.

Challenges and future developments include the choice and optimization of surfactants and co-surfactants, deeper understanding of the mechanisms governing nucleation and growth within microemulsions, and integration of the microemulsion method with other techniques to enhance the capabilities of nanoparticle synthesis.

Advancements in the microemulsion method include the reverse micelle method, which involves the encapsulation of metal ions within water droplets dispersed in an oil phase. Researchers are exploring biosurfactants produced by microorganisms as an alternative to chemical surfactants, temperature-sensitive surfactants, and multifunctional nanoparticles.

Despite its scalability, challenges related to reproducibility on a large scale still exist. Researchers are working on optimizing conditions for industrial-scale production, understanding interactions between surfactants, co-surfactants, and metal precursors, and incorporating different metals, coatings, or functionalities within a single particle. As the field progresses, the microemulsion method is likely to play a pivotal role in the development of advanced nanomaterials with tailored functionalities.

C- Photochemical Synthesis:Photochemical synthesis is a method for producing metal nanoparticles using light as a driving force. It involves the introduction of metal salts, such as gold, silver, and platinum, and a photosensitizer that absorbs light energy to initiate the reduction reaction. The solution is exposed to light, typically ultraviolet or visible, depending on the photosensitizer's absorption characteristics. Control over reaction conditions allows researchers to fine-tune the synthesis process and achieve desired nanoparticle properties. Stabilizing agents or capping ligands are often added to prevent agglomeration.

Advantages of photochemical synthesis include precise control over size, shape, and composition, environmental friendliness, rapid production, and high-purity photosensitizers. However, it may not be suitable for all metals due to limitations in light penetration and the choice of photosensitizer.[15,16]

Photochemically synthesized nanoparticles find applications in catalysis, photothermal therapy, sensors, imaging, diagnostics, solar cells, and other photovoltaic devices. Future developments include developing multicomponent systems, enabling in vivo applications, and exploring advanced light sources like lasers. Understanding and mitigating potential environmental impacts is essential, and comprehensive assessments of the life cycle and eco-toxicological aspects of photochemically synthesized nanoparticles are necessary.

In conclusion, photochemical synthesis is a powerful and versatile method for producing metal nanoparticles with tailored properties. Ongoing research and technological innovations are expected to broaden its applications and contribute to the development of advanced materials for diverse scientific and technological purposes.

Pharmacological applications of metallic nanoparticles

Diabetes mellitus (DM) is a metabolic disorder causing uncontrolled blood sugar levels. While insulin medication can help prevent the disease, full treatment is difficult. Nanoparticles, such as gold and silver nanoparticles, have shown potential in treating the disease. Gold nanoparticles significantly decreased liver amounts, serum creatinine, alkaline phosphatase, alanine transaminase, and uric acid levels in diabetic mice under treatment. Silver nanoparticles were found to be powerful medicinal substances for managing diabetes, with clinical research in mice successfully regulating 140 mg/dl sugar levels in the group receiving silver nanoparticle treatment.[17]

The body's largest organ, skin, is crucial for various functions and has been the subject of extensive research in the field of nanomedicine. Skin wounds are a complex process that requires effective treatments to prevent microbial colonization. Current treatments for wounds in underdeveloped nations include chlorhexidine, sodium hypochlorite, cetrimide solution, and other medications that have negative side effects when taken over an extended period.[18]

The field of nano-medicine is rapidly expanding, combining life sciences, nano-biotechnology, nano-engineering, and nano-science to produce medical discoveries. Nanoparticles offer new insights in material science and are being used as effective therapeutic candidates in medicine due to their antifungal and antibacterial properties against various pathogens. Metal nanoparticles, particularly silver and gold capping phyto-constituents, have gained attention due to their superior properties such as electronic, optical, magnetic, and catalytic activities, electrical conductivity, and chemical stability.[19]

Silver and gold nanoparticles (AgNPs and AuNPs) are particularly important due to their wide range of applications in various fields, including pharmaceutical and medical industry, ecological applications, sensing, solar cells, catalysis, and energy conversion. Surface modification of nanoparticles by altering their concentration, size, and capping with both metals results in superior improvement in anticancer and antitumor properties.

Various physicochemical approaches have been investigated for the preparation of AgNPs and AuNPs, including polyol preparation technique, chemical reduction of silver ions by sodium citrate, photochemical method, biological technique, electrochemical method, and sonochemical method. However, chemical techniques often pollute due to poisonous solvents, risky by-products, and precursor substances, while physical techniques for the production of metal nanoparticles frequently produce low yields.[20]

There is an increasing need for ecologically acceptable, eco-friendly, non-toxic, biocompatible procedures, trustworthy, and clean ways for producing AgNPs and AuNPs with various sizes that do not generate harmful wastes during the synthesis. Plant extracts contain numerous phenolic derivatives, such as alkaloids, polyphenols, terpenes, glycosides, and terpene derivatives, which can prevent the growth of pathogens and have clinical benefits.

In this work, a green route approach was used to synthesize CSR-AuNPs and CSR-AgNPs by reducing chloroauric acid and silver nitrate in the presence of Caralluma sarkariae root (CSR) extract used as a capping agent.

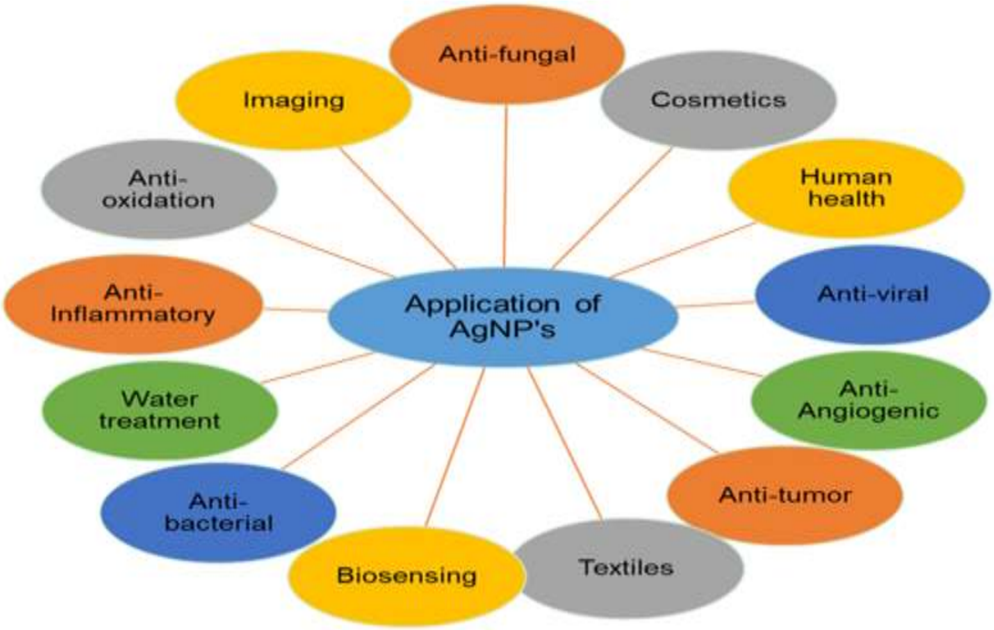

Figure-2.2: Applications of silver nanoparticles. [21]

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Classification of nanoparticles

The classification of nanoparticles (NPs) is based on several parameters such as origin, composition, dimensions, morphology, and physical or chemical properties. These classifications help in understanding their synthesis, behavior, and applications across fields like medicine, electronics, environmental science, and materials engineering.

1. Based on Origin

Nanoparticles can be classified into three types depending on their source:[22]

a) Natural Nanoparticles

These are formed through natural processes such as volcanic eruptions, forest fires, ocean sprays, or biological processes.

- Examples: Clay particles, volcanic ash, pollen grains, and magnetotactic bacteria-derived magnetite NPs.

b) Anthropogenic (Engineered) Nanoparticles

Deliberately synthesized by humans for specific purposes using physical, chemical, or biological methods.

- Examples: Silver NPs, gold NPs, carbon nanotubes.

c) Incidental Nanoparticles

By-products of industrial, combustion, or mechanical processes.

- Examples: Diesel exhaust particles, welding fumes, combustion aerosols.

2. Based on Chemical Composition [23]

a) Carbon-based Nanoparticles

Contain carbon as the primary element. They may have different morphologies like spherical (fullerenes) or cylindrical (carbon nanotubes).

- Examples: Fullerenes (C_{60}), carbon nanotubes (CNTs), graphene, carbon black.

b) Metal-based Nanoparticles

Composed of pure metals or metal oxides. Widely used for their antimicrobial, optical, and catalytic properties.

- Examples: Silver (Ag), Gold (Au), Iron oxide (Fe_3O_4), Zinc oxide (ZnO), Titanium dioxide (TiO_2).

c) Ceramic Nanoparticles

Inorganic and non-metallic solids. They are heat-resistant and chemically stable.

- Examples: Silica (SiO_2), alumina (Al_2O_3), zirconia (ZrO_2).

d) Polymeric Nanoparticles

Made from natural or synthetic polymers. Useful in drug delivery due to biodegradability and controlled release.

- Examples: Poly(lactic-co-glycolic acid) (PLGA), chitosan, polyethylene glycol (PEG).

e) Composite Nanoparticles

Contain two or more components, typically a core and a shell, such as metal-polymer or metal-ceramic composites.

- Examples: Silica-coated gold nanoparticles.

3. Based on Dimensions [24]

a) Zero-Dimensional (0D) Nanoparticles

All dimensions are in the nanoscale (1–100 nm). Shape is usually spherical.

- Examples: Quantum dots, gold/silver NPs.

b) One-Dimensional (1D) Nanoparticles

One dimension (length) is outside the nanoscale.

- Examples: Nanorods, nanotubes, nanowires.

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c) Two-Dimensional (2D) Nanoparticles

Two dimensions are outside the nanoscale; thin-layered materials.

- Examples: Graphene sheets, nanosheets.

d) Three-Dimensional (3D) Nanoparticles

All dimensions are large but have nanoscale features like porosity.

- Examples: Nanoflowers, dendrimers, nanocages.

4. Based on Morphology [25]

- Spherical nanoparticles: Common morphology, used in drug delivery (e.g., gold NPs).
- Rod-shaped nanoparticles: Exhibit anisotropic properties (e.g., nanorods).
- Tubular nanoparticles: Used in sensors and electronics (e.g., carbon nanotubes).
- Plate-like nanoparticles: Used in coatings and catalysts (e.g., graphene sheets).
- Dendritic nanoparticles: Highly branched and used in diagnostics and imaging.

Reference:

5. Based on State of Matter

- Solid nanoparticles: Most commonly used; stable structures.
- Liquid nanoparticles (nanoemulsions): Used in cosmetics and food industries.
- Gas-phase nanoparticles: Formed during combustion or vapor deposition.

The classification of nanoparticles is crucial for selecting the appropriate type for specific applications, understanding their environmental and biological behavior, and ensuring their safe handling. As nanotechnology evolves, newer hybrid and multifunctional nanoparticles are being developed to meet complex challenges in healthcare, electronics, and materials science.

SUMMARY AND CONCLUSION

Nanotechnology is a rapidly evolving field that involves the synthesis and manipulation of nanoparticles, which have been used unknowingly for millennia in various applications such as agriculture, environmental, physicochemical, and biological domains. The primary biological systems involved in nanotechnology include plants, fungi, and bacteria. Recently, the biosynthetic technique of using plant extracts for nanoparticle production has gained prominence, with researchers focusing on the synthesis and research of silver nanoparticles obtained from diverse plant sources.

Nanotechnology has led to the development of new materials with unique properties, such as carbon nanotubes, graphene, and nanoparticles. These materials may exhibit enhanced strength, conductivity, reactivity, and other characteristics compared to their bulk counterparts. Nanomedicine uses nanoscale materials for drug delivery, imaging, and diagnostics, while nanoparticles can be designed to target specific cells or tissues, improving the effectiveness of medical treatments while minimizing side effects.

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Nanotechnology has significant implications for various industries, including medicine, electronics, energy, and materials science. It offers precise control over drug delivery systems, enabling targeted delivery to specific cells or tissues, enhancing therapeutic effects while minimizing side effects. Nanoparticles are being developed for targeted cancer therapy, improving treatment efficacy and reducing damage to healthy tissues. They are also used in the development of highly sensitive diagnostic tools for early disease detection, such as biosensors and imaging agents.

Nanomaterials are employed in developing antimicrobial and barrier coatings for food packaging, extending shelf life and ensuring food safety. Nanoencapsulation allows for the controlled release of nutrients in food, enhancing their absorption and bioavailability. Advanced water purification technologies use nanomaterials to remove pollutants and contaminants, providing clean and safe drinking water.

The history of nanoparticles spans centuries, with significant advancements occurring in the 20th and 21st centuries. Chemical reduction is a widely used method for synthesizing metal nanoparticles, offering a cost-effective and versatile approach to producing nanoscale materials with unique properties. Advancements in the microemulsion method, reverse micelle method, biosurfactants produced by microorganisms, and multifunctional nanoparticles are crucial for the development of advanced nanomaterials with tailored functionalities.

Photochemical synthesis is a method for producing metal nanoparticles using light as a driving force. Advantages of photochemical synthesis include precise control over size, shape, and composition, environmental friendliness, rapid production, and high-purity photosensitizers. Photochemically synthesized nanoparticles find applications in catalysis, photothermal therapy, sensors, imaging, diagnostics, solar cells, and other photovoltaic devices. Future developments include developing multicomponent systems, enabling in vivo applications, and exploring advanced light sources like lasers.

Pharmacological applications of metallic nanoparticles include treating diabetes mellitus (DM), a metabolic disorder causing uncontrolled blood sugar levels. Gold and silver nanoparticles have shown potential in treating the disease, with clinical research showing significant decreases in liver amounts, serum creatinine, alkaline phosphatase, alanine transaminase, and uric acid levels in diabetic mice under treatment.

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