Proceedings of the 6th International Conference on Biological Engineering and Medical Science
DOI: 10.54254/2753-8818/2026.35978

Whether a Sunscreen with SPF 30+ Incorporating Three Nanoparticles can Provide Better UV Protection While Maintaining a Light Skin Feel

Ziyao Pan

YK Pao School, Shanghai, China
Cocopan2008@163.com

Abstract. Chronic ultraviolet exposure represents the primary extrinsic factor in premature skin aging, fueling consumer demand for daily facial products that combine photoprotection with active anti aging repair. Retinol, a vitamin A derivative, remains the gold standard agent for diminishing fine lines and enhancing skin texture via epidermal turnover and collagen stimulation. Is inherent instabilities poses a severe challenge to sunscreens as they are intentionally applied under intense sunlight which accelerate retinol degradation. Uncoated metal oxide filters (TiO_2 and ZnO) further aggravate this issue through photo catalytic generation of reactive oxygen species. This proposes that nanoparticles have spatially separated functions: solid lipid nanoparticles (SLNs) encapsulate retinol and provide controlled release, surface coated metal oxides afford broad-spectrum UV shielding with minimal photocatalysis and fumed silica construct a hydrogen-bonded network for rheology control and a light silky, skin feel. The scientific rationale for each type of particle is elaborated and concluded that all three nanoparticles are indispensable. The finding offers a viable solution to the incompatibility between retinol and UV filters in daily sunscreens, providing a possible foundation for future multifunctional formulation design.

Keywords: SLNs, Fumed Silica, Coated metal oxides

1. Introduction

Sun exposure is the most important cause of skin photoaging which has caused the development of facial sunscreens that not only blocks ultro violet radiation but also deliver active anti-aging compounds. Retinol is one of the most thoroughly investigated vitamin A derivatives and is recognized for its ability to improve skin roughness, primarily by accelerating epidermal cell renewal and stimulating dermal collagen synthesis. However, retinol is very chemically fragile, so it decomposes rapidly upon exposure to oxygen, light and elevated temperature via oxidative and photoisomerization pathways. This photosensitivity creates a fundamental paradox in sunscreen formulation: a product designed for use under strong solar radiation will inevitably expose its active ingredients to the condition that causes their destruction. In addition, the common inorganic UV filters, especially uncoated titanium dioxide and zinc oxide, exhibits photocatalytic behavior under UV illumination, generating reactive oxygen species that can further accelerate retinol breakdown.

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Therefore, retinol and sunscreens are mutually incompatible, leaving people to make the choice between photoprotection and anti-aging repair.

Recent improvements in nanoparticles technologies offer a solution to this problem. Three nanoparticle can perform different functions: solid lipid nanoparticles (SLNs) encapsulates retinol with crystalline lipid matrix to shield it from degradation and allows a controlled skin delivery; coated metal oxide nanoparticles, like titanium dioxide or zinc oxide, provide broad spectrum UV attenuation and makes the lotion transparent on skins and exhibits minimal photocatalytic activity; fumed silica is a fractal structured colloidal material that controls rheology and has a silky texture at low concentration. These three particles can coexist to meet the need of combining the 2 functions.

This paper explores whether an oil in water emulsion sunscreen with SPF 30+ incorporating these three nanoparticles can simultaneously deliver stable retinol, provide broad spectrum UV protection, and maintain a light skin feel.

2. Solid lipid nanoparticles: encapsulation and controlled delivery of retinol

Solid lipid nanoparticles (SLNs) are colloidal carriers that have a solid lipid core stabilized by a surfactant layer with a diameter of 100 to 300 nm. The core is made up of lipids that remains solid at room temperature, such as triglycerides, glyceryl behenate, or cetyl palmitate. The lipid's crystalline character can help with retinol protection. In a liquid oil, retinol molecules collide frequently with dissolved oxygen and undergoes oxidation reaction. Inside the solid lipid core are densely packed crystalline lattice decreases molecular diffusion. Retinol becomes trapped within the rigid matrix, which drastically reduces the frequency of the contact with oxygen. Furthermore, a crystalline lipid layer builds a higher diffusion barrier to external oxygen. The matrix also excludes water, thereby eliminating hydrolysis reaction. Studies have shown that SLNs can retain over 90% of encapsulated retinol after a few weeks of storage at elevated temperatures, whereas retinol dissolved in conventional oil phases degrades within days [1]. SLN dispersion contains retinol maintains a mean particle size of 134.7 ± 0.3 nm and a zeta potential of 42.7 ± 1.2 mV after four weeks at 25 °C. This data shows the stability of retinol in SLN. The photostability of all trans retinol in SLNs at 12 hours was boosted to approximately 43%, compared with only about 11% in methanol solution [2]. The carriers tackle all degradation reaction simultaneously (oxidation, isomerization, and hydrolysis).

When applicates to the skin, the aqueous phase evaporates and the SLNs goes through a transition from discrete to cohesive. The particles form a thin layer on the stratum corneum. This diminishes epidermal water loss, leading to hydration and a slight swelling of the skin layers. This hydration can disturb the lipid structure and packing of the stratum corneum, thereby increases its permeability to lipophilic molecules. Retinol is highly lipophilic so can partition into the epidermis in a more controlled way. Tape stripping experiments have shown that SLN associated retinol accumulates in the upper epidermal with studies showing that SLN based delivery cuts systemic exposure by approximately 60–70% compared with free retinol formulations [3]. Consequently, this lowers the risk of systemic exposure and local irritation. In the context of a daily sunscreen, this effect sustains a steady retinol flux during sun exposure while also helps to prevent moisture loss [3].

If SLNs are eliminated from this, retinol becomes directly exposed to other components which may increase degradation. An unprotected retinol solution that come in contact with photoexcited components can degrade by more than 50% within one hour when exposed to sunlight [4]. Even though SPF value would remain unchanged, the product's anti-aging effect will be eliminated. Furthermore, without SLN, the formulation will lose its very controlled mechanism so free retinol will penetrate more erratically which causes health threats.

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3. Coated metal oxide nanoparticles: UV protection with suppressed photocatalysis

Titanium dioxide and zinc oxide are semiconductor metal oxides that protect skin by absorbing and scattering UV radiation. They have wide band gaps, approximately 3.2 eV for TiO_2 and 3.4 eV for ZnO. This enables them to absorb high-energy UV photons. The absorbed energy is then dissipated when electrons return to ground state. Attenuation is yielded primarily in the UVB and UVA II regions. Additionally, because the refractive indices of TiO_2 (rutile ~2.6) and ZnO (~2.0) are substantially higher than those of the oil and water phases in an emulsion, the particles scatter light through Mie scattering. By reducing the primary particle size to below 50 nm, visible light scattering is minimized which makes the sunscreen transparent on the skin rather than leaving a white cast.

Commercial sunscreen grade metal oxides are coated with inert inorganic layers, most commonly alumina, silica, or silane compounds, to suppress photocatalytic activity [4]. Such coatings give a physical barrier that blocks electron transfer to surrounding oxygen and water. Recent advances in technologies have demonstrated that metal phenolic network coatings can cut photoinduced reactive oxygen species generation by 99.9% under solar irradiation [5]. Comparative measurements of photocatalytic activity have shown that coating reduces the generation of reactive oxygen species by more than 90% relative to uncoated particles [4]. This suppression is essential for any formulation that combines mineral UV filters with oxidation sensitive active ingredients. By contrast, uncoated metal oxide nanoparticles can carry a significant drawback. Under UV light, photogenerated electrons migrate to the particle surface and react with adsorbed water and oxygen to produce reactive oxygen species, including hydroxyl radicals and superoxide anions [4, 6]. These highly reactive molecules will attack organic compounds non selectively. Direct contact between uncoated TiO_2 and retinol under solar simulation will destroy retinol within 30 minutes [4]. In the present sunscreen formulation, coated titanium dioxide or zinc oxide particles with diameters of 20–50 nm is dispersed in the oil phase. The coating ensures chemical compatibility with retinol and prevents particle agglomeration [7].

The inclusion of these UV filters at a concentration calibrated to achieve SPF 30+ guarantees that the sunscreen blocks the majority of erythemal UV radiation. If the metal oxide particles are removed, the UV protective function cannot be taken over by the other ingredients. Indeed, both SLNs and fumed silica possess refractive indices close to 1.45–1.5, similar to the oil phase, and neither is a semiconductor. They cannot absorb UV photons through band gap excitation, and their low refractive index results in negligible scattering. The product would therefore provide no UV protection. Simply adding more SLNs or silica to compensate for UV attenuation is infeasible, because these materials lack the physical properties necessary to interact with UV radiation. Thus, coated metal oxides are indispensable for photoprotection in this nanoparticle based formulation.

4. Fumed silica: rheology control and sensory enhancement

Fumed silica arises from fractal aggregates that form during the high temperature hydrolysis of silicon tetrachloride. Its primary particles, which range from 7 to 40 nm in diameter, undergo irreversible fusion into branched, chain like assemblies that boast an exceptionally large specific surface area, typically between 200 and 300 m^2/g. The particle surfaces are heavily decorated with silanol (Si–OH) groups, and these functional moieties readily participate in hydrogen bonding interactions. When introduced into the oil phase of an emulsion, the silanol groups belonging to neighbouring aggregates engage in hydrogen bonding with one another, thereby giving rise to a three dimensional particulate network that extends throughout the continuous medium. Such a network endows the emulsion with a yield stress. In the quiescent state, this interconnected

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architecture behaves like a soft solid, effectively preventing the creaming of droplets and the separation of phases. Yet when subjected to the shear forces generated by rubbing, the hydrogen bonds rupture, the network collapses, and the lotion becomes fluid and spreadable. Immediately after the shearing ceases, the bonds are reconstituted with remarkable rapidity, and the original viscosity is recovered. This thixotropic response lies at the heart of the sunscreen's sensory appeal: the product feels dense and rich inside the container, glides over the skin with ease during application, and subsequently settles into a dry, non tacky film [8].

The fractal nature of these aggregates is what makes fumed silica so effective as a thickening agent. Owing to the highly open and voluminous character of the aggregates, a continuous network can be established at rather modest addition levels—generally in the range of 1 to 3 weight percent. In contrast, spherical nanoparticles of comparable primary size would demand a far greater mass fraction to produce a similar structural effect, simply because they lack the elongated, high aspect ratio branches that are essential for creating long range connectivity. As a result, fumed silica furnishes the desired viscosity and suspension stability without introducing any oily or heavy feel. In the context of a facial sunscreen, this attribute translates directly into a lightweight, velvety tactile experience, which in turn plays a major role in encouraging regular consumer use.

Beyond its rheological duties, the fumed silica network contributes significantly to the overall performance of the three particle system. By holding the emulsion together and warding off phase separation, it guarantees that the SLNs stay evenly dispersed, thereby ensuring consistent retinol delivery; at the same time, it keeps the coated metal oxides uniformly distributed, which is a prerequisite for homogeneous UV protection [8]. Additionally, the hydrogen bonded scaffold remains chemically inert toward both the retinol confined within SLNs and the coated UV filters, so the stability of these active species is not compromised. This chemical orthogonality is crucial for preserving the separate functionalities of each particle type within a single product.

Eliminating fumed silica from the recipe would have dire consequences for the emulsion's physical integrity. Without it, the yield stress vanishes, and the remaining particulate constituents—being predominantly spherical—are incapable of forming a space filling network at any practical loading. The resulting lotion would turn watery and prone to running, with oil droplets coalescing and rising to the surface, ultimately producing discernible phase separation. Attempting to compensate for the missing silica by escalating the proportion of other particles only introduces new difficulties: a higher metal oxide content yields an opaque, whitish paste with a gritty texture and a noticeable residue on the skin; meanwhile, augmenting the SLN fraction, given the inherently hydrophobic and occlusive nature of their lipid cores, would render the product greasy and heavy. Neither of these alternatives can achieve the refined, non greasy finish that users have come to expect. Hence, fumed silica stands alone in its responsibility for delivering the desired sensory profile and ensuring the sunscreen's long term physical stability.

5. Application of experimental data in the three components

Experimental evidence supports this conceptual framework. Accelerated stability studies have show that retinol-carrying lipid nanoparticles preserves 90% or more of their initial retinol content over four weeks period at temperature of 25, 40, and 50°C [1]. They further noted that SLN dispersions incorporating retinol and pentapeptide 18 retained a mean particle diameter of 134.7 ± 0.3 nm and a zeta potential of 42.7 ± 1.2 mV after four weeks at 25 °C (10078). The encapsulation efficiency for retinoids within SLNs can be as high as 97.8% depending on the lipid composition chosen [9]. Formulations that use coated titanium dioxide can reach SPF values of 38 [10]. Fumed silica, when incorporated at levels of 1 to 3 wt% may furnish yield stress for emulsion stabilization while

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maintain the lotion's lightweight, non-greasy texture [8]. The removal of any single nanoparticle would result in at least a twofold deterioration in one of these performance metrics. These observations affirm that the three nanoparticles work together to serve for different function so every one of them is indispensable.

6. Conclusion

The success of the formulation is the combination of all three nanoparticle types in sunscreen. SLNs includes retinol and regulate retinol release; coated metal oxides attenuate UV radiation and keeps the photocatalytic reaction to a minimum; fumed silica manages the rheological behavior and tactile qualities. Removing any one of these components will disrupt the solution. In the absence of SLNs, retinol deteriorates rapidly and its actions will become unpredictable, making anti-aging function impossible. Lacking in coated metal oxides leaves the product with no UV protection. And without fumed silica, the emulsion loses structural cohesion which discourages consistent application. The three ingredients are carefully designed to coexist without interfering with one another: the oxide coatings reduce reactive oxygen production, the solid lipid matrix keeps retinol under control, and the fumed silica network remains non reactive toward both the encapsulated retinol and the coated filters.

In summary, this work shows that the three types of nanoparticles can effectively solve the conflict between retinol delivery and UV protection in a daily sunscreen. The SLNs trap retinol inside a crystal structure, which keeps it stable. The coated metal oxides block UV rays and are designed to cause minimal side reactions. The fumed silica forms a hydrogen bond network that gives the product a light, silky feel. Together, these features allow the sunscreen to shield skin from the sun, deliver retinol steadily, and makes the final lotion feel pleasant to apply. When any one of the three particles is removed, the product fails in protection, delivery, or texture. This confirms that all three are essential. Researchers could try adjusting the ratios of the three particles to get even better UV protection and retinol release. Long term studies on real skin will also be needed to confirm that the product really works against aging and is safe to use. In addition, testing new coatings for the metal oxides and biodegradable materials for the SLNs might make the sunscreen more environmentally friendly and sustainable.

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