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REVIEW ARTICLE

A Review on Metallic Nanoparticles

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ABSTRACT
Nanotechnology's particular qualities, such as its strength, small size, and unusual behaviour with light and electricity, have made it a significant research topic in recent years. It combines several disciplines, such as nanobiotechnology, nanomaterials, and nanoelectronics. Among these, metallic nanoparticles (MNPs) have demonstrated significant potential, particularly in the medical domain. Because MNPs can help medications reach the precise biocompatible location in the body, they can enhance their effectiveness, which is why they are frequently utilized in drug delivery. This can help avoid issues like multidrug resistance and lessen adverse effects. In addition to drug delivery, MNPs find application in nutraceuticals, materials, and diagnostics. Increasing the stability and duration of a drug's circulation in the body is one of the main benefits of employing MNPs in drug delivery. Additionally, they can be altered to actively or passively target tissues or cells. The field of green synthesis of MNPs is young and expanding. Compared to physical or chemical treatments, it is safer and more environmentally friendly. The utilization of various MNPs, such as silver, gold, copper, and zinc oxide, in drug delivery systems, as well as environmentally friendly techniques for creating metallic nanocarriers and surface modifications, are the main topics of this review.
Keywords: *MNPs, Drug delivery, Nanotechnology, Targeted delivery, Biocompatibility.*

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INTRODUCTION

Nanoparticles have been used since antiquity, long before their scientific knowledge. Because metallic nanoparticles have special optical qualities, they were unintentionally employed to paint cathedral windows in the Middle Ages, producing vivid colors. Faraday was the first scientist to explore metallic nanoparticles in 1908, [1] and Mie subsequently used light interaction to explain their colors. Metallic nanoparticles (MNPs), which are usually 10–100 nm in size, have drawn a lot of interest because of their special qualities, which include high surface area, size-dependent color, and surface plasmon resonance [2] . Depending on their size, gold nanoparticles, for instance, can appear red at 20 nm and bluish at bigger sizes. Recent studies have focused a lot of attention on metallic nanoparticles (MNPs) because of their special optical, physical, and chemical characteristics [3]. They are perfect for targeted drug administration because of their high surface area to volume ratio, which minimizes harm to healthy cells while increasing reactivity and enabling faster diffusion at lower temperatures. Additionally, they augment sophisticated methods such as optical sensing, Raman spectroscopy, and fluorescence enhancement [4]. Noble metals, such as gold and silver, are commonly employed in nanotechnology, diagnostics, and catalysis because of their exceptional antibacterial and anticancer qualities. For instance, gold nanorods' optical qualities have allowed for data storage capabilities of up to 10 terabytes [5].

METALLIC NANOPARTICLES

Solid nanoscale particles made of pure metals or their derivatives are called metallic nanoparticles, or metal nanoparticles (MNPs) [6]. A variety of techniques, including chemical reduction, microemulsion, and thermal breakdown of metal salts, are used to create them. Since these particles are usually between 1 and 100 nanometers in size, they have special qualities that aren't seen in bulk materials [7].

CLASSIFICATION OF METALLIC NANOPARTICLES

Based on a number of factors, including their size, shape, composition, production process, and functional uses, metallic nanoparticles (MNPs) can be classified in a systematic manner. Their characteristics, behavior, and possible uses in the industrial, pharmaceutical, and medicinal domains are better understood thanks to this classification [8].

1. On the basis of composition

The following categories can be used to classify metallic nanoparticles according to their elemental composition: Pure metallic nanoparticles, such as those made of copper (Cu), zinc (Zn), iron (Fe), silver (Ag), or gold (Au), are made up of just one substance [9]. Two distinct metals combine to form bimetallic nanoparticles, which can be found as alloys or in a core-shell arrangement [10]. Examples are iron-gold (Fe-Au) and gold-silver (Au-Ag) nanoparticles. Because of their catalytic or antibacterial qualities, metal oxide nanoparticles—which are oxidized metals—are frequently employed. Iron oxide (FeO_4), titanium dioxide (TiO_2), and zinc oxide (ZnO) are a few examples [11].

2. On the basis of Morphology and Shape

The surface area and reactivity of metallic nanoparticles are strongly influenced by their form which includes spherical, rod-shaped, cubic, star-shaped, and flower-like [12]

3. On the basis of Size

The physicochemical and biological behavior of nanoparticles is significantly influenced by their size [13]. They are frequently divided into:

Table 1: Physicochemical and biological behavior of nanoparticles on the basis of size

Size Category	Size Range
Extremely Tiny	Under 10 nm
Small	Between 10 and 50 nm
Medium	Between 50 and 100 nm
Large	Over 100 nm

4. On the basis of Synthesis Method

Various methods can be used to create metallic nanoparticles, depending on the intended uses and properties:

Chemical techniques; physical techniques; biological or green synthesis techniques employing microbes or plant extracts [14] .

5. On the basis of Useful Applications

The classification of metallic nanoparticles is also influenced by their functional purpose. Typical applications for them include:

- - Drug delivery systems [15] .

Formulations that are antimicrobial and antibacterial; medical imaging and diagnostics; chemical reaction catalysis; sensor development and environmental monitoring [16] .

UNIQUE PROPERTY OF METALLIC NANOPARTICLES

The arrangement of atoms in metallic nanoparticles has a direct impact on their special surface characteristics. Reactivity and surface area are enhanced by a high proportion of surface atoms, particularly in tiny, scattered clusters [17]. Due to the creation of inner shells, which reduces available surface area, the proportion of surface atoms falls as cluster size grows. Compared to aggregated clusters, dispersed clusters are more chemically reactive because they have more exposed atoms [18]. One of the main causes of MNPs' improved catalytic and chemical behavior is their high surface-to-volume ratio [19].

ADVANTAGES OF METALLIC NANOPARTICLES

Because of their distinctive optical and electrical characteristics, metallic nanoparticles are extremely helpful in a variety of applications [20]. Because of the impacts of Surface-Enhanced Raman Scattering (SERS) and strong light scattering, enhanced Rayleigh and Raman scattering increase the sensitivity of optical sensing detection [21].

Plasmonic Absorption: MNPs' potent plasmon resonance makes it possible for them to absorb energy efficiently, which is advantageous for photothermal therapy and imaging [22].

Biological Imaging: They are appropriate contrast agents for imaging biological systems due to their adjustable optical characteristics [23].

Chemical Analysis: On metallic nanoscale surfaces, they enable the sensitive detection and analysis of chemical species [24].

DISADVANTAGES OF METALLIC NANOPARTICLES

Metallic nanoparticles offer a number of difficulties in spite of their potential:

Instability: Nanoparticles are thermodynamically unstable due to their high surface energy, which leaves them vulnerable to corrosion and structural alterations [25].

Impurity Risk: Because of their strong reactivity, they are more likely to become contaminated during synthesis, necessitating encapsulation to preserve size and purity [26].

Biotoxicity: Certain MNPs have been shown to be harmful, irritating, or carcinogenic despite their ability to cross biological barriers [27].

Explosion Hazard: Exothermic reactions brought on by fine metal particles could result in explosions [28].

Synthesis Challenges: It is still difficult and technically demanding to maintain the stability and size of nanoparticles, particularly in solution [29].

SYNTHESIS OF METALLIC NANOPARTICLES

The top-down and bottom-up methods are the two primary methods for creating metallic nanoparticles [30]. Using a bottom-up approach, atoms or molecules self-assemble into nanoparticles under the influence of nanoscale physical forces. For creating structures like colloidal dispersions or quantum dots, it is both economical and perfect. Starting with bulk material, the top-down approach uses methods like ball milling or extreme plastic [31] . deformation to break it down into nanoparticles. Because of its high cost and complexity, it is less appropriate for large-scale production, despite its speed [32].

Comparatively:

Large-to-nanoscale top-down: rapid, costly, and less scalable.

Bottom-up: cheap and scalable; begins small and grows [33].

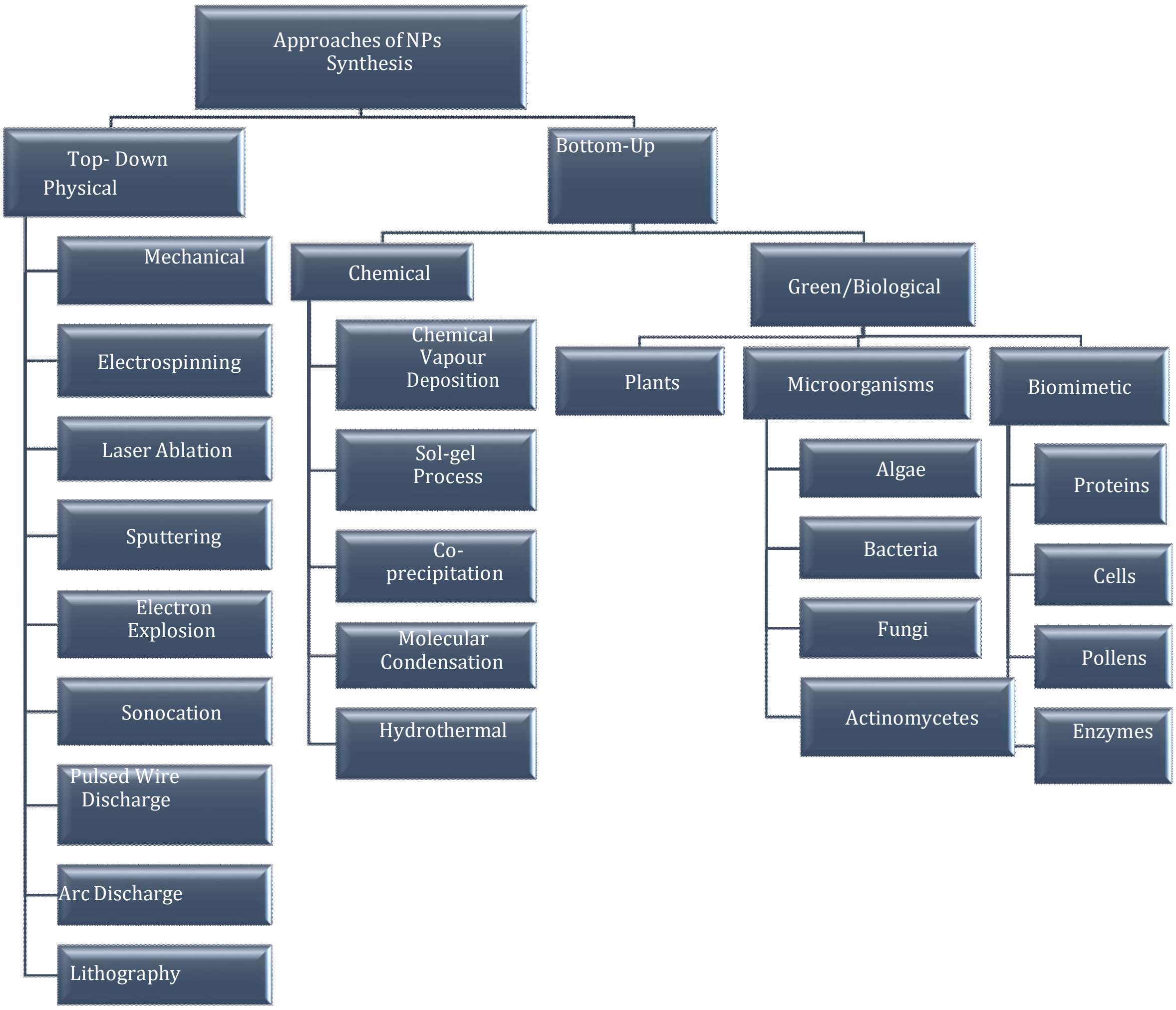

Figure 1 Approaches of NPs Synthesis

CHARACTERISTIC FEATURES OF METALLIC NANOPARTICLES:

Because metal nanoparticles have such a vibrant hue, UV-visible spectroscopy is used for rapid, qualitative investigation. Beer's law is followed by absorbance, which yields information on extinction coefficients and concentration [34].

Infrared (IR) spectroscopy: Provides information about organic surface layers and aids in comprehending the chemistry of nanoparticle surfaces.

TEM: Particle size, shape, crystallinity, and interparticle interactions can all be ascertained using high-resolution pictures from transmission electron microscopy (TEM). It makes chemical analysis and imaging at the atomic level possible.

SEM or scanning electron microscopy: It is useful for analyzing purity and surface morphology at resolutions of up to 1 nm. The secondary electrons produced by the electron beam are detected by it [35].

Atomic Force Microscopy (AFM): Provides sub-nanometer vertical resolution, making it perfect for non-conductive samples. It offers information on surface structure and bonding at the atomic level [36].

X-Ray Diffraction (XRD): Identifies particle size, strain, and crystal structure. Size estimate using the Debye-Scherrer formula is made possible by the broadening of diffraction peaks with smaller particles [37].

METALLIC NANOPARTICLES: FROM COPPER TO MULTIFUNCTIONAL APPLICATIONS

Among the vast array of metallic nanoparticles explored for their potential, copper nanoparticles (CuNPs) have emerged as a promising candidate in industrial, biomedical, and environmental sectors [38]. Their appeal lies in a rare combination: exceptional electrical conductivity, potent antibacterial properties, and affordability—qualities that make CuNPs both accessible and efficient [39]. However, copper's natural tendency to oxidize poses a challenge for long-term applications [40]. To counter this, scientists are now turning to green synthesis routes, using plant extracts to create more stable and less toxic forms of CuNPs. These environmentally friendly methods not only preserve nanoparticle integrity but also support sustainable innovation [41].

The journey doesn't stop with copper. In the field of nanomedicine and diagnostics, silver nanoparticles (AgNPs) shine brightly [42]. Celebrated for their broad-spectrum antimicrobial activity, AgNPs are widely incorporated into wound dressings, antimicrobial coatings, and medical devices [43]. Their unique surface plasmon resonance properties enhance biosensing capabilities, making them indispensable in modern diagnostic tools [44]. Yet, concerns about cytotoxicity and environmental accumulation have led to growing interest in biogenic and encapsulated forms of AgNPs that balance safety with performance [45].

Equally fascinating are gold nanoparticles (AuNPs)—regarded as the gold standard in nanotechnology. With exceptional biocompatibility, tunable optical properties, and easy surface functionalization, AuNPs have revolutionized cancer diagnostics and treatment. Their versatility allows them to be synthesized in various shapes, such as spheres, rods, and cages—each unlocking specific interactions with light and biological tissues. As a result, they are extensively used in photothermal therapy, tumor imaging, and precision drug delivery [46].

Meanwhile, zinc oxide nanoparticles (ZnO NPs) have found their niche in the cosmetic, environmental, and electronic industries. Known for their UV-blocking capabilities and antimicrobial action, ZnO NPs are incorporated into sunscreens, cosmetics, and antimicrobial textiles. As semiconductors, they are being explored in biosensors and photocatalytic systems. However, their interactions with biological systems demand thorough biosafety evaluations to ensure responsible usage.

APPLICATIONS OF METALLIC NANOPARTICLES: BEYOND THE LAB

The true value of metallic nanoparticles lies in their ability to translate nanoscale phenomena into macroscale benefits across industries.

- In biomedicine, MNPs serve as smart agents for targeted drug delivery, cancer therapy, and molecular imaging—reducing side effects and improving therapeutic outcomes. Their surface can be engineered to interact with specific cells, making treatments more precise than ever before.
- In diagnostics, their ability to enhance signals—be it through fluorescence, Raman scattering, or plasmon resonance—has enabled early detection of diseases with unmatched sensitivity.
- In environmental applications, MNPs play a role in water purification, pollutant degradation, and air filtration, acting as catalysts that transform toxic substances into benign compounds.
- In industry, they are revolutionizing coatings, paints, electronics, and catalysts, enabling materials that are lighter, stronger, and more efficient [47].

CONCLUSION

Metallic nanoparticles represent a dynamic frontier of science where materials at the nanoscale open gateways to solutions across medicine, environment, and technology. From the antimicrobial strength of copper and silver to the biocompatibility of gold and the functional versatility of zinc oxide, each nanoparticle type contributes uniquely to the evolving landscape of nanotechnology. As research continues to refine synthesis methods and enhance safety profiles, the integration of metallic nanoparticles into daily life becomes not just possible, but inevitable ushering in a new era of precision, efficiency, and sustainability.

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