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Review Article

Advances in Sunscreen Formulation: Novel UV Filters, Photostability and Skin Protection

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ABSTRACT

Sunscreens are essential components of modern photoprotection because exposure to ultraviolet (UV) radiation contributes to sunburn, photoaging, pigmentation disorders, immunological changes, and skin cancer. Although conventional sunscreen formulations provide effective protection when appropriately formulated and applied, several challenges remain, including inadequate protection across the entire UVA spectrum, photodegradation of certain UV filters, formulation instability, cosmetic acceptability, and uncertainties concerning some safety and environmental endpoints. Recent advances in sunscreen technology focus on the development of novel organic UV filters, optimized inorganic filters, broad-spectrum filter combinations, encapsulation systems, antioxidant-assisted formulations, and improved delivery systems. Photostability has emerged as a particularly important formulation parameter because degradation of UV filters may alter protective efficacy and generate photoproducts. Furthermore, the effectiveness of a sunscreen depends not only on the intrinsic properties of its active ingredients but also on the vehicle, film formation, application thickness, water resistance, and reapplication practices. This review discusses the biological effects of UV radiation, the classification and mechanisms of sunscreen filters, emerging formulation technologies, photostability assessment, skin protection outcomes, safety considerations, and future research directions. Particular emphasis is placed on the need to balance photoprotection, formulation performance, human safety, environmental considerations, and consumer acceptability.

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Evidence indicates that sunscreen innovation should integrate filter chemistry, formulation science, standardized testing, and appropriate regulatory evaluation to achieve reliable real-world skin protection.

INTRODUCTION

Solar ultraviolet radiation is an important environmental factor affecting human skin. While limited exposure to sunlight contributes to vitamin D synthesis, excessive UV exposure can produce acute and chronic skin damage. The consequences include erythema, oxidative stress, DNA damage, premature skin aging, pigmentation changes, and an increased risk of skin cancer. UVA radiation penetrates relatively deeply into the skin and contributes substantially to photoaging and oxidative damage, whereas UVB radiation is strongly associated with sunburn and direct DNA photolesions. Both UVA and UVB can contribute to carcinogenic processes [1,2].

Sunscreens are topical preparations designed to reduce the amount of biologically damaging UV radiation reaching the skin. They generally contain organic UV filters, inorganic UV filters, or combinations of both, incorporated into vehicles such as emulsions, gels, creams, lotions, sticks, and sprays. The effectiveness of a sunscreen depends on the performance of the active filters and the ability of the formulation to form a sufficiently uniform film on the skin.

Traditional sunscreen development has focused on increasing the sun protection factor (SPF), improving water resistance, and making products cosmetically acceptable. However, SPF primarily reflects protection against erythema and does not independently describe the full extent of UVA protection. Consequently, modern sunscreen development emphasizes broad-spectrum protection, photostability, long-wavelength UVA coverage, formulation robustness, and practical usability [1,3].

Recent research has investigated new UV-absorbing molecules, combinations of existing filters, particulate mineral filters, encapsulation technologies, and antioxidant-containing formulations. Reviews published in 2025 and 2026 describe continued progress in broad-spectrum protection and formulation design while identifying persistent challenges involving safety evaluation, photostability, environmental effects, and regulatory approval [3–5].

This review aims to provide an integrated overview of advances in sunscreen formulation, with particular attention to novel UV filters, photostability, formulation strategies, skin protection, and future research opportunities.

2. Objectives of the Review

The principal objectives are:

1. To explain the biological effects of UVA and UVB radiation on human skin.
2. To classify sunscreen filters and describe their mechanisms of action.
3. To discuss emerging UV filters and advances in broad-spectrum protection.
4. To evaluate the importance of photostability and methods used to assess it.
5. To review formulation strategies that improve sunscreen performance.
6. To examine skin safety, environmental considerations, and regulatory challenges.
7. To identify research gaps and future directions in sunscreen technology.

3. Review Methodology

This article is structured as a narrative literature review. Relevant scientific themes include sunscreen filter chemistry, photochemistry, formulation stability, skin photoprotection, delivery systems, safety assessment, and regulatory developments.

Relevant literature can be identified through PubMed, Scopus, Web of Science, Google Scholar, and official regulatory websites. Suggested search terms include “sunscreen formulation,” “novel UV filters,” “photostability of sunscreen,” “broad-spectrum photoprotection,” “encapsulation of UV filters,” “mineral sunscreen nanoparticles,” and “sunscreen safety.”

Priority should be given to peer-reviewed review articles, original experimental studies, standardized testing methods, and authoritative regulatory documents. Literature from approximately 2015 to October 2026 can

provide a contemporary perspective, supplemented by foundational studies where necessary.

As this is a narrative review, it does not claim to be a systematic review or meta-analysis. A formal journal submission should include the actual search dates, databases, eligibility criteria, screening procedure, and verified references. The discussion below synthesizes established principles and selected recent literature rather than reporting new experimental findings.

4. Ultraviolet Radiation and Its Effects on Skin

4.1 UVA radiation

UVA radiation occupies approximately 320–400 nm. It penetrates more deeply into the skin than UVB and contributes to the generation of reactive oxygen species (ROS). These reactive species can damage cellular lipids, proteins, and DNA and can activate pathways associated with inflammation and degradation of extracellular matrix components.

Long-term UVA exposure is associated with photoaging, including wrinkles, reduced elasticity, and changes in skin texture. UVA can also contribute to pigmentation and skin carcinogenesis. Protection against UVA is therefore an essential component of comprehensive photoprotection [1,2].

4.2 UVB radiation

UVB radiation occupies approximately 280–320 nm, although its intensity reaching the Earth's surface is strongly affected by atmospheric conditions. It is a major cause of erythema and can directly induce DNA lesions, including cyclobutane pyrimidine dimers. If DNA damage is not adequately repaired, mutations may accumulate and contribute to skin cancer.

UVB also influences inflammatory responses and local immune function. Effective UVB protection is particularly important for preventing sunburn and reducing cumulative UV-related skin injury [1,2].

4.3 Visible light and infrared radiation

Visible light occupies approximately 400–700 nm, while infrared radiation extends to longer wavelengths. Certain wavelengths of visible light, particularly high-energy visible light, can contribute to persistent pigmentation in some skin phototypes. The biological effects vary with wavelength, dose, skin type, and exposure conditions.

Conventional SPF testing does not measure protection against all visible wavelengths. Tinted formulations containing suitable iron oxides may provide additional attenuation of visible light, although performance depends on pigment composition and the resulting film. Evidence for routine sunscreen-based protection against infrared radiation is less established than the evidence for UV protection.

Table 1: Major Radiation Bands and Their Biological Effects

Radiation	Approximate wavelength	Principal skin effects
UVA	320–400 nm	Oxidative stress, photoaging, pigmentation, DNA damage
UVB	280–320 nm	Sunburn, direct DNA damage, inflammatory responses
Visible light	400–700 nm	Can contribute to pigmentation in susceptible skin
Infrared	Approximately 700 nm onward	Thermal effects; biological responses depend on exposure

Note: The boundaries are approximate and are used for scientific classification.

5. Sunscreen Filters: Classification and Mechanisms

Sunscreen filters are commonly classified as organic or inorganic according to their chemical nature.

5.1 Organic UV filters

Organic filters contain molecular structures that absorb UV radiation and dissipate the absorbed energy through photophysical and photochemical processes. Different molecules have different absorption spectra; therefore, several filters are often combined to achieve broad-spectrum protection.

Examples include:

- **Avobenzone:** A UVA filter widely used for long-wavelength UVA protection in formulations where permitted.
- **Octocrylene:** A UVB and short-UVA-absorbing filter that can also contribute to the photostabilization of certain other filters.
- **Octinoxate:** Primarily a UVB filter.
- **Homosalate:** Primarily a UVB filter.
- **Bemotrizinol:** A broad-spectrum filter absorbing both UVA and UVB radiation in jurisdictions where it is authorized.
- **Bisoctrizole:** A particulate organic filter with broad-spectrum absorption characteristics in jurisdictions where permitted.

The permitted ingredients, concentration limits, and labeling requirements vary by country. The presence of an ingredient in scientific literature does not automatically mean it is approved for sunscreen use in every market [3,4].

Organic filters can provide effective protection with relatively transparent films. However, some may undergo photochemical degradation, interact with other formulation ingredients, or have solubility limitations that complicate product development.

5.2 Inorganic UV filters

The principal inorganic sunscreen filters are zinc oxide (ZnO) and titanium dioxide (TiO_2). Their photoprotective action involves UV absorption and, depending on particle characteristics, scattering and reflection.

Zinc oxide can provide broad-spectrum protection, including substantial UVA coverage. Titanium dioxide is particularly useful for UVB and shorter-wavelength UVA protection, although its spectral performance depends on particle size, surface treatment, and formulation.

Potential advantages of mineral filters include relatively good photostability and suitability for some sensitive-skin formulations. Important challenges include visible white residue, particle aggregation, film uniformity, and cosmetic acceptability. Certain untreated or inadequately surface-modified particles may generate ROS under illumination; particle coatings and appropriate formulation design can help manage this concern [3,5].

5.3 Combination of organic and inorganic filters

Combining different filters can improve spectral coverage and may reduce the limitations associated with individual ingredients. For example, an appropriate combination of UVA and UVB filters can increase broad-spectrum performance while maintaining a cosmetically acceptable product.

However, combinations must be evaluated for compatibility, solubility, photostability, interactions, and regulatory compliance. A mixture of individually effective filters does not automatically produce a stable or superior sunscreen.

6. Advances in Novel UV Filters

6.1 Development of next-generation organic filters

Research into new organic UV filters aims to improve spectral coverage, photostability, safety, and formulation compatibility. Conventional filters may have limitations in the long-wavelength UVA region or may require stabilizing combinations. Consequently, researchers are investigating new molecular structures capable of absorbing a wider range of UV wavelengths.

A 2026 review of organic UV filter research from 2015 –2025 categorized nearly 500 investigated compounds into derivatives of established filters, natural-product-inspired compounds, and other chemical structures. The review reported progress in broad-spectrum absorption, photostability, and selected additional properties, while these findings should not be interpreted as meaning that all investigated compounds are approved or commercially available [4].

6.2 Broad-spectrum and long-wavelength UVA protection

Broad-spectrum protection is a central objective of modern sunscreen development. UVB-focused products can achieve a high SPF without necessarily providing proportionate UVA protection. Therefore, the UVA protection profile must be evaluated independently using suitable methods.

Newer and established filters with complementary absorption spectra can be combined to improve coverage. Long-wavelength UVA protection is especially important because UVA extends to 400 nm and contributes to cumulative skin damage.

The performance of a formulation depends on the spectral distribution of its filters, their concentration, interactions, and the uniformity of the applied film. Consequently, filter selection should be guided by measured performance rather than ingredient lists alone [1,3,4].

6.3 Photostable filter combinations

Photostability is an important criterion when selecting and combining UV filters. A photostable filter maintains its chemical structure and protective performance to a greater extent during irradiation.

Avobenzone, for example, can undergo photochemical changes under certain conditions. Combining it with suitable photostabilizing ingredients and compatible UV filters can improve its stability. Octocrylene has historically been used in some formulations for this purpose, although the performance of any combination must be tested experimentally.

Other approaches include selecting inherently photostable filters, optimizing solvent systems, adjusting the polarity of the vehicle, and incorporating filters into protective delivery systems.

6.4 Natural-product-inspired UV filters

Naturally occurring compounds, including selected plant-derived chromophores and polyphenols, have attracted interest because some absorb UV radiation or exhibit antioxidant activity. Nevertheless, natural origin does not guarantee adequate UV protection, safety, or stability.

A compound that absorbs UV in a laboratory experiment may not provide meaningful SPF in a finished product. Its efficacy must be established in the complete formulation using standardized testing. Potential problems include discoloration, oxidation, low solubility, variability in raw materials, and inadequate protection across the required spectrum.

At present, such compounds are better considered promising research candidates or complementary ingredients unless sufficient evidence supports their use as primary UV filters.

6.5 Regulatory considerations for novel filters

A major challenge in sunscreen innovation is that a promising laboratory compound cannot automatically be marketed as an active sunscreen ingredient. Depending on the jurisdiction, approval or inclusion in an applicable regulatory framework may require evidence of efficacy, toxicology, phototoxicity, photoallergy, stability, and other relevant safety parameters.

In the United States, the FDA's sunscreen regulatory framework has historically required additional data for several commonly used organic filters. The agency announced a final order in June 2026 adding bemotrizinol as a sunscreen active ingredient to the relevant over-the-counter monograph. Regulatory status remains jurisdiction-specific, and the latest applicable requirements must be verified before product development or commercialization [6].

7. Photostability of Sunscreen Formulations

7.1 Definition and importance

Photostability refers to the ability of a substance or formulation to maintain its chemical and physical properties when exposed to light. In sunscreen products, it is particularly important because UV filters are intentionally exposed to solar radiation during use.

Photodegradation may decrease the concentration of an active filter, alter the absorption spectrum, generate degradation products, or affect interactions among ingredients. These changes can influence the protective performance and safety profile of the formulation [3,5].

7.2 Factors affecting photostability

Several factors influence the stability of sunscreen filters:

1. **Molecular structure:** The chemical structure determines how an ingredient absorbs and dissipates energy.
2. **Filter combinations:** Some ingredients stabilize one another, whereas other combinations can accelerate degradation.

3. **Solvent and vehicle:** Solubility, polarity, and local molecular environment affect photochemical behavior.
4. **Oxygen exposure:** Oxidative reactions may contribute to degradation.
5. **Temperature:** Heat can influence chemical reactions and physical stability.
6. **Particle characteristics:** Particle size, surface coating, and aggregation affect the behavior of mineral filters.
7. **Light exposure:** Wavelength distribution, intensity, and exposure duration influence degradation.

7.3 Strategies to improve photostability

Photostable filter selection: Choosing suitable filters can reduce the need for complex stabilization strategies.

Optimized filter combinations: Complementary filters may improve spectral coverage and stability when their interactions are understood.

Encapsulation: Lipid carriers, polymeric systems, and other encapsulation technologies can modify the environment around UV filters and may reduce unwanted interactions.

Surface modification: Suitable coatings on mineral particles can improve dispersion and reduce surface reactivity.

Antioxidant-assisted formulations: Selected antioxidants may reduce oxidative processes and complement photoprotection. However, they do not replace validated UV filters.

Packaging: Light-resistant and air-limiting packaging can help preserve product quality during storage, although it cannot substitute for photostability testing during actual use.

7.4 Evaluation of photostability

Photostability is typically evaluated by exposing a formulation or filter to a controlled light source and measuring changes before and after irradiation.

Common analytical approaches include:

- UV–visible spectrophotometry to evaluate changes in absorption spectra.
- High-performance liquid chromatography (HPLC) to quantify active ingredients.
- Liquid chromatography–mass spectrometry (LC–MS) to investigate degradation products.
- Complementary physical stability tests to assess changes in the vehicle.

Testing should consider the intended product, realistic exposure conditions, and relevant validated protocols. A reduction in absorbance alone does not always identify the chemical cause of degradation; chromatographic analysis can provide additional information.

Photostability should also be distinguished from shelf-life stability. A formulation can remain stable during storage but degrade under UV exposure, or it can be photostable yet develop physical instability during storage.

8. Innovative Sunscreen Formulation Technologies

8.1 Nanoencapsulation and controlled delivery

Nanoencapsulation involves incorporating UV filters into nanoscale or nanostructured delivery systems. Potential carriers include polymeric particles, lipid-based nanoparticles, nanoemulsions, and other suitable materials.

Potential advantages include improved dispersion, reduced direct contact between incompatible ingredients, enhanced photostability, and better formulation performance. Encapsulation may also influence the distribution of a filter within the applied film.

However, encapsulation does not automatically improve SPF or guarantee reduced skin penetration. The outcome depends on the carrier, particle properties, encapsulation efficiency, release behavior, and complete formulation. Toxicological and environmental assessment is necessary, particularly for systems containing engineered nanomaterials [5].

8.2 Mineral nanoparticle formulations

Nanoscale ZnO and TiO_2 can reduce visible white residue compared with some larger-particle formulations, improving cosmetic acceptability. These materials require careful characterization, including particle size distribution, aggregation, surface treatment, and photoreactivity.

The safety of a particle depends on more than its nominal size. The final product's application route, exposure conditions, formulation, and potential inhalation exposure must be considered. Sprayable or powder formulations can raise different exposure concerns from products applied as creams or lotions.

8.3 Antioxidant-enriched sunscreen formulations

Antioxidants such as selected forms of vitamin C, vitamin E, and certain polyphenols are investigated as complementary ingredients in sunscreen formulations. They may help address oxidative processes that are not fully represented by SPF measurements.

Their performance depends on concentration, stability, compatibility, and delivery. Some antioxidants are sensitive to light, oxygen, or pH, requiring appropriate formulation and packaging.

An antioxidant-containing sunscreen should not be assumed to provide a higher SPF or comprehensive UVA protection unless the finished product has been tested. Antioxidants are complementary agents rather than substitutes for approved UV filters.

8.4 Film-forming polymers and water resistance

Uniform film formation is crucial for effective sunscreen performance. Film-forming polymers can improve adhesion, reduce uneven coverage, and help a formulation resist removal by water or sweat.

The effectiveness of these polymers depends on their concentration, compatibility, flexibility, and interaction with the skin surface. Excessively heavy or uncomfortable films may discourage regular application.

Water resistance must be established through appropriate standardized testing. It should not be inferred solely from the presence of a film-forming polymer.

8.5 Emulsions, gels, and hybrid systems

The vehicle influences the spreading, sensory properties, stability, and distribution of UV filters. Oil-in-water emulsions often provide a lighter feel, whereas water-in-oil systems may offer greater water resistance in appropriately designed formulations.

Gel-based and hybrid systems can be useful for specific skin types and product preferences. However, the vehicle must maintain filter solubility or dispersion, prevent separation, and support uniform film formation.

Table 2: Formulation Innovations and Their Potential Benefits

Technology	Potential benefit	Main challenge
UV-filter encapsulation	Improved stability and compatibility	Carrier safety and validation
Surface-modified mineral filters	Better dispersion and controlled surface reactivity	Particle characterization
Antioxidant-assisted formulations	Complementary oxidative-stress protection	Ingredient stability and clinical validation
Film-forming polymers	Improved film uniformity and water resistance	Sensory acceptability
Hybrid filter systems	Broader spectral coverage	Compatibility and regulatory compliance
Advanced emulsion systems	Better spreading and filter distribution	Physical and chemical stability

9. Evaluation of Sunscreen Efficacy

9.1 Sun protection factor

SPF is an established measure of protection against erythema induced primarily by UV radiation. It is commonly determined by comparing the minimal erythema dose on protected and unprotected skin under standardized conditions.

A high SPF is valuable, but it does not independently describe the entire protection spectrum or guarantee real-world effectiveness. Application thickness, film uniformity, water exposure, sweating, and reapplication affect practical performance.

SPF testing should follow the applicable standardized method, such as the relevant edition of ISO 24444 or another accepted regulatory method.

9.2 UVA protection

UVA protection can be assessed using validated in vivo or in vitro methods, depending on the applicable standard and jurisdiction. Common measures include UVA protection factor (UVA-PF) and critical wavelength.

The critical wavelength is calculated from the cumulative UV absorbance spectrum. A value of at least 370 nm is used as a broad-spectrum criterion in the United States framework. This criterion indicates spectral breadth and should not be interpreted as a complete measure of the magnitude of UVA protection.

The UVA-PF and SPF provide different information and should be considered together when evaluating a sunscreen.

9.3 Water resistance

Water resistance is important for products intended for swimming, sports, or heavy perspiration. Standardized testing evaluates the persistence of protection after specified water immersion conditions.

Claims such as "water resistant" must comply with local regulatory requirements. No sunscreen should be considered permanently water resistant.

9.4 In vitro and instrumental testing

Laboratory methods are useful during formulation development. These may include:

- UV transmission measurements through standardized substrates.
- Spectral absorbance analysis.
- Filter concentration and degradation measurements.
- Rheology and viscosity testing.
- Particle size and dispersion analysis.
- Accelerated and real-time stability testing.
- Packaging compatibility assessment.

Instrumental screening can help compare prototype formulations, but it should not be treated as a substitute for required regulatory SPF or UVA testing.

10. Skin Protection and Clinical Relevance

10.1 Prevention of sunburn

Sunscreens reduce erythema when they are applied adequately and provide sufficient UVB protection. Their performance is affected by the amount applied and the uniformity of coverage. Users commonly apply less sunscreen than the amount used during standardized testing, so actual protection may be lower than the labeled SPF.

10.2 Prevention of photoaging

Cumulative UV exposure contributes to wrinkles, uneven pigmentation, and loss of skin elasticity. Broad-spectrum sunscreen use, alongside shade and protective clothing, can help reduce cumulative UV damage.

Clinical and experimental evidence supports photoprotection as an important part of strategies intended to reduce photoaging. However, the magnitude of benefit depends on regular use and other exposure-related factors.

10.3 Skin cancer prevention

UV radiation is a major modifiable risk factor for skin cancer. Sunscreens form one component of a broader prevention strategy, which includes protective clothing, hats, sunglasses, shade, and avoidance of excessive exposure.

Sunscreen should not be treated as permission to remain in intense sunlight for prolonged periods. Evidence concerning cancer prevention depends on the type of cancer, study design, duration of follow-up, and patterns of sunscreen use [1,2].

10.4 Pigmentation and visible-light protection

Some pigmentation disorders can be aggravated by UVA and visible light. Tinted products containing suitable pigments may provide additional visible-light attenuation. Their benefits depend on the pigmentation system, formulation, and amount applied.

The presence of a tint alone does not establish effective visible-light protection. Performance should be evaluated with appropriate spectral and clinical methods.

11. Safety and Environmental Considerations

11.1 Human safety

Sunscreen ingredients require evaluation for irritation, sensitization, phototoxicity, photoallergy, systemic exposure where relevant, and other toxicological endpoints. Safety conclusions should be based on the available evidence for a specific ingredient, concentration, exposure route, and product type.

Concerns raised about an ingredient do not automatically establish that the ingredient causes harm under ordinary use. Similarly, evidence of low systemic exposure or long-term use does not eliminate the need for continued safety evaluation.

11.2 Photodegradation products

Some UV filters can form transformation products following exposure to light. Their formation and biological significance depend on the filter, irradiation conditions, and formulation. Analytical identification and toxicological evaluation are needed before making conclusions about the safety of specific photoproducts.

11.3 Environmental impact

Some UV filters have been detected in aquatic environments, raising questions about their persistence, bioaccumulation, and effects on aquatic organisms. Environmental outcomes vary with the ingredient, concentration, environmental conditions, and organism studied.

Claims such as “reef-safe” should be interpreted cautiously because there is no single universally accepted definition that guarantees the absence of environmental effects. Environmental evaluation should consider the complete formulation and its lifecycle rather than one ingredient in isolation.

11.4 Regulatory differences

Sunscreen regulation differs among countries. Ingredients, permitted concentrations, labeling claims, testing requirements, and product classifications may vary. For products intended for the Indian market, developers should consult current applicable requirements issued by the relevant Indian authorities and verify the legal classification of the product and its claims.

A formulation should not be described as approved, safe, or environmentally harmless solely because its ingredients have been reported in published research.

12. Current Challenges in Sunscreen Formulation

Despite technological advances, several challenges remain.

Insufficient long-wavelength UVA coverage: Not all combinations provide balanced protection across the full UVA range.

Photoinstability: Certain filters and combinations can undergo degradation during irradiation.

Solubility and compatibility: Some organic filters require carefully selected solvents or emulsifiers to remain dissolved and uniformly distributed.

Cosmetic acceptability: White residue, greasiness, stickiness, eye irritation, and poor spreadability may reduce regular use.

Safety assessment: New molecules, nanocarriers, and degradation products require appropriate toxicological evidence.

Environmental uncertainty: Data on persistence, biodegradation, and chronic aquatic effects remain incomplete for some ingredients.

Testing limitations: Laboratory measurements do not always predict performance under diverse real-world conditions.

Consumer behavior: Inadequate application and failure to reapply can substantially reduce effective protection.

Addressing these challenges requires collaboration among cosmetic scientists, pharmacists, dermatologists, toxicologists, analytical chemists, and regulatory specialists.

13. Future Perspectives

Future sunscreen development is likely to emphasize multifunctional formulations that integrate high-performance UV filters with improved stability, pleasant sensory properties, and responsible environmental design.

13.1 Molecular design and computational screening

Computational chemistry and predictive modeling may help identify candidate UV filters with suitable absorption spectra, photochemical stability, and physicochemical properties. Experimental confirmation remains essential because predicted performance cannot replace laboratory, safety, and clinical testing.

13.2 Advanced encapsulation systems

Encapsulation research may improve filter compatibility and stability while providing better control over dispersion and release. Future studies should establish whether these benefits translate into measurable improvements in protection, exposure, or safety.

13.3 Improved UVA and visible-light protection

New molecular structures, carefully designed filter combinations, and pigment-containing formulations may improve protection in wavelength regions where conventional products have limitations. Validated spectral and clinical testing will be necessary to support these claims.

13.4 Sustainable formulation design

Future products may incorporate more biodegradable materials, lower-impact manufacturing processes, and packaging that reduces waste. Sustainability claims should be supported by appropriate environmental and lifecycle evidence.

13.5 Personalized photoprotection

Skin phototype, pigmentation tendency, occupational exposure, outdoor activities, and individual product preferences may inform sunscreen selection. Personalized recommendations should be based on reliable clinical evidence and should not compromise adequate broad-spectrum protection.

13.6 Better real-world performance

Future innovations should prioritize consistent film formation, convenient application, resistance to removal, and improved cosmetic acceptability. Increasing regular use may be as important as improving the intrinsic performance of individual UV filters.

14. Research Gaps

The following areas deserve further investigation:

1. Long-term performance of novel UV filters under realistic solar exposure.
2. Identification and toxicological characterization of photodegradation products.
3. Comparative evaluation of encapsulated and non-encapsulated formulations.
4. Effects of formulation vehicles on filter distribution and film uniformity.
5. Standardized evaluation of environmental persistence and aquatic toxicity.
6. Clinical evidence supporting antioxidant-assisted photoprotection.
7. Correlation between instrumental measurements and actual user protection.
8. Performance and acceptability across different skin phototypes and climates.
9. Stability of sunscreen products under high-temperature and high-humidity storage conditions.
10. Harmonization of testing and regulatory approaches across markets.

Research should report the formulation composition, test conditions, irradiation dose, analytical methods, controls, statistical analyses, and limitations clearly to facilitate reproducibility.

14.1 Recent Developments in UV-Filter Research

Recent literature published in 2025–2026 highlights two continuing priorities in sunscreen research: improving protection in the long-wavelength UVA region and developing formulations that remain effective under practical conditions. A 2025 review by Ziglar and colleagues describes emerging filters and formulation approaches intended to improve broad-spectrum protection, while also noting limitations in UVA and visible-light coverage [3]. A 2026 review mapping research on organic UV filters from 2015 to 2025 identified nearly 500 investigated compounds, including derivatives of established filters and natural-product-inspired structures. These molecules represent research candidates; their laboratory absorption or

photostability does not by itself establish regulatory approval or commercial suitability [4,11].

Bemotrizinol is an example of a filter whose regulatory status has recently changed in one major market. On 10 June 2026, the United States Food and Drug Administration issued Final Administrative Order OTC000039, adding bemotrizinol to the US OTC sunscreen monograph at concentrations up to 6%, subject to the conditions specified in that order [12]. This development should not be generalized to other countries: authorization, permitted concentrations, labeling and product classification remain jurisdiction-specific. Formulators must check the current local positive lists and requirements before selecting any UV filter.

14.2 Formulation Development: From Filter Selection to Finished Product

Sunscreen development should begin with a target product profile that defines the intended users, dosage form, SPF and UVA claims, water-resistance requirement, sensory characteristics, packaging and markets where the product will be sold. UV filters should then be selected according to their absorption spectra, photostability, solubility or dispersibility, compatibility and regulatory status. Combining filters with complementary spectra may improve coverage, but the finished combination must be tested because interactions can alter stability and performance [3,13].

The vehicle is a functional part of the sunscreen rather than an inert carrier. The oil phase, emollients, emulsifiers, solvents, rheology modifiers and film-forming polymers influence filter solubilization, crystallization, spreading and the uniformity of the dried film. During prototype development, useful quality attributes include appearance, pH where relevant, viscosity or rheology, particle-size distribution for dispersions, homogeneity, active-filter assay, microbial quality, packaging compatibility and accelerated as well as real-time stability. A 2026 review emphasizes that formulation, application and environmental conditions collectively affect measured and real-world sunscreen performance [13].

Photostability testing should compare samples before and after controlled irradiation. UV–visible spectroscopy can show changes in spectral absorbance, while HPLC can quantify remaining filter content and LC–MS can help characterize transformation products. Testing should document the light source, spectral range, irradiance, exposure duration or dose, sample preparation, temperature and analytical controls. Storage stability and photostability should be assessed separately because a product may remain stable in the package but change during sunlight exposure [3,13].

14.3 Real-World Use and Consumer Performance

The SPF value is determined under standardized conditions and should not be interpreted as the protection a person will necessarily obtain in daily use. The amount applied, evenness of the film, missed areas, sweating, swimming, towel drying and failure to reapply all influence practical protection. A 2026 review identifies inadequate application and insufficient reapplication as continuing barriers to real-world photoprotection [13].

For routine outdoor use, the American Academy of Dermatology advises applying sunscreen generously to all uncovered skin and reapplying approximately every two hours, and immediately after swimming or sweating [14]. The amount needed varies with body size and the area exposed. Sunscreen should be used together with shade, protective clothing, a broad-brimmed hat and sunglasses; it should not be used to justify prolonged exposure to intense sunlight. Consumer acceptability is therefore a formulation requirement: a product that spreads easily and feels comfortable may support more consistent use.

14.4 Indian Regulatory and Standards Considerations

For products intended for the Indian market, regulatory review should begin with the Cosmetics Rules, 2020 and the applicable provisions of the Drugs and Cosmetics Act and Rules. The Central Drugs Standard Control Organization (CDSCO) publishes the Cosmetics Rules and related regulatory material. Rule 39 addresses standards of cosmetics and requires imported or manufactured cosmetics to comply with applicable specifications and standards [15]. The exact legal route and requirements should be confirmed for the specific product, claims, ingredients and manufacturing or import activity.

The Bureau of Indian Standards (BIS) standards relevant to sunscreen testing and ingredient suitability should also be checked in their current editions. Internationally, ISO 24444:2019 specifies an in-vivo method for determining SPF and was confirmed as current in 2026 [7]. ISO 24443:2021 describes an in-vitro method for determining UVA photoprotection; Amendment 1:2026 was published in February 2026 [8,16]. These methods support standardized testing, but the applicable Indian legal and labeling requirements must be checked independently rather than assumed to be identical to those in the United States or Europe.

14.5 Environmental Assessment and Responsible Claims

Environmental evaluation should consider the individual UV filters and the complete finished formulation. Relevant questions include environmental release, persistence, biodegradation, bioaccumulation and effects on aquatic organisms. Results may vary with the test organism, concentration, exposure duration and environmental conditions. Consequently, broad claims such as “reef-safe” or “environmentally harmless” should not be made without a clearly defined test basis and adequate evidence. Sustainable formulation development should also consider raw-material sourcing, manufacturing impacts, packaging and end-of-life waste [3,13].

CONCLUSION

Advances in sunscreen formulation have expanded the possibilities for achieving effective and cosmetically acceptable photoprotection. Novel UV-filter research, complementary filter combinations, mineral-particle modification, encapsulation technologies, antioxidant-assisted formulations, and improved film-forming systems offer potential benefits for broad-spectrum protection and formulation stability.

Nevertheless, innovation must be evaluated carefully. Photostability, SPF, UVA protection, water resistance, storage stability, human safety, and environmental effects are distinct parameters and cannot be inferred from a single test or ingredient property. Similarly, promising experimental compounds should not be described as approved sunscreen filters without verifying their regulatory status.

The future of sunscreen technology depends on integrating molecular design, formulation optimization, standardized testing, toxicological evaluation, and consumer-centered product development. A successful sunscreen must not only provide measurable protection under controlled conditions but also remain stable, comfortable, and practical enough to encourage consistent use. Comprehensive photoprotection should continue to combine appropriate sunscreen use with shade, protective clothing, and other sun-safe behaviors.

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