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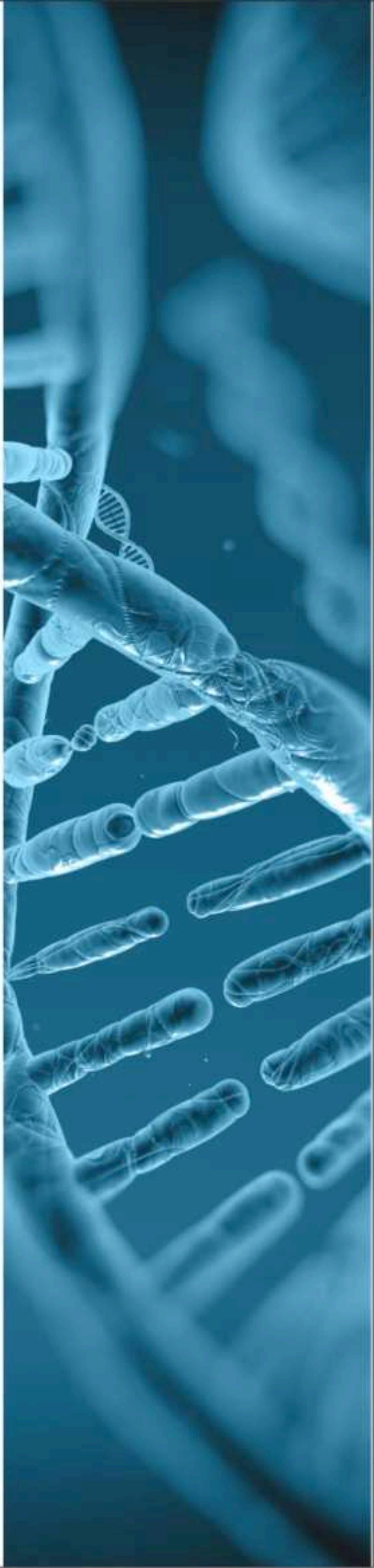

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REVIEW ARTICLE

Shielding the Skin: A Comprehensive Review of Inorganic Sunscreens and Their Role in Photoprotection

Melindungi Kulit: Tinjauan Komprehensif tentang Tabir Surya Anorganik dan Perannya dalam Fotoproteksi

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ABSTRACT

Sunscreens are topical agents that protect the skin from the damaging effects of ultraviolet (UV) radiation, a major contributor to premature aging and skin cancer. These products are typically categorized into two main types: physical (inorganic or mineral) and chemical (organic) sunscreens. Physical sunscreens primarily consist of zinc oxide (ZnO) and titanium dioxide (TiO_2), which reflect and scatter UV rays, thereby providing broad-spectrum protection. Compared with chemical sunscreens, which absorb UV radiation and convert it into heat, inorganic agents are associated with a lower risk of systemic absorption and skin irritation, making them particularly suitable for sensitive skin and pediatric use. This review explores the fundamental mechanisms of action, formulation challenges, and comparative effectiveness of inorganic sunscreens. Special attention is given to their photostability, which contributes to longer-lasting protection, and to their safety profiles in both acute and chronic use. Additionally, recent innovations in nanoparticle technology have enhanced the aesthetic appeal of these agents by reducing visible residue. However, this has also raised new concerns about nanoparticle penetration and environmental impact. Finally, the review addresses public health considerations, including regulatory updates, consumer preferences, and the role of education in promoting informed use of sunscreen.

Keywords: Inorganic Sunscreens; Nanoparticle Technology; Photoprotection; Titanium Dioxide;Zinc Oxide.

ABSTRAK

Tabir surya adalah produk topikal yang dirancang untuk melindungi kulit dari dampak merugikan radiasi ultraviolet (UV), yang merupakan faktor utama penuaan dini dan kanker kulit. Tabir surya umumnya diklasifikasikan ke dalam dua jenis utama: fisik (anorganik atau mineral) dan kimiawi (organik). Tabir surya fisik terutama mengandung seng oksida (ZnO) dan titanium dioksida (TiO_2), yang bekerja dengan memantulkan dan menyebarkan sinar UV, sehingga memberikan perlindungan spektrum luas. Dibandingkan dengan tabir surya kimiawi yang menyerap radiasi UV dan mengubahnya menjadi panas, agen anorganik memiliki risiko lebih rendah terhadap penyerapan sistemik dan iritasi kulit, sehingga lebih cocok digunakan untuk kulit sensitif dan anak-anak. Ulasan ini membahas mekanisme kerja, tantangan formulasi, dan efektivitas tabir surya anorganik. Fokus khusus diberikan pada fotostabilitasnya, yang berkontribusi terhadap perlindungan jangka panjang, serta profil keamanannya dalam penggunaan akut dan kronis. Selain itu, inovasi terbaru dalam teknologi nanopartikel telah meningkatkan daya tarik estetika produk ini dengan mengurangi residu putih yang tampak, meskipun juga menimbulkan kekhawatiran baru terkait penetrasi partikel nano dan dampak lingkungan. Ulasan ini juga membahas implikasi kesehatan masyarakat, termasuk regulasi terbaru, preferensi konsumen, dan pentingnya edukasi dalam mendorong penggunaan tabir surya yang tepat.

Kata Kunci: Fotoproteksi; Seng oksida; Tabir surya anorganik; Teknologi nanopartikel; Titanium dioksida.

INTRODUCTION

Early sun protection techniques date back to ancient civilizations, such as the Egyptians, who employed natural extracts as early as 4000 BC. Sunscreen has a long and varied history. Centuries ago, the Greeks and Indians also employed zinc oxide and olive oil for photoprotection. In 1891, Friedrich Hammer created the first chemical sunscreen in Germany using acidified quinine sulphate. In 1896, Dr. Paul Unna identified the link between sun exposure and skin cancer.[1,2,3] As tanning gained popularity in the 1930s, further inventions followed. The first commercially available sunscreens were developed in the late 1920s and early 1930s, with popular products from Australia's H.A. Milton Blake and France's Eugène Schueller of L'Oréal. Benjamin Green created Coppertone, a sunscreen, for the US soldiers during World War II. Swiss chemist Franz Greiter first presented "Gletscher Crème" in 1946. In 1962, he developed the Sun Protection Factor (SPF) method, which is now the industry standard for measuring sunscreen effectiveness of sunscreen.[2,4] Sunae have evolved over the years to become more user-friendly, water-resistant, and practical, reflecting both changing societal attitudes toward sun exposure and skin health as well as scientific advancements.[5]

Standardized methodological criteria, including selection bias, measurement bias, confounding control, and completeness of outcome reporting, were used to systematically evaluate the risk of bias across all included studies in this review. Overall, most studies showed low to moderate risk of bias; however, some reports had limitations related to inadequate confounding adjustment and poor exposure evaluation.

Summary information for the intervention and comparison groups was taken from each included study. These data included safety outcomes (such as irritation or adverse reactions), environmental impact parameters when available, and measures of photoprotection efficacy (such as reduction in erythema, UV-induced oxidative stress, and DNA damage).

Through centuries of observation and scientific advancement, the connection between ultraviolet (UV) light and sunburn has been understood. Scientists started examining the elements of sunlight in the 19th century. By the early 20th century, they had established that UV radiation, more especially UVB rays, was the cause of sunburn and skin damage.[6] Studies over time have shown that UVA (320–400 nm) also plays a role in the development of skin cancer and aging. This knowledge led to improvements in sunscreen formulas and enhanced public health activities promoting UV protection. The importance of sun protection is further supported by the well-established fact that excessive UV exposure damages DNA in skin cells, leading to inflammation (sunburn) and increasing the risk of skin cancer.[7]

One in five Americans is expected to develop skin cancer at some point in their lives, making it one of the most prevalent cancers in the country. More than 3 million Americans are diagnosed with nonmelanoma skin cancers (basal and squamous cell carcinomas) annually. In 2022, approximately 200,000 new melanoma cases are anticipated, making it the sixth most commonly diagnosed cancer.[8] Factors contributing to skin cancer include excessive sun exposure, use of tanning beds, childhood sunburns, skin that burns easily, red or blonde hair, numerous or atypical moles, and family history. To detect skin cancer early, the American Academy of Dermatology (AAD) recommends monthly self-examinations to look for any suspicious sores or moles that change color or shape, grow significantly, do not heal, or bleed.[9] Annual skin examinations by a dermatologist are strongly recommended, particularly for high-risk groups, including those with a history of childhood sunburns, immunosuppressed individuals, individuals with fair skin, and those with a history of skin cancer. When melanoma is detected early, the 5-year survival rate reaches 99 percent.[10]

One of the main environmental factors causing photoaging, erythema, and the emergence of skin cancer is ultraviolet (UV) radiation. Because of their broad-spectrum coverage, photostability, and suitability for sensitive skin, inorganic sunscreens based on zinc oxide and titanium dioxide have drawn more scientific and commercial interest in recent decades. Even though they have been used for a long time, advances in formulation science, nanotechnology, and safety assessment have significantly changed our current understanding of their performance traits and protective mechanisms.

Ultraviolet (UV) radiation is a form of electromagnetic energy emitted by the sun. There are three main types of UV radiation, categorized by wavelength: UV-A (320–400 nm), UV-B (280–320 nm), and UV-C (100–280 nm). Although UV-A and UV-B rays penetrate the atmosphere and significantly impact biological systems, UV-C is primarily absorbed by the Earth's ozone layer, preventing it from reaching the surface.[11] UV-B radiation is hazardous because it can directly damage DNA, leading to mutations and an increased risk of skin cancer.

UV-A penetrates deeper into the skin, leading to oxidative stress and photoaging, even though it is less harmful. Prolonged exposure to UV radiation is associated with adverse health effects, including eye damage, immunosuppression, and erythema. However, the skin's vitamin D production depends on controlled exposure to UV-B radiation. This study aims to understand the mechanisms of action of UV radiation, develop effective protection methods such as sunscreens and protective clothing, and encourage their safe and beneficial use.[12,13] Ultraviolet (UV) radiation is divided into three primary categories based on wavelength[14,15]:

1. UV-A (320–400 nm): This is the most common and least intense form of UV radiation reaching Earth's surface. It penetrates deeply into the skin and is primarily responsible for long-term skin damage and photoaging. Additionally, indirect DNA damage caused by reactive oxygen species can contribute to the development of skin cancer.
2. UV-B (280–320 nm): This ultraviolet radiation carries more energy than UV-A and is partially filtered by the ozone layer. It affects the skin's outer layer and is the primary cause of sunburn. UV-B directly damages DNA and is closely linked to skin cancers, including

melanoma. Nonetheless, UV-B plays a crucial role in the production of vitamin D in the human body.

3. UV-C (100–280 nm): This is the most energetic and potentially harmful form of UV radiation; however, it is entirely absorbed by the Earth's atmosphere, especially by the ozone layer. Due to its strong germicidal properties, UV-C is commonly used in artificial sources for sterilization and disinfection.

Classification of Sunscreens

1. A list of 16 authorized sunscreen ingredients was included in the most recent FDA sunscreen monograph, published in 1999. The adjectives "chemical" and "physical" should be replaced by the terms "organic" and "inorganic," respectively, for sunscreens. Sunscreen agents are typically referred to by three names.[16] These include the US Adopted Name (USAN), trade name, and International Nomenclature of Cosmetic Ingredients (INCI). For instance, avobenzone (USAN) has several trade names, including Parsol 1789, and its INCI name is butylmethoxydibenzoylmethane [17,18]

2. **Organic or chemical Sunscreens**

UV rays are absorbed by organic UV filters found in chemical sunscreens. Every filter is adjusted to absorb particular UV rays:[19]

- UVA filters (320–400 nm): avobenzone, oxybenzone, and ecamsule.
- UVB filters (280–320 nm): octinoxate, octocrylene, homosalate, etc.
- UVA + UVB filters: Ecamsule (Mexoryl SX), Silatriazole (Mexoryl XL), Bemotrizinol (Tinosorb S), Bisoctrizole (Tinosorb M)

To prevent DNA damage, photoaging, and carcinogenesis, these molecules are excited by UV light and then return to their ground state, releasing energy as heat. Avobenzone is a powerful UVA filter (fig. 1). However, it has the disadvantage of being photostable, as it is the only sunscreen ingredient with an absorption peak in the UVA1 spectrum (357 nm). This is slightly reduced by adding photostabilizers to the finished sunscreen lotion.[20] These medications include broad-spectrum filters like bemotrizinol (not yet FDA authorized), inorganic filters like zinc oxide and titanium dioxide, salicylates, octocrylene, UVB filters like enzacamene (not yet FDA approved), and other UVA filters like oxybenzone.[21]

Chemical sunscreens are typically more cosmetically elegant than mineral sunscreens due to their thinner consistency and transparency upon application. The effectiveness of chemical sunscreens has been confirmed by numerous studies to prevent are erythema and sunburn (UVB),

chronic pigmentation and photodamage (UVA), and skin cancers, especially squamous cell carcinoma, and maybe melanoma.

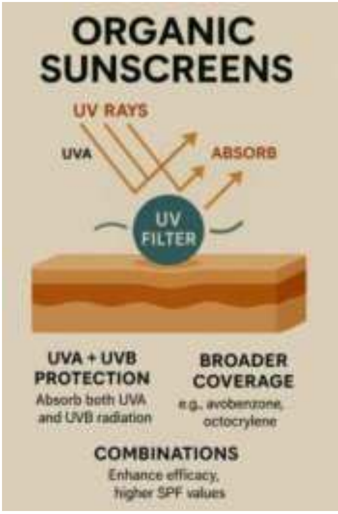

Figure 1. Mechanism of action of organic sunscreen

The FDA has called for additional safety data because recent studies have raised concerns about the systemic absorption of several UV filters (such as oxybenzone, homosalate, and octinoxate). Although evidence on these chemicals' clinical significance in humans is conflicting, some in vitro and animal research indicates they may have endocrine-disrupting properties.[23]

Specific filters (e.g., avobenzone, oxybenzone) may cause photoallergic contact dermatitis in sensitive individuals. Stabilizers and preservatives in formulations can also contribute to irritation.[24]

3. **Inorganic or physical Sunscreens**

Inorganic sunscreens, commonly called physical blockers, offer a compelling alternative to organic (chemical) sunscreens, especially for individuals with sensitive skin. The two FDA-approved inorganic filters (ZnO and TiO_2) are widely used because they reflect, scatter, and absorb UV radiation [25]

Zinc oxide and titanium dioxide work by physically interacting with UV radiation. ZnO provides broad-spectrum protection across UVA and UVB wavelengths. At the same time, TiO_2 is primarily effective in the UVB and short UVA range (Fig. 2). Its photoprotective efficacy stems from high refractive indices and strong UV attenuation. Modern formulations use micronized or nanoparticulate forms to minimize the characteristic white cast and enhance cosmetic acceptability.[26,27]

Particle size, surface coating, and formulation matrix all impact the safety and effectiveness of inorganic sunscreens. Although concerns remain about environmental toxicity and dermal penetration, nanoparticles (less than 100 nm) improve transparency and spreadability.[28] Surface coatings, such as silica or alumina, improve photostability and reduce reactive oxygen species (ROS) generation. Hybrid formulations combining inorganic and organic filters are also being developed to maximize coverage and cosmetic appeal.[29]

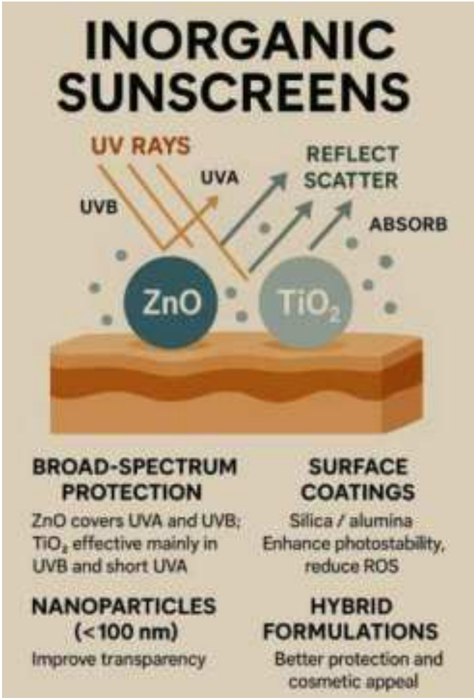

Figure 2. Mechanism of action of inorganic sunscreen

Several studies support the safety of inorganic sunscreens. Dermal penetration of ZnO and TiO_2 nanoparticles is minimal in healthy skin, with negligible systemic absorption. These agents are less likely than organic filters to cause allergic or irritant reactions. Nevertheless, their potential to generate reactive oxygen species (ROS) under UV exposure has raised concerns, particularly when used as uncoated nanoparticles. Environmental impact studies have suggested that TiO_2 nanoparticles may harm aquatic ecosystems, contributing to regulatory scrutiny.[27,30]

Antioxidants such as vitamin C, vitamin E, silymarin, and green tea polyphenols are found in many sunscreens. Vitamin C protects against UV-induced damage, which leads to sunburn and erythema. Vitamin E reduces immunosuppression, erythema, photoaging, and photocarcinogenesis, among other protective effects.[31] Silymarin, which is extracted from milk thistle plants, functions as a scavenger of reactive oxygen species (ROS) and assists in preventing lipid and lipoprotein oxidation. The topical application reduces UVB-induced sunburn cells and decreases the formation of UVB-induced pyrimidine dimers. In mice, it has been shown to reduce the number of UVB-induced tumors ([32]. Green tea polyphenols have more potent antioxidants than vitamins C and E. These polyphenols are anti-inflammatory and anticarcinogenic and function as scavengers of singlet oxygen, superoxide radicals, hydroxyl radicals, peroxyl radicals, and hydrogen peroxide.[33]

Mechanism of Action

Sunscreens protect the skin by reducing or preventing the penetration of ultraviolet (UV) radiation.[30,32] They primarily function through two mechanisms: Chemical sunscreens, which absorb UV radiation, and physical (or mineral) sunscreens, which reflect and scatter both UVA and UVB rays.

An essential measure of sunscreen efficacy is the Sun Protection Factor (SPF), which indicates how well a product protects against UVB radiation, the leading cause of sunburn and DNA damage [34]. An SPF rating indicates how much longer a person can be exposed to the sun without sunburn compared with unprotected skin. For example, SPF 30 blocks about 97% of UVB radiation, allowing only 3.3% to pass through the skin. However, SPF does not protect against UVA rays, which penetrate more deeply and may accelerate signs of aging and even encourage the development of melanoma [35,36].

As recent studies have consistently demonstrated, the amount of sunscreen used significantly affects the actual level of protection, frequently resulting in lower-than-labeled SPF. The SPF value of sunscreen products is determined by applying them at a standardized dose of 2 mg/cm² of skin. However, research shows that most users apply only 25–50% of the recommended dosage, resulting in an 80% reduction in protection.[37] The in vivo determination of SPF values is carried out through the emission of artificial light by a solar simulator in both exposed and unprotected conditions. Moreover, sunscreen protects areas of the body, and it is applied in the latter condition. After 24 hours of exposure, the regions are evaluated for pigmentation and erythema response. These testing methodologies may vary across regulatory agencies and are harmonized by the ISO (International Organization for Standardization). According to surveys conducted in Denmark, Australia, Southern Europe, and Egypt over a 25-year period, the amount of sunscreen used ranged from 0.39 to 0.79 mg/cm².[38]

A study of 1000 students in India by Yashovardhana et al.[4] found that only 11.88% of participants knew the ideal amount of sunscreen to use. The effectiveness of sun protection depends directly on the photo-protective product.[39] Additionally, research by Cruz et al.[40] emphasized the importance of even application and complete coverage for optimal protection, noting that increasing the amount applied can greatly enhance real-world effectiveness.

Ingredients of sunscreen

In addition to the active compounds found in chemical and physical sunscreens, there are inactive compounds, as shown in Fig. 3.

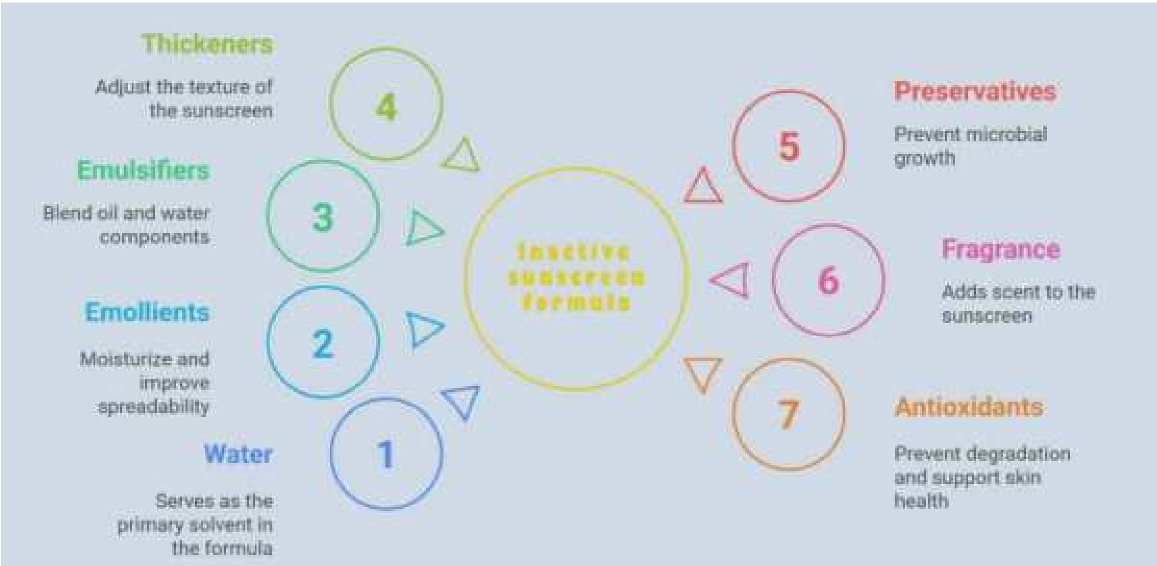

Figure 3. Inactive sunscreen compounds

Nano and non-nano particles

Zinc oxide (ZnO) and titanium dioxide (TiO_2), in both nano and non-nano forms, are commonly used as physical UV filters in sunscreens.[41,42] However, their effects on performance, safety, and the environment vary significantly, as shown in Table 1.

According to available research, TiO_2 nanoparticles can reach the superficial stratum corneum slightly more than ZnO under UV-damaged skin conditions. Nevertheless, neither substance has been shown to cause significant systemic exposure or to penetrate viable skin layers. With ZnO exhibiting a little better surface-restricted behavior, this confirms the conclusion that both substances have a minimal risk of systemic toxicity.[43-45]

Table 1. The difference between nano and non-nanoparticles.

Feature	Non-Nano Particles	Nano Particles
Size	Larger than 100 nm	Less than 100 nanometers (nm)
Appearance on skin	white or chalky	Transparent or invisible
Effectiveness	Effective, especially at blocking UVB	Still provides UV protection, especially UVA
Aesthetic feel	Thicker, can leave a white cast	Lighter, more cosmetically elegant
Environmental impact	Larger particles may pose less of a threat to aquatic systems	Can be more easily ingested by marine life
Safety concerns	Generally considered safe, not absorbed	Concerns about absorption into the skin, but studies show minimal penetration

Delivery system

The method or technology used to deliver the active components (primarily UV filters) to the skin in a controlled and effective manner is known as the sunscreen delivery system.[47] An efficient delivery system ensures even distribution, improved absorption, stability, prolonged effectiveness, and reduced irritation, as shown in Table 2.[43,46,48,49]

Table 2. Delivery system for active compound in sunscreen

Delivery System	Form/Type	Function	Key Benefits
Topical Application	Lotion, cream, gel, spray, stick, powder	Applies sunscreen directly onto the skin	Easy to use, widely available, good coverage
Liposomes	Encapsulated vesicles in lotions/gels	Encapsulate UV filters for better skin absorption	Enhanced penetration, less irritation
Hydrogels	Gel-based formulations	Deliver actives with a cooling, hydrating effect	Good for oily/sensitive skin, refreshing feel
Solid Lipid Nanoparticles (SLNs)	Micro/nano particles in creams	Provide controlled release of UV filters	Long-lasting protection, more stable formulation
Mineral-Based Formulations	Zinc oxide, titanium dioxide in cream/powder	Reflect and scatter UV rays on the skin's surface	Broad-spectrum, non-irritating, safe for sensitive skin
Nanoemulsions	Submicron droplets in creams/gels	Disperse UV filters more evenly and increase lightness	Lightweight feel, better spreadability
Film-Forming Polymers	Found in water-resistant sunscreens	Form a protective barrier over the skin	Water/sweat resistance, long-lasting coverage

Safety and Efficacy of Sunscreens

Skin Irritation and Hormone Disruption

- **Skin Irritation:** Burning, stinging, and contact dermatitis are common adverse reactions to sunscreens, along with comedogenicity. In rare cases, the chemical components of sunscreens may cause photoallergic reactions and allergic contact dermatitis. The most frequently implicated allergenic chemicals include octyl methoxycinnamate, oxybenzone, and octocrylene [50]
- **Hormone Disruption:** There are concerns about potential endocrine-disrupting effects because certain UV filters, such as oxybenzone, have been detected in human tissues, including breast tissue and breast milk. Animal studies have shown that exposure alters thyroid, androgen, and estrogen hormone levels. However, further research is necessary to determine the clinical significance of these findings.[51,52]

Environmental Impact

- **Coral Reef Damage:** Studies have shown that certain sunscreen ingredients can lead to coral bleaching by promoting viral infections in symbiotic algae (zooxanthellae). Even at low sunscreen concentrations, these effects have been observed. Up to 10% of the world's coral reefs may be at risk due to the estimated 4,000–6,000 tons of sunscreens released into coral reef areas each year.[46,53]
- **Regulatory Actions:** Some areas have banned sunscreens that contain harmful ingredients in response to these concerns. For instance, to protect marine habitats, Palau and Hawaii have prohibited the sale and use of sunscreens that include oxybenzone and octinoxate [54]
- **Reef-Safe Alternatives:** Mineral-based sunscreens, such as those containing zinc oxide and titanium dioxide, are considered safer for human skin and the environment. These physical blockers remain on the skin's surface and reflect UV rays, decreasing the risk of irritation and environmental harm. However, concerns persist about the effects of nanoparticle forms of these minerals on marine life.[55,56]

Regulatory Guidelines[57]

- FDA (United States): The FDA classifies sunscreens as over-the-counter drugs, requiring rigorous safety and efficacy testing. As of 2021, only zinc oxide and titanium dioxide are recognized as Generally Recognized as Safe and Effective (GRASE) for use in sunscreens. Other ingredients, including oxybenzone and octinoxate, are under review due to insufficient safety data.
- European Union: The EU has strict regulations regarding sunscreen ingredients. The Scientific Committee on Consumer Safety (SCCS) evaluates UV filters before they can be incorporated into cosmetic products. Certain chemicals, such as oxybenzone, are permitted at limited concentrations due to concerns about skin irritation and potential endocrine disruption.

Recent Advances

1. Recent developments in sunscreen technology have produced novel formulations that offer additional skincare benefits and environmental sustainability, in addition to adequate sun protection.[52,58] A review of the most recent developments in biodegradable and smart sunscreens is available.
2. Biodegradable and Eco-Friendly Sunscreens

Biopolymer-Based Sunscreens: Researchers have used lignin, a natural polymer, in sunscreen formulations to develop high-performing, environmentally friendly products. Significant increases in sun protection factor (SPF) and photostability have been observed in modified lignin loaded with titanium dioxide (TiO_2) nanoparticles and grafted with methylene bis-benzotriazole tetramethylbutylphenol (MBBT3) [59] After three hours of UV exposure, these lignin-based sunscreens maintained their color and protective properties, with an SPF of 66.20. They were also found to be non-toxic to human keratinocytes, indicating they are safe for topical application. [60]

Encapsulation Technologies for Enhanced Stability: Encapsulation of UV filters in nanocarriers, for instance, sol-gel silica capsules, has been explored to improve the photostability and skin penetration of sunscreens.[61] Studies have shown that encapsulated formulations of avobenzone and octinoxate remain on the skin's surface and exhibit enhanced stability, comparable to their free forms. This approach improves the efficacy of sunscreen products and reduces potential safety concerns associated with deeper skin penetration of UV filters.[60]

3. Smart Sunscreens

Hybrid Sunscreen-Serum Formulations: Integrating sunscreen with skincare serums has led to hybrid formulations that address specific skin concerns while providing sun protection.[62] Products like SkinCeuticals Daily Brightening UV Defense combine niacinamide and tranexamic acid to reduce melanin production, offering both brightening effects and UV protection. Similarly, Zitsticka's MegaShade targets acne-prone Skin, providing a blemish treatment alongside sun defense. These multifunctional products streamline skincare routines by combining multiple benefits into one application.[63]

Advancements in Nanotechnology for Sunscreen Efficacy: As mentioned above, Developments in Nanotechnology for the Effectiveness of Sunscreen

By enhancing the dispersion, photostability, and water resistance of active components, nanotechnology has been used to improve sunscreen performance.[60] Using nanosystems such as polymeric nanoparticles, liposomes, and solid lipid nanoparticles, UV filter release can be better controlled, resulting in more extended protection and fewer reapplications. Furthermore, adding antioxidants to these nanosystems enhances protection against UV-induced oxidative stress.[64]

Sunscreens have undergone significant evolution in recent years to address challenges related to stability, transparency, broad-spectrum protection, and public education. Here is an in-depth look at these developments and ongoing efforts to enhance sunscreen effectiveness and customer loyalty.[60]

It is crucial to ensure that the active ingredients in sunscreen retain their protective properties when exposed to sunlight. Recent formulations include stabilizers such as octocrylene, which absorb UV radiation, thereby shielding more delicate ingredients from deterioration.[54] Moreover, encapsulation technologies, including lipid microparticles, have been created to enhance the photostability of UV filters such as avobenzone and octinoxate. These encapsulated formulations show greater resistance to UV-induced degradation, thus ensuring extended effectiveness.[65]

4. Transparent and Aesthetic Appeal

Conventional mineral sunscreens containing zinc oxide or titanium dioxide often leave a white cast. Advances in nanotechnology have led to nanoemulsions and liposomal systems that improve the spreadability and transparency of these sunscreens. These innovations reduce the potential for systemic absorption by keeping the active ingredients on the skin's surface while enhancing cosmetic appeal.[66]

5. Broad-Spectrum Protection

Recent studies emphasize the importance of protecting the skin from visible light and both UVA and UVB radiation, as these factors can contribute to pigmentation and skin aging. A significant advancement is the inclusion of phenylene bis-diphenyl triazine (TriAsorB™), an advanced UV filter that shields against the UV-to-visible light spectrum. Formulations containing TriAsorB™ have been shown to prevent oxidative DNA damage and signs of premature aging.[67]

Public Education

1. Optimal Application Techniques

For sunscreen to be effective, it must be applied correctly. According to studies, people should apply approximately 2 mg/cm², or 36 grams (6 teaspoons), to the average adult's body to achieve the SPF indicated on the product. However, many users apply considerably less, resulting in diminished protection. Furthermore, to ensure adequate sun protection, reapplication is crucial every two hours or more often after swimming or sweating.

2. Leveraging Social Media for Awareness

Public health messages can be effectively shared through social media platforms. According to a study in Northern Ireland, information-based messages were most commonly shared in skin cancer prevention efforts, reaching over 23% of the population. These initiatives have shown promise in raising awareness and attitudes toward sun protection, though further research is needed to determine their direct impact on behavior change.[62,66]

3. Tailored Sunscreen Recommendations

Personalized sunscreen recommendations are becoming increasingly popular. Individuals with aging skin may prefer products enriched with antioxidants and moisturizing ingredients, while those with oily or acne-prone skin might benefit from non-comedogenic, oil-free formulas. Dermatologists emphasize that the best sunscreen is one people will apply regularly, underscoring the importance of products tailored to specific skin types and concerns.[68]

In the context of current photoprotection research, this study attempts to gather current data on the mechanisms, effectiveness, safety concerns, and technological advancements of inorganic sunscreens. It emphasizes significant developments, information gaps, and emerging issues related to the behavior of nanoparticles, their environmental effects, and regulatory trends. The objective is to provide a brief, up-to-date summary that encourages informed application and further research in dermatology, cosmetics, and public health.

Future research should assess novel nanoparticle coatings and compositions as well as look at the impacts of regular, long-term sunscreen use. To determine how environmental factors such as temperature, perspiration, and water exposure affect nanoparticle penetration, additional research is required. The accuracy of assessing potential systemic absorption can be further increased by using sophisticated isotope-tracing methods

CONCLUSION

Neuro-schistosomiasis, with symptoms of *Schistosoma* involvement in the CNS, is a serious condition. Despite increasing reports of the disease in endemic areas and among tourists, it remains underdiagnosed. *Schistosoma* infestations can result in harm to the central nervous system and spinal cord. The stage of infection and the clinical form have a significant impact on the etiology, clinical presentation, and prognosis. Reducing irreversible neurological consequences and improving clinical outcomes requires the immediate identification and intervention of these conditions. To effectively treat neuroschistosomiasis, the best treatment is to combine targeted anti-*Schistosoma* treatment with rapid surgical debridement. Early diagnosis, accompanied by prompt and appropriate treatment, can significantly improve a patient's prognosis.

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AUTHORS CONTRIBUTION

All researchers have equal contribution to the work.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in this study or in any previous studies.

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REVIEW ARTICLE

Shielding the Skin: A Comprehensive Review of Inorganic Sunscreens and Their Role in Photoprotection

Melindungi Kulit: Tinjauan Komprehensif tentang Tabir Surya Anorganik dan Perannya dalam Fotoproteksi

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ABSTRACT

Sunscreens are topical agents that protect the skin from the damaging effects of ultraviolet (UV) radiation, a major contributor to premature aging and skin cancer. These products are typically categorized into two main types: physical (inorganic or mineral) and chemical (organic) sunscreens. Physical sunscreens primarily consist of zinc oxide (ZnO) and titanium dioxide (TiO_2), which reflect and scatter UV rays, thereby providing broad-spectrum protection. Compared with chemical sunscreens, which absorb UV radiation and convert it into heat, inorganic agents are associated with a lower risk of systemic absorption and skin irritation, making them particularly suitable for sensitive skin and pediatric use. This review explores the fundamental mechanisms of action, formulation challenges, and comparative effectiveness of inorganic sunscreens. Special attention is given to their photostability, which contributes to longer-lasting protection, and to their safety profiles in both acute and chronic use. Additionally, recent innovations in nanoparticle technology have enhanced the aesthetic appeal of these agents by reducing visible residue. However, this has also raised new concerns about nanoparticle penetration and environmental impact. Finally, the review addresses public health considerations, including regulatory updates, consumer preferences, and the role of education in promoting informed use of sunscreen.

Keywords: Inorganic Sunscreens; Nanoparticle Technology; Photoprotection; Titanium Dioxide;Zinc Oxide.

ABSTRAK

Tabir surya adalah produk topikal yang dirancang untuk melindungi kulit dari dampak merugikan radiasi ultraviolet (UV), yang merupakan faktor utama penuaan dini dan kanker kulit. Tabir surya umumnya diklasifikasikan ke dalam dua jenis utama: fisik (anorganik atau mineral) dan kimiawi (organik). Tabir surya fisik terutama mengandung seng oksida (ZnO) dan titanium dioksida (TiO_2), yang bekerja dengan memantulkan dan menyebarkan sinar UV, sehingga memberikan perlindungan spektrum luas. Dibandingkan dengan tabir surya kimiawi yang menyerap radiasi UV dan mengubahnya menjadi panas, agen anorganik memiliki risiko lebih rendah terhadap penyerapan sistemik dan iritasi kulit, sehingga lebih cocok digunakan untuk kulit sensitif dan anak-anak. Ulasan ini membahas mekanisme kerja, tantangan formulasi, dan efektivitas tabir surya anorganik. Fokus khusus diberikan pada fotostabilitasnya, yang berkontribusi terhadap perlindungan jangka panjang, serta profil keamanannya dalam penggunaan akut dan kronis. Selain itu, inovasi terbaru dalam teknologi nanopartikel telah meningkatkan daya tarik estetika produk ini dengan mengurangi residu putih yang tampak, meskipun juga menimbulkan kekhawatiran baru terkait penetrasi partikel nano dan dampak lingkungan. Ulasan ini juga membahas implikasi kesehatan masyarakat, termasuk regulasi terbaru, preferensi konsumen, dan pentingnya edukasi dalam mendorong penggunaan tabir surya yang tepat.

Kata Kunci: Fotoproteksi; Seng oksida; Tabir surya anorganik; Teknologi nanopartikel; Titanium dioksida.

INTRODUCTION

Early sun protection techniques date back to ancient civilizations, such as the Egyptians, who employed natural extracts as early as 4000 BC. Sunscreen has a long and varied history. Centuries ago, the Greeks and Indians also employed zinc oxide and olive oil for photoprotection. In 1891, Friedrich Hammer created the first chemical sunscreen in Germany using acidified quinine sulphate. In 1896, Dr. Paul Unna identified the link between sun exposure and skin cancer.[1,2,3] As tanning gained popularity in the 1930s, further inventions followed. The first commercially available sunscreens were developed in the late 1920s and early 1930s, with popular products from Australia's H.A. Milton Blake and France's Eugène Schueller of L'Oréal. Benjamin Green created Coppertone, a sunscreen, for the US soldiers during World War II. Swiss chemist Franz Greiter first presented "Gletscher Crème" in 1946. In 1962, he developed the Sun Protection Factor (SPF) method, which is now the industry standard for measuring sunscreen effectiveness of sunscreen.[2,4] Sunae have evolved over the years to become more user-friendly, water-resistant, and practical, reflecting both changing societal attitudes toward sun exposure and skin health as well as scientific advancements.[5]

Standardized methodological criteria, including selection bias, measurement bias, confounding control, and completeness of outcome reporting, were used to systematically evaluate the risk of bias across all included studies in this review. Overall, most studies showed low to moderate risk of bias; however, some reports had limitations related to inadequate confounding adjustment and poor exposure evaluation.

Summary information for the intervention and comparison groups was taken from each included study. These data included safety outcomes (such as irritation or adverse reactions), environmental impact parameters when available, and measures of photoprotection efficacy (such as reduction in erythema, UV-induced oxidative stress, and DNA damage).

Through centuries of observation and scientific advancement, the connection between ultraviolet (UV) light and sunburn has been understood. Scientists started examining the elements of sunlight in the 19th century. By the early 20th century, they had established that UV radiation, more especially UVB rays, was the cause of sunburn and skin damage.[6] Studies over time have shown that UVA (320–400 nm) also plays a role in the development of skin cancer and aging. This knowledge led to improvements in sunscreen formulas and enhanced public health activities promoting UV protection. The importance of sun protection is further supported by the well-established fact that excessive UV exposure damages DNA in skin cells, leading to inflammation (sunburn) and increasing the risk of skin cancer.[7]

One in five Americans is expected to develop skin cancer at some point in their lives, making it one of the most prevalent cancers in the country. More than 3 million Americans are diagnosed with nonmelanoma skin cancers (basal and squamous cell carcinomas) annually. In 2022, approximately 200,000 new melanoma cases are anticipated, making it the sixth most commonly diagnosed cancer.[8] Factors contributing to skin cancer include excessive sun exposure, use of tanning beds, childhood sunburns, skin that burns easily, red or blonde hair, numerous or atypical moles, and family history. To detect skin cancer early, the American Academy of Dermatology (AAD) recommends monthly self-examinations to look for any suspicious sores or moles that change color or shape, grow significantly, do not heal, or bleed.[9] Annual skin examinations by a dermatologist are strongly recommended, particularly for high-risk groups, including those with a history of childhood sunburns, immunosuppressed individuals, individuals with fair skin, and those with a history of skin cancer. When melanoma is detected early, the 5-year survival rate reaches 99 percent.[10]

One of the main environmental factors causing photoaging, erythema, and the emergence of skin cancer is ultraviolet (UV) radiation. Because of their broad-spectrum coverage, photostability, and suitability for sensitive skin, inorganic sunscreens based on zinc oxide and titanium dioxide have drawn more scientific and commercial interest in recent decades. Even though they have been used for a long time, advances in formulation science, nanotechnology, and safety assessment have significantly changed our current understanding of their performance traits and protective mechanisms.

Ultraviolet (UV) radiation is a form of electromagnetic energy emitted by the sun. There are three main types of UV radiation, categorized by wavelength: UV-A (320–400 nm), UV-B (280–320 nm), and UV-C (100–280 nm). Although UV-A and UV-B rays penetrate the atmosphere and significantly impact biological systems, UV-C is primarily absorbed by the Earth's ozone layer, preventing it from reaching the surface.[11] UV-B radiation is hazardous because it can directly damage DNA, leading to mutations and an increased risk of skin cancer.

UV-A penetrates deeper into the skin, leading to oxidative stress and photoaging, even though it is less harmful. Prolonged exposure to UV radiation is associated with adverse health effects, including eye damage, immunosuppression, and erythema. However, the skin's vitamin D production depends on controlled exposure to UV-B radiation. This study aims to understand the mechanisms of action of UV radiation, develop effective protection methods such as sunscreens and protective clothing, and encourage their safe and beneficial use.[12,13] Ultraviolet (UV) radiation is divided into three primary categories based on wavelength[14,15]:

1. UV-A (320–400 nm): This is the most common and least intense form of UV radiation reaching Earth's surface. It penetrates deeply into the skin and is primarily responsible for long-term skin damage and photoaging. Additionally, indirect DNA damage caused by reactive oxygen species can contribute to the development of skin cancer.
2. UV-B (280–320 nm): This ultraviolet radiation carries more energy than UV-A and is partially filtered by the ozone layer. It affects the skin's outer layer and is the primary cause of sunburn. UV-B directly damages DNA and is closely linked to skin cancers, including

melanoma. Nonetheless, UV-B plays a crucial role in the production of vitamin D in the human body.

3. UV-C (100–280 nm): This is the most energetic and potentially harmful form of UV radiation; however, it is entirely absorbed by the Earth's atmosphere, especially by the ozone layer. Due to its strong germicidal properties, UV-C is commonly used in artificial sources for sterilization and disinfection.

Classification of Sunscreens

1. A list of 16 authorized sunscreen ingredients was included in the most recent FDA sunscreen monograph, published in 1999. The adjectives "chemical" and "physical" should be replaced by the terms "organic" and "inorganic," respectively, for sunscreens. Sunscreen agents are typically referred to by three names.[16] These include the US Adopted Name (USAN), trade name, and International Nomenclature of Cosmetic Ingredients (INCI). For instance, avobenzone (USAN) has several trade names, including Parsol 1789, and its INCI name is butylmethoxydibenzoylmethane [17,18]

2. **Organic or chemical Sunscreens**

UV rays are absorbed by organic UV filters found in chemical sunscreens. Every filter is adjusted to absorb particular UV rays:[19]

- UVA filters (320–400 nm): avobenzone, oxybenzone, and ecamsule.
- UVB filters (280–320 nm): octinoxate, octocrylene, homosalate, etc.
- UVA + UVB filters: Ecamsule (Mexoryl SX), Silatriazole (Mexoryl XL), Bemotrizinol (Tinosorb S), Bisoctrizole (Tinosorb M)

To prevent DNA damage, photoaging, and carcinogenesis, these molecules are excited by UV light and then return to their ground state, releasing energy as heat. Avobenzone is a powerful UVA filter (fig. 1). However, it has the disadvantage of being photostable, as it is the only sunscreen ingredient with an absorption peak in the UVA1 spectrum (357 nm). This is slightly reduced by adding photostabilizers to the finished sunscreen lotion.[20] These medications include broad-spectrum filters like bemotrizinol (not yet FDA authorized), inorganic filters like zinc oxide and titanium dioxide, salicylates, octocrylene, UVB filters like enzacamene (not yet FDA approved), and other UVA filters like oxybenzone.[21]

Chemical sunscreens are typically more cosmetically elegant than mineral sunscreens due to their thinner consistency and transparency upon application. The effectiveness of chemical sunscreens has been confirmed by numerous studies to prevent are erythema and sunburn (UVB),

chronic pigmentation and photodamage (UVA), and skin cancers, especially squamous cell carcinoma, and maybe melanoma.

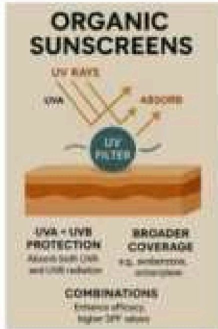

Figure 1. Mechanism of action of organic sunscreen

The FDA has called for additional safety data because recent studies have raised concerns about the systemic absorption of several UV filters (such as oxybenzone, homosalate, and octinoxate). Although evidence on these chemicals' clinical significance in humans is conflicting, some in vitro and animal research indicates they may have endocrine-disrupting properties.[23]

Specific filters (e.g., avobenzone, oxybenzone) may cause photoallergic contact dermatitis in sensitive individuals. Stabilizers and preservatives in formulations can also contribute to irritation.[24]

3. **Inorganic or physical Sunscreens**

Inorganic sunscreens, commonly called physical blockers, offer a compelling alternative to organic (chemical) sunscreens, especially for individuals with sensitive skin. The two FDA-approved inorganic filters (ZnO and TiO_2) are widely used because they reflect, scatter, and absorb UV radiation [25]

Zinc oxide and titanium dioxide work by physically interacting with UV radiation. ZnO provides broad-spectrum protection across UVA and UVB wavelengths. At the same time, TiO_2 is primarily effective in the UVB and short UVA range (Fig. 2). Its photoprotective efficacy stems from high refractive indices and strong UV attenuation. Modern formulations use micronized or nanoparticulate forms to minimize the characteristic white cast and enhance cosmetic acceptability.[26,27]

Particle size, surface coating, and formulation matrix all impact the safety and effectiveness of inorganic sunscreens. Although concerns remain about environmental toxicity and dermal penetration, nanoparticles (less than 100 nm) improve transparency and spreadability.[28] Surface coatings, such as silica or alumina, improve photostability and reduce reactive oxygen species (ROS) generation. Hybrid formulations combining inorganic and organic filters are also being developed to maximize coverage and cosmetic appeal.[29]

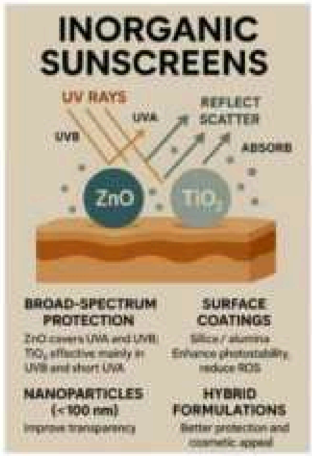

Figure 2. Mechanism of action of inorganic sunscreen

Several studies support the safety of inorganic sunscreens. Dermal penetration of ZnO and TiO_2 nanoparticles is minimal in healthy skin, with negligible systemic absorption. These agents are less likely than organic filters to cause allergic or irritant reactions. Nevertheless, their potential to generate reactive oxygen species (ROS) under UV exposure has raised concerns, particularly when used as uncoated nanoparticles. Environmental impact studies have suggested that TiO_2 nanoparticles may harm aquatic ecosystems, contributing to regulatory scrutiny.[29,30]

Antioxidants such as vitamin C, vitamin E, silymarin, and green tea polyphenols are found in many sunscreens. Vitamin C protects against UV-induced damage, which leads to sunburn and erythema. Vitamin E reduces immunosuppression, erythema, photoaging, and photocarcinogenesis, among other protective effects.[31] Silymarin, which is extracted from milk thistle plants, functions as a scavenger of reactive oxygen species (ROS) and assists in preventing lipid and lipoprotein oxidation. The topical application reduces UVB-induced sunburn cells and decreases the formation of UVB-induced pyrimidine dimers. In mice, it has been shown to reduce the number of UVB-induced tumors ([32] Green tea polyphenols have more potent antioxidants than vitamins C and E. These polyphenols are anti-inflammatory and anticarcinogenic and function as scavengers of singlet oxygen, superoxide radicals, hydroxyl radicals, peroxyl radicals, and hydrogen peroxide.[33]

Mechanism of Action

Sunscreens protect the skin by reducing or preventing the penetration of ultraviolet (UV) radiation.[34,35] They primarily function through two mechanisms: Chemical sunscreens, which absorb UV radiation, and physical (or mineral) sunscreens, which reflect and scatter both UVA and UVB rays.

An essential measure of sunscreen efficacy is the Sun Protection Factor (SPF), which indicates how well a product protects against UVB radiation, the leading cause of sunburn and DNA damage [34]. An SPF rating indicates how much longer a person can be exposed to the sun without sunburn compared with unprotected skin. For example, SPF 30 blocks about 97% of UVB radiation, allowing only 3.3% to pass through the skin. However, SPF does not protect against UVA rays, which penetrate more deeply and may accelerate signs of aging and even encourage the development of melanoma [35,36]

As recent studies have consistently demonstrated, the amount of sunscreen used significantly affects the actual level of protection, frequently resulting in lower-than-labeled SPF. The SPF value of sunscreen products is determined by applying them at a standardized dose of 2 mg/cm^2 of skin. However, research shows that most users apply only 25–50% of the recommended dosage, resulting in an 80% reduction in protection.[37] The in vivo determination of SPF values is carried out through the emission of artificial light by a solar simulator in both exposed and unprotected conditions. Moreover, sunscreen protects areas of the body, and it is applied in the latter condition. After 24 hours of exposure, the regions are evaluated for pigmentation and erythema response. These testing methodologies may vary across regulatory agencies and are harmonized by the ISO (International Organization for Standardization). According to surveys conducted in Denmark, Australia, Southern Europe, and Egypt over a 25-year period, the amount of sunscreen used ranged from 0.39 to 0.79 mg/cm^2.[38]

A study of 1000 students in India by Yashwardhana et al.[4] found that only 11.88% of participants knew the ideal amount of sunscreen to use. The effectiveness of sun protection depends directly on the photo-protective product.[39] Additionally, research by Cruz et al.[40] emphasized the importance of even application and complete coverage for optimal protection, noting that increasing the amount applied can greatly enhance real-world effectiveness.

Ingredients of sunscreen

In addition to the active compounds found in chemical and physical sunscreens, there are inactive compounds, as shown in Fig. 3.

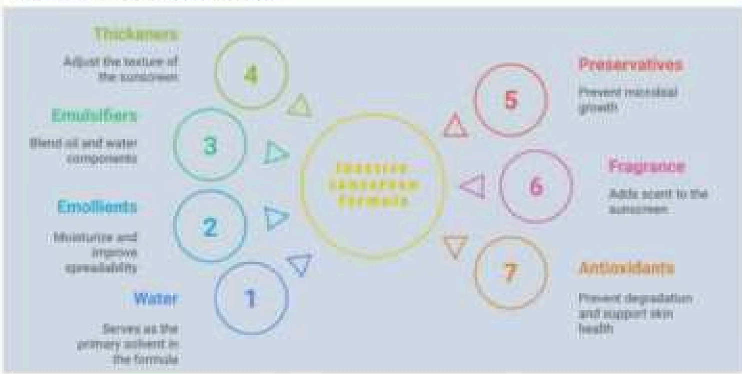

Figure 3. Inactive sunscreen compounds

Nano and non-nano particles

Zinc oxide (ZnO) and titanium dioxide (TiO_2), in both nano and non-nano forms, are commonly used as physical UV filters in sunscreens.[41,42] However, their effects on performance, safety, and the environment vary significantly, as shown in Table 1.

According to available research, TiO_2 nanoparticles can reach the superficial stratum corneum slightly more than ZnO under UV-damaged skin conditions. Nevertheless, neither substance has been shown to cause significant systemic exposure or to penetrate viable skin layers. With ZnO exhibiting a little better surface-restricted behavior, this confirms the conclusion that both substances have a minimal risk of systemic toxicity.[43-45]

Table 1. The difference between nano and non-nanoparticles.

Feature	Non-Nano Particles	Nano Particles
Size	Larger than 100 nm	Less than 100 nanometers (nm)
Appearance on skin	white or chalky	Transparent or invisible
Effectiveness	Effective, especially at blocking UVB	Still provides UV protection, especially UVA
Aesthetic feel	Thicker, can leave a white cast	Lighter, more cosmetically elegant
Environmental impact	Larger particles may pose less of a threat to aquatic systems	Can be more easily ingested by marine life
Safety concerns	Generally considered safe, not absorbed	Concerns about absorption into the skin, but studies show minimal penetration

Delivery system

The method or technology used to deliver the active components (primarily UV filters) to the skin in a controlled and effective manner is known as the sunscreen delivery system.[47] An efficient delivery system ensures even distribution, improved absorption, stability, prolonged effectiveness, and reduced irritation, as shown in Table 2.[43,46-48,49]

Table 2. Delivery system for active compound in sunscreen

Delivery System	Form/Type	Function	Key Benefits
Topical Application	Lotion, cream, gel, spray, stick, powder	Applies sunscreen directly onto the skin	Easy to use, widely available, good coverage
Liposomes	Encapsulated vesicles in lotions/gels	Encapsulate UV filters for better skin absorption	Enhanced penetration, less irritation
Hydrogels	Gel-based formulations	Deliver actives with a cooling, hydrating effect	Good for oily/sensitive skin, refreshing feel
Solid Lipid Nanoparticles (SLNs)	Micro/nano particles in creams	Provide controlled release of UV filters	Long-lasting protection, more stable formulation
Mineral-Based Formulations	Zinc oxide, titanium dioxide in cream/powder	Reflect and scatter UV rays on the skin's surface	Broad-spectrum, non-irritating, safe for sensitive skin
Nanoemulsions	Submicron droplets in creams/gels	Disperse UV filters more evenly and increase lightness	Lightweight feel, better spreadability
Film-Forming Polymers	Found in water-resistant sunscreens	Form a protective barrier over the skin	Water/sweat resistance, long-lasting coverage

Safety and Efficacy of Sunscreens

Skin Irritation and Hormone Disruption

- **Skin Irritation:** Burning, stinging, and contact dermatitis are common adverse reactions to sunscreens, along with comedogenicity. In rare cases, the chemical components of sunscreens may cause photoallergic reactions and allergic contact dermatitis. The most frequently implicated allergenic chemicals include octyl methoxycinnamate, oxybenzone, and octocrylene [50]

- **Hormone Disruption:** There are concerns about potential endocrine-disrupting effects because certain UV filters, such as oxybenzone, have been detected in human tissues, including breast tissue and breast milk. Animal studies have shown that exposure alters thyroid, androgen, and estrogen hormone levels. However, further research is necessary to determine the clinical significance of these findings.[51,52]

Environmental Impact

- **Coral Reef Damage:** Studies have shown that certain sunscreen ingredients can lead to coral bleaching by promoting viral infections in symbiotic algae (zooxanthellae). Even at low sunscreen concentrations, these effects have been observed. Up to 10% of the world's coral reefs may be at risk due to the estimated 4,000–6,000 tons of sunscreens released into coral reef areas each year.[49-53]
- **Regulatory Actions:** Some areas have banned sunscreens that contain harmful ingredients in response to these concerns. For instance, to protect marine habitats, Palau and Hawaii have prohibited the sale and use of sunscreens that include oxybenzone and octinoxate [54]
- **Reef-Safe Alternatives:** Mineral-based sunscreens, such as those containing zinc oxide and titanium dioxide are considered safer for human skin and the environment. These physical blockers remain on the skin's surface and reflect UV rays, decreasing the risk of irritation and environmental harm. However, concerns persist about the effects of nanoparticle forms of these minerals on marine life.[55,56]

Regulatory Guidelines[57]

- FDA (United States): The FDA classifies sunscreens as over-the-counter drugs, requiring rigorous safety and efficacy testing. As of 2021, only zinc oxide and titanium dioxide are recognized as Generally Recognized as Safe and Effective (GRASE) for use in sunscreens. Other ingredients, including oxybenzone and octinoxate, are under review due to insufficient safety data.
- European Union: The EU has strict regulations regarding sunscreen ingredients. The Scientific Committee on Consumer Safety (SCCS) evaluates UV filters before they can be incorporated into cosmetic products. Certain chemicals, such as oxybenzone, are permitted at limited concentrations due to concerns about skin irritation and potential endocrine disruption.

Recent Advances

1. Recent developments in sunscreen technology have produced novel formulations that offer additional skincare benefits and environmental sustainability, in addition to adequate sun protection.[51,58] A review of the most recent developments in biodegradable and smart sunscreens is available.
2. Biodegradable and Eco-Friendly Sunscreens

Biopolymer-Based Sunscreens: Researchers have used lignin, a natural polymer, in sunscreen formulations to develop high-performing, environmentally friendly products. Significant increases in sun protection factor (SPF) and photostability have been observed in modified lignin loaded with titanium dioxide (TiO_2) nanoparticles and grafted with methylene bis-benzotriazole tetramethylbutylphenol (MBBT3) [59] After three hours of UV exposure, these lignin-based sunscreens maintained their color and protective properties, with an SPF of 66.20. They were also found to be non-toxic to human keratinocytes, indicating they are safe for topical application. [60]

Encapsulation Technologies for Enhanced Stability: Encapsulation of UV filters in nanocarriers, for instance, sol-gel silica capsules, has been explored to improve the photostability and skin penetration of sunscreens.[61] Studies have shown that encapsulated formulations of avobenzone and octinoxate remain on the skin's surface and exhibit enhanced stability, comparable to their free forms. This approach improves the efficacy of sunscreen products and reduces potential safety concerns associated with deeper skin penetration of UV filters.[62]

3. Smart Sunscreens

Hybrid Sunscreen-Serum Formulations: Integrating sunscreen with skincare serums has led to hybrid formulations that address specific skin concerns while providing sun protection.[62] Products like SkinCeuticals Daily Brightening UV Defense combine niacinamide and tranexamic acid to reduce melanin production, offering both brightening effects and UV protection. Similarly, Zitsticka's MegaShade targets acne-prone Skin, providing a blemish treatment alongside sun defense. These multifunctional products streamline skincare routines by combining multiple benefits into one application.[63]

Advancements in Nanotechnology for Sunscreen Efficacy: As mentioned above, Developments in Nanotechnology for the Effectiveness of Sunscreen

By enhancing the dispersion, photostability, and water resistance of active components, nanotechnology has been used to improve sunscreen performance.[60] Using nanosystems such as polymeric nanoparticles, liposomes, and solid lipid nanoparticles, UV filter release can be better controlled, resulting in more extended protection and fewer reapplications. Furthermore, adding antioxidants to these nanosystems enhances protection against UV-induced oxidative stress.[64]

Sunscreens have undergone significant evolution in recent years to address challenges related to stability, transparency, broad-spectrum protection, and public education. Here is an in-depth look at these developments and ongoing efforts to enhance sunscreen effectiveness and customer loyalty.[60]

It is crucial to ensure that the active ingredients in sunscreen retain their protective properties when exposed to sunlight. Recent formulations include stabilizers such as octocrylene, which absorb UV radiation, thereby shielding more delicate ingredients from deterioration.[54] Moreover, encapsulation technologies, including lipid microparticles, have been created to enhance the photostability of UV filters such as avobenzone and octinoxate. These encapsulated formulations show greater resistance to UV-induced degradation, thus ensuring extended effectiveness.[65]

4. Transparent and Aesthetic Appeal

Conventional mineral sunscreens containing zinc oxide or titanium dioxide often leave a white cast. Advances in nanotechnology have led to nanoemulsions and liposomal systems that improve the spreadability and transparency of these sunscreens. These innovations reduce the potential for systemic absorption by keeping the active ingredients on the skin's surface while enhancing cosmetic appeal.[66]

5. Broad-Spectrum Protection

Recent studies emphasize the importance of protecting the skin from visible light and both UVA and UVB radiation, as these factors can contribute to pigmentation and skin aging. A significant advancement is the inclusion of phenylene bis-diphenyl triazine (TriAsorB™), an advanced UV filter that shields against the UV-to-visible light spectrum. Formulations containing TriAsorB™ have been shown to prevent oxidative DNA damage and signs of premature aging.[67]

Public Education

1. Optimal Application Techniques

For sunscreen to be effective, it must be applied correctly. According to studies, people should apply approximately 2 mg/cm², or 36 grams (6 teaspoons), to the average adult's body to achieve the SPF indicated on the product. However, many users apply considerably less, resulting in diminished protection. Furthermore, to ensure adequate sun protection, reapplication is crucial every two hours or more often after swimming or sweating.

2. Leveraging Social Media for Awareness

Public health messages can be effectively shared through social media platforms. According to a study in Northern Ireland, information-based messages were most commonly shared in skin cancer prevention efforts, reaching over 23% of the population. These initiatives have shown promise in raising awareness and attitudes toward sun protection, though further research is needed to determine their direct impact on behavior change.[61,66]

3. Tailored Sunscreen Recommendations

Personalized sunscreen recommendations are becoming increasingly popular. Individuals with aging skin may prefer products enriched with antioxidants and moisturizing ingredients, while those with oily or acne-prone skin might benefit from non-comedogenic, oil-free formulas. Dermatologists emphasize that the best sunscreen is one people will apply regularly, underscoring the importance of products tailored to specific skin types and concerns.[58]

In the context of current photoprotection research, this study attempts to gather current data on the mechanisms, effectiveness, safety concerns, and technological advancements of inorganic sunscreens. It emphasizes significant developments, information gaps, and emerging issues related to the behavior of nanoparticles, their environmental effects, and regulatory trends. The objective is to provide a brief, up-to-date summary that encourages informed application and further research in dermatology, cosmetics, and public health.

Future research should assess novel nanoparticle coatings and compositions as well as look at the impacts of regular, long-term sunscreen use. To determine how environmental factors such as temperature, perspiration, and water exposure affect nanoparticle penetration, additional research is required. The accuracy of assessing potential systemic absorption can be further increased by using sophisticated isotope-tracing methods

CONCLUSION

Neuro-schistosomiasis, with symptoms of *Schistosoma* involvement in the CNS, is a serious condition. Despite increasing reports of the disease in endemic areas and among tourists, it remains underdiagnosed. *Schistosoma* infestations can result in harm to the central nervous system and spinal cord. The stage of infection and the clinical form have a significant impact on the etiology, clinical presentation, and prognosis. Reducing irreversible neurological consequences and improving clinical outcomes requires the immediate identification and intervention of these conditions. To effectively treat neuroschistosomiasis, the best treatment is to combine targeted anti-*Schistosoma* treatment with rapid surgical debridement. Early diagnosis, accompanied by prompt and appropriate treatment, can significantly improve a patient's prognosis.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in this study or in any previous studies.

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