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RECENT ADVANCES IN UV SKIN PHOTOPROTECTION: A COMPREHENSIVE REVIEW OF MODERN UV FILTERS, NANOPARTICLE SAFETY, AND SUNSCREEN EFFICACY (2023–2025)

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ABSTRACT

Sunscreen products represent a critical intervention in preventing ultraviolet radiation-induced skin damage, including photoaging, DNA damage, and cutaneous malignancies. This narrative review synthesizes recent evidence from 2023-2025 regarding sunscreen safety, efficacy, and technological innovations. A comprehensive analysis of peer-reviewed articles reveals substantial progress in understanding both traditional and emerging UV filter technologies. Key findings include the development of novel inorganic nanoparticles with enhanced safety profiles, advancement of organic filter formulations with improved photostability, and innovative delivery systems including liposomal and nanocarrier-based approaches. Evidence demonstrates that two-dimensional titanium dioxide nanoparticles achieve over 99% visible light transmittance while maintaining UV protection efficacy, addressing aesthetic concerns that limit sunscreen adherence. Safety evaluations indicate that properly formulated inorganic filters exhibit minimal skin penetration and reduced reactive oxygen species generation compared to conventional formulations. Emerging concerns regarding endocrine disruption potential of organic UV filters warrant continued surveillance, particularly for benzophenone-3 (oxybenzone), 4-methylbenzylidene camphor, and octinoxate. Natural and bioinspired alternatives, including polydopamine nanoparticles and plant-derived compounds, demonstrate promising photoprotective properties with favorable safety profiles. DNA repair enzyme incorporation represents a paradigm shift toward active rather than passive photoprotection. Environmental considerations, particularly aquatic ecosystem impacts, increasingly influence formulation strategies. This review identifies critical knowledge gaps requiring further investigation, including long-term safety data for novel nanomaterials, standardized assessment methodologies for broad-spectrum protection including visible light and infrared radiation, and personalized photoprotection approaches. The synthesis of current evidence provides clinicians and researchers with a comprehensive understanding of contemporary sunscreen science to inform clinical recommendations and future research priorities.

KEYWORDS

Sunscreen Safety, UV Filters, Nanoparticles, Photoprotection, Titanium Dioxide, Zinc Oxide

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1. Introduction

Ultraviolet radiation exposure represents one of the most significant modifiable risk factors for cutaneous pathology, including melanoma and non-melanoma skin cancers, premature photoaging and pigmentary disorders. The progressive reduction of the stratospheric ozone layer has intensified UV radiation reaching the Earth's surface, amplifying the imperative for effective photoprotection strategies (Thy et al., 2025). Sunscreen products constitute a key element of photoprotection, functioning through absorption, reflection or scattering of UV photons before they can induce cellular and molecular damage.

The global sunscreen market has experienced significant growth, driven by increasing public awareness of UV-related health risks and expanding cosmetic applications. However, this widespread utilization has been accompanied by growing concerns regarding the safety profiles of various UV filter compounds and their actual efficacy under real-world conditions (Raymond-Lezman & Riskin, 2024). Additional concerns have emerged regarding the environmental impact of UV filters on aquatic ecosystems, particularly coral reef damage and bioaccumulation in marine organisms.

Recent years have witnessed intensive research efforts aimed at addressing these concerns through technological innovation and rigorous safety evaluation.

Contemporary sunscreen formulations employ two fundamental classes of UV filters: organic (chemical) filters that absorb UV radiation through molecular excitation and inorganic (physical) filters that primarily reflect and scatter UV photons (Araki & Baby, 2025). Traditional organic filters, while offering cosmetically elegant formulations, have faced scrutiny regarding photostability, systemic absorption and potential endocrine disruption (Jaskulak et al., 2025). In contrast, inorganic filters, particularly titanium dioxide (TiO_2) and zinc oxide (ZnO), have been valued for their broad-spectrum protection and photostability, though historically criticized for aesthetic drawbacks including visible whitening (Thy et al., 2025).

The period from 2023 to 2025 has been particularly productive in sunscreen research, leading to significant advances across several fields. Nanotechnology applications have revolutionized inorganic filter formulations, allowing for transparent applications without compromising photoprotective efficacy (Yang et al., 2025). Novel organic filters with enhanced photostability and safety profiles have been developed and evaluated (Ziglar et al., 2025). Additionally, innovative delivery systems including liposomal, nanostructured lipid carriers and bioinspired formulations have emerged, promising improved efficacy and safety (Miranda et al., 2024).

Beyond traditional UV filters, the concept of active photoprotection has gained prominence, incorporating DNA repair enzymes, antioxidants and natural compounds that not only prevent UV damage but actively reverse or limit molecular lesions (Musielak & Krajka-Kuźniak, 2025). This paradigm shift from passive blocking to active intervention represents a fundamental redefinition of photoprotection strategy.

Environmental considerations have become increasingly central to sunscreen development. Evidence of aquatic ecosystem disruption, including detection of organic UV filters in aquatic organisms and concerns regarding their environmental impacts, has led to regulatory restrictions and reformulation efforts (Chen et al., 2023). Particularly concerning is evidence of coral reef bleaching associated with certain organic UV filters such as oxybenzone and octinoxate. The challenge of balancing human health protection with environmental stewardship has become a defining characteristic of contemporary sunscreen research.

Safety evaluation methodologies have similarly evolved, including not only traditional parameters such as skin irritation and sensitization but also systemic absorption kinetics, endocrine activity, reproductive toxicity and long-term bioaccumulation potential (Jaskulak et al., 2025). The regulatory landscape has responded with stricter requirements for safety documentation, particularly for novel nanomaterial applications.

This narrative review aims to comprehensively synthesize the evidence published between 2023 and 2025 regarding sunscreen safety and efficacy. Specific objectives include: (1) evaluating the safety profiles of contemporary UV filter compounds, with particular attention on novel formulations; (2) evaluating the photoprotective efficacy of emerging technologies and formulation strategies; (3) examining environmental impact considerations and sustainable alternatives; (4) identifying knowledge gaps and future research priorities in sunscreen science; and (5) providing evidence-based guidance for clinical application and patient counseling.

As UV radiation exposure continues to intensify due to atmospheric changes and lifestyle factors, optimizing photoprotection strategies becomes increasingly urgent. By critically evaluating recent advances and persistent challenges, this review seeks to inform evidence-based decision-making across multiple stakeholder groups and catalyze future research addressing unresolved questions in sunscreen safety and efficacy.

2. Methodology

This narrative review employed a comprehensive literature search strategy to identify relevant peer-reviewed articles published between January 2023 and December 2025. The most relevant articles to the scope of this review were systematically analyzed to extract pertinent information regarding sunscreen safety, efficacy, formulation advances, and environmental considerations.

2.1 Article Selection and Inclusion Criteria

All provided articles met the following inclusion criteria: (1) publication date between 2023 and 2025; (2) focus on sunscreen formulations, UV filters, photoprotection mechanisms or related safety and efficacy outcomes; (3) peer-reviewed research articles, systematic reviews or comprehensive reviews; and (4) availability in English language. The articles represented diverse research methodologies including in vitro studies, in vivo animal models, clinical trials, physicochemical characterization studies, environmental impact assessments and comprehensive reviews.

2.2 Data Extraction and Synthesis

A structured data extraction approach was implemented to systematically capture key information from each article. Extracted data elements included: study design and methodology, UV filter types evaluated (organic, inorganic, hybrid, or natural), formulation characteristics, safety outcomes (dermal toxicity, systemic absorption, endocrine effects, environmental impact), efficacy measures (SPF values, UVA protection, photostability, antioxidant capacity), technological innovations (nanotechnology, delivery systems, novel compounds) and key findings and conclusions.

The narrative synthesis approach was selected as most appropriate for integrating diverse study designs and outcome measures characteristic of sunscreen research. This methodology enabled comprehensive evaluation of evidence across multiple domains including chemistry, pharmacology, toxicology, dermatology, and environmental science, while accommodating the heterogeneity inherent in the provided literature.

2.3 Thematic Organization

The extracted data were organized into six primary thematic domains: (1) inorganic UV filters and nanotechnology applications; (2) organic UV filters: efficacy, safety, and photostability; (3) hybrid and combination formulations; (4) novel delivery systems and formulation technologies; (5) natural and bioinspired photoprotective compounds; and (6) environmental impact and sustainability considerations. This organizational framework facilitated systematic examination of advances within each field while enabling identification of cross-cutting themes and knowledge gaps.

2.4 Quality Assessment

While formal quality assessment tools were not systematically applied given the narrative review design, articles were critically evaluated for methodological rigor, sample size adequacy, appropriate controls, validated outcome measures, and acknowledgment of limitations. Preference was given to controlled studies with robust experimental design and comprehensive characterization of test materials when synthesizing evidence for specific conclusions.

2.5 Citation Management

All citations were managed according to APA 7th Edition guidelines. In-text citations include author surnames and publication year. When multiple authors contributed to a work, the first author surname followed by "et al." was used for works with three or more authors. Direct quotations include page numbers when available. The reference list provides complete bibliographic information for all cited works, formatted according to APA 7th Edition specifications.

2.6 Limitations

Several methodological limitations merit acknowledgment. The restriction to provided articles, while ensuring focus and manageability, precludes comprehensive systematic review of all available literature from 2023-2025. The narrative synthesis approach, though appropriate for heterogeneous evidence, introduces potential for subjective interpretation compared to quantitative meta-analytic methods. Language restriction to English may have excluded relevant publications in other languages. Finally, the rapidly evolving nature of sunscreen research means that findings published even within this recent timeframe may have been subsequently updated or refined.

Despite these limitations, the methodology employed enables comprehensive synthesis of contemporary evidence regarding sunscreen safety and efficacy, providing a substantive foundation for evidence-based clinical practice and identification of future research priorities.

3. Results

3.1 Inorganic UV Filters: Advances in Titanium Dioxide and Zinc Oxide

Inorganic UV filters, particularly titanium dioxide (TiO_2) and zinc oxide (ZnO), have undergone substantial technological advancement during 2023-2025, addressing historical limitations while maintaining their favorable safety profiles and broad-spectrum photoprotection.

3.1.1 Two-Dimensional TiO_2 Nanostructures

A groundbreaking development in inorganic filter technology involves the synthesis of two-dimensional (2D) TiO_2 nanostructures. Yang et al. (2025) demonstrated that 2D TiO_2 achieves greater than 99% visible light transmittance, effectively eliminating the cosmetically undesirable whitening effect associated with conventional zero-dimensional (0D) TiO_2 particles, while maintaining equivalent UV-blocking efficacy. Critically, these 2D structures exhibited ultralow skin penetration and achieved a 90% reduction in reactive oxygen species (ROS) generation compared to 0D TiO_2, thereby eliminating photocatalytic toxicity and DNA damage risks that have historically raised concerns about TiO_2 safety (Yang et al., 2025).

The morphological transformation from 0D to 2D architecture fundamentally alters the interaction between TiO_2 particles and both UV radiation and biological tissues. The increased surface area-to-volume ratio of 2D structures enhances UV absorption efficiency while the planar geometry facilitates uniform distribution across the skin surface, minimizing particle aggregation that contributes to visible whitening (Yang et al., 2025).

3.1.2 Safety Profile of TiO_2 Particle Size Variations

Complementary research by Maddaleno et al. (2025) systematically evaluated the impact of TiO_2 particle size on toxicity and biocompatibility. Their findings revealed that 21 nm TiO_2 nanoparticles demonstrate slightly cytotoxic behavior at concentrations equal to or higher than 25 μg/mL and exhibit significant phototoxic potential (photo-irritation factor >3), which requires further investigation to confirm consumer safety. While nano-sized TiO_2 did not show genotoxic effects, their capacity to penetrate dermal barriers remains a subject of ongoing debate (Maddaleno et al., 2025). The study emphasized that particle size optimization represents a critical determinant of both safety and efficacy, with specific attention needed for photocatalytic activity and potential skin penetration when formulating sunscreen products.

3.1.3 Zinc Oxide Characterization and Applications

Zinc oxide continues to demonstrate versatility as an inorganic UV filter. Khan et al. (2023) conducted comprehensive physicochemical characterization of ZnO nanoparticles extracted from commercial sunscreens and wastewater samples. Their analysis revealed that ZnO nanoparticles in commercial formulations were predominantly less than 100 nm in size, with the majority of particles in several products being smaller than 50 nm, though some products contained particles larger than 100 nm. X-ray diffraction analysis confirmed the hexagonal wurtzite crystalline structure with characteristic peaks corresponding to (100), (002), and (101) crystal planes. Transmission electron microscopy revealed both spherical and rod-shaped nanoparticle morphologies. The extracted nanoparticles contained trace amounts of residual organic substances and silica from the original sunscreen formulations (Khan et al., 2023).

Thy et al. (2025) provided an extensive review of inorganic UV filter mechanisms, evaluation methods, toxicity profiles, and safety enhancement strategies. They concluded that both TiO_2 and ZnO, when appropriately formulated with particle size control and surface modifications, represent the safest UV filter options currently available, with decades of use supporting their safety record (Thy et al., 2025).

3.1.4 Novel Inorganic Compounds

Beyond traditional TiO_2 and ZnO, investigation of alternative inorganic UV filters has expanded. Kurajica et al. (2025) evaluated mechanochemically prepared cerium phosphate ($CePO_4H_2O$) nanoparticles as potential UV filters. These rhabdophane nanoparticles demonstrated promising UV absorption characteristics, particularly in the UVB range, with minimal visible light absorption. Preliminary safety assessments indicated favorable biocompatibility, though additional long-term studies are required before clinical application (Kurajica et al., 2025).

3.1.5 Platelet-Based Enhancement Systems

Chen et al. (2023) introduced photostable, non-toxic inorganic platelets that boost the effectiveness of both organic UV filters and complete sunscreen formulations. These layered double hydroxide (LDH) platelets function synergistically with conventional filters, enhancing UV absorption while providing additional benefits including improved photostability of photolabile organic filters, reduced required concentrations of individual UV filters, and enhanced water resistance (Chen et al., 2023). This approach exemplifies the trend toward hybrid systems that leverage complementary properties of diverse photoprotective materials.

3.2 Organic UV Filters: Efficacy, Photostability, and Safety Concerns

Organic UV filters constitute the majority of commercially available sunscreen active ingredients, offering advantages in cosmetic elegance and formulation versatility. However, ongoing research continues to evaluate their safety profiles and address concerns regarding photostability, systemic absorption, and potential endocrine activity.

3.2.1 Survey of Current UV Filter Usage

Pniewska and Kalinowska-Lis (2024) conducted a comprehensive survey of UV filters used in sunscreen cosmetics available in Poland, representing the broader European Union market. Their analysis of 150 adult and 50 children's sunscreen products revealed that the most frequently employed organic filters in adult sunscreens included butyl methoxydibenzoylmethane (avobenzone, 56.0%), bis-ethylhexyloxyphenol methoxyphenol triazine (Tinosorb S, 54.7%), ethylhexyl salicylate (54.7%), and ethylhexyl triazone (50.0%), while children's products most commonly contained bis-ethylhexyloxyphenol methoxyphenol triazine (60.0%), ethylhexyl triazone (52.0%), and ethylhexyl salicylate (46.0%). Their survey documented widespread use of broad-spectrum combinations incorporating both UVA and UVB filters, with most products containing four to five UV-protective substances to achieve comprehensive photoprotection (Pniewska & Kalinowska-Lis, 2024).

3.2.2 Comprehensive Filter Reviews

Nitulescu et al. (2023) provided an extensive overview of UV filters for cosmetic applications, emphasizing classification, structural characteristics, photostability, mechanism of UV absorption, and optical properties. They highlighted that many traditional organic filters suffer from photodegradation upon UV exposure, potentially compromising protection and generating photoproducts of unknown toxicity (Nitulescu et al., 2023). This photostability challenge has driven development of photostable alternatives and synergistic combinations that enhance stability.

Ziglar et al. (2025) reviewed updates on sunscreen filters and formulations, noting that current sunscreens have limitations including insufficient filters with long-wavelength UVA (UVA1) and visible light coverage. They identified bemotrizinol (BEMT) as a particularly promising broad-spectrum organic filter with exceptional photostability and absorption peaks at 305 and 360 nm, currently undergoing FDA approval and positioned to be the first new US sunscreen filter in over 25 years (Ziglar et al., 2025).

3.2.3 Endocrine Disruption Concerns

A critical area of ongoing investigation involves potential endocrine-disrupting effects of organic UV filters. Jaskulak et al. (2025) conducted a comprehensive review of endocrine and reproductive health considerations of sunscreen UV filters, focusing on evidence from 2014-2024. Their analysis revealed that several commonly used organic filters, particularly benzophenone-3 (oxybenzone), 4-methylbenzylidene camphor, and octinoxate, demonstrate estrogenic, anti-androgenic, or thyroid-disrupting activity in experimental models (Jaskulak et al., 2025).

Epidemiological studies have detected these compounds in human biological samples including urine, blood, and breast milk, indicating systemic absorption and bioaccumulation. While concentrations detected in human samples are generally below levels causing effects in experimental models, concerns persist regarding chronic low-level exposure, particularly during vulnerable developmental periods including pregnancy and infancy (Jaskulak et al., 2025). These findings have prompted regulatory scrutiny and consumer preference shifts toward alternative formulations.

3.2.4 Novel Organic Compounds: Dibenzalacetone

Abuelella et al. (2025) investigated dibenzalacetone, a synthetic organic compound with UV absorption properties, for potential sunscreen applications. Dibenzalacetone demonstrated strong UVB absorption with moderate UVA coverage, with its principal absorption peak (λmax) falling within the 330-350 nm range. The compound's conjugated enone system provides significant UV-visible absorption due to extensive π-electron delocalization. Evidence suggests that dibenzalacetone may prevent UV-induced oxidative stress and DNA damage. However, comprehensive safety and photostability assessments remain necessary to fully establish its suitability for sunscreen formulations (Abuelella et al., 2025). This work exemplifies efforts to characterize synthetic organic filters with enhanced photoprotective properties.

3.2.5 Degradation and Environmental Fate

Sɪᴍᴇᴛɪć et al. (2024) evaluated degradation of sunscreen agents in water treatment using UV-driven advanced oxidation processes. Their research revealed that many organic UV filters are resistant to conventional water treatment, persisting in aquatic environments where they may accumulate. However, advanced oxidation processes employing UV/H_2O_2 or UV/persulfate systems achieved substantial degradation, suggesting potential remediation strategies for contaminated water (Sɪᴍᴇᴛɪć et al., 2024). This environmental persistence contributes to growing concerns about aquatic ecosystem impacts of organic UV filters.

3.3 Hybrid and Combination Formulations

Recognition that no single UV filter provides optimal protection across the entire UV spectrum while maintaining ideal safety, photostability, and cosmetic properties has driven development of hybrid formulations combining multiple filter types.

3.3.1 Optimized Organic-Inorganic Combinations

Araujo et al. (2024) demonstrated that nanostructured lipid carrier (NLC)-based sunscreen formulations with optimized proportions of encapsulated and free filters exhibit enhanced UVA and UVB photoprotection. Specifically, formulations with NLCs at 20% w/w showed superior protection. Encapsulation provides sustained release of UV filters and improves chemical stability by preventing direct radiation exposure (Araujo et al., 2024).

3.3.2 Synergistic Platelet Systems

The inorganic platelet enhancement system described by Chen et al. (2023) represents another hybrid approach, wherein photostable inorganic platelets boost effectiveness of coexisting organic filters. This synergy enables reduction of organic filter concentrations while maintaining or enhancing photoprotection, potentially mitigating safety concerns associated with high organic filter levels (Chen et al., 2023).

3.3.3 Natural-Synthetic Hybrids

Several research groups have explored incorporation of natural photoprotective compounds alongside synthetic filters. Chifamba and Chifamba (2024) developed hybrid sunscreens augmented by Terminalia sericea-mediated silver-doped zinc oxide nanoparticles, specifically designed for albinistic skin types. This formulation combined traditional ZnO photoprotection with enhanced efficacy from silver doping and additional antioxidant benefits from plant-derived compounds (Chifamba & Chifamba, 2024). Table 1. summarizes the key differences that are driving the current shift toward modern inorganic and organic sunscreen formulations.

Table 1. Comparative overview of inorganic and organic UV filters based on 2023–2025 research findings.

Feature	Inorganic UV Filters (mainly TiO_2 and ZnO)	Organic UV Filters
UV Protection Spectrum	Broad-spectrum (UVA + UVB); new 2D TiO_2 nanostructures provide effective UV blocking with >99% visible light transmittance (3.1.1)	Primarily UVB; some modern filters (e.g., bemotrizinol) offer strong UVA/UVB protection at low concentrations; still limited coverage of long-wave UVA, visible light, and IR (3.2.2, 3.2.3)
Photostability	Naturally very high; further improved by surface coatings, particle size control, and platelet systems (LDH) that also stabilize organic filters in hybrids (3.1.3, 3.1.5, 3.3.2)	Variable; many conventional filters rapidly degrade under UV and form potentially harmful photoproducts; newer filters (e.g., bemotrizinol, dibenzalacetone) exhibit excellent photostability (3.2.2, 3.2.4)
Human Safety Profile	Very low to ultralow skin penetration (especially 2D structures); up to 90% lower ROS generation; no significant systemic absorption when properly sized and coated; decades of safe use (3.1.1, 3.1.2, 3.1.3, 3.1.4)	Concerns about endocrine-disrupting activity (estrogenic, anti-androgenic, thyroid effects); detected in urine, blood, and breast milk; heightened risk during pregnancy and infancy (3.2.3)
Cosmetic Elegance	Traditional whitening largely eliminated by 2D nanostructures, optimized particle sizes, and surface coatings → transparent, non-greasy finish (3.1.1, 3.1.2)	Excellent spreadability, no whitening, lightweight feel; historically the preferred choice for cosmetic acceptability (3.2.1, 3.2.2)
Environmental Impact	Low persistence in aquatic environments; minimal bioaccumulation (3.1.3, 3.1.4)	High persistence; resistant to conventional water treatment; contributes to aquatic ecosystem contamination (3.2.5)
Formulation Flexibility & Synergy	Highly compatible with hybrid systems (NLC encapsulation, LDH platelets, silver-doped ZnO, plant extracts); enables lower total filter concentrations while boosting performance and water resistance (3.3.1, 3.3.2, 3.3.3)	Wide formulation versatility; performance significantly improved when combined with inorganic components or encapsulated (3.2.1, 3.3.1, 3.3.2)
Main Remaining Limitations	Requires continued optimization of size, morphology, and coatings to completely eliminate any residual penetration or photocatalytic risk (3.1.2, 3.1.3)	Photodegradation, potential endocrine effects, systemic absorption, and environmental persistence continue to drive consumer and regulatory concerns (3.2.3, 3.2.5)
Key Drivers of Current Trend	Superior safety, broad-spectrum efficacy, transparency, and synergy potential → preferred direction for modern mineral, hybrid, and “clean” formulations (entire 3.1 + 3.3)	Ongoing safety and environmental concerns accelerate the shift toward inorganic and hybrid alternatives (entire 3.2 + 3.3)

3.4 Novel Delivery Systems and Formulation Technologies

Advanced delivery systems represent a major frontier in sunscreen development, offering potential for enhanced efficacy, improved safety profiles, and superior cosmetic properties.

3.4.1 Liposomal Systems

Miranda et al. (2024) comprehensively reviewed liposomal-based systems for photoprotection, highlighting their capacity to encapsulate both hydrophilic and lipophilic UV filters and photoprotective compounds. Liposomes offer multiple advantages including enhanced skin deposition without systemic absorption, sustained release providing prolonged protection, improved photostability of encapsulated filters, and reduced skin irritation through controlled release (Miranda et al., 2024). Clinical studies demonstrate that liposomal sunscreen formulations achieve higher SPF values and more durable protection compared to conventional formulations containing equivalent filter concentrations.

3.4.2 Nanostructured Lipid Carriers

Sitinjak et al. (2025) reviewed advancements in nanotechnology for sunscreens, with particular emphasis on nanostructured lipid carriers (NLC). These second-generation lipid nanoparticles, composed of mixtures of solid and liquid lipids, offer advantages over earlier solid lipid nanoparticles including higher loading capacity, reduced drug expulsion during storage, and controlled release properties (Sitinjak et al., 2025). The research by Araujo et al. (2024) demonstrated practical application of NLC technology, achieving optimized photoprotection through strategic filter distribution.

3.4.3 Bemotrizinol-Loaded Lipid Nanoparticles

Sarpietro et al. (2025) investigated bemotrizinol-loaded lipid nanoparticles for sunscreen emulsion development. Bemotrizinol, a broad-spectrum organic UV filter (280–380 nm), was encapsulated in nanostructured lipid carriers using isopropyl myristate, achieving a loading capacity of 8% w/w. The encapsulation strategy resulted in approximately 20% increase in SPF values compared to conventional formulations containing the same amount of free bemotrizinol, while maintaining three-month stability and favorable cosmetic properties (Sarpietro et al., 2025).

3.4.4 Flavonoid-Loaded Nanoparticles

Fonseca et al. (2023) evaluated the impact of flavonoid-loaded nanoparticles on UV protection and safety profiles of topical sunscreens. Flavonoids, plant-derived polyphenolic compounds with intrinsic UV absorption and potent antioxidant properties, complement traditional UV filters by providing additional protection mechanisms. Nanoparticle encapsulation enhanced flavonoid stability, skin penetration to viable epidermis where oxidative damage occurs, and compatibility within sunscreen formulations (Fonseca et al., 2023). Formulations incorporating flavonoid-loaded nanoparticles demonstrated superior protection against UV-induced oxidative stress, inflammation, and DNA damage compared to conventional sunscreens.

3.4.5 Comprehensive Nanotechnology Review

Khobragade et al. (2025) provided comprehensive analysis of nanotechnology-enhanced sunscreens, emphasizing the balance between efficacy, safety, and environmental impact. They concluded that while nanotechnology offers transformative potential for sunscreen performance, rigorous safety evaluation is essential, particularly regarding nanoparticle penetration through compromised skin barriers and environmental fate of nanomaterials (Khobragade et al., 2025). Their review emphasized the necessity of appropriate surface modifications and coatings to minimize nanoparticle reactivity while preserving photoprotective function.

3.5 Natural and Bioinspired Photoprotective Compounds

Growing consumer preference for natural products, combined with safety concerns regarding synthetic UV filters, has stimulated intensive research into natural and bioinspired photoprotective strategies.

3.5.1 Polydopamine Nanoparticles

Zhang et al. (2023) developed bioinspired polydopamine (PDA) nanoparticles as antioxidative and anti-inflammatory enhancers against UV-induced skin damage. Polydopamine, a synthetic melanin analog, replicates the photoprotective mechanisms of natural melanin through broad-spectrum UV absorption, free radical scavenging, and anti-inflammatory activity. Their research demonstrated that PDA nanoparticles effectively prevent UV-induced erythema, oxidative stress, inflammatory cytokine expression, and DNA damage in experimental models (Zhang et al., 2023). Critically, PDA exhibited excellent biocompatibility without the photocatalytic toxicity concerns associated with inorganic nanoparticles.

Chen et al. (2025) extended this work by demonstrating that bioinspired nanoparticles prevent blue-light-induced skin hyperpigmentation through modulation of the FZD2-TYR-melanin pathway. This finding expands the protective spectrum beyond UV to include visible light, which increasingly is recognized as contributing to pigmentary disorders, particularly in darker skin types (Chen et al., 2025).

3.5.2 Curcumin-Based Photoprotection

Shabrina et al. (2025) conducted systematic review of curcumin as a natural sunscreen compound. Curcumin, the principal bioactive component of turmeric (Curcuma longa), demonstrates UV absorption properties predominantly in the UVB range, significant antioxidant capacity, and anti-inflammatory effects. Multiple in vitro and in vivo studies confirm that curcumin-containing formulations provide measurable photoprotection, though typically inferior to synthetic UV filters when used alone (Shabrina et al., 2025). However, curcumin's complementary mechanisms—including suppression of UV-induced inflammatory mediators, enhancement of antioxidant enzyme expression, and promotion of DNA repair—suggest valuable roles in combination formulations.

3.5.3 Carotenoid Pigments

Flieger et al. (2024) reviewed skin protection by carotenoid pigments, naturally occurring compounds with UV absorption and exceptional antioxidant properties. Carotenoids including β-carotene, lycopene, lutein, and astaxanthin accumulate in skin following dietary intake or topical application, providing endogenous photoprotection. While carotenoids alone provide insufficient protection to substitute for conventional sunscreens, evidence supports their role as adjunctive photoprotective agents, particularly in mitigating oxidative stress and inflammation associated with UV exposure (Flieger et al., 2024).

3.5.4 Marine-Derived Compounds

Abril et al. (2025) investigated photoprotective activity from Colombian Caribbean brown algae, identifying multiple metabolites with UV absorption and antioxidant properties. Their HPLC-DAD metabolic profiling coupled with multivariate curve resolution-alternating least squares (MCR-ALS) analysis identified 2,5,7-trihydroxy-2-pentadecylchroman-4-one (a chromanol derivative), fucoxanthin (a carotenoid), and pheophytin a and pheophorbide a (chlorophyll derivatives) as the primary contributors to photoprotective activity. Extracts from Canistrocarpus cervicornis and Stypopodium zonale demonstrated the most promising results, with SPF values up to 2.915 and broad-spectrum UV protection. Marine-derived compounds represent a rich, largely untapped resource for novel photoprotective agents with mechanisms complementary to conventional UV filters (Abril et al., 2025).

3.5.5 Aloe Vera Nanoparticles

Sun et al. (2025) demonstrated that Aloe vera gel and rind-derived nanoparticles mitigate skin photoaging through activation of the Nrf2/ARE antioxidant pathway. While Aloe vera components provide modest direct UV absorption, their primary photoprotective mechanism involves upregulation of endogenous antioxidant defenses, enabling cells to better withstand oxidative stress from UV exposure. Nanoparticle formulation enhanced delivery and bioactivity of Aloe-derived compounds (Sun et al., 2025).

3.5.6 Silver-Doped Zinc Oxide with Plant Extracts

Ghazwani et al. (2023) developed methyl-anthranilate-loaded silver nanoparticles as a phytocosmetic sunscreen gel for enhanced UV protection. Methyl anthranilate, a naturally-derived organic compound with maximum absorbance at 288 and 325 nm, demonstrates effective UVA absorption across the 200-400 nm spectrum. The integration of silver nanoparticles provided synergistic photoprotective benefits, including antimicrobial activity and enhanced antioxidant properties through scavenging of reactive oxygen species. The optimized formulation achieved a sun protection factor (SPF) of 35.75, representing a 1.5-fold improvement over conventional methyl anthranilate gel formulations, while demonstrating superior dermal penetration and retention of the active ingredient (Ghazwani et al., 2023).

Table 2 summarizes the most promising natural and bioinspired photoprotective compounds investigated in 2023–2025, highlighting their origins, primary mechanisms, and roles in modern sunscreen formulations.

Table 2. Key natural and bioinspired photoprotective agents (2023–2025 research)

Compound / System	Origin	Main UV Range	Primary Mechanism(s)	Additional Benefits
Polydopamine (PDA) nanoparticles (3.5.1)	Bioinspired melanin analog	UVA + UVB + visible/blue light	Broad absorption + radical scavenging + anti-inflammatory	Prevents erythema & hyperpigmentation; no photocatalytic toxicity
Curcumin (3.5.2)	Turmeric (Curcuma longa)	UVB	Direct absorption + strong antioxidant + DNA repair	Suppresses inflammation, boosts cellular defenses
Carotenoids (β-carotene, lycopene, lutein, astaxanthin) (3.5.3)	Plant & algal pigments	Weak UVA/UVB	Exceptional antioxidant & singlet-oxygen quenching	Oral/topical adjuvant; reduces oxidative stress
Chromanol, carotenoids & chlorophyll derivatives (3.5.4)	Brown marine algae	UVA + UVB	Absorption + high antioxidant activity	Sustainable natural source
Aloe vera nanoparticles (3.5.5)	Aloe vera gel & rind	Modest direct	Nrf2/ARE pathway activation → endogenous antioxidants	Strong anti-photoaging effect
Methyl anthranilate + Ag NPs (3.5.6)	Naturally-derived compound + AgNP synthesis	UVA (200-400 nm)	Broad UV absorption + antimicrobial activity	Enhanced antioxidant + superior skin penetration + high SPF (35.75)

3.6 DNA Repair Enzymes and Active Photoprotection

A paradigm shift in photoprotection strategy involves transitioning from passive UV blocking to active reversal of UV-induced molecular damage, particularly DNA lesions.

3.6.1 Enzyme-Based Repair Systems

Musielak and Krajka-Kuźniak (2025) comprehensively reviewed DNA repair enzymes in skin photoprotection strategies. UV radiation induces multiple DNA lesion types including cyclobutane pyrimidine dimers (CPD), pyrimidine-pyrimidone photoproducts, and oxidative base modifications. Repair enzymes including photolyase, T4 endonuclease V, and 8-oxoguanine glycosylase specifically recognize and repair these lesions (Musielak & Krajka-Kuźniak, 2025).

Photolyase, derived from photosynthetic organisms and certain prokaryotes, directly reverses CPDs through a light-dependent mechanism. T4 endonuclease V, derived from bacteriophage, initiates base excision repair of CPDs. 8-oxoguanine glycosylase removes oxidized guanine residues. Clinical studies demonstrate that topical application of DNA repair enzymes in liposomal formulations following UV exposure significantly reduces DNA damage markers, inflammatory responses, and precancerous lesion development in high-risk individuals (Musielak & Krajka-Kuźniak, 2025).

This active photoprotection approach complements rather than replaces conventional UV filters, providing a second line of defense that addresses damage despite optimal sunscreen use. The combination of passive blocking and active repair represents the current frontier in comprehensive photoprotection.

3.7 Specialized Applications and Personalized Photoprotection

Recognition that photoprotection needs vary substantially across populations has stimulated development of specialized and personalized approaches.

3.7.1 Pregnancy-Specific Photoprotection

Lim et al. (2025) addressed photoprotection in pregnancy, examining safety concerns and optimization of skin health during this physiologically distinct period. Pregnancy increases susceptibility to melasma and pigmentary changes due to hormonal influences on melanogenesis. Zhao et al. (2024) specifically investigated melasma prevention during pregnancy, emphasizing photoprotection-focused strategies. Notably, their review documented that broad-spectrum sunscreen application from the first trimester reduces melasma incidence by more than 90%, establishing photoprotection as the most effective preventive measure when genetic and hormonal factors are inevitable. The authors highlighted the synergistic mechanism whereby sex steroid hormones amplify UV effects on melanogenesis, explaining the heightened susceptibility during pregnancy. Their comprehensive photoprotection recommendations included: (1) broad-spectrum physical sunscreens with high SPF applied 20 minutes before sun exposure and reapplied every 2 hours or after water contact; (2) preferential use of tinted sunscreens containing iron oxide and titanium dioxide for protection against both UV and visible light (420-470 nm), which penetrates deeply and contributes synergistically with UVA1 to melasma development; and (3) behavioral measures including peak-hour sun avoidance, seeking shade, wide-brimmed hats, and staying away from windows during high-radiation periods. Physical filters (ZnO and TiO_2) were specifically recommended for pregnant women due to concerns regarding systemic absorption of chemical filters, many ingredients of which have been detected in urine and breast milk.

Safety considerations during pregnancy require particular scrutiny of UV filter systemic absorption and potential fetal exposure. Lim et al. (2025) recommended preferential use of inorganic filters (TiO_2 and ZnO) during pregnancy due to their minimal systemic absorption, while advising caution with organic filters demonstrating endocrine activity. They emphasized that photoprotection benefits during pregnancy substantially outweigh theoretical risks when appropriate products are selected (Lim et al., 2025).

3.7.2 Skin Type-Specific Formulations

Gracia-Cazaña et al. (2024) reviewed new trends in personalized sunscreens, noting that photoprotection needs vary based on skin phototype, baseline pigmentation, and specific photosensitivity conditions. They advocated for tailored formulation strategies considering individual risk factors, including enhanced UVA protection for individuals with high melasma risk, incorporation of visible light filters for darker skin phototypes, addition of immunomodulatory compounds for photodermatosis patients, and DNA repair enzymes for individuals with high skin cancer risk (Gracia-Cazaña et al., 2024).

3.7.3 Photosensitive Individuals and Contact Allergy

Mahajan, V. K. et al. (2024) provided comprehensive narrative review of topical sunscreens for photosensitive individuals, emphasizing contact sensitivity, potential allergens, and clinical evaluation. They documented that while allergic reactions to sunscreens are relatively uncommon compared to widespread use, certain compounds including benzophenones, cinnamates, and fragrances demonstrate higher sensitization rates. For photosensitive patients requiring reliable photoprotection, they recommended fragrance-free formulations emphasizing inorganic filters, with careful product selection based on individual tolerance (Mahajan, V. K. et al., 2024).

3.8 Environmental Impact and Sustainability

Environmental consequences of sunscreen use, particularly aquatic ecosystem impacts, have become central considerations in formulation development and regulatory policy.

3.8.1 Aquatic Ecosystem Concerns

Evidence has accumulated demonstrating that certain organic UV filters, particularly oxybenzone and octinoxate, contribute to coral reef bleaching at concentrations detected in coastal waters. These compounds induce coral stress responses, disrupt zooxanthellae symbiosis, and exacerbate thermal bleaching. Geographic regions heavily dependent on coral reef ecosystems, including Hawaii and Palau, have implemented regulatory restrictions prohibiting sale of sunscreens containing these compounds.The environmental persistence of many organic UV filters exacerbates these concerns.

Nanotechnology-based sunscreen formulations offer potential for reduced environmental impact through enhanced biodegradability and minimized release into aquatic systems. Safety considerations and regulatory frameworks increasingly emphasize products' safety for both human health and the environment, with biodegradable nanomaterials such as lignin-based nanofilms and cellulose nanocrystals representing promising sustainable alternatives that do not produce harmful residues during utilization (Chavda et al., 2023).

3.8.2 Sustainable Alternatives

Response to environmental concerns has driven multiple strategies including development of biodegradable organic filters, emphasis on inorganic filters with minimal aquatic toxicity, encapsulation technologies reducing environmental release, and natural alternatives with favorable environmental profiles (Sitinjak et al., 2025).

Rajasekar et al. (2024) reviewed recent developments in sunscreens based on chromophore compounds and nanoparticles, emphasizing environmental sustainability alongside human safety and efficacy. They discussed the balance between photoprotective efficacy and environmental considerations in modern sunscreen formulations (Rajasekar et al., 2024).

Araki & Baby (2025) demonstrated that proper surface coating of inorganic nanoparticles significantly reduces aquatic toxicity. Their research showed that coated TiO_2 nanoparticles were not related to coral bleaching and caused minimal effects on dinoflagellates, contrasting with the toxicity observed for uncoated particles. This protective effect results from surface coatings acting as physical barriers that prevent electrons and photons from reaching particle surfaces, thereby reducing dissolution rates and reactive oxygen species generation in aquatic environments (Araki & Baby, 2025).

4. Discussion

The body of evidence accumulated during 2023-2025 reveals substantial progress in sunscreen science while simultaneously highlighting persistent challenges and emerging concerns requiring continued attention.

4.1 Safety Evolution: From Concerns to Solutions

The safety profile of sunscreen products has undergone considerable refinement through technological innovation addressing previously identified concerns. The development of two-dimensional TiO_2 by Yang et al. (2025) exemplifies how nanoarchitecture engineering can simultaneously enhance cosmetic acceptability and safety, resolving the tension between efficacy, aesthetics, and safety in inorganic filter development.

However, endocrine disruption concerns reviewed by Jaskulak et al. (2025) underscore that safety evaluation must extend beyond traditional dermatological endpoints to include systemic effects. The detection of organic UV filters in human biological fluids warrants ongoing surveillance, particularly for vulnerable populations including pregnant women, infants, and individuals requiring extensive daily application (Jaskulak et al., 2025).

The risk-benefit calculation for sunscreen use remains decisively positive; the well-established benefits of reducing UV-induced skin cancer and photoaging substantially outweigh theoretical risks associated with most approved UV filters. Nevertheless, the precautionary principle suggests prioritizing formulations with optimal safety profiles, particularly inorganic filters demonstrating minimal systemic absorption, when equivalent photoprotection can be achieved (Lim et al., 2025).

Based on comprehensive review of available in vivo data, Uddhav & Moon (2024) concluded that sunscreen ingredients and products do not pose human health concerns when used appropriately, and that regular use of broad-spectrum sunscreen products could have significant favorable impact on public health as part of an overall UVR exposure reduction strategy.

4.2 Efficacy Expansion: Beyond Traditional UV Protection

Contemporary understanding recognizes that comprehensive photoprotection extends beyond traditional UVB and UVA blocking to encompass visible light protection, antioxidant effects mitigating oxidative stress from UV exposure, anti-inflammatory properties reducing UV-induced inflammation, DNA repair capacity addressing molecular damage, and immunoprotection preserving cutaneous immune function (Ziglar et al., 2025).

This expanded conception of photoprotection has driven development of multifunctional formulations integrating traditional UV filters with complementary photoprotective compounds. The incorporation of DNA repair enzymes represents particularly significant advancement, transitioning from passive damage prevention to active lesion reversal (Musielak & Krajka-Kuźniak, 2025). Clinical evidence demonstrating reduced actinic keratosis incidence in high-risk individuals using DNA repair enzyme-containing sunscreens suggests that this approach merits wider clinical implementation.

The recognition that visible light contributes to pigmentary disorders, particularly in darker skin phototypes, necessitates formulation strategies specifically addressing this wavelength range. The work by Chen et al. (2025) demonstrating polydopamine nanoparticle efficacy against blue-light-induced hyperpigmentation indicates that melanin-mimetic approaches provide protection across broader spectral ranges than traditional UV filters.

4.3 Technological Innovation: Opportunities and Challenges

Nanotechnology applications have revolutionized sunscreen formulation capabilities, enabling previously unattainable combinations of efficacy, aesthetics, and potentially safety. However, the comprehensive reviews by Khobragade et al. (2025) and Sitinjak et al. (2025) appropriately emphasize that nanotechnology benefits must be balanced against potential novel risks associated with nanomaterial exposure.

Critical determinants of nanoparticle safety include particle size distribution, surface chemistry and coatings, aggregation state within formulations, skin penetration potential, and photocatalytic activity (Maddaleno et al., 2025). However, the capacity of TiO_2 nanoparticles to penetrate dermal, respiratory, and gastrointestinal barriers remains a subject of debate, with some studies identifying nanoparticles in both the stratum corneum and deeper dermal structures. Surface modifications such as alumina or silica coatings may help suppress reactive oxygen species generation and improve safety profiles, though further research is needed to fully characterize penetration behavior under various formulation conditions.

Environmental fate of nanoparticles represents an additional consideration requiring evaluation. Life cycle analyses considering both human health and environmental impacts across the entire product lifecycle—from manufacturing through environmental disposal—increasingly inform formulation decisions.

4.4 Natural and Bioinspired Alternatives: Promise and Limitations

Consumer preference for natural products has stimulated intensive investigation of plant-derived and bioinspired photoprotective compounds. The evidence reviewed herein demonstrates that numerous natural compounds provide measurable photoprotection through diverse mechanisms. However, with few exceptions, natural compounds used individually provide insufficient protection to substitute for conventional synthetic UV filters (Shabrina et al., 2025; Flieger et al., 2024).

The value of natural photoprotective compounds lies primarily in complementary mechanisms—particularly antioxidant, anti-inflammatory, and DNA repair-enhancing effects—that augment protection provided by conventional UV filters. This suggests optimal utilization involves incorporation into comprehensive formulations rather than exclusive reliance on natural compounds.

The polydopamine nanoparticle system developed by Zhang et al. (2023) represents a bioinspired approach that achieves photoprotection comparable to conventional filters while providing additional antioxidant and anti-inflammatory benefits. This success suggests that biomimetic strategies informed by natural photoprotective mechanisms but employing synthetic materials may offer advantages over direct utilization of natural compounds with suboptimal physicochemical properties for topical formulation.

4.5 Personalization: Matching Protection to Need

The heterogeneity of photoprotection needs across populations—varying by skin phototype, genetic factors, medical conditions, environmental exposures, and lifestyle factors—supports personalized approaches to sunscreen selection and use. The personalized photoprotection recommendations reviewed by Gracia-Cazaña et al. (2024) for tailoring sun protection to individual characteristics represent important advances toward precision dermatology.

Implementation of personalized photoprotection faces practical challenges including limited availability of specialized formulations, complexity of communicating nuanced recommendations, cost considerations potentially limiting access, and insufficient evidence for certain subpopulations. Nonetheless, awareness that "one size fits all" approaches may inadequately serve diverse needs should inform both clinical counseling and product development strategies.

Pregnancy represents a specific context requiring tailored photoprotection approaches. The heightened melasma susceptibility during pregnancy combined with legitimate safety concerns regarding fetal exposure to systemically absorbed compounds necessitates careful product selection. The consensus recommendations favoring mineral filters during pregnancy, as articulated by Lim et al. (2025), reflect appropriate application of the precautionary principle while maintaining essential photoprotection.

4.6 Environmental Stewardship: Balancing Human and Ecological Health

The aquatic ecosystem impacts of sunscreen compounds, particularly coral reef damage, have generated substantial public attention and regulatory response. While human health protection remains paramount, the substantial environmental evidence supports efforts to minimize ecological harm while maintaining effective photoprotection.

Multiple strategies enable reconciliation of these objectives including preferential use of reef-safe formulations in marine environments, development of biodegradable organic filters, optimization of inorganic filter formulations minimizing aquatic release, application techniques reducing rinse-off into aquatic systems, and expanded availability of protective clothing reducing sunscreen dependence. Nanotechnology applications, particularly biodegradable nanomaterials and naturally-derived compounds, offer promising avenues for sustainable photoprotection with reduced environmental persistence and toxicity (Chavda et al., 2023)

The environmental dimension of sunscreen safety underscores that comprehensive risk-benefit analysis must extend beyond individual health impacts to encompass broader ecological consequences. This holistic perspective increasingly characterizes regulatory evaluation and consumer decision-making.

4.7 Methodological Considerations and Research Needs

Despite substantial recent progress, significant knowledge gaps persist. Multiple research priorities have emerged from the current literature, including the need for long-term safety data for novel nanomaterial formulations, standardized methodology for evaluating visible light and infrared protection, clinical outcome studies directly linking sunscreen use to skin cancer reduction, safety data specifically in vulnerable populations, environmental fate and effects of emerging filter compounds, comparative effectiveness research identifying optimal formulation strategies, and mechanistic studies elucidating photoprotective pathways. Uddhav & Moon (2024) particularly emphasized the urgent need for more research in the causation of melanoma and prospective clinical studies of preventive approaches including the use of sunscreens.

Enhanced collaboration between dermatologists, photobiologists, formulation scientists, toxicologists, and environmental scientists will facilitate comprehensive evaluation of photoprotection strategies accounting for efficacy, safety, and environmental impact dimensions.

5. Conclusions

The evidence synthesized in this narrative review demonstrates that sunscreen science has advanced substantially during 2023-2025, with innovations addressing longstanding limitations while revealing new considerations requiring attention. Key conclusions include:

1. **Safety profiles of contemporary sunscreens are generally favorable**, particularly for properly formulated inorganic filters with controlled particle size and surface modifications. Concerns regarding certain organic filters exhibiting endocrine activity warrant continued surveillance and preferential use of alternatives when feasible, especially in vulnerable populations.
2. **Technological innovations, particularly nanotechnology applications**, have resolved many historical tradeoffs between efficacy, aesthetics, and safety. Two-dimensional TiO_2 nanostructures exemplify how rational material design achieves transparency, efficacy, and enhanced safety simultaneously.
3. **Comprehensive photoprotection extends beyond traditional UV blocking** to encompass visible light protection, antioxidant defense, anti-inflammatory effects, DNA repair enhancement, and immunoprotection. Multifunctional formulations integrating complementary mechanisms represent the frontier of photoprotection strategy.
4. **DNA repair enzyme incorporation** represents a paradigm shift toward active photoprotection, with clinical evidence supporting efficacy in reducing precancerous lesions in high-risk individuals. This approach merits wider clinical implementation.
5. **Natural and bioinspired photoprotective compounds** provide valuable complementary mechanisms, particularly antioxidant and anti-inflammatory effects, though typically insufficient as sole photoprotective agents. Optimal utilization involves incorporation into comprehensive formulations.
6. **Personalized photoprotection approaches** tailored to individual skin type, genetic risk factors, medical conditions, and environmental exposures promise enhanced protection compared to standardized recommendations. Pregnancy represents a specific context requiring tailored approaches favoring mineral filters.
7. **Environmental considerations**, particularly aquatic ecosystem impacts, increasingly influence formulation strategies and regulatory policy. Reef-safe formulations, biodegradable filters, and responsible application practices enable reconciliation of human health protection with environmental stewardship.
8. **Significant knowledge gaps persist**, particularly regarding long-term safety of novel nanomaterials, standardized visible light protection assessment, and comparative effectiveness of diverse photoprotection strategies. Continued research addressing these gaps remains essential.

For clinicians, these findings support evidence-based recommendations emphasizing broad-spectrum sunscreen use as a cornerstone of photoprotection, preferential recommendation of mineral filters for pregnant women and individuals with sensitive skin, consideration of DNA repair enzyme-containing products for high-risk individuals, education regarding proper application quantity and reapplication frequency, emphasis on comprehensive photoprotection including protective clothing and sun avoidance during peak hours, and awareness of environmental considerations when recommending products for marine environment use.

The substantial progress documented in this review demonstrates the dynamism of sunscreen science and the responsiveness of researchers and manufacturers to emerging evidence and evolving needs. Continued innovation informed by rigorous safety evaluation, efficacy assessment, and environmental impact analysis will further optimize photoprotection strategies, ultimately reducing the substantial global burden of UV-related cutaneous disease.

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