

The Influence of Nanomaterial Components in Cosmetics on The Degree of Skin Absorption

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Abstract. The efficacy and skin absorption of cosmetic products are of key interest to the industry. To study the effect of nanocomponents in cosmetics on the skin, ZnO and TiO₂ nanoparticles in sunscreens were analyzed in this paper. This paper describes the working principle and preparation process of ZnO and TiO₂ nanoparticles in sunscreen, and analyzes the requirements of ZnO and TiO₂ nanoparticles for skin absorption. The results of this paper indicate that nanoscale ZnO and TiO₂ particles are inorganic substances, forming a physical protective film on the surface of the skin and do not need to be inhaled into the skin to exert their effectiveness. Excessive amounts of titanium dioxide and zinc oxide can have toxic effects on skin cells. TiO₂ has stronger photoactivity than ZnO, and the reactive oxygen produced by the reaction with sunlight will damage collagen and other dermal matrix proteins. A layer of inactive shells, such as aluminum oxide, can be applied to the surface of nanomaterials to achieve the effect of reducing photocatalysis, so as to better protect the skin. In addition, this paper points out the potential risks of the application of nanomaterials in cosmetics, and the preparation process can be improved to ensure lower harm to the human body.

Keywords: Nanomaterials; ZnO; TiO₂; Cosmetics.

1. Introduction

Nanotechnology has brought breakthroughs in product quality to the cosmetics industry due to its excellent physical and chemical properties. Statistical data shows that the nanomaterials market has shown a sustained growth trend from 2018 to 2025. Nanotechnology has been proven to improve the performance of cosmetics through various methods. By processing active ingredients into nano-sized particles, the nanoparticles give cosmetics a silky texture that is easy to apply evenly and non-greasy. Nanotechnology also improves product stability by protecting active ingredients from environmental degradation, thereby extending shelf life. The skin can better absorb and penetrate the active ingredients through absorbing nanoparticles into the target epidermal layer, thereby improving the efficacy of functional ingredients. This significantly improves the absorption rate of active ingredients and skin permeability.

The advancement of nanotechnology has promoted the development of nanoscale packaging technology, such as the application of liposomes in nano-permeation systems. These technologies enable more precise delivery of cosmetic ingredients to targeted skin layers. MIT develops gold nanoparticle carrier, targeting efficiency of melanoma up to 90%; L'oréal pH-responsive nanocapsule achieved controlled release and the effect was prolonged for 8 hours. South Korea's AmorePacific Group has launched green tea nano-essential oil, which improves antioxidant indicators by 35%. Shiseido developed 50 nm zinc oxide particles, ultraviolet blocking rate of 99%, without white turbidity phenomenon.

Although nanoparticles can enhance the function of cosmetics, their small size may break through the skin barrier, thereby causing safety issues. In 2022, the Cosmetics Regulation will be updated to require a life-cycle assessment of nanomaterials, and the reporting cycle will be extended to 18 months. The FDA's 2023 guidelines recommend that nanoparticle ingredients provide transdermal absorption data, and 50% of companies will adjust their formulations. However, because the toxicity of nanoparticles is difficult to assess, there is no clear regulation on nanoparticles internationally. Kumah et al. reported that these tiny particles can penetrate tissues. They enter the human body through the lungs, intestines, or skin, causing inflammation to the brain and lungs. It also leads to

heart attacks [1]. In 2024, Nature Nanotechnology pointed out that some metal nanoparticles can enter the blood through damaged skin, causing an increase of 20% in inflammatory factors.

Nano-sunscreens is one of the important applications of nanotechnology in cosmetics. Nano-titanium dioxide and nano-zinc oxide, as two primary nano-sunscreen agents, can reflect, scatter, and partially absorb ultraviolet radiation, providing shielding effects against both UVB (280-320 nm) and UVA (320-400 nm). Compared with traditional physical sunscreen agents, nano-sunscreens not only offer superior sun protection but also maintain high transparency without compromising cosmetic appearance. Particularly, titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles (NPs) are gaining popularity as inorganic physical sunscreen agents, as they can reflect and scatter both UVA and UVB radiation while avoiding skin irritation and endocrine disruptions commonly caused by chemical UV filters. Furthermore, these NPs exhibit transparency and provide comfortable tactile properties [2]. This article will analyze the ZnO and TiO_2 nanoparticles added to sunscreen in the following sections.

2. The Principle of ZnO and TiO_2 Sunscreen

With the deepening understanding of the harm of ultraviolet radiation to the human body, sunscreen has become a daily necessity for skin care. Among many sunscreens, ZnO and TiO_2 nanoparticles stand out due to their unique physical sunscreen protection properties. Sunlight consists of 50% visible light, 45% infrared light, and 5% ultraviolet light [3]. In the spectrum, ultraviolet radiation can be divided into three categories: UVA, UVB, and UVC. Among them, UVC is absorbed by the ozone layer during transmission and does not directly reach the Earth's surface. Therefore, UVA and UVB are considered harmful ultraviolet radiation. Especially UVB, which has a shorter wavelength and higher energy, has strong radiation [4].

The working principle of ZnO and TiO_2 is based on the reflection, scattering, and partial absorption of ultraviolet rays. Nanometer ZnO has a wide absorption spectrum, which can absorb ultraviolet rays in the UVA and UVB bands. When ultraviolet rays are irradiated on the surface of nanometer ZnO , part of the energy is converted into heat energy and dispersed. The particle size of nanometer ZnO scattering ultraviolet rays is smaller than the wavelength of visible light. When ultraviolet rays are exposed to the surface of nanometer ZnO s, scattering occurs. The scattered ultraviolet energy is dispersed in various directions, thereby reducing the radiation intensity. The bandgap of ZnO is about 3.3 eV, corresponding to an absorption wavelength of 375 nm, so it has some absorption for the adjacent UVA (320-375 nm), converting the light energy into heat energy. For the longer wavelength UVA (375-400 nm), scattering becomes the main protection mechanism, reducing the penetration of ultraviolet rays through the skin through scattering.

TiO_2 nanoparticles have a very high specific surface area, which can scatter and absorb ultraviolet rays. Titanium dioxide has a high refractive index (about 2.5-2.7), which can effectively reflect and scatter ultraviolet rays, especially the shorter wavelength UVB (290-320 nm). The bandgap energy of TiO_2 is about 3.2 eV (rutile) and 3.0 eV (anatase), corresponding to absorption wavelengths of 387 nm and 413 nm, respectively, so it can effectively absorb short-wave ultraviolet rays (UVB, 280~320 nm) and some long-wave ultraviolet rays (UVA, 320~400 nm). TiO_2 particles form a physical barrier on the skin surface, reflecting ultraviolet rays back into the environment through their high refractive index. For sunlight with a wavelength less than the particle diameter (such as UVB), the particles mainly block it through reflection, for light with a wavelength close to or greater than the particle diameter (such as UVA), it is mainly scattering. They disperse ultraviolet rays from the skin surface. When the energy of the ultraviolet photon exceeds the bandgap of TiO_2 , its valence band electrons are excited to the conduction band, absorbing part of the ultraviolet energy and converting it into heat or fluorescence release. This absorption characteristic is particularly significant in the UVB band, but the protection against UVA depends on the optimization of particle size or blending with other components such as zinc oxide.

It has been proven that sunscreen formulations can also affect the sunscreen efficacy of nanoparticles. 57-micron-sized TiO₂ is most effective against UVB, while micron-sized ZnO is most effective against UVA, so a combination of the two oxides can ensure the desired broad-spectrum UV protection. In human SC, particle size leads to higher UV absorption and scattering and lower UV transmittance, thus improving UV attenuation [5].

3. Preparation of ZnO and TiO₂

ZnO naturally exists in the Earth's crust in two main crystalline forms: fibrolite and sphalerite. TiO₂ occurs naturally in three crystal structures: redstone, perovskite and masonry [6]. Both nanomaterials are made by chemical synthesis. The main preparation method is Sol Gel Method. The Sol Gel Method is a chemical synthesis technique for preparing materials by solution chemical reaction. Its core is converted by a solution (liquid colloid) into a gel (solid-state network structure) and subsequent processing to obtain the target material. To prepare ZnO nanoparticles, firstly, the precursor is dissolved. A zinc-containing compound, such as zinc nitrate, is dissolved in water or ethanol to form a transparent solution. Then slowly add an alkaline solution, such as NaOH, and adjust the pH to 8-10. Zinc ion hydrolysis produces zinc hydroxide precipitation, which is then heated and kept at a temperature of 60 to 80 degrees Celsius while stirring. The dehydration of zinc hydroxide is converted into zinc oxide nanoparticles, and surfactants are added to coat the surface of the granules and prevent them from agglomerating. Finally, after centrifugation, impurities are removed by washing with water or ethanol, and ZnO nano powder is obtained by drying.

Conde et al. found that a slower rate of adding NaOH can lead to a steadier growth of ZnO nanoparticles, while also providing better optical properties and UV protection [7]. To prepare nanometer TiO₂, firstly, the titanate was dissolved in ethanol, and then slowly add an acidic aqueous solution with a pH value between 1-3, which will trigger hydrolysis reaction. The hydrolysate condensed to form TiO₂ sol. The solution is then left to stand at room temperature and let it age for several hours to several days to form a gel. Then calcination is carried out at high temperature. These amorphous TiO₂ are converted into detitanite or rutile crystal forms. Dispersion and stability are then enhanced by silanization or inorganic coating, such as Al₂O₃. Nano-scale TiO₂ powder was prepared by supercritical drying or spray drying. Hema et al. discovered that the thermal stability of TiO₂ nanoparticles is improved up to 700 degree celsius through Sol Gel Method [8]. Therefore, the nanomaterials that undergo Sol Gel Method show better effectiveness as ingredients in sunscreen.

4. Requirements for skin absorption

The effectiveness of cosmetics is closely related to the skin absorption. It has been considered that the nanoparticles were rubbed into the skin for maximum protection against the incident radiation [9]. However, there are some concerns of using nanoparticles on humans' face because of their toxicity. TiO₂ and ZnO nanoparticles are inorganic ingredients in sunscreen that block UVA and UVB directly through the surface of the particles. They mainly form a protective barrier on the skin surface and do not need to be absorbed by the skin to show an effect. So, how to control the degree of skin absorption of ZnO and TiO₂ nanoparticles is a key concern for the general public; do they penetrate the skin and damage the tissue? Zvyagin et al. have found that in the human body, ZnO nanoparticles remain in the stratum corneum (SC) and accumulate in the skin folds and/or the root of the hair follicles in the human skin. Given that these nanoparticles cannot penetrate the SC and that the outermost layer of the SC has a good turnover rate, these data suggest that ZnO nanoparticles are unlikely to pose a safety issue [10]. It is also important to control the amount of these nanoparticles in sunscreen. Guatam have found that lower doses of TiO₂ and ZnO nanoparticles induce autophagy in keratinocytes, as a survival mechanism, to protect cells from oxidative stress and inflammation [11]. At higher doses, they cause toxic effects on cells, but they do not significantly affect skin physiology or wound healing.

However, TiO₂ is relatively more toxic. TiO₂ may produce reactive oxygen under ultraviolet light excitation, which is closely related to its photochemical activity. This characteristic may damage skin cells. This reactive oxygen activates different matrix metalloproteinases, thereby damaging collagen and other dermal matrix proteins [2]. In order to mitigate the toxicity, what can be done to improve the performance of TiO₂ and ZnO nanoparticles? If the composition of the formulation matrix is changed, the stability, safety, and photoprotection function of the sunscreen will become unbalanced, and it will not work as expected. So far, the photocatalytic performance can be reduced by coating a layer of inert shell on the surface of nanomaterials while retaining the light scattering properties. For example, aluminum oxide (Al₂O₃), zirconium dioxide (ZrO₂), silicon dioxide (SiO₂), silicon tetrahydride (SiH₄), or polydimethylsiloxane (PDMS)[12].

Therefore, the ZnO and TiO₂ nanoparticles in sunscreens do not require a high degree of skin absorption, and there is no need to consider how to transport these nanoparticles to the specified stratum, as they only act on the skin surface. In normal conditions, these nanoparticles do not penetrate the epidermis. The ratio of ZnO and TiO₂ and the photochemical activity should be paid more attention to. Applying an inert coating on the surface of the material or adding a photochemical inhibitor is feasible, but it also increases the complexity of the formulation. In order to reduce the impact of other additives on the effect of the product, the nanoparticles themselves can be optimized. By increasing the particle size or changing the morphology, the specific surface area can be reduced, thus effectively reducing the photochemical activity. By synthesizing larger-sized nanoparticles, such as nanoparticles with a diameter of 50 to 100 nm, spherical or plate-shaped nanoparticles can be synthesized instead of needle-like structures to reduce the surface energy. Future research can develop more biocompatible coatings to reduce skin irritation.

5. Conclusion

The application of ZnO and TiO₂ nanoparticles in sunscreens exemplifies the dual-edged potential of nanotechnology in cosmetics. These nanomaterials significantly enhance UV protection efficacy through their unique ability to reflect, scatter, and partially absorb harmful UVA and UVB radiation, while maintaining cosmetic elegance via transparency and lightweight textures. The sol-gel synthesis method has proven instrumental in optimizing their physicochemical properties, enabling controlled particle size, crystallinity, and stability—critical factors for achieving high-performance sunscreens. Current evidence suggests that ZnO and TiO₂ nanoparticles predominantly remain on the skin's surface, accumulating in the stratum corneum (SC) and hair follicles without significant penetration into deeper epidermal layers. This limited absorption minimizes systemic toxicity risks, as the SC's natural turnover mechanism facilitates the removal of superficial particles. However, dose-dependent cytotoxicity remains a concern: lower nanoparticle concentrations induce protective autophagy in keratinocytes, whereas higher doses may trigger oxidative stress and inflammation. Notably, TiO₂ exhibits greater photochemical reactivity under UV exposure, necessitating surface modifications (e.g., Al₂O₃, SiO₂ coatings) to mitigate reactive oxygen species (ROS) generation while preserving optical performance. There are a number of limitations across the nanocosmetics industry. There is a lack of long-term safety data to demonstrate whether the potential toxicity of nanoparticles affects human health. These nanoparticles can enter the ecosystem during the use of cosmetics and may also have a negative impact on the environment. There are still some limitations at the technical level, for example, maintaining the stability of nanoparticles requires the addition of additional stabilizers, which complicates formulations. The extent of transdermal absorption is also difficult to control. Precise delivery of nanoparticles is a challenge, with no global harmonization of nanoparticle use and a confusing market. But if a breakthrough is to be achieved, research must be intensified. A better model of nanoparticle skin penetration should be established to clarify the distribution and transportation of nanoparticles. The international community should strengthen the safety assessment of nanoparticles and formulate unified regulations. Education should keep pace with the times, scientifically introduce nanoparticles and popularize related knowledge. The application of

nanoparticles in cosmetics has great potential, and breakthroughs in technology and regulations will drive the innovative development of nanoparticles.

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