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A comprehensive overview of sunscreen cream: Key actives and methods of formulation

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Abstract

Sunscreen creams are essential topical formulations designed to protect the skin from the harmful effects of ultraviolet (UV) radiation, particularly UV-A and UV-B rays. Excessive exposure to UV radiation is associated with acute skin damage, photoaging, and increased risk of skin cancers. This review provides a comprehensive analysis of sunscreen formulations, focusing on the classification of UV filters (chemical, physical, and hybrid), their mechanisms of action, and the key ingredients used. Advances in formulation technologies, including the use of emulsifiers, nanocarriers, and natural antioxidants, have led to the development of more effective and consumer-friendly products. Evaluation parameters such as Sun Protection Factor (SPF), photostability, and water resistance are discussed to assess product efficacy and safety. Additionally, the review examines regulatory guidelines and market trends, highlighting the importance of compliance and innovation in sunscreen development. The study concludes that continuous research and improved formulation strategies are vital for creating sunscreens that are both safe for human use and environmentally sustainable. Keywords: Sunscreen, UV radiation, SPF, UV filters, chemical sunscreen, physical sunscreen, nanotechnology, photoprotection, formulation, evaluation.

Keywords: Sunscreen, UV filters, photoprotection

Introduction

Overview of Skin Exposure to Ultraviolet (UV) Radiation

Nature and Sources of UV Radiation

Ultraviolet (UV) radiation is a ubiquitous environmental factor, primarily from sunlight, but also from artificial sources like tanning lamps and medical devices. The skin, as the body's largest and outermost organ, is directly exposed to UV radiation, making it particularly vulnerable to its effects [1, 2].

Harmful Effects on the Skin

Excessive UV exposure is a well-established risk factor for various skin disorders:

- **Acute Effects:** Sunburn, inflammation, and discomfort are common immediate responses, with UVB being especially potent in causing these effects [3, 4].
- **Chronic Effects:** Long-term or repeated exposure leads to photoaging (wrinkling, pigment changes, atrophy), immunosuppression, and significantly increases the risk of skin cancers, including basal cell carcinoma, squamous cell carcinoma, and malignant melanoma [5, 6, 165].
- **Molecular Impact:** UV radiation causes DNA damage (e.g., cyclobutane pyrimidine dimers), oxidative stress, and disrupts skin barrier homeostasis, which can drive both short-term and long-term health consequences [7].

Vulnerable Populations and Risk Factors

Children and individuals with fair skin are particularly susceptible to UV-induced skin damage. A significant proportion of lifetime UV exposure occurs before age 20, and early-life exposure is linked to higher risks of skin cancer later in life. Genetic factors, such as MC1R gene polymorphisms, also influence individual sensitivity and risk [8].

Beneficial Effects and Medical Uses

Despite its risks, UV radiation has beneficial roles:

Vitamin D Synthesis: UV exposure is essential for natural vitamin D production in the skin.

Medical Therapies: Controlled UV exposure is used to treat skin conditions like psoriasis, atopic dermatitis, and vitiligo, and may have broader immunomodulatory effects ^[9].

Prevention and Protective Strategies

Effective protection against UV radiation includes seeking shade, wearing protective clothing, and avoiding sun exposure during peak hours. Sunscreen alone is not considered sufficient. Educational and policy interventions in schools and recreational settings have shown effectiveness in promoting sun-protective behaviors, especially among children ^[10].

Table 1: (Prevention and Protective Strategies)

Effect/Aspect	Harmful Outcomes	Key Populations at Risk
Acute Exposure	Sunburn, inflammation	All, especially children
Chronic Exposure	Photoaging, skin cancer	Fair-skinned, high UV areas
Medical Applications	-	Patients with skin conditions
Prevention	Protective behaviours	Children, outdoor workers

Harmful effects of UV-A and UV-B rays (e.g., sunburn, premature aging, skin cancer).

Ultraviolet (UV) radiation from the sun, specifically UV-A and UV-B rays, is a major environmental risk factor for skin health. Both UV-A and UV-B rays can cause sunburn, premature skin aging, and increase the risk of skin cancers. Protective measures are essential to reduce these harmful effects.

Harmful Effects of UV-A and UV-B Rays

- **Sunburn:** UV-B rays are primarily responsible for causing sunburn (erythema), an acute inflammatory response of the skin. Severe sunburn can overwhelm the skin's ability to repair DNA damage, increasing the risk of cancer development (Chiou, 2022a).
- **Premature Aging (Photoaging):** Chronic exposure to both UV-A and UV-B rays leads to premature aging, including wrinkling, atrophy, and pigmentary changes. UV-A penetrates deeper into the skin and contributes significantly to photoaging ^[12, 13].
- **Skin Cancer:** UV radiation is a well-established carcinogen. Both UV-A and UV-B can cause DNA mutations and immune suppression, leading to basal cell carcinoma, squamous cell carcinoma, and malignant melanoma. UV-B is more directly linked to

DNA damage, while UV-A contributes to indirect DNA damage and oxidative stress ^[14-17].

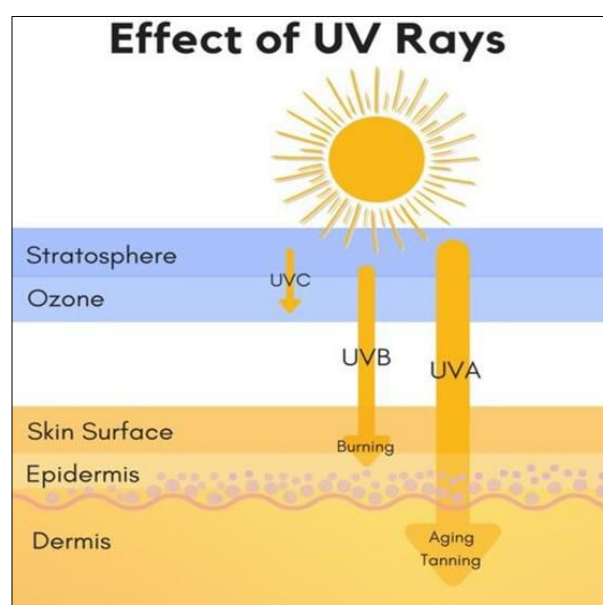


Fig 1: Effects of UV Rays

Table 2: Effects of UV Rays

Effect	UV-B Rays.	UV-A Rays
Sunburn	Major cause	Minor role
Premature Aging	Contributes	Major contributor
Skin Cancer	Strongly linked	Contributes (less direct)

Additional Health Risks

- **Immune Suppression:** Both UV-A and UV-B can suppress local and systemic immune responses, making the skin more susceptible to infections and reducing its ability to fight cancerous changes.
- **Other Effects:** UV exposure can also lead to eye damage (e.g., cataracts), and, in rare cases, affect reproductive and overall health.

Mechanisms

- **DNA Damage:** UV rays cause direct DNA damage (especially UV-B) and generate reactive oxygen species (especially UV-A), leading to mutations and cellular dysfunction.

- **Impaired Repair:** Overwhelming or repeated exposure can exceed the skin's repair capacity, increasing the risk of lasting damage and cancer.

Importance of using sunscreens as a protective barrier

Sunscreens are essential for protecting the skin from the harmful effects of solar ultraviolet (UV) radiation. Regular and correct use of sunscreen significantly reduces the risk of sunburn, skin cancer, and premature skin aging by acting as a protective barrier against UV damage.

Protective Benefits

- **Prevention of Skin Cancer and Sunburn:** Sunscreens, when applied properly, lower the risk of developing skin cancers such as squamous cell carcinoma and actinic keratoses, and help prevent acute sunburns.

They also reduce the risk of photoaging, which includes wrinkles and pigmentation changes caused by cumulative sun exposure ^[21-24].

- **Barrier Function:** Sunscreens protect the skin's natural barrier from UV-induced oxidative damage and help maintain its biomechanical integrity. Some formulations, especially those with ceramides, may further support the skin barrier ^[25-27].

Application and Effectiveness

- **Broad-Spectrum Protection:** It is important to use broad-spectrum sunscreens that protect against both UVA and UVB rays for comprehensive coverage ^[28].
- **Proper Usage:** The effectiveness of sunscreen depends on correct and sufficient application. Under-application is common and can significantly reduce protection. Sunscreen should be reapplied regularly, especially after swimming or sweating ^[29].
- **Combination with Other Measures:** Sunscreen should be used alongside other protective strategies such as wearing hats, clothing, sunglasses, and seeking shade for optimal sun safety ^[30].

Safety and Recommendations

- **Safety:** Sunscreens are generally safe for regular use and do not significantly affect vitamin D levels, bone density, or overall health. Side effects are rare and usually mild.
- **Regulation and Education:** High-quality, regulated sunscreen products and public education on proper use are crucial for maximizing protective benefits.

History and development of sunscreens.

The history and development of sunscreens reflect humanity's evolving understanding of sun exposure and its health effects. Early sun protection relied on physical barriers and natural substances, but scientific advances in the 20th century led to the creation of modern sunscreen products. Today, sunscreens are sophisticated formulations designed to protect against both UVB and UVA radiation, with ongoing innovation to improve safety, efficacy, and user experience.

Early Sun Protection Methods

- **Ancient and Pre-Modern Practices:** Early humans used clothing, veils, hats, and umbrellas to shield themselves from the sun. Ancient Greeks, Egyptians, Mesopotamians, Chinese, and Indians all employed such physical barriers for sun protection ^[32-34].
- **Folk Remedies:** Plant extracts, such as chestnut-derived aesculin, were used in traditional medicine for sun protection. By the late 19th and early 20th centuries, substances like quinine sulfate and tightly woven veils were applied to prevent sunburn and treat photosensitive conditions ^[35].

Emergence of Chemical Sunscreens

Early Chemical Agents: The late 19th and early 20th centuries saw the use of acidified quinine sulfate, tannic acid, and aesculin as some of the first chemical sunscreens ^[36].

Key Milestones

- **1928:** Benzyl salicylate and benzyl cinnamate emulsion developed in the US ^[37].
- **1935:** Eugène Schueller (L'Oréal) introduced "Ambre Solaire Huile," a UV-filtering product.
- **1943:** P-aminobenzoic acid (PABA) patented.
- **1946:** Franz Greiter developed "Gletscher Crème."
- **1956:** Introduction of the Sun Protection Factor (SPF) concept.

Advances in Formulation and Regulation

- **Broad-Spectrum Protection:** Early sunscreens mainly blocked UVB. Later, ingredients were developed to protect against UVA as well.
- **Formulation Improvements:** Advances include better photostability, water resistance, and cosmetic acceptability. Nanotechnology has enabled more effective and aesthetically pleasing sunscreens.
- **Regulatory Frameworks:** Governments and agencies have established lists of approved sunscreen chemicals and standards for efficacy and safety ^[40].

Changing Perceptions and Uses

- **From Lifestyle to Health:** Sunscreens were initially marketed for tanning without burning, then for skin cancer prevention, and now also for anti-aging and beauty.
- **Public Awareness:** Increased understanding of UV risks has driven sunscreen innovation and widespread use, with ongoing education needed for optimal protection ^[43].

Types of sunscreens available in the market (chemical, physical, and hybrid): Sunscreens are essential for protecting the skin from harmful ultraviolet (UV) radiation, which can cause skin aging, burns, and cancer. The market offers a variety of sunscreen types, mainly categorized as chemical (organic), physical (inorganic), and hybrid formulations. Understanding these types helps consumers make informed choices based on their skin needs and preferences.

Chemical (Organic) Sunscreens

- **Active Ingredients:** Contain organic compounds that absorb UV radiation, such as oxybenzone, avobenzone, and octyl methoxycinnamate ^[44, 45].
- **Mechanism:** Absorb UV rays and convert them into heat, which is then released from the skin ^[46].
- **Advantages:** Typically lightweight, transparent, and cosmetically elegant, making them popular for daily use ^[47].
- **Considerations:** Some chemical filters can cause allergic reactions, such as allergic contact dermatitis, especially with ingredients like oxybenzone. There are also concerns about long-term safety and skin penetration ^[48].

Physical (Inorganic) Sunscreens

- **Active Ingredients:** Use mineral filters like titanium dioxide and zinc oxide.
- **Mechanism:** Reflect and scatter UV radiation away from the skin.
- **Advantages:** Less likely to cause skin allergies or irritation; suitable for sensitive skin.

- **Considerations:** Can leave a visible white residue, which may be less cosmetically appealing, especially for individuals with darker skin tones ^[52]. Application amount may be less than chemical sunscreens, potentially reducing effectiveness.

Hybrid and Novel Sunscreens

Hybrid Formulations: Combine chemical and physical filters to achieve broad-spectrum protection and improved cosmetic properties.

Innovative Approaches

Include encapsulation of chemical filters in natural or synthetic carriers (e.g., lignin, lipid-silica nanoparticles) to enhance stability, reduce skin penetration, and increase sun protection factor (SPF) ^[54].

Natural Alternatives

Research is ongoing into natural UV-blocking agents like mycosporine-like amino acids (MAAs) from algae and cyanobacteria, which may offer safer, eco-friendly options

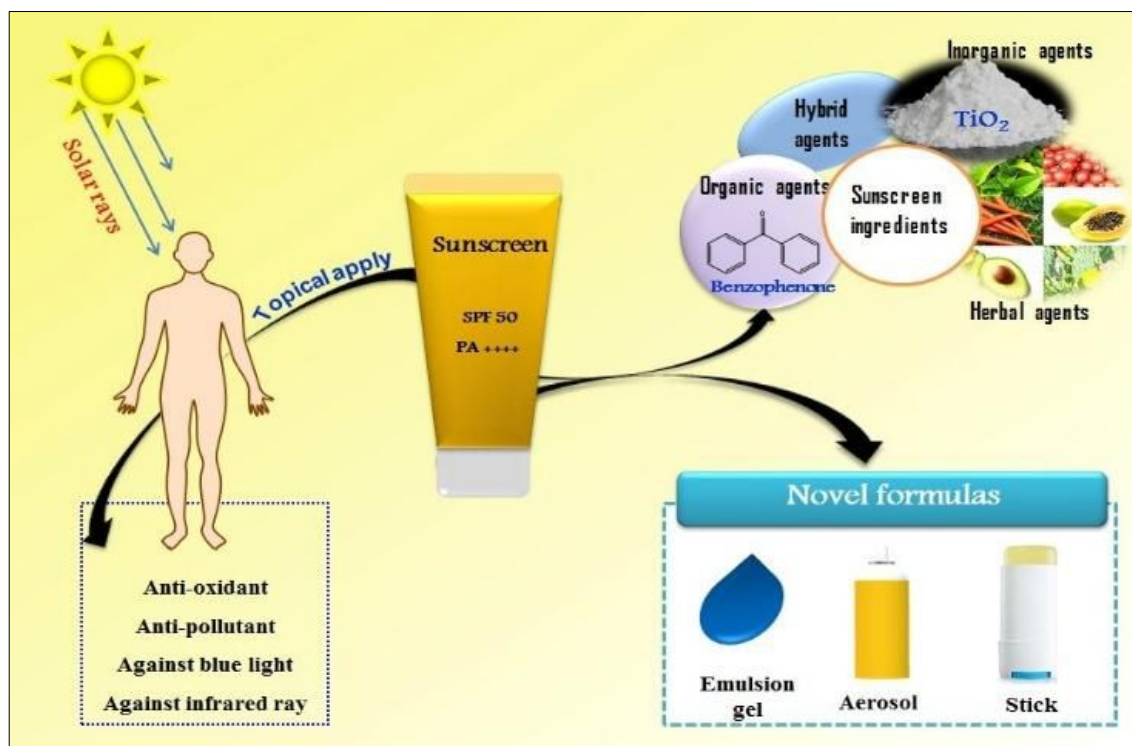


Fig 2: Ingredients and effects

Table 3: Sunscreen Type, ingredients, mechanism and characters

Sunscreen Type	Main Ingredients	Mechanism	Key Features
Chemical	Oxybenzone, Avobenzone, etc.	Absorb UV	Lightweight, may cause allergies
Physical	Titanium dioxide, Zinc oxide	Reflect/Scatter	Low allergy risk, visible residue
Hybrid/Novel	Mix of above, encapsulated	Both	Enhanced protection, stability

Effectiveness and Applications

- **Prevention of Skin Damage:** Sunscreens are proven to reduce the risk of actinic keratoses, squamous cell carcinomas, nevi, melanomas, photo immunosuppression, and signs of photoaging when used correctly ^[57].
- **SPF Levels:** Higher SPF sunscreens (SPF 100+) provide significantly better protection against sunburn and erythema than lower SPF products (SPF 50+), both in single-day and multi-day real-world settings ^[58, 59].
- **Broad-Spectrum Protection:** Sunscreens that protect against both UVA and UVB are more effective in preventing immunosuppression and other UV-induced effects than those that primarily block UVB ^[60, 61].

Types and Ingredients

Chemical vs. Physical Filters: Traditional sunscreens use

organic (chemical) UV absorbers and inorganic (physical) blockers like titanium dioxide (TiO_2) and zinc oxide (ZnO). Micronized and nanoparticle forms of these minerals improve cosmetic acceptability and broaden UV protection ^[62].

Natural Components

There is growing interest in natural antioxidants (e.g., lignin, melanin, silymarin) as sunscreen ingredients. These offer photoprotective and antioxidant effects but often have lower UV absorption and require formulation enhancements for effectiveness ^[63].

Nanotechnology

Incorporating polyphenolic nanocarriers and nanotechnology can enhance UV protection and stability, though safety and regulatory concerns remain ^[64].

Table 4: Comparison of Sunscreen Types and Features

Type	Key Features	Limitations/Concerns
Chemical	Strong UVB absorption	Allergic reactions, environmental
Physical (TiO ₂ /ZnO)	Broad-spectrum, non-absorptive	Cosmetic appearance, nanoparticle safety
Natural	Antioxidant, anti-inflammatory	Lower UV absorption, formulation

Challenges and Considerations

- **Application and Compliance:** Effectiveness depends on correct and sufficient application. Variability in user behaviour can reduce protection.
- **Safety and Regulation:** Ongoing concerns include nanoparticle safety, environmental impact, and the need for standardized testing methods, especially for UVA protection.
- **Public Education:** Continued education on proper sunscreen uses and combining with other protective measures (clothing, shade) is essential.

Formulation Techniques: Formulation of sunscreens involves careful selection and combination of actives and excipients to optimize efficacy, stability, and user acceptability. Emulsifier type and concentration significantly influence SPF, texture, and sensory properties [66]. Nanotechnology-based approaches, such as nanostructured lipid carriers (NLCs), polymeric nanoparticles, and liposomes, enhance the distribution, photostability, and water resistance of sunscreens, while also allowing for reduced filter content without compromising protection [67, 68]. Incorporating natural antioxidants as enhancers or modifiers is another strategy to boost SPF and provide additional skin benefits [69]. The formulation process must also address challenges like photostability, potential toxicity, and environmental impact [70].

Evaluation Parameters

Key evaluation parameters for sunscreen products include

- **Sun Protection Factor (SPF):** Measures UVB protection and is calculated using standardized methods, such as spectrophotometry and the Mansur equation.
- **UVA Protection Factor (PFA):** Assesses protection against UVA rays, with higher values indicating better broad-spectrum efficacy.
- **Photostability:** Evaluates the stability of actives (e.g., avobenzone) under UV exposure, as photostabilizers and formulation strategies are crucial for sustained protection [73].
- **Skin Permeation:** *In vitro* and *in vivo* assays determine the extent of active ingredient absorption, aiming to minimize systemic exposure while maintaining efficacy [73, 74].
- **Mechanical and Sensory Properties:** Parameters like thixotropy, work of shear, and user sensory experience are assessed to ensure product usability and consumer acceptance.
- **Water Resistance:** Tests the durability of protection after water or sweat exposure, especially important for outdoor use.

Analysis of Marketed Sunscreen Products and Ingredients: Marketed sunscreens often use combinations of approved UV filters to achieve broad-spectrum protection and high SPF values. Ingredients such as OMC, BP-3, OC, avobenzone, BEMT, and DHHB are common, with some

products incorporating boosters like lignosulfonate or antioxidants to enhance efficacy and safety [75, 76]. The inclusion of zinc oxide, while effective, can sometimes increase photodegradation and toxicity when combined with certain organic filters [77].

Safety, Regulatory, and Environmental Aspects

Safety concerns include skin irritation, sensitization, and rare photoallergic reactions. Regulatory agencies (e.g., FDA, EU) set limits on filter concentrations and require safety and efficacy testing. Environmental considerations are increasingly important, with efforts to minimize the impact of UV filters on marine ecosystems and to develop eco-friendly formulations using fewer or less harmful ingredients [78]. Ongoing research focuses on improving photostability, reducing toxicity, and expanding filter options to meet evolving safety and environmental standards [79].

Classification of UV filters

UV filters are key ingredients in sunscreens and other products, designed to protect skin and materials from harmful ultraviolet (UV) radiation. They are broadly classified based on their chemical structure and mode of action. The two main categories are chemical (organic) UV filters and physical (inorganic or mineral) UV filters.

Main Types of UV Filters

Chemical (Organic) UV Filters

Mechanism: Absorb UV radiation and convert it into less harmful energy (usually heat) [80, 81].

Common Classes

- Aminobenzoic acid derivatives (e.g., PABA)
- Salicylic acid derivatives
- Cinnamic acid derivatives
- Benzophenones
- Dibenzoylmethane derivatives
- Benzyldiene camphor derivatives
- Triazines
- Benzimidazole derivatives
- Benzotriazole derivatives [82, 83]
- Examples: Octocrylene, p-methoxycinnamic acid derivatives [84]

Physical (Inorganic/Mineral) UV Filters

Mechanism: Reflect and scatter UV radiation away from the skin.

Common Types

- Titanium dioxide (TiO₂)
- Zinc oxide (ZnO)
- Iron oxides
- Mica-titanium oxide systems
- Particle Size: Can be used as larger colored pigments (200-300 µm) or as micronized/nanoparticles (20-80 nm) for more transparent formulations.

Table 4: UV Filter types

UV Filter Type	Mechanism	Common Examples
Chemical (Organic)	Absorb UV, convert to heat	Benzophenones, Cinnamates, PABA
Physical (Mineral)	Reflect/Scatter UV	Titanium dioxide, Zinc oxide

Additional Notes

- **Combination Use:** Many sunscreens use a mix of chemical and physical filters for broad-spectrum protection.
- **Emerging Filters:** Research continues to develop new UV filters, including both natural and synthetic compounds, to improve safety and photostability [86].

Chemical filters: Avobenzone, Oxybenzone, Octocrylene, Octinoxate: Chemical filters such as Avobenzone, Oxybenzone, Octocrylene, and Octinoxate are widely used in sunscreens to protect skin from ultraviolet (UV) radiation. While these compounds are effective at UV absorption, concerns have emerged regarding their environmental impact, potential toxicity, and safety for human health.

Effectiveness and Applications

- **UV Protection:** All four filters are effective at absorbing UV radiation, with Octocrylene also stabilizing Avobenzone to enhance broad-spectrum protection in cosmetic products [87].
- **Usage:** These filters are commonly found in sunscreens and other personal care products to prevent skin damage and skin cancer [88].

Environmental Impact

- **Aquatic Contamination:** Oxybenzone, Octocrylene, Avobenzone, and Octinoxate are frequently detected in coastal and marine environments, especially in areas with high beach use [89, 90].
- **Ecological Risks:** These filters have been linked to coral bleaching, reduced coral growth, and toxicity in various marine organisms. Oxybenzone and Octinoxate, in particular, are associated with coral bleaching and impaired coral recruitment, leading to bans in places like Hawaii and Palau [91].
- **Plant Toxicity:** All four filters can inhibit plant growth and photosynthesis, with Oxybenzone causing the most severe damage, followed by Avobenzone, Octinoxate, and Octocrylene [92].

Human Health and Safety

- **Endocrine Activity:** Most studies show weak or negligible endocrine-disrupting activity for these filters at concentrations found in human plasma, with

Oxybenzone showing slightly higher activity but still well below levels of concern [93].

- **Photo-stability and Sensitization:** Avobenzone and Octinoxate have low photo-stability, which can be improved with stabilizers. Octocrylene is a rare sensitizer but can cause photoallergic reactions, especially in combination with certain drugs.
- **Regulatory Safety:** When used within regulated concentrations, these filters are considered safe for human use, though prolonged exposure can lead to accumulation in the bloodstream.

Environmental Persistence and Removal

- **Wastewater Treatment:** Conventional wastewater treatments are generally ineffective at removing these filters, leading to their accumulation in aquatic environments.
- **Transformation Products:** Ozonation can degrade some filters (OMC, OXY) but may leave transformation products that retain toxicity concerns [97].

Physical filters: Zinc oxide, Titanium dioxide

Physical (inorganic) filters such as zinc oxide (ZnO) and titanium dioxide (TiO₂) are widely used in sunscreens and other products for their ability to block ultraviolet (UV) radiation. These mineral filters are often chosen as alternatives to organic (chemical) filters due to their safety profile and broad-spectrum protection.

Mechanisms of Action and Efficacy

- **UV Protection Spectrum:** ZnO provides broad UVA and UVB protection, while TiO₂ is more effective in the UVB range but less so in UVA [98, 99].
- **Efficacy Differences:** TiO₂, especially in coated forms, can achieve higher sun protection factors (SPF) than ZnO. For example, coated TiO₂ can reach an SPF of 38, while ZnO typically does not exceed SPF 10 at its maximum allowed concentration.
- **Particle Size and Cosmetic Acceptability:** Both ZnO and TiO₂ are used as nanoparticles (<100 nm) to reduce visible residue on the skin, improving cosmetic appeal [100].

Table 5: UV Filters

Filter	UV Range Covered	Max SPF (commercial)	Cosmetic Appearance
Zinc Oxide	UVA + UVB	~10	Less visible (nano)
Titanium Dioxide	UVB (mainly)	~38 (coated)	Less visible (nano)

Safety and Allergenicity

Human Health: Both ZnO and TiO₂ have extremely low risk of skin absorption and are not associated with allergic or photoallergic contact dermatitis, unlike many organic filters.

Inhalation Risk: There is some concern about inhalation of nanoparticles, leading to recommendations against spray formulations containing these filters.

Toxicity: ZnO may have some toxicity concerns, while TiO₂ can generate free radicals under UV exposure, but coatings can reduce this effect.

Environmental Impact

Aquatic Toxicity: Both nZnO and nTiO₂ can persist in aquatic environments, bioaccumulate, and release metal ions or generate reactive oxygen species, potentially harming aquatic organisms [104].

Environmental Risk: Current evidence suggests low environmental risk, but ongoing monitoring is recommended as usage increases.

Innovations and Alternatives

New Materials: Research is ongoing into alternative UV filters like zinc stannate (Zn₂SnO₄), which may offer effective UV protection with lower toxicity and less free radical production compared to ZnO and TiO₂.

Nanostructure Modifications

Coating TiO₂ with silica or silver can improve safety and add antibacterial properties, while maintaining or enhancing UV protection.

Combination formulations for broad-spectrum coverage

Combination formulations are increasingly used to achieve broad-spectrum coverage in both antimicrobial and sunscreen applications. These formulations aim to enhance effectiveness, address resistance, and provide protection against a wider range of pathogens or environmental factors.

Types and Purposes of Combination Formulations

Antimicrobial Combinations: Used to treat infections involving multiple pathogens or to prevent resistance. Examples include combining antibiotics with different mechanisms or combining agents effective against bacteria and fungi for broader coverage^[107, 108].

Sunscreen Combinations

Formulated to protect against a wider spectrum of solar radiation, including UVB, UVA, and visible light, by combining multiple UV filters or integrating natural antioxidants^[109].

Effectiveness and Applications

Antibiotic Combinations

- Combination therapy can select for broad-spectrum resistance in bacteria like *Pseudomonas aeruginosa*, sometimes leading to multidrug resistance through mechanisms such as efflux pump deregulation.
- In local drug delivery (e.g., PMMA bone cement), combining antibiotics extends antimicrobial activity duration and allows for post-implantation refilling, which is useful for recurrent or chronic infections.
- Dual drug-loaded nanofibrous inserts for ophthalmic use provide sustained, broad-spectrum antibiotic coverage and improved drug delivery compared to single-drug solutions^[112].
- Combining agents with different targets (e.g., cerium oxide nanoparticles and nitric oxide donors) can yield synergistic, broad-spectrum antimicrobial effects against bacteria and fungi^[113].
- Common clinical combinations include cell wall-active agents with aminoglycosides, beta-lactamase inhibitors with beta-lactams, and agents targeting sequential metabolic steps.

Sunscreen Combinations

- New formulations combine innovative filters (e.g., TriAsorB) with other UV filters to achieve SPF50+ and protection against UVB, UVA, and blue light, reducing cellular photo damage.
- Nanoparticle-based sunscreens co-incorporate multiple organic filters for enhanced broad-spectrum protection, improved water resistance, and reduced skin absorption risks^[114].
- Combining natural antioxidants (e.g., green tea polyphenols) with UV absorbers in nanoparticles offers broad-band absorption and improved biosafety.

Benefits and Limitations

Table 6: Benefits and Limitations

Application Area	Benefits of Combination Formulations	Limitations/Considerations
Antimicrobials	Broader pathogen coverage, synergy, prolonged activity, resistance prevention	Risk of selecting for multidrug resistance, potential antagonism, need for careful evaluation ^[115]
Sunscreens	Enhanced spectrum of protection, improved stability, reduced skin absorption, antioxidant effects	Need for safety and efficacy validation, potential for decreased mechanical properties in some formulation

Challenges and Future Directions

- Antimicrobials:** Combination therapy can inadvertently select for multidrug-resistant organisms, requiring careful selection and monitoring of combinations.
- Sunscreens:** Ongoing development focuses on improving safety, efficacy, and environmental impact, with interest in natural and nanoparticle-based ingredients.

Nanotechnology in Modern Sunscreens

Types of Nanotechnology Used

Sunscreens now utilize various nanosystems such as polymeric nanoparticles, liposomes, solid lipid nanoparticles, nanoemulsions, nanocrystals, and mesoporous silica particles to encapsulate UV filters and active ingredients.

Regulatory Guidelines (BIS, FDA, EU)

Table 7: Regulatory Agencies

Region/Agency	Key Regulatory Focuses
EU	- Precautionary principle - Mandatory disclosure of nano-ingredients on product labels - Emphasis on consumer information
FDA (USA)	- Approval of specific UV filters (e.g., avobenzone, octocrylene) - Evaluation of safety and photostability - Consideration of environmental impact
BIS (India)	- Ensures product safety and efficacy - Compliance with international standards - Addresses formulation stability and toxicity

Global Trends: Regulatory frameworks are evolving to address the unique properties and potential risks of nanomaterials, with a focus on transparency, safety, and environmental impact ^[119].

Recent Research Trends and Innovative Ingredients

- **Botanical Actives and Antioxidants:** Plant-derived polyphenols, flavonoids, carotenoids, and green tea extracts are being incorporated for their antioxidant and anti-aging properties.
- **Nanocarriers for Natural Compounds:** Encapsulation of botanical actives and antioxidants in nanocarriers enhances their stability, skin penetration, and efficacy while reducing potential toxicity ^[121].
- **Combination and Broad Spectrum Formulations:** New sunscreens combine multiple UV filters and antioxidants for comprehensive protection and improved safety profiles ^[122].

Challenges and Future Directions

- **Safety and Environmental Concerns:** Ongoing research is needed to fully assess the long-term safety of nanomaterials and their environmental impact, especially on marine ecosystems.
- **Consumer Awareness:** Improved labeling and education are recommended to ensure informed use and minimize potential risks ^[124].
- **Regulatory Harmonization:** Continued collaboration among regulatory bodies is essential to keep pace with technological advancements and ensure global product safety.

Methods of Formulation: Formulating topical and encapsulated products such as sunscreens, cosmetics, and drug delivery systems requires careful selection of base types, precise formulation steps, and attention to stability and packaging. Recent research explores various emulsion systems, encapsulation techniques, and stabilization strategies to optimize product performance and shelf life.

Table 8: Emulsification Methods and Their Effects

Method	Droplet Size	Stability Duration	Application Area
Microfluidizer	~105 nm	≥35 days	Food, cosmetics.
Two-step emulsification	Variable	Up to 3 months	Fragrance, drugs.
One-step (Pickering)	Variable	≥2 months	Biocompatible products.

Packaging and Application

Packaging: Use of UV-protective containers and materials that prevent degradation of sensitive ingredients is recommended for maintaining product stability.

Spray Drying: For some emulsions, spray drying enables reconstitution and extends shelf life, especially in food and nutraceutical applications ^[137].

Key Ingredients in Sunscreen Formulations

Sunscreen formulations rely on active ingredients known as UV filters to protect the skin from harmful ultraviolet radiation. These filters are categorized as organic (chemical) or inorganic (physical) agents, each with distinct properties, effectiveness, and safety profiles. Common organic filters include avobenzone, octocrylene, and homosalate, while titanium dioxide and zinc oxide are widely used inorganic filters.

Types of Formulation Bases

- **Emulsions:** Oil-in-water (O/W), water-in-oil (W/O), and double emulsions (W/O/W, O/W/O) are widely used for encapsulating both hydrophilic and lipophilic actives. Double emulsions allow for co-encapsulation and controlled release of multiple ingredients, including fragrances and bioactives ^[126].
- **Gels, Lotions, Sprays:** While not detailed in the abstracts, these are common forms derived from emulsion bases, often chosen for their application properties and user experience.

Key Formulation Steps

- **Phase Preparation:** Separate preparation of oil and aqueous phases is standard, followed by the incorporation of active ingredients (e.g., UV filters, antioxidants, drugs) ^[127].
- **Emulsification and Homogenization:** High-energy methods (e.g., microfluidization, ultrasonic homogenization, rotor-stator mixing) are used to achieve fine droplet sizes and stable emulsions ^[128].
- **Addition of Additives:** Preservatives, stabilizers, fragrances, and antioxidants are incorporated to enhance stability, sensory properties, and shelf life ^[129].
- **Stabilization:** Use of surfactants (hydrophilic and lipophilic), biopolymers, or particles (Pickering stabilization) is critical for emulsion stability and encapsulation efficiency ^[130].

Stability and Optimization Considerations

- **Photostability and pH Adjustment:** Ensuring the stability of actives (e.g., UV filters, antioxidants) against light and maintaining optimal pH are important for product efficacy and safety ^[131].
- **Encapsulation Efficiency:** Double and solid-in-oil-in-water emulsions improve retention and controlled release of actives, reducing burst release and enhancing stability.

Types and Roles of Key UV Filters

Organic (Chemical) Filters

Avobenzone: Provides broad-spectrum UVA protection but is prone to photodegradation unless stabilized in formulation ^[137].

Octocrylene and Homosalate

Commonly used for their UVB protection and ability to stabilize other filters like avobenzone ^[138].

Inorganic (Physical) Filters

Zinc Oxide (ZnO)

Offers broad UVA and UVB protection, superior UVA attenuation compared to titanium dioxide, and is less whitening in appearance ^[139].

Titanium Dioxide (TiO₂): More effective in the UVB range, often combined with ZnO for broad-spectrum coverage.

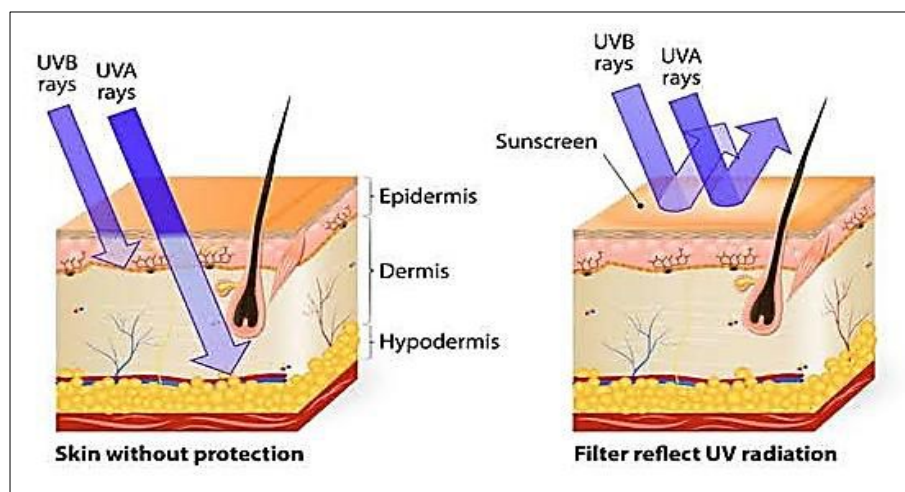


Fig 3: Skin and UV Rays

Effectiveness and Photostability

UVA and UVB Protection

- Avobenzone and ZnO provide superior UVA protection, especially at wavelengths >360 nm, compared to TiO₂.
- TiO₂ is effective for UVB but less so for long-wave UVA.

Photostability

- Avobenzone requires stabilizing agents or formulation strategies to prevent degradation under UV exposure [140].
- Combining avobenzone with octocrylene or using nanoporous carriers can enhance stability and reduce skin penetration [141].
- The presence of ZnO can increase photodegradation and toxicity of some organic filters under UV exposure, highlighting the need for careful formulation.

Safety and Toxicity Considerations

Organic Filters: Generally show low endocrine-disrupting activity and low risk of toxicity at typical human exposure levels, with oxybenzone being a notable exception for higher activity.

Inorganic Filters: ZnO and TiO₂ nanoparticles have minimal percutaneous absorption and low human health risks, though inhalation (e.g., from sprays) should be avoided.

Both can induce some cytotoxicity and genotoxicity in specific conditions, especially with long-term exposure or in nanoparticle form.

Trends and Market Usage

Avobenzone, octocrylene, and titanium dioxide are among the most frequently used UV filters in commercial sunscreens [146]. There is a trend toward increased use of inorganic filters, especially in products for children, due to safety and environmental concerns.

Other excipients

Excipients such as emulsifiers, emollients, humectants, preservatives, and antioxidants are essential components in pharmaceutical, cosmetic, and food formulations. They

influence product stability, efficacy, safety, and user acceptability. Recent research explores both synthetic and natural alternatives, their roles, and their impact on product performance and health.

Functions and Types of Excipients

Emulsifiers: Enable the mixing of oil and water phases, crucial for creams, lotions, and food emulsions. Examples include glyceryl stearate and surfactants like Tween 20/80. Emulsifier type affects the stability and bioavailability of active ingredients, such as curcumin and β-carotene, by influencing droplet formation and digestion behavior [148].

Mollients: Soften and soothe the skin, improving texture and barrier function. Common emollients include cetyl alcohol and caprylic triglyceride. They are vital in treating dry skin and barrier disorders [149].

Humectants: Attract and retain moisture in the skin or product, with glycerin being a typical example. Humectants are often combined with emollients in moisturizers (Pratik Gunwant Bobade & Akhil Maske, 2024) want Bobade & Akhil Maske, 2024).

Preservatives: Prevent microbial growth, extending product shelf life. Examples include parabens and phenoxyethanol. Both synthetic and natural preservatives are used, with a trend toward safer, eco-friendly options.

Antioxidants: Protect formulations from oxidative degradation and may provide skin benefits. Vitamin E and green tea extract are common antioxidants [151].

Impact on Product Performance and Safety

- **Skin Barrier and Tolerability:** Emulsifiers and other excipients can affect skin barrier integrity. Some may weaken the barrier, while others, like petrolatum or ceramide mixtures, can repair it. Patient acceptance is influenced by sensory properties and potential irritation.
- **Bioavailability Enhancement:** In food and nutraceuticals, excipient emulsions can significantly increase the bioaccessibility and absorption of hydrophobic nutrients and antioxidants, depending on emulsifier type and formulation [152].

Natural vs. Synthetic Excipients

Natural Excipients: Increasingly favored for their safety, biodegradability, and environmental benefits. Studies show natural emulsifiers, emollients, and preservatives can match or exceed synthetic counterparts in performance, though more research is needed for full replacement.

Synthetic Excipients: Still widely used due to established efficacy and regulatory acceptance, but concerns about sensitization and environmental impact drive the search for alternative.

Formulation Considerations

Excipient Type	Key Role	Example	Impact
Emulsifier	Mixes oil/water	Glyceryl stearate, Tween 80	Affects stability Bioavailability ^[154]
Emollient	Softens skin	Cetyl alcohol	Improves barrier texture
Humectant	Retains moisture	Glycerin	Hydrates skin
Preservative	Prevents spoilage	Parabens	Extends shelf lifeClick or tap here to enter text.
Antioxidant	Prevents oxidation	Vitamin E	Protects actives

Evaluation Parameters

Physical and chemical evaluation parameters are essential for assessing the quality, stability, and performance of various materials and formulations. These parameters help predict changes over time, such as aging or degradation, and guide maintenance or improvement strategies.

Physical Parameters

Appearance, Color, Odor: These basic properties are commonly assessed to detect visible or sensory changes that may indicate material degradation or contamination.

Viscosity: Viscosity is a key indicator of a material's flow properties and is particularly important in predicting the aging of substances like asphalt binder. The viscosity ratio, in particular, serves as a reliable indicator for assessing long-term aging in both laboratory and field conditions ^[156].

Spreadability: While not specifically mentioned in the abstract, spreadability is often evaluated alongside viscosity to determine how easily a material can be applied or used.

Chemical Parameters

pH: pH measurement is a standard chemical parameter for assessing the acidity or alkalinity of a formulation, which can affect stability and performance.

Content Uniformity: Ensures that the active or functional components are evenly distributed throughout the material.

Component and Functional Group Analysis: For asphalt binders, component analysis and functional group analysis (such as measuring the carbonyl area index) are used to identify chemical changes associated with aging. The carbonyl area index is highlighted as an effective chemical indicator of aging level.

Functional Tests

Performance-Related Tests: Functional tests are designed to assess how well a material performs its intended function after aging or under stress. In the context of asphalt binders, rheological properties are tested to evaluate performance changes due to aging.

Table 9: Key Indicators

Parameter	Type	Purpose/Use
Viscosity Ratio	Physical	Predicts aging in lab and field
Carbonyl Area Index	Chemical	Reflects chemical aging level
Rheological Tests	Functional	Assesses performance after aging

To ensure the safety and effectiveness of sunscreens and topical formulations, several key tests are performed: SPF determination, water resistance, photostability, skin irritation/sensitivity, and microbial testing. These assessments help verify product claims, user safety, and shelf life.

SPF Determination Methods

***In vitro* UV Spectrophotometric Methods:** SPF values can be measured using UV-Vis spectrophotometry, which quantifies the product's ability to absorb or block UV radiation in a laboratory setting. This method is widely used for initial screening and product development ^[159].

***In vivo* Testing:** Traditional *in vivo* methods involve applying the product to human skin and measuring the minimal erythral dose (MED) after UV exposure. Newer techniques, such as Hybrid Diffuse Reflectance Spectroscopy (HDRS), combine *in vivo* skin measurements with *in vitro* data, providing accurate SPF and UVA-PF values without inducing skin reactions ^[160].

Comparative Effectiveness: *In vitro* and *in vivo* SPF results generally correlate well, and advanced methods like HDRS offer ethical and practical advantages ^[161].

Water Resistance Testing

***In vitro* Water Resistance:** A novel *in vitro* technique uses excised human epidermis and transmission spectrometry to assess SPF before and after water immersion. This method closely matches *in vivo* results and allows for detailed analysis of how water exposure affects sunscreen performance and ingredient retention ^[162].

Photostability Assessment

- **Photostability Testing:** Photostability is evaluated by exposing sunscreen formulations to controlled UV irradiation and measuring SPF at intervals. This process helps determine how well the product maintains its protective effect over time and under sunlight, allowing classification of filters by their stability ^[163].
- **Release of Active Ingredients:** Some formulations, such as those with nanoparticles, are tested for their

ability to release active compounds while maintaining photostability ^[164].

Skin Irritation/Sensitivity and Microbial Testing

- **Skin Irritation/Sensitivity:** Patch tests and *in vitro* cell viability assays are used to assess irritation and phototoxicity. Products are applied to human skin or cell cultures, and reactions such as erythema, edema, or cell death are monitored. Most tested natural and

nanoemulsion-based sunscreens show minimal to no irritation or phototoxicity ^[166].

- **Microbial Testing:** Microbial safety and shelf life are evaluated by testing for contamination and resistance. Some studies also assess the product's effect on antibiotic-resistant bacteria and overall microbial safety in water and topical applications ^[167].

Marketed Formulations

Brand & Product Name	Manufacturer	Key Ingredients	SPF / PA Rating
TAC Eladi Sunscreen	The Ayurveda Co.	Neem, Aloe Vera	SPF 50 PA+++
Earth Rhythm Ultra Defence Hybrid Sunscreen Fluid	Earth Rhythm	Mineral & Chemical Filters	SPF 50 PA++++
TNW Sun Defence SPF 50 Cream	The Natural Wash	Licorice, Herbal Ingredients	SPF 50 PA+++
Nourish Mantra Sun Protection Cream	Nourish Mantra	Natural Oils & Extracts	SPF 30 PA+++
Foxtale Dewy Sunscreen	Foxtale	Niacinamide, Vitamin E	SPF 50 PA+++
Dot & Key Vitamin C + E Super Bright SPF	Dot & Key	Vitamin C, Vitamin E	SPF 50 PA+++
Mamaearth Vitamin C Daily Glow Sunscreen	Mamaearth	Vitamin C	SPF 50 PA+++
Minimalist Sunscreen SPF 50 PA++++	Minimalist	Multivitamins	SPF 50 PA++++
Lakme Sun Expert Ultra Matte SPF 50	Lakme	Vitamin B3, Vitamin C	SPF 50 PA++
Biotique Bio Carrot SPF 40+ Sunscreen	Biotique	Carrot Extract	SPF 40+
Neutrogena Ultra Sheer Dry Touch Sunblock	Neutrogena	Helioplex Technology	SPF 50 PA+++
La Shield Sunscreen Gel	Glenmark Pharmaceuticals	Oil-Free Formula	SPF 40
Aqualogica Glow+ Dewy Sunscreen	Aqualogica	Hyaluronic Acid, Vitamin C	SPF 50
Dr. Sheth's Ceramide & Vitamin C Sunscreen	Dr. Sheth's	Ceramides, Hyaluronic Acid, Vitamin C	SPF 50+
Cetaphil Sun SPF 50 Light Gel	Cetaphil	Vitamin E	SPF 50
Re'equil Ultra Matte Dry Touch Sunscreen Gel	Re'equil	Matte Finish Formula	SPF 50
Fixderma Shadow Sunscreen Gel	Fixderma	Lightweight Formula	SPF 30
WOW Skin Science Matte Finish Sunscreen	WOW Skin Science	Non-Greasy Formula	SPF 55
Kaya Clinic Sunscreen SPF 50	Kaya Clinic	Dermatologically Tested Formula	SPF 50

Challenges and Future Directions

The development of effective sunscreens is a significant challenge, particularly in achieving an optimal balance between performance, safety, sensory properties, and compliance with regulations, an issue further complicated by increasing restrictions on the use of certain chemical actives. At the same time, progress in nanotechnology and the emergence of new natural ingredients are stimulating innovative development in this field, with promising potential for enhanced photoprotection. However, such advances must be supported by continued research and diligent testing to determine their long-term safety, stability, and performance under conditions of normal use.

Conclusion

Sunscreen creams play a vital role in protecting the skin from the harmful effects of ultraviolet (UV) radiation, including sunburn, premature aging, and skin cancer. This review highlights the evolution, classification, and formulation of sunscreen products with a special focus on the key active ingredients and their mechanisms of action. Through an in-depth study of chemical, physical, and hybrid sunscreen agents, it is evident that each type has unique advantages and limitations. The incorporation of natural antioxidants and the use of nanotechnology have significantly improved the effectiveness and user acceptability of modern sunscreens. Evaluation parameters such as SPF, photostability, and water resistance remain crucial for product performance, while regulatory compliance ensures safety and consumer trust. Moreover, the analysis of marketed products reveals a growing trend towards eco-friendly, broad-spectrum, and cosmetically appealing formulations. Despite advancements,

challenges like formulation stability, ingredient safety, and environmental impact persist, requiring ongoing research and innovation.

In conclusion, understanding the science behind sunscreen formulations not only aids in the development of safer and more effective products but also promotes informed consumer choices and better skin health outcomes.

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