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Metal Nanoparticle: Synthesis, Properties, and Their Dermatological and Cosmetic Impacts

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Abstract

Nanoparticles (NPs) are materials with dimensions under 100 nm and various shapes, such as spheres and rods. Their advancement offers transformative potential in medical and healthcare fields. The increased application of NPs across molecular biology, chemistry, medicine, and material science reflects their growing importance. Due to their large surface area, NPs enhance substance delivery through the skin, benefiting cosmetic applications by improving penetration, efficacy, and targeted delivery of active ingredients. With the prominent uses in dermatology as antioxidants and anti-reflectants, metal nanoparticles (NPs) have recently attracted the attention due to their unique physical and chemical characteristics when compared to their bulk counterparts. Metal NPs, particularly silver and gold, exhibit significant antibacterial properties and have diverse synthesis methods, including chemical, physical, and the biological approaches. Biological synthesis using organisms, like fungi and plants, offers an environmentally friendly alternative, reducing toxic byproducts and energy consumption while enhancing biocompatibility and scalability for potential applications in medical, pharmaceutical, and cosmetic industries. Nanoparticles' high surface area-to-volume ratio facilitates efficient interaction with other substances, making them valuable in treatments that minimize harm to healthy cells. This review explores the types, synthesis, and applications of metal-based NPs, highlighting their antibacterial activity and potential for enhancing skincare and other industries.

Keywords: Metal nanoparticles, antimicrobial activity, green synthesis, skin penetration, dermatology, cosmetics, silver and gold nanoparticles

INTRODUCTION

According to one definition, nanoparticles (NPs) are materials that are smaller than 100 nm and can have a range of shapes, such as spheres, rods, dendritic shapes, etc. [1]. The development of technologies to control materials at the nanoscale holds the potential for fundamentally changing medical and healthcare medicines and treatments. Recently, there has been an unanticipated growth in the use of nanoparticles in several fields, including physics, organic and inorganic chemistry, molecular biology, medicine, and science of materials [2, 3]. Because of their vast surface area, nanoparticles can transmit things through the skin more effectively.

By using nanomaterials. Several key objectives can be fulfilled in cosmetics. These include increased substance delivery via effective skin penetration [4]. Nanomaterials (NMs) can be modified to have the desired composition and functions, making them useful for a variety of applications. The recent surge in interest in metal nanoparticles (NPs) stems from the discovery of their unique physical and chemical properties of biological activity, which frequently differ from the properties of this substance in its macro dispersed form [5]. Metal nanoparticles have promising clinical applications, particularly in dermatology

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[6]. As anti-reflectants and antioxidants, nanoparticles are frequently found in cosmetic goods [7].

ANTIMICROBIAL PROPERTIES OF METAL NANOPARTICLES

The use of metal nanoparticles with antibacterial capabilities has emerged as a groundbreaking method for cosmetic product development. Metal nanoparticles and metal oxides, such as silver (Ag), copper (Cu), and zinc oxide (ZnO), have broad-spectrum antibacterial activity against a variety of microorganisms, including bacteria, fungus, and viruses. AgNPs, or silver nanoparticles, have long been identified for their strong antibacterial characteristics. They have a distinct method of action in which the release of silver ions interrupts critical cellular processes in bacteria, causing their inactivation or annihilation. Silver nanoparticles' antibacterial activity is enhanced by their tiny size and wide surface area, which facilitates interaction with microbial cells [8]. Creams, lotions, soaps, and deodorants are just a few of the cosmetic products that include silver nanoparticles. Their insertion inhibits the growth of bacteria and fungi, lowering the risk of infections, body odor, and microbiological deterioration in cosmetic compositions.

Silver nanoparticles have also been investigated for their possible use in wound healing and acne treatment due to their antimicrobial and anti-inflammatory characteristics [9]. Zinc oxide nanoparticles have shown antibacterial activity against bacteria, fungi, and viruses. Zinc oxide nanoparticles are widely employed in sunscreen compositions due to their UV-blocking capabilities. However, they also contribute to these products' antibacterial properties, offering extra protection against microbes on the skin's surface. The dual activity of zinc oxide nanoparticles improves the photoprotective and antibacterial properties of sunscreens [10]. It has been found that copper nanoparticles exhibit antibacterial action against a range of pathogens, including viruses, fungi, and bacteria. Copper nanoparticles have been used in cosmetics to provide antibacterial and preservation properties. They serve to prevent microbiological contamination and increase the shelf life of formulations, maintaining product safety and integrity. Copper nanoparticles are very effective in water-based cosmetic compositions traditional preservatives may be less effective [11, 12].

SYNTHESIS OF METAL NANOPARTICLES

In the top-down technique, nanoparticles are created using the size reduction method, which breaks down bulk materials into small components. Using high-intensity ultrasonic generators with frequencies about 1,200,000 rpm [13]. can help achieve this. Another dispersion approach is to generate an electric arc within the liquid. Metal is distributed as a vapor from the electrode due to the extreme heat created by the electric arc, which condenses further to form MNPs [14]. The synthesis techniques can be divided into three broad groups based on these two approaches: physical, chemical, and biological (often known as "green synthesis") methods [15].

GREEN SYNTHESIS

As previously pointed out, physical and/or chemical methods for generating nanoparticles involve the reaction of a precursor material with reducing agents. Nevertheless, both approaches have been shown to be hazardous to the environment and living beings. Furthermore, physical-based synthesis methods require expensive equipment, high temperatures, and high pressures, making them unprofitable and unscalable. Chemical procedures, on the other hand, use and produce hazardous compounds that, in addition to being cytotoxic and carcinogenic, can have serious environmental consequences [16]. Several hazardous compounds that are attached to the particles synthesized using the above methods have been identified [17].

For these reasons, there has been an increased interest in ecologically friendly nanoparticle synthesis processes, sometimes known as "green synthesis" or "nanoparticle biosynthesis" approaches. Both internal and extracellular locations, where cell-produced biomolecules are found, can support the green synthesis of NPs.In addition to being environmentally benign, these approaches provide improved performance, lower energy costs (temperature and pressure), and are profitable, biocompatible, safe, and easy to scale up [16, 18]. Bio-mediated synthesis with microorganisms and plants has emerged as a promising alternative to classic nanoparticle synthesis methods. For the low-cost and environmentally safe synthesis of metallic nanoparticles, like silver, gold, palladium, copper, and metal oxides, microorganisms and plants are potential nanofactories [19].

SKIN PENETRATION

The skin is made up of multiple layers, including the epidermis, dermis, hypodermis, and appendages. The epidermis is made up of keratinocytes that have been separated into layers, beginning with initially viable cells and progressing to terminally differentiated keratinocytes at the top. Three main components make up the stratum corneum (SC), a thin layer of around 10 µm: (1) differentiated keratinocytes called corneocytes that are lipid-bound and loaded with NMF; (2) corneodesmosomes, which are proteinaceous rivets that join corneocytes; and (3) lipids. The lipid bilayers in the SC are well-organized and have a lamellar structure. Due to its high protein and lipid content, including ceramides (50%) that contain phytosphingosine, fatty acids (10–20%, which are significantly concentrated in linoleic acid), and cholesterol (25%), the SC serves as a barrier [20]. Ag-NPs, TiO_2-NPs, ZnO-NPs, and $CaCO_3$-NPs are examples of NPs with inadequate penetration that can be applied to the skin's surface as photoprotective and antibacterial agents. The use of nanoparticles as carriers in so-called transdermal drug delivery systems (TDDSs) has gained popularity in recent years [21]. The drug must reach therapeutic concentration, enter the bloodstream, and pass through the skin barrier to be used with a TDDS. Carriers containing NPs may improve not only the penetration and bioavailability of macromolecular drugs via the skin, but also reduce their immunogenicity [22].

DERMATOLOGICAL INTERVENTIONS METAL NANOPARTICLES

In terms of skin applications, metal nanoparticles are frequently employed to combat dermatological infections caused by adventitious agents and to speed up wound healing. Arafa et al. (2018) recently reported an improved version of heat sensitive gels containing gold nanoparticles, with important to note antibacterial properties (against Staphylococcus aureus) and enhanced remedial capacities [23]. Recent articles have aptly highlighted the potential of both silver and gold nanoparticles to promote wound healing and combat antimicrobial infections. These capabilities include the ability to control cytokine secretion, induce differentiation and proliferation of cell types (such as keratinocytes and myofibroblasts), disrupt bacterial reproduction, avoid on-site microbial settlement, and exhibit both "bactericidal" and "bacteriostatic" properties [24].

METAL OXIDES NANOPARTICLES

Metal oxide nanoparticles, which involve zinc, iron, aluminum, magnesium, and copper, have been successfully used to treat dermatological conditions and encourage wound healing (Figure 1) [24]. However, in this context, zinc and iron oxide nanoparticles have received study interest [25]. Zinc oxide nanoparticles have been found to have a wide range of applications, including the creation of novel wound dressings, the bi-metal synthesis of "core-shell nanocomposites," the induction of punctures in bacterial cellular membranes, the generation of hydrogen peroxide, the remarkable absorption capacity of wound exudates, and the promotion of blood clots, among many others [26].

COSMETIC INTERVENTIONS METAL NANOPARTICLES

Inorganic nanoparticle applications in the cosmetic industry are broad in scope, including lip, nail, hair, and skin care, and have become more prevalent in recent years. This is primarily because of the development of extremely efficient ingredients and carrier vehicles for the targeted delivery of active chemical compounds, such as nanoemulsions, nanoliposomes, nanocapsules, and niosomes, among others, which allow them to be classified as cosmeceuticals. The authors claim that gold and silver nanoparticles have drawn the greatest attention as cutting-edge cosmeceuticals with anti-perspiration properties when it comes to pure metallic nanoparticles and how they compare to dermatological usage. sprays and age-delaying cream. Silver nanoparticles have been shown to have stabilizing and antibacterial properties in cosmetic applications. However, the gold and silver nanoparticles reveal there is a basic difference in terms of aggregation when they are used in cosmetic products and services. Gold nanoparticles do not concentrate due to their higher electrokinetic surface potential [27].

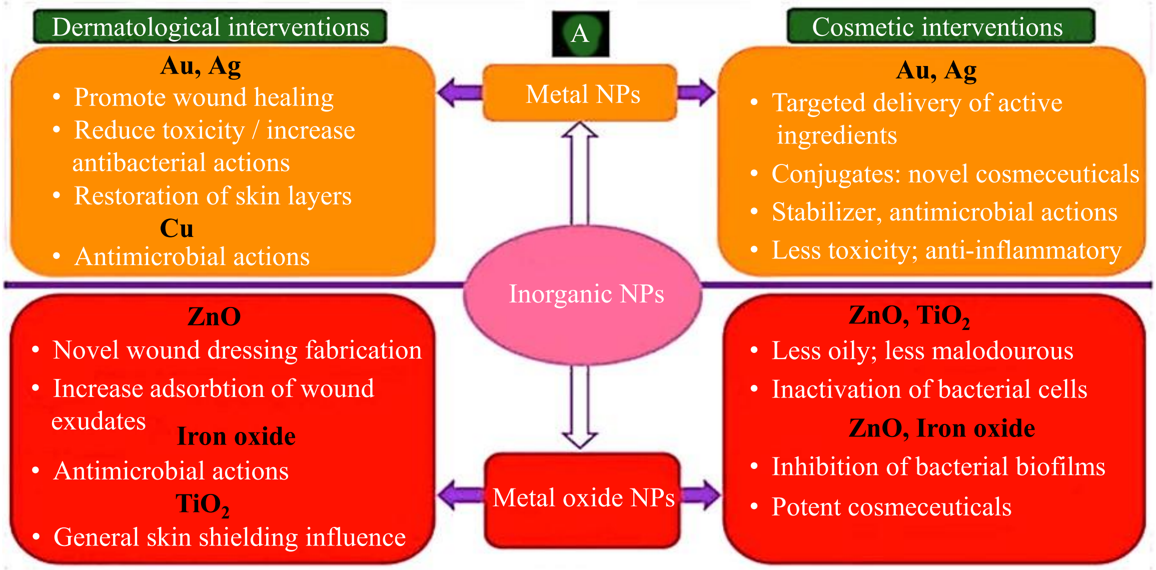

Figure 1. Role of metal and metal oxide nanoparticles in skin care and treatment.

METAL OXIDES NANOPARTICLES

Applications of zinc oxide and titanium dioxide nanoparticles in skin care products are highlighted, including their ability to make sunscreen more odorless and lightweight. Because of their antifungal qualities, the same authors discussed the effective use of zinc and silver/other metal oxide nanoparticles in nail care applications [28].

From another angle, the zinc and titanium dioxide nanoparticles' protective properties against many strains of Staphylococcus and Streptococcus have been discovered. While definitive conclusions about specific antimicrobial activity or processes have yet to be established, the authors compiled information pointing out several possible pathways. One of them consists of the inactivation of cells of bacteria due to the combination of thiol and nanometal groups on the peptidoglycan of the cell wall [29]. Favorite metal oxide nanomaterials, such as zinc and iron oxide nanoparticles, have been linked to inhibitory effects against the formation of bacterial biofilms, making them effective cosmetic agents [28].

SKIN WHITENING AND ANTI-AGING PROPERTIES

Metal nanoparticles, particularly gold (Au) nanoparticles, have received a lot of attention in the field of cosmetology since they have their potential use in skin whitening and anti-aging compositions. Gold nanoparticles' unique properties, such as their optical properties and their ability to interact with light, make them promising candidates for skin brightening and anti-aging properties treatments [30].

PHOTO-PROTECTION

Metal nanoparticles and oxides can also offer photoprotection in cosmetic compositions. They can operate as physical sunscreens by absorbing or deflecting harmful UV rays, decreasing their penetration into the skin. Titanium dioxide (TiO_2) nanoparticles TiO_2 nanoparticles have been used frequently in sunscreens and cosmetics because of their remarkable UV-blocking characteristics. They effectively scatter and reflect UVA and UVB light, ensuring broad-spectrum protection. TiO_2 Nanoparticles are often coated or surface-treated to improve dispersibility and reduce the possibility for skin whitening [31]. Zinc oxide (ZnO) nanoparticles are another common sunscreen an essential part [32]. By reflecting and dispersing UVA and UVB rays, they help provide broad-spectrum UV protection, much like TiO_2. ZnO nanoparticles are frequently used because of their higher photostability and a reduced potential for skin irritation [29]. Iron oxide (Fe_2O_3) nanoparticles: Iron oxide nanoparticles, particularly those in the red and yellow color ranges, are utilized in cosmetic products to protect against visible light. They absorb and reflect visible light, which can promote skin premature ageing and hyperpigmentation. Iron oxide nanoparticles are used in therapies to shield the skin from the harmful effects of sunlight. Silver nanoparticles have unique antibacterial and antioxidant capabilities, making them ideal for usage in sunscreens and other photoprotective products [27].

CONCLUSIONS

In conclusion, the integration of metal nanoparticles into dermatology and cosmetics represents a significant advancement in skincare technology. Metal nanoparticles, such as silver, gold, and zinc oxide, offer unique benefits due to their nanoscale size, which allows them to interact with biological systems at a more precise level than conventional particles. These nanoparticles can improve the delivery and absorption of active ingredients, providing enhanced therapeutic and cosmetic effects. Because of their strong antibacterial qualities, silver nanoparticles are especially well-known for their ability to treat and prevent infections in wound care and acne treatments. Gold nanoparticles are utilized for their anti-inflammatory and anti-aging benefits, helping to reduce wrinkles and improve skin elasticity through targeted delivery and cellular interaction. Zinc oxide nanoparticles, commonly used in sunscreens, offer broad-spectrum UV protection with less visible residue compared to traditional formulations. Despite these advantages, the use of metal nanoparticles in cosmetics and dermatology raises concerns about safety and environmental impact. Issues, such as potential toxicity, skin penetration, and long-term effects necessitate rigorous research and regulatory oversight. It is crucial to balance the benefits of enhanced performance with a thorough understanding of possible risks to ensure the safe and effective use of these advanced materials in skincare and cosmetic products. Overall, while metal nanoparticles hold considerable promise for improving dermatological and cosmetic applications, continued research and development are essential to address safety concerns and optimize their use in everyday skincare.

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