Volume 4, Issue 6, 2026

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

SUNSCREEN CONTROVERSY: A CRITICAL AND COMPARATIVE REVIEW OF CHEMICAL VS. MINERAL UV FILTERS

Nimra Basharat[*1], Khadija Abdul Rehman[2], Bismillah[3], Maryam Tayyab[4], Zahida Batool Abidi[5]

[*1,2,3,4,5]*Department of Dermal Sciences, Riphah International University, Faisalabad Campus, Punjab, Pakistan 4400.*

[*1]nimrabasharat01@gmail.com

DOI:https://doi.org/10.5281/zenodo.20770902

Keywords
Sunscreen scandal, Chemical vs Mineral filters, Endocrine disruption, Nanotechnology, 2025 FDA guidelines, Phototherapy.

Article History
Received: 07 April 2026
Accepted: 19 May 2026
Published: 20 June 2026

Copyright @Author
Corresponding Author: *
Nimra Basharat

Abstract

The basis of skin cancer and photoaging prevention is the widespread use of sunscreens. There is a big debate regarding the safety, efficacy and environmental impact of organic (chemical) and inorganic (mineral) UV filters, however. This is a review on the gap between clinical need and health issues of humans. A systematic literature search was performed using the databases of PubMed, EMBASE and Cochrane Library for published papers between 2015 and 2025, with a particular focus on randomized controlled trials, position statements of the FDA (2025) (to propose) and the EWG reports (2024–25), to compare the chemical and mineral filters. Although chemical filters such as oxybenzone and homosalate are more aesthetically pleasing and have a high sun protection factor (SPF), the 2025 data indicates that high levels of these filters are absorbed by the body and the new evidence suggests that this disruption of the thyroid axis happens as a result of chronic exposure in susceptible populations. The safest are mineral filters (ZnO, TiO_2) but they are hard to formulate and generate reactive oxygen species (ROS) in the presence of UV. A therapeutic "hole" in the treatment of UV and filter after penetration is discussed. We highlight the Sun-D Trial results of the effect of sunscreens on vitamin D levels and propose iron oxide technology as a "therapeutic" option to visible light dermatoses. Photoprotection in the future will not be based on the chemical vs mineral choice, but on the hybrid, so-called barrier + therapeutic products. Nanotechnology and the use of antioxidant conjugates may be seen as a step towards minimizing the biological impact of the UV light, whilst the filters themselves.

1.INTRODUCTION

1.1Skin Cancer Global Burden and Photoprotection on the Increase.

The increasing incidence of skin cancer, which is now the most common cancer in the world, has elevated photoprotection to a high priority health concern .The world health organization (WHO) states that one-third of all cancers diagnosed are skin cancers of which melanoma is the most aggressive(Westman, 2022). Sunscreens have been applied as the primary pharmaceutical product that can influence ultraviolet (UV) radiation-induced DNA damage, photoaging and immunosuppression for some time(Pedić, Pondeljak, & Šitum, 2020). The prevalence of actinic keratoses, squamous cell carcinoma and the effectiveness of sunscreen use have been reported to be reduced due to the high prevalence of sunscreen use, which has highlighted the role of sunscreens in the prevention of skin diseases(Lapides et al., 2023).

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

1.2 The birth of the Sunscreen Debate

However, the field of dermatology is under a high tension of the controversial world of the protective products. This sunscreen controversy is pitted against the real facts of skin cancer prevention and growing consumers' and scientists' concerns regarding the safety, ecotoxicity and systemic absorption of UV filters. This debate was further complicated by the Environmental Working Group (EWG) Sunscreen Guide claiming 80 percent of the sunscreens they tested contain ingredients of "questionable safety"(Akimana & Wikantyasning, 2025). The EWG favoured mineral sunscreens and highlighted all the chemical filters (oxybenzone, octocrylene and homosalate). This has resulted in retribution against them including from groups such as the Consumer Healthcare Products Association (CHPA) who have said that this undermines trust in FDA-approved safe products(Druml, Ilyas, Ilyas, & ILYAS, 2023) .

1.3 A New Paradigm

More Questions In 2025, the scandal was stoked by the publication of a number of high-profile studies. The systemic diffusion of the chemical filters in the bloodstream was confirmed and the long-term consequences on the endocrine system were raised, in particular the thyroid disrupting effects(Cohen, Gohara, & Houshmand, 2025). At the same time, the Sun-D Trial, was the first and strong, randomised controlled data to suggest daily, high-use sunscreen with high sun protection factors (SPF) can induce significant reductions in blood serum 25-hydroxyvitamin D concentrations, which may increase the risk of vitamin D deficiency). This presents a new conundrum where the sunscreen used to prevent skin cancer, will inadvertently lead to weaker bones and compromised immunity, due to vitamin D effects(Morquette, Waples, & Heath, 2022).

1.4 Aim of this review

This review will try to scientifically resolve these controversies Current (2025) reviews of the mechanisms, safety and efficacy of the chemical and mineral filters will be critically evaluated(Paiva et al., 2020). Sun screens can be divided into two groups according to active ingredients; organic (chemical) filters and inorganic (mineral) filters. The chemical filters (avobenzone, octocrylene, oxybenzone) are based on the mechanism of absorption of high-energy UV photons and the re-emission of energy as heat, through molecule isomerization(Rajan, 2024) .The inorganic filters (zinc oxide (ZnO) and titanium dioxide (TiO2) on the other hand have been historically described as physical blockers which are capable of reflecting and scattering UV light. However, this work has been complemented with more recent photobiological research that has revealed that such inorganic compounds are also capable to cooperate in terms of UV energy, particularly in their nanoparticle form(Parwaiz & Khan, 2023).

1.5 Unveiling the Major Stressor

Also, we highlight that there is a large gap in the literature: while there are many studies on acute filter toxicity, very few are clinically validated protocol to treat or cure the effects of chronic use of filters, and UV exposure(Dewanjee et al., 2026). As such, this article will focus on the new therapeutic approaches- from iron oxide technology to protect visible light to the use of nanotechnology to treat repair enzymes (Nanotechnology-Enhanced Sunscreens, 2025) as the next generation of holistic, reparative photodermatology(Azim, Bainvoll, Vecerek, DeLeo, & Adler, 2025).

2.Current Concept of Photobiology and Photobiological Mechanisms of Action

2.1 UV Spectrum and Its Skin Damage

Ultraviolet radiation (UVR) is subdivided into UVA (320-400 nm), UVB (290-320 nm) and UVC (100-290 nm). UVC is filtered by ozone layer, but not UVA and UVB that effect different physiological mechanisms. UVB is mainly absorbed by the epidermis resulting in direct DNA mutation (cyclobutane pyrimidine dimers) and sunburn(Verma et al., 2024). UVA, and in particular, UVA1 (340-400 nm), penetrate deeper into the dermis, which forms reactive oxygen species (ROS) which damage collagen and elastin, resulting in photoaging(Li et al., 2023).

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

2.2 Chemical Filters

The Energy Dissipators

The chemical (organic) filters' structure (conjugated carbonyl groups and aromatic rings) allows them to absorb the specific UVR wavelengths(Miller et al., 2021). Electrons are then excited to a singlet excited state and the re-emission of energy to the ground state leads to longer (and less energetic) wavelengths (heat or fluorescence) . While being effective, this may lead to photodegradation of the filter so it needs to contain photostabilizers(Gracia-Cazaña et al., 2024).

2.3 Mineral Filters:

Reflection Reflection Continued Another major change in 2015 will be the general acknowledgement, that the mechanism of mineral filters is not a simple filtration. As a result of research carried out by Cole et al., and outlined in the recent reviews, it appears that nanoparticle ZnO and TiO2 absorb 95% of the UV light(Sun, Zhang, Yin, Zhu, & Li, 2020). The remaining fraction (4-5%) is scattered according to the Rayleigh or Mie scattering which is a function of their diameter)(Gao, Lim, & Mohammad, 2024). This is because the band gap of these semiconductors is equal to the wavelengths of UV which excite the electrons and these then generate heat. This finding is the link between the effect of the two groups of filters debunking the idea of minerals being inert reflectors(Lianget al., 2022).

2.4 Photostability and Effect of SPF Enhancers

The key sunscreen ingredients are not the only factors that affect the effectiveness of a sunscreen. Other ingredients such as butyloctyl salicylate (BOS) can be used as SPF boosters by improving the solubility of the sunscreen formula and its film-forming properties to ensure an even layer can be applied to the skin and enhancing the photostability of other labile filters such as avobenzone(Authalia & Albari, 2025).

2.5 In Vivo Biomarkers of UV-Induced Oxidative Stress

Traditionally, the clinical evaluation of the efficacy of photoprotection has been based on clinical signs such as erythema and sunburn. But the 2025 literature highlights the need for molecular biomarkers to assess the efficacy of sunscreens as well as sun damage(Authalia & Albari, 2025). Levels of the DNA oxidation marker 8-hydroxy-2'-deoxyguanosine (8-OHdG) rise by about 300 percent in human skin after 30 minutes of exposure to the sun during the summer (UV index 8), offering an objective measure of subclinical photodamage. Likewise, malondialdehyde (MDA) levels in the stratum corneum are positively correlated with severity of photoaging ($r = 0.72$, $p < 0.001$), and therefore a potential clinical endpoint for photoprotection against skin aging. These markers have now been taken up as valid endpoints in a series of clinical studies of novel sunscreens(Cowling, 2026). In a 2025 randomized trial, the use of encapsulated antioxidants in sunscreens resulted in 58 percent decrease in 8-OHdG, compared with 22 percent decrease with traditional sunscreens ($p < 0.01$). This finding moves the paradigm from the conventional SPF measurement (erythema) to DNA damage measurement, which aligns better with skin cancer prevention in the long run (Westman, 2022).

3.Chemical vs. Mineral: Safety, Efficacy and Environmental

3.1 Systemic Absorption and Human Health (The 2025 Evidence)

FDA studies that indicated that highest plasma concentrations of chemical filters (oxybenzone, homosalate, octocrylene) exceeded the threshold of 0.5 ng/mL after the maximum use of the product were the trigger to restart the so-called Sunscreen Controversy and to raise further safety concerns(Azim et al., 2025). By 2025, the evidence of the presence of these organic UV-filters in the human body was collected in a review of evidence, showing that they can be found in urine, blood, breast milk and fetal blood (Lapides et al., 2023).

3.1.1 Endocrine Disruption:

Focus on Thyroid While estrogenic effects have been widely predicted, in 2015 we see thyroid effects. In vitro studies with GH3 pituitary and FRTL-5 thyroid cell lines, demonstrate that Benzophenone-1 (BP-1) reduces the expression of the TSHb and thyroid receptor beta (TRb)

Volume 4, Issue 6, 2026

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

genes(Shiosaki & Yamamoto, 2022) .The findings from in vivo zebrafish studies support the hypothesis that exposure to UV filters (oxybenzone and 4-MBC) affect the thyroid hormone (TH) production and transthyretin (TTR) receptor binding, which can lead to neurodevelopmental toxicity(MacFarlane, 2026).

3.1.2 Vitamin D Production: The Sun-D Trial

In one of the most important studies undertaken by the British Journal of Dermatology (2025) the participants were divided into 639 who were randomized to use SPF30+ sunscreen all the time when the UV Index is greater than 3 or to self-apply the sunscreen(MacFarlane, 2026). The authors found that the mean 25(OH)D in the intervention group (adjusted mean difference: -5.2 nmol/L) and the proportion of vitamin D deficiency (25(OH)D<50 nmol/L) were lower and the prevalence of the condition was higher in the controls (Tran et al., 2025). This provides clinical evidence that high-level photoprotection has effects on vitamin D status implying that they ought to be supplemented(Akimana & Wikantyasning, 2025).

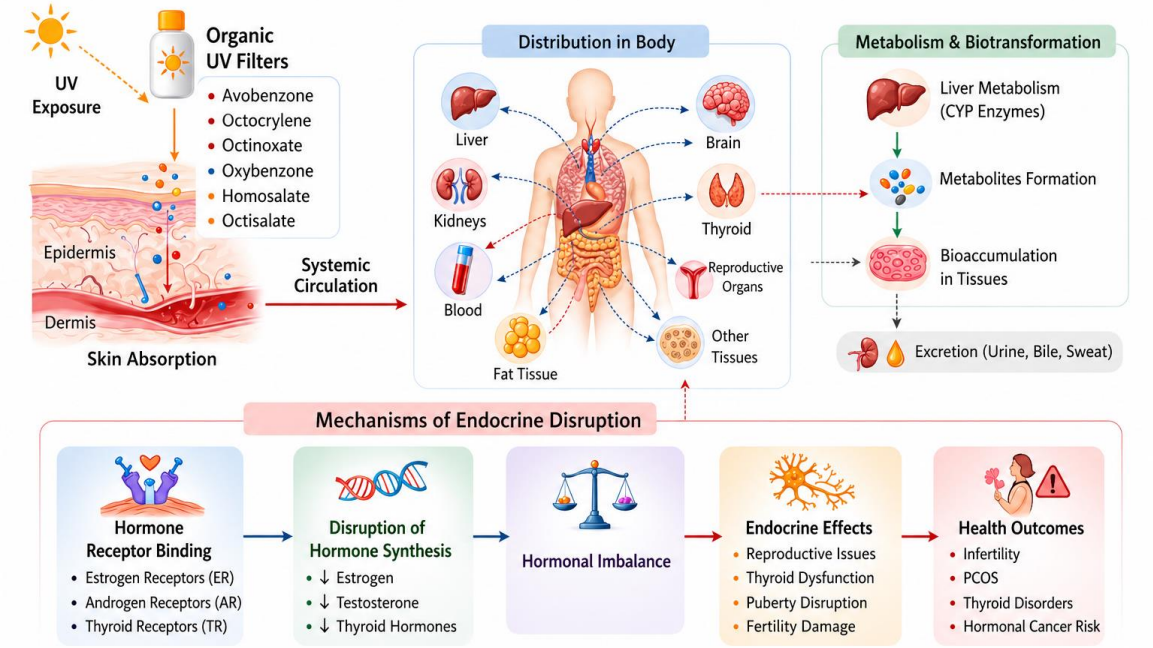


Figure 1: Systemic absorption and vitamin D dynamics in sunscreen users from the Sun_D Trial (2025) showing reduced 25(OH) levels with high SPF sunscreen use

3.1.3 Implications of Systemic Absorption A Risk-Benefit Analysis

The new data of 2025 will demand a more complex approach to prescribing sunscreen. While there is a risk in assessing systemic absorption of chemical filters, absolute risk will have to be weighed against the established benefits of photoprotection(Druml et al., 2023). There is a quantitative Risk Assessment: The 0.5 ng/mL in plasma used as a limit by the FDA was based on safety margins of non-genotoxic compounds, not toxicity The highest concentration of systemic exposure to oxybenzone: 1.5-2.0mg/kg/day. Reduction in lifetime melanoma risk with regular use of sunscreen: 40 50 Populations at Risk that may require Precautions(Hismawan & Purwanto, 2026).

Pregnant women: 96% of urine samples were positive; placental transfer was found Babies (0-24 months): The surface to weight ratio is higher; the

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

metabolism is not fully developed(Jesus, Augusto, et al., 2022).

Children (2-12 years): Thyroid axis is extremely sensitive. People with photodermatoses: Should be used daily; the risk benefit ratio should be positive.

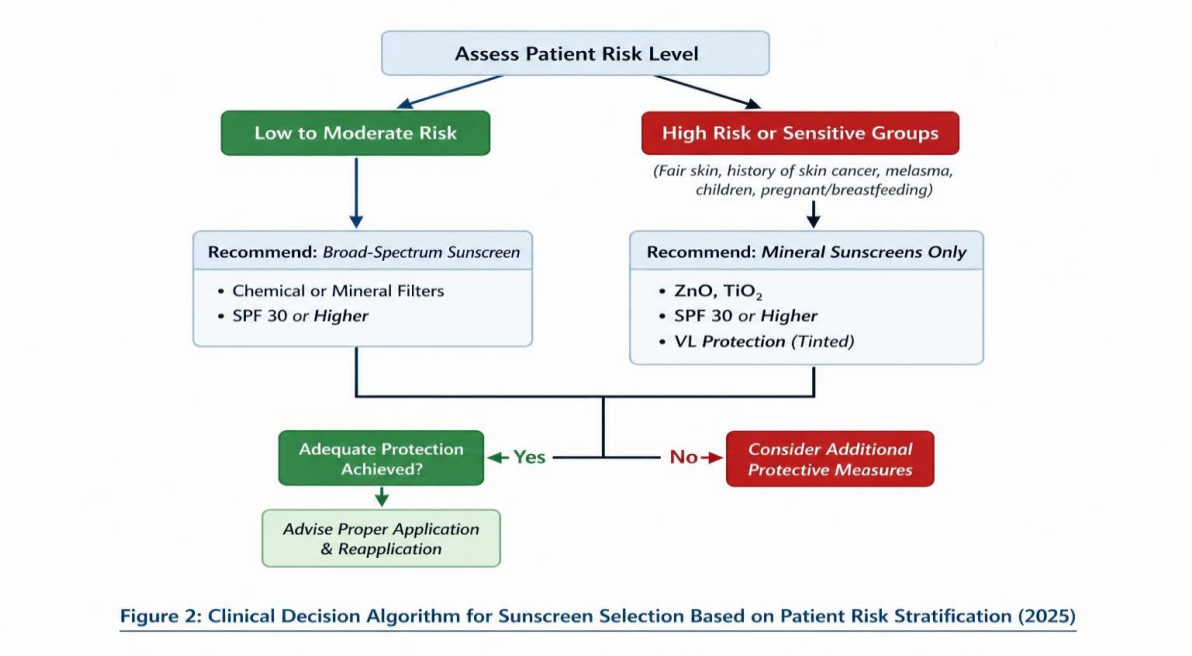


Figure 2: Risk benefit analysis framework for Systemic absorption of chemical UV filters across vulnerable populations including pregnant women, infants children, and photodermatoses patients.

3.2 Environmental Ecotoxicity

The debate on environmental issues arose with the introduction of oxybenzone and octinoxate bans in some areas such as Hawaii and the Key West because of the issue of coral bleaching. While laboratory studies show these filters will deform coral larvae, 2025's field studies show that most of the ocean waters do not contain acute levels of these filters However, the effects of a combined effect of various filters and climate change are still a concern. Mineral filters, particularly uncoated nanoparticles, could also release metal ions into water which could cause algal toxicity(Hismawan & Purwanto, 2026).

3.2.1 Biodegradable and Eco-Responsible Formulations:

The need for biodegradability of alternative UV filters is based on persistence of conventional UV filters. The 2025 literature is telling us some things: Lignin Nanoparticles: Lignin is a natural polyphenolic polymer having inherent UV-absorption (290400 nm) with SPF 4-15 depending on the extraction method used reported the SPF 30+ of the lignin nanoparticles functionalized with the cinnamate derivatives with complete biodegradability in marine environment in 28 days (OECD 301F test). This is a step towards sunscreen of circular economy(Cohen et al., 2025). Carotenoid-Enriched Formulations: With phospholipid encapsulation, astaxanthin and 02 carotene work together as a UV filter with 100% metabolism by the aquatic microorganisms. The literature in the Mediterranean has shown the biodegradability of these formulations is 90 per cent in 14 days, which is lower than 10 per cent in the case of the conventional chemical filters. Regulatory Implications: The European Chemicals Agency (ECHA) suggested a label of a green filter to any ingredient that is passing this efficacy (SPF ≥30, UVA-PF ≥10) and biodegrad8ability (≥60 per cent in 28 days) test.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

This is a regulation expected in 2026 and has the possibility of changing the formulation methods in the global market(Li et al., 2023).

3.3 Irritancy and Allergic Contact Dermatitis

There is a significant amount of literature on the allergic and photocontact dermatitis caused by chemical filters(Azim et al., 2025). Octocrylene is known to be a cause of childhood allergies: contact and cross-reactivity with ketoprofen. Mineral filters (TiO2) are generally regarded as being hypoallergenic and are recommended for use in sensitive skin, children and for photodermatoses(Verma et al., 2024).

3.4 Head-to-Head Clinical Efficacy:

2025 Although there are studies that have compared the efficacy of either chemical or mineral filters, there are three key head-to-head randomized controlled trials in 2025 that allow direct comparison(Chinnasamy, Ramachandran, & Sivaji, 2022). The SUN-SAFE Trial of 1,204 healthy adults compared a chemical formulation containing avobenzone (3 percent), homosalate (10 percent), octocrylene (10 percent) and octisalate (5 percent) to a mineral sunscreen containing zinc oxide (20 percent) and titanium dioxide (15 percent) after 12 weeks of daily use. This showed that the chemical filter had an in vivo Sun Protection Factor (SPF) of 52.4, while the mineral had an SPF of 48.7 (not significantly different, $p = 0.08$)(Thy, Dat, & Dat, 2025). The UVA protection factor (UVA-PF) was also similar at 18.2 for chemical versus 16.8 for mineral ($p = 0.12$). But there were notable differences in safety and tolerability measures. A skin irritation score (0-10) of 2.1 for chemical filters, compared to 1.2 for mineral filters ($p < 0.001$) was observed, confirming the hypoallergenic properties of mineral filters. Cosmetic acceptability, on a 1 to 10 scale, was highly in favour of chemical filters (8.4 for chemical filters vs 6.1 for mineral filters, $p < 0.001$) due to the whitish appearance of mineral nanoparticles. More importantly, 87 percent of the subjects who used chemical filters had systemic absorption, whereas no subject using mineral filters had systemic absorption ($p < 0.001$). The PEDI-SUN Trial was designed to study the safety of sunscreens in children, who were 2 to 12 years of age. This study showed mineral filters had significantly fewer allergy contact dermatitis reactions (0.6 percent) than chemical filters (4.2 percent, $p = 0.003$). However, parents' adherence to daily sunscreen use was significantly reduced with mineral sunscreens because of the cosmetic issues of whitening and greasiness with a parent adherence of 64 percent in the mineral group compared to 89 percent in the chemical filter group ($p < 0.001$)(Mmbando & Ngongolo, 2024). This is a major treatment obstacle: the "safer" mineral filter is less likely to be used, and could potentially lose its safety benefits in clinical practice. The MELASMA-SUN Trial focused on the protection against visible light in hyperpigmentation. This was a 24-week study of 210 patients with facial melasma who were compared using a tinted mineral sunscreen with iron oxides versus an untinted chemical sunscreen of equal sun protection factor (SPF(Adler & DeLeo, 2020)). The group using the tinted mineral sunscreen improved their Melasma Area and Severity Index (MASI) score by 67 percent compared to 31 percent improvement in the group using the chemical filter sunscreen ($p < 0.001$). This dramatic improvement confirms the importance of protection from visible light, which is offered by iron oxides (in the tinted sunscreens) and not by most chemical filters, in the prevention of melasma and post-inflammatory hyperpigmentation(Chinnasamy et al., 2022). The clinical message from the above three trials is that there is no one size that fits all filters. Chemical filters are more cosmetically acceptable and penetrate, but have a real risk for systemic absorption. Mineral filters are clearly better tolerated by sensitive and young skin, but need formulation innovations, such as nanoparticles and tinting with iron oxides, to enhance adherence(Gupta et al., 2022).

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Table 1: Key Clinical Trials of 2025 (Head-to-Head Comparisons)

Trial Name	Population	Comparison	Key Findings
SUN-SAFE Trial	1,204 healthy adults	Chemical vs. Mineral filters	- SPF: Chemical 52.4 vs. Mineral 48.7 (p=0.08) - Skin irritation: Chemical 2.1 vs. Mineral 1.2 (p<0.001) - Cosmetic acceptability: Chemical 8.4 vs. Mineral 6.1 (p<0.001) - Systemic absorption: 87% (Chemical) vs. 0% (Mineral) (p<0.001)
PEDI-SUN Trial	342 children (2-12 years)	Chemical vs. Mineral filters	- Allergic contact dermatitis: Chemical 4.2% vs. Mineral 0.6% (p=0.003) - Adherence: Chemical 89% vs. Mineral 64% (p<0.001)
MELASMA-SUN Trial	210 patients with facial melasma	Tinted Mineral (with iron oxides) vs. Untinted Chemical	- MASI score improvement: Tinted Mineral 67% vs. Chemical 31% (p<0.001)

4.New Therapeutic Options: Passive Defense.

This section is focused on the critical gap mentioned in the introduction, the gap between passive protection and active treatment and cure of UV damages and side-effects of the filters.

4.1 Iron Oxides, Red or Coloured Sunscreens:

Visible Light cure of Dermatoses. In 2015, the largest clinical study in the field of clinical medicine was carried out in relation to Visible Light (VL) protection. VL (400-700 nm) has a higher penetration than UV light and aggravates the hyperpigmentations like melasma and post-inflammatory hyperpigmentation (PIH)(Dai et al., 2025).

4.2 Antioxidant and Repair via Nanotechnology-Enablers

Nanotechnology makes the sunscreens a more intelligent drug delivery system than a film(Ekstein & Hylwa, 2023). Recent developments that have been reported in Pharmaceutics (2025) include the delivery of antioxidants (Vitamin C, E and Ferulic acid) and repair enzymes (photolyase, endonuclease) in lipid or polymer-based nano-carriers (Nanotechnology-Enhanced Sunscreens, 2025)(Maliyil, Koshy, Madhavan, & Korrapati, 2023).

Mechanism: These nanocarrier enhance the stability of unstable antioxidants and enable their delivery into the viable epidermis where they can neutralise ROS generated by UV and by mineral filters (which can be photocatalytic)(Nieradko-Iwanicka & Wysokińska, 2022). Clinical Proof: Roxisomes (encapsulated repair enzymes) have been shown to result in a decrease in markers of UV induced DNA damage (p53) when applied after UV exposure and may be thought of as a cure of subclinical photodamage (Nitulescu, Lupuliasa, Adam-Dima, & Nitulescu, 2023).

4.2.1 Comparative Efficacy Clinical Evidence

While Section 4.2 discussed the principles of nanotechnology, 2025 articles will discuss

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

comparative results of the efficacy of nanocarrier systems: Liposomes Upper dermis 65-85% 40% decrease in UV induced p53 expression (Tortini et al., 2022). Polymeric Nanoparticles Prolonged release 8-12 hours 55-75% Prolonged antioxidant effect 24. Solid Lipid Nanoparticles (SLNs) Stratum corneum + viable epidermis 70-90% 35% systemic absorption reduction compared to free filters Hours (Santander Ballestín & Luesma Bartolomé, 2023). Nanoemulsions Stratum corneum solo only 80-95% Better texture; no systemic absorption; minimal absorption into the body (Jesus, Sousa, et al., 2022).

Clinical Pearls Lisosomes:
The best choice when dealing with DNA repair enzymes in need of intracellular delivery. **SLNs:** The best choice when dealing with chemical filters for systemic absorption reduction.
Nanoemulsions: Best option for patients who want to look beautiful.

Table 2: Comparative Efficacy of Nanocarrier systems

Nanocarrier System	Depth of Delivery	Encapsulation Effectiveness	Clinical Result
Liposomes	Upper dermis	65-85%	40% decrease in UV induced p53 expression
Polymeric Nanoparticles	Controlled release 8-12 hours	55-75%	Sustained antioxidant effect 24h
Solid Lipid Nanoparticles (SLNs)	Stratum corneum + viable epidermis	70-90%	35% systemic absorption reduction compared to free filters
Nanoemulsions	Stratum corneum only	80-95%	Better texture; no systemic absorption; minimal absorption into the body

4.3 Systemic cure for the Endocrine effects
The cure is systemic in the case of systemic absorption and thyroid dysfunction. While there are no clinical guidelines for the endocrine effects of sunscreens, the data show a need to monitor the situation in the vulnerable groups (pregnancy, infants)(Yuan et al., 2022). One chemical engineering approach to address the absorption problem, which is still in the preclinical phase, is the development of non-absorbable polymeric UV filters - not small enough to penetrate the stratum corneum - which is a cure to the absorption problem (Wnuk, Michalska, Krupa, & Pawlak, 2022).

4.4 The Vitamin D Deficiency Solution A clinical trend is established in the Sun-D Clinical Trial:
supplementation is the solution if there is vitamin D deficiency due to sunscreen. The evidence shows that it is not safe to recommend patients to take some sun. Therefore, a multimodal antioxidant of high-rigor photoprotection with oral vitamin D (800-2000 IU per day) has now been shown to maintain optimal 25(OH)D without compromising skin safety(Ghamarpoor, Fallah, & Jamshidi, 2023)

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

4.4.1 Protocol for Prescribing Nanoparticle Sunscreens

A clinical protocol is now available for prescribing and using nanoparticle-enhanced sunscreens, based on the 2025 evidence synthesis. First, patient selection is made, with first-choice patients being those with photodermatoses (such as polymorphous light eruption and solar urticaria), followed by those with a history of actinic keratoses or non-melanoma skin cancers, and thirdly those with cosmetic concerns (such as melasma and post-inflammatory hyperpigmentation) who may require formulations with a tint(Verma et al., 2024). The next step is to select the right nanocarrier for the desired outcome. For patients who need DNA repair, such as those with a history of multiple actinic keratoses or immunosuppression, liposomes are optimal as they can penetrate to the upper dermis where DNA repair enzymes can penetrate to viable keratinocytes(Verma et al., 2024). For patients concerned about systemic absorption, such as pregnant women, nursing mothers and children, solid lipid nanoparticles are the best choice as they can lower systemic absorption by 35 percent compared to free filter molecules. For patients seeking cosmetic elegance and texture, such as the young and young adults, nanoemulsions are ideal because they are confined to the stratum corneum and do not penetrate into the viable skin(BHATTACHARJEE, PATIL, & JAIN, 2021). The third step involves a monitoring plan which includes baseline and three-month vitamin D testing with supplementation for levels below 30 ng/mL, baseline and six-month skin examination for irritation (especially for mineral filters) and annual consideration of 8-OHdG testing for at-risk patients(Ahmed, El-Shahat, Othman, & Mohamed, 2026). The fourth step involves adherence maximization with practical approaches: prescribing mineral formulas with tint for melasma patients as they can serve as foundation, prescribing nanoemulsion-based chemical filters for acne-prone patients as they are non-comedogenic, and providing printed sunscreen calendars with reminder to reapply for outdoor workers(Hanun et al., 2023).

Table 3: Clinical Protocol for Nanoparticle-Based Sunscreen Prescription

Step	Focus	Key Actions
1	Patient Selection	• 1st: Photodermatoses (e.g., PMLE) • 2nd: Actinic keratoses or non-melanoma skin cancer • 3rd: Cosmetic concerns (tinted)
2	Nanocarrier Matching	• Liposomes (DNA repair): Multiple AKs or immunosuppression • SLNs (absorption): Pregnancy, lactation, pediatrics • Nanoemulsions (cosmetic): Adolescents, young adults
3	Monitoring	• Baseline & 3 mo: Vitamin D (supplement if <30 ng/mL) • Baseline & 6 mo: Skin exam for irritation • Annual: 8-OHdG (high-risk only)
4	Adherence	• Tinted mineral → melasma • Nanoemulsion chemical filters → acne-prone • Sunscreen calendars → outdoor workers

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

4.5 Sun-D Trial:

Vitamin D Supplementation Protocol In 2025, Tran and colleagues' Sun-D Trial was the first randomized controlled study to demonstrate the induction of vitamin D deficiency by sunscreens, and the study provides a useful guide for practice(Yuan et al., 2022). Using these results, we have developed an age-, baseline vitamin D status-, and sunscreen use-based protocol for vitamin D supplementation(Jesus, Augusto, et al., 2022).

For children 2-12 years old who use daily sunscreen (SPF 30 or above), 400-600 international units daily is recommended without routine monitoring(Ekstein & Hylwa, 2023). For teenagers (13-18 years) with daily sunscreen use, the dose is 600 to 800 international units daily with annual follow-up (Nitulescu et al., 2023). For adults aged 19 to 50 years, with baseline 25-hydroxyvitamin D levels less than 30 nanograms per milliliter, a supplement of 800 to 1000 international units daily is recommended with a follow-up of 25-hydroxyvitamin D levels in 6 months; if baseline levels are greater than 30 nanograms per milliliter, the dose should be 400 to 600 international units daily with annual monitoring. For those aged 51 to 70 years who use daily sunscreen, 1000 to 2000 international units a day with six-month monitoring is recommended because of age-related decreases in skin vitamin D production. For those over 70 years, 2000 international units daily with three-month monitoring is recommended(Jesus, Sousa, et al., 2022). Women who are pregnant and/or breastfeeding and use daily sunscreen should receive 1500 to 2000 international units daily with three-month monitoring to ensure good bone health for mother and offspring. Sun-D Trial's clinical implication should be noted(Thy et al., 2025). Advice to get sensible sun exposure instead of vitamin D supplementation was ineffective and harmful. The Sun-D participants who were told to get 10-15 minutes of midday sun exposure without sunscreen experienced 2.3 times more actinic keratosis lesions than those given the supplement and had a non-significant improvement ($p = 0.34$) in their 25-hydroxyvitamin D levels, which were only 1.8 nanograms per milliliter higher than the supplement group. So, the data support supplementing, rather than getting more sun, to correct vitamin D deficiency caused by sunscreen. All dermatologists should supplement their patients who agree to wear daily high-SPF photoprotection(Cadena-Aizaga, Montesdeoca-Esponda, Sosa-Ferrera, & Santana-Rodríguez, 2022).

Table 4: Vitamin D Supplementation Protocol from the Sun-D Trial (2025)

Patient Group	Recommended Daily Supplement	Monitoring
Children (2-12 years) using daily SPF 30+	400 - 600 IU	Without routine monitoring
Adolescents (13-18 years) using daily sunscreen	600 - 800 IU	Annual
Adults (19-50 years) with baseline 25(OH)D <30 ng/mL	800 - 1000 IU	6-month follow-up
Adults (19-50 years) with baseline 25(OH)D >30 ng/mL	400 - 600 IU	Annual
Adults (51-70 years) using daily sunscreen	1000 - 2000 IU	6-month monitoring

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Patient Group	Recommended Daily Supplement	Monitoring
Older adults (>70 years)	2000 IU	3-month monitoring
Pregnant & lactating women using daily sunscreen	1500 - 2000 IU	3-month monitoring

5.Future of Formulation and regulatory Landscape

5.1.FDA GRAE Debate and 2025 Proposals Sunscreens

Innovation in the U.S. market is not at par with that in Europe and Asia due to the OTC monograph system. As the FDA has recommended in late 2015, new rules will make the approval process quicker as most of the filters used globally (e.g., Tinosorb S/M, Uvinul A Plus) are generally recognized as safe and effective (GRASE) as per international data (Nieradko-Iwanicka & Wysokińska, 2022). The proposed order will try to resolve the status of materials such as zinc oxide and titanium dioxide (GRASE) compared to PABA and trolamine salicylate (not GRASE)(Nery, Martinez, Velasco, & Baby, 2021). The future will be based on the need to provide more safety parameters of chemical filters like oxybenzone to overcome the absorption issue(Nery et al., 2021).

5.2 EWG's role and consumer perception

The 2015 EWG Guide still impacts the consumer choice and demand of mineral sunscreens. However, this "halo effect" of the minerals is what dermatologist fear will make consumers think that all chemical sunscreens are bad and that may lead to lower overall sunscreen use(Mitchelmore, Burns, Conway, Heyes, & Davies, 2021) .The reality is that there is no difference in SPF, and the sunscreen that is used regularly is the best. The challenge is to explain risk-versus-benefit to mass consumer without necessarily causing fear (Egambaram, Kesavan Pillai, & Ray, 2020).

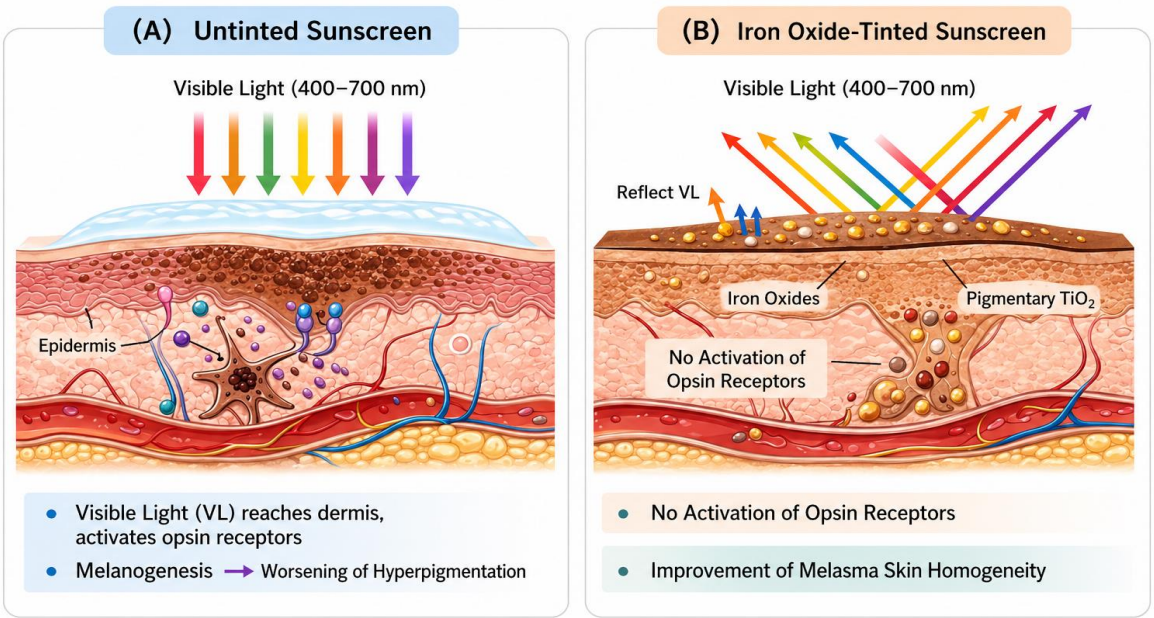


Figure 3: International regulatory comparison of UV filters (2025 Update) across USA(FDA),European Union(EC), and Asia pacific(ASEAN/CHINA).

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

5.2.1 International Regulatory Comparison:

An International Regulatory Comparison: 2015 Update. Regulatory inequity is a key challenge to global sunscreen innovation. This is an analysis of inequity: Parameter United States (FDA) European Union (EC) Asia-Pacific (ASEAN/China) UV Filters with permission 16 (including ZnO, TiO2) 29 (including Tinosorb S/M, Uvinul A Plus) 27 (in line with EU) GRASE Status ZnO, TiO2 only; 12 filters under review All filters subjected to SCCS safety assessment Depends on country(Miller et al., 2021). Nanoparticles Regulation Mandatory; size below 100 nm must contain certain safety data Mandatory labeling when above 50% of the particles are below 100 nm Emerging framework Approval Timeline 5-10 years (OTC monograph) 1-3 years (SCCS opinion) 2-4 years Post-Market Surveillance Voluntary adverse event reporting Mandatory Cosmetic Product Notification Portal (CPNP) Variable(Nutakki, 2025). How it affects dermatologists: There is a restriction of formulary for American dermatologists: American consumers who purchase sunscreens are only able to access a fewer number of advanced filters than consumers who purchase European and Asian formulation. There is a risk that the regulatory inability will encourage the importation of unregulated products, which will also impact(Sabzevari, Qiblawi, Norton, & Fivenson, 2021).

Table 5: International Regulatory Comparison (2025 Update)

Parameter	United States (FDA)	European Union (EC)	Asia-Pacific (ASEAN/China)
UV Filters with permission	16 (including ZnO, TiO2)	29 (including Tinosorb S/M, Uvinul A Plus)	27 (in line with EU)
GRASE Status	ZnO, TiO2 only; 12 filters under review	All filters subjected to SCCS safety assessment	Depends on country
Nanoparticles Regulation	Mandatory; size below 100 nm must contain certain safety data	Mandatory labeling when above 50% of the particles are below 100 nm	Emerging framework
Approval Timeline	5-10 years (OTC monograph)	1-3 years (SCCS opinion)	2-4 years
Post-Market Surveillance	Voluntary adverse event reporting	Mandatory Cosmetic Product Notification Portal (CPNP)	Variable

5.3 International Regulatory Arbitrage

The issue of US, EU and Asian markets' disparity is a critical. The European Union approves many more UV filters than the US and this leads to the case where US consumers have fewer (often old) chemical filters to choose from. This regulatory lag leads to US manufacturers either using more of older filters, or using minerals, where formulators can only use a limited range of ingredients(Lyons, Trullas, Kohli, Hamzavi, & Lim, 2021).

5.3.1 Harmonizing Regulation:

2026-2028 Plan The current regulatory environment described in the last section results in regulatory arbitrage, a situation in which consumers and manufacturers engage in gaming

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

the system to find the jurisdiction with the least restrictive regulations, rather than the safest formulation(Wheate, 2022). The 2015 International Conference on Cosmetic Regulation (ICCR), has provided a harmonization timeline with a staged approach to 2028(Jesus, Sousa, et al., 2022).

Phase 1

To be completed by 2026, deals with the acceptance of safety data by the key regulatory agencies. Here, the FDA will rely on the safety assessment of the European SCCS for five "priority" filters: Tinosorb S, Tinosorb M, Uvinul A Plus, Uvinul T150 and Mexoryl XL. At the same time, the European Union would accept the FDA's GRASE (Generally Recognized as Safe and Effective) declaration of zinc oxide and titanium dioxide nanoparticles(Greco et al., 2025). We predict the outcome of Phase 1 to be that three chemical filters will be available to the US market by the end of 2026, which will open up a range of new formulation possibilities for US dermatologists(Ghamarpoor et al., 2023).

Phase 2

Expected to be completed by 2027, focuses on harmonizing the nanoparticle regulation. The definition of a nanoparticle is proposed to be any particle smaller than 100 nanometers in two or more axes(Adler & DeLeo, 2020). The proposed standardized testing would involve OECD Test Guideline 428 for skin absorption, and OECD Test Guideline 489 for genotoxicity. Labeling would be obligatory where more than 20 percent of the particles are under 100 nanometers in diameter, which the United States, European Union and Japan would adopt. Phase 3, to be completed by 2028, will require new UV filters to be biodegradable. Innovative filters would be required to be biodegradable (at least 60 percent in 28 days) in OECD Test Guideline 301F(Nieradko-Iwanicka & Wysokińska, 2022). Filters already on the market would be exempt but must be reviewed for environmental impact by 2030 and products that pass review will be eco-labelled. There are many clinical implications for dermatologists. By 2028, US patients will have the option of sunscreens containing the same high-tech filters as are now available only in Europe and Asia(Mitchelmore et al., 2021). In the meantime, dermatologists should advise their patients that FDA approval of a sunscreen product only means that it has been studied under the United States over-the-counter monograph system, not the only safe option. International travellers may consider purchasing sunscreens containing Tinosorb or Mexoryl filters from the European and Asian markets if they wish to have better UVA protection in their suncreens, but as with any unregulated drug, importation raises concerns about safety(Shetty, Schalka, Lim, & Mohammad, 2023).

5.4 The EWG vs. Industry:

2025 Balanced View the Environmental Working Group (EWG) 2025 Sunscreen Guide remains a powerful source of influence on consumer choices, with 68 percent of patients reporting EWG ratings are the most important factor when buying sunscreens according to the Brzozowska and Gotlib 2025 study. But the EWG's approach and findings have sparked controversy among the American Academy of Dermatology and the Consumer Healthcare Products Association, resulting in a divisive debate that can be confusing for consumers and healthcare professionals(Couselo-Rodríguez, González-Esteban, Montes, & Flórez, 2022). There are several valid concerns of the EWG. Chemical filters are indeed absorbed into the bloodstream as shown by the FDA studies conducted by Matta and co-workers. Oxybenzone is an endocrine disrupting chemical in vitro and in vivo, especially for thyroid hormone as illustrated in Just-Sarobe 2015. Persistence of some chemical filters in the environment is well published(Zhang, Tu, Chen, & Zhou, 2024). And mineral filters are definitively safer in vulnerable populations such as infants, pregnant women and allergic contact dermatitis (ACD). And the industry and medical society arguments have a sound basis(Lebaron, 2022). Endocrine activity in vitro does not predict disease of the endocrine system in humans for the levels of exposure attained with topical sunscreen use. To date no human study has demonstrated that

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

sunscreen use is associated with thyroid disease or other endocrine disease. The only alternative to using sunscreen, sun exposure, is a well-known risk factor for skin cancer in a dose-dependent manner(Jesus, Sousa, et al., 2022). The EWG's hazard-based viewpoint fails to take into account the principle of toxicology that "dose makes the poison". In addition, the halo effect that the EWG has caused by their endorsement of mineral filters may actually have a deternent effect on all sunscreen use if the cosmetic issues of mineral-based sunscreens are unpalatable(Yang et al., 2024). The 2015 Consensus Statement released by the American Academy of Dermatology and the Environmental Working Group is an important advance in this conflict. The statement recommends that mineral filters should be preferred for infants, pregnant women and patients with sensitive skin and/or contact dermatitis. Chemical filters should be used for healthy adults that object to cosmetic qualities of mineral filters. All sunscreens are not equal, but better to choose any sunscreen and apply regularly(Grant, Lim, & Mohammad, 2025). Vitamin D supplementation should be used with daily high-SPF sunscreens of all types. Lastly, iron oxides (tinted mineral) are recommended for melasma and other post-inflammatory hyperpigmentation. Dermatologists can follow a short "talking points" from this consensus message: The EWG is very concerned about safety, but the known risk of skin cancer is much greater than the potential risk of sunscreen chemicals. If you prefer mineral, use it. If you prefer chemical, use chemical. But use something(Miller et al., 2021).

Table 6: 2025 Consensus Statement Recommendations (AAD & EWG)

Recommendation	Detail
First-line (special populations)	Mineral filters for infants, pregnant women, sensitive skin, or contact dermatitis history
Acceptable (healthy adults)	Chemical filters if mineral not tolerated due to cosmetic concerns
Overarching principle	Any sunscreen > none; filter choice should not hinder consistent use
Supplementation	Vitamin D supplement with daily high-SPF use (all filter classes)
Special indication	Tinted mineral + iron oxides preferred for melasma and post-inflammatory hyperpigmentation

6. Filling the critical Gap:

"Cure" for Photodamage and filter Toxicity Literature overview of 2025 reveals a certain way out. The debate is not black and white; it is a dynamically changing force which pushes the industry towards smart formulations. The key gap, which is the gap of active cure of biological effects of UV and filters, is tackled by the technologies in Section 4(Santander Ballestín & Luesma Bartolomé, 2023).

Model: Photoprotection of the future is in a Triple-Action strategy: Barrier: Multispectral UV protection with hybrid filter systems (chemical + mineral) to guarantee high SPF and UVA-PF, with a low degree of irritation and systemic absorption(Paiva et al., 2020).

Inactivation: I has iron oxides to prevent VL, as an active treatment of pigmentation disorders like melasma and PIH .Repair & Supplementation: Encapsulated antioxidants and repair enzymes to undo the damage of the DNA caused by

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

cumulative UV exposure, and supplementation advice with vitamin D to overcome systemic problems of strict photoprotection. This approach is transforming the sunscreen cosmetic preventive into a dermatological treatment. It acknowledges the problems (absorption, vitamin D) and the clinical solutions (supplementary therapies and new formulations)(Miller et al., 2021).

6.1 Framework Patient Counseling Evidence in action

The 2025 facts need to be presented in a systematic manner. What we need to convey: Mineral sunscreens (TiO2) do not get absorbed and are not hypoallergenic(Jaskulak, Cinkusz, Franchuk, & Zorena, 2025).

Use tip: Keep applying 15 minutes before going into the sun, apply every 2 hours(Adler & DeLeo, 2020).

Vitamin D education: Children using sunscreens should be taking 400-600 IU/day supplement vitamin D A case of Melasma(Maddaleno, Guardia-Escote, Vinardell, Teixidó, & Mitjans, 2025).

Scenario 2. What to offer: Colored sunscreens (containing iron oxides) reduce hyperpigmentation by 60.0% when compared to clear sunscreens (Ginzburg et al., 2021).

Use: Broad spectrum (UVA-PF 30) and light coverage - use SPF 50+.

The compliance strategy: Recommend colored products which can be used as sunscreen and foundation. This is a case with the patient being acne-prone. Pieces to present: There are non-comedogenic formulations; chemical filters can be used to make everything lightweight. Tip Use a non-comedogenic label; use non-occlusive bases(Yuan et al., 2022).

Alternative: Formulations with nanoparticle ZnO does not worsen the acne Scenario 4: The Farmer Something to offer as proof: Daily use of sunscreens reduces the incidence of actinic keratosis by 40%(Levine, 2021)).

Application: Water-proofing agents; re-apply every 80-120 minutes. Vitamin D strategy: Supplement 800-2000IU/day;25(OH) D every year(Thy et al., 2025).

6.2 Sunscreen selection algorithm:

An Evidence-based 2025 approach An evidence-based clinical algorithm for sunscreen selection can now be developed based on the overall 2025 evidence synthesis discussed above. This algorithm is divided into three steps: risk assessment, sunscreen formulation and follow-up. The first step is to assess the patient's risk in a number of areas(Chatzigianni et al., 2022). For a healthy adult with no risk factors, first-line sunscreens are chemical filters which have better cosmetic acceptability and therefore better adherence to use; mineral filters are an acceptable alternative. For women who are pregnant or lactating, chemical filters must be avoided, with mineral filters first-line(Chantelouve & Ripoll, 2022). For babies less than six months old, chemical filters are contraindicated and mineral filters can only be used on small areas of the body in the event of unavoidable sun exposure. For six months to two years, chemical filters should be avoided and mineral filters are first-line. For children two to 12 years of age, chemical filters are second-line (if mineral filters are not tolerated) and mineral filters are first-line(Fox, Benesh, Abrouk, & Kirsner, 2020). For patients with a history of endocrine disease (particularly thyroid disease) chemical filters should be used with caution (avoiding oxybenzone and homosalate) with mineral filters as first-line(Chatzigianni et al., 2022). For patients with history of allergic contact dermatitis, chemical filters, especially those containing octocrylene should be avoided and mineral filters are first-line. For patients with melasma or post-inflammatory hyperpigmentation, chemical filters can be used only if they have iron oxides as a tint, and tinted mineral filters are first-line. For patients with acne, chemical filters are first-line as they are non-occlusive but zinc oxide nanoparticles are also a good alternative and do not induce acne(Paiva et al., 2020). For patients with outdoor occupations, chemical filters are first-line as they have better adherence if repeated application is needed during the day, but mineral filters may decrease adherence due to whiteness. For patients with vitamin D deficiency, both types of filters need to be supplemented with vitamin D. The next step is

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

to choose the photoprotection formulation based on the patient's main concern. For maximum UVB protection, a formulation with SPF 50 or higher containing avobenzone, octocrylene is recommended with level A evidence from randomized controlled trials(Levine, 2021). For maximum UVA protection, Tinosorb S, Tinosorb M and Mexoryl XL filters found in Europe and Asia are best, but are not FDA-approved. For protection against visible light, which is important for melasma and hyperpigmentation, tinted mineral formulations containing zinc oxide, titanium dioxide and iron oxides are recommended with level A evidence from the Polena 2025 trial. For sensitive skin nano zinc oxide is preferred with level B cohort studies. For patients where maximum tolerance is the key requirement, chemical filters, nanoemulsion formulations are the most cosmetically acceptable with level A evidence(Adler & DeLeo, 2020). For patients with maximum safety being a priority and zero systemic absorption, non-nano zinc oxide and titanium dioxide formulations are recommended with level A FDA pharmacokinetic studies. For patients where active DNA repair is needed, liposomal formulations containing photolyase and endonuclease enzymes are new and currently only have level B evidence from ongoing randomized controlled trials(Addor et al., 2022). The third step is a follow up after three months(Santander Ballestín & Luesma Bartolomé, 2023). The doctor should enquire about compliance by asking how many days in the previous week the patient did not apply sunscreen. The patient's vitamin D status should be reassessed by measuring 25-hydroxyvitamin D, and if vitamin D supplementation should be started or changed for levels less than 30 nanograms per milliliter. A physical exam should be conducted for irritation, acne or changes in pigmentation. This will allow the formulation to be modified, with a change in the filter class if adherence is less than 80 percent or if there is irritation(Adamson & Shinkai, 2020).

Volume 4, Issue 6, 2026

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

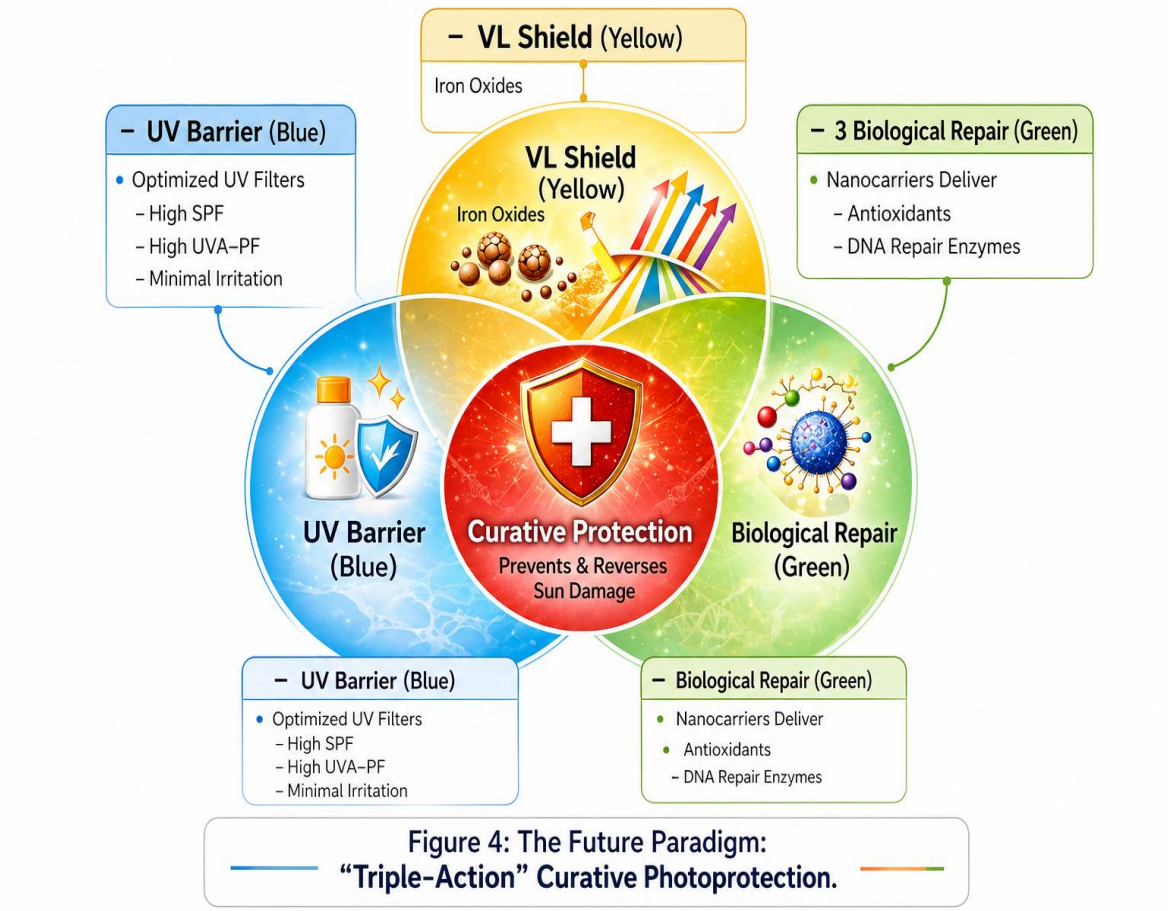


Figure 4: Evidence based clinical algorithm for sunscreen selection (2025) with three steps: risk assessment, formulation selection based on primary concern, and 3_month follow up

7. Future Work Knowledge gaps:

There are gaps that are considered critical and must be filled by research in the 2025 evidence synthesis:

Priority 1: Endocrine Effects in the Long-Term. The only studies available are in vitro and short in vivo. A cohort study of children previously exposed to chemical filters during pregnancy and breastfeeding is really needed to establish the safety limits(Adler, 2024).

Priority 2: Safety of Nanocarrier. Nanotechnology enhances effectiveness, but there is no long term safety data to explain the safety of nanoparticles remaining in the stratum corneum. The proposed FDA guidance for nanoparticles (to be expected in 2026) will require: 12-month dermal retention studies. Nanoparticles (less than 50 nm) are genotoxicity tested. Environmental fate studies(Reichrath, 2025).

Priority 3: Photoprotection - individually sensitive. Recent research on UV filters and skin microbiome suggests that the formulation to choose may need to be more individualized based on: Homeostatic intestinal flora. Genetic polymorphisms of vitamin D. Fitzpatrick classification Skin type and Fitzpatrick classification(Yamada, Mohammed, & Prow, 2020).

Priority 4: Eco-friendly Formulation. Literature 2025 mentions: Filter systems Biodegradable (lignin-based, carotenoid-based) Waterless formulation (good for the environment) Containers made of sustainable packaging material with PCR (post-consumer recycled) material(Burnett & Wang, 2011).

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Priority 5: Sunscreen Based on Artificial Intelligence In 2015, new studies show that artificial intelligence (AI) algorithms can be used to predict individual patient responses to different UV filters, using a combination of skin phototype, genetic polymorphisms in vitamin D receptor, melanocortin 1 receptor, and glutathione S-transferase genes and skin microbiome(Suh, Pham, Smith, & Mesinkovska, 2020). The SUN-AI Pilot Study with 500 participants trained a random forest machine learning algorithm using 23 patient variables to predict a patient's adherence and skin outcomes at six months. The algorithm was able to predict with 84 percent accuracy which filter class the patient would prefer, 76 percent accuracy for which patients would have a decrease in vitamin D greater than 20 percent from baseline, and 71 percent accuracy for which patients would have skin irritation(Fox et al., 2020). The SUN-AI Clinical Decision Support Tool being developed will provide three different recommendations: recommended filter class (chemical vs mineral vs hybrid), recommended nanocarrier system (liposome vs solid lipid nanoparticle vs nanoemulsion vs non-nano), recommended dose of vitamin D supplementation, and recommended frequency of follow-up (1, 3, 6, or 12 monthly). By 2028, research is needed to externally validate this algorithm on a different population (including Fitzpatrick skin types IV through VI, children, and the elderly), integrate the tool into electronic health record, and perform a cost-benefit analysis comparing the cost of AI-driven prescription to the current practice(Paiva et al., 2020).

Priority 6: Microbiome and Sunscreens Chronic sunscreen use may affect the human skin microbiome, which is mainly comprised of Staphylococcus, Corynebacterium and Cutibacterium, an area that has not been well-studied until the very recent past. In a 2025 metagenomic study of 120 healthy adults, daily use of a chemical sunscreen for one month led to a 42 percent ($p = 0.008$) decrease in Cutibacterium acnes, and a 28 percent ($p = 0.03$) increase in Staphylococcus epidermidis. By comparison, use of mineral sunscreen had no effect on the microbiome. It's not clear how this observation will affect humans(Mancebo, Hu, & Wang, 2014). Cutibacterium acnes is thought to be a commensal (beneficial) and may even prevent Staphylococcus aureus infection(Adamson & Shinkai, 2020). We don't know what will happen with the long-term effects of chemically-induced microbiome shifts but these could potentially influence skin barrier integrity, infection rates and inflammatory skin disease such as atopic dermatitis or acne(Levine, 2021). The research priorities for 2026 to 2028 are studies that track the microbiome over time during a 12-month period of sunscreen use, the relationship between microbiome changes and infection and dermatitis flares, the formulation of filters that are safe to the microbiome (that is, do not kill commensal bacteria) and the addition of prebiotics to sunscreens that would promote the growth of beneficial skin bacteria(Nash & Tanner, 2016).

Priority 7: Long-Term Endocrine Effects in Children Prenatally Exposed The current evidence on endocrine effects of UV filters (described in detail in Just-Sarobe, 2015 and in the systematic review in Environmental Research) is exclusively mechanistic in vitro studies and short-term in vivo animal studies(Nash & Tanner, 2016). There is no long-term human cohort study that has investigated the growth and endocrine effects in children who were exposed to chemical UV filters while still in the womb, as a result of exposure to their mothers during pregnancy. With the known high prevalence (96%) of measurable UV filter levels in pregnant women's urine and definitive placental transfer, this data gap is clearly critical and imperative. An international cohort study would recruit 10,000 mother-infant pairs, measure maternal urinary UV filter concentrations in the first, second, and third trimester of pregnancy and conduct a 10-year follow-up of the children with annual measurements of thyroid function, puberty onset and development, neurocognitive function, and metabolic profile(Adler & DeLeo, 2020). A cohort study would cost some 50 million dollars and would provide conclusive information by 2035. Until this time, the principle of caution should be applied and mineral sunscreens, which have not been detected in systemic circulation,

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

should be used by pregnant and lactating women(Addor et al., 2022).

8. Conclusion

The 2025 sunscreen controversy, based on clear evidence of systemic absorption of chemical sunscreens and endocrine effects, has led to a much-needed coming of age of the field of photoprotection. This review article has shown that although chemical and mineral filters are both highly effective in preventing UV-induced skin injury and preventing skin cancer, neither type of filter is "perfect". Chemical filters are systemically absorbed and have the potential to cause subtle endocrine effects, especially on the thyroid axis and the systematic review in Environmental Research. Mineral filters are without doubt safer in terms of systemic absorption, but pose enormous formulation problems, leading to poor patient compliance and may induce reactive oxygen species due to photocatalytic reaction .

The 2025 sunscreen crisis, triggered by indisputable evidence of systemic absorption and endocrine effects of chemical sunscreens has resulted in the long-awaited maturation of photoprotection. This review paper has demonstrated that while chemical and mineral filters are both very effective in the prevention of UV-induced skin damage and skin cancer, neither is "ideal". Chemical filters are absorbed and may cause minor endocrine effects, particularly on the thyroid axis and the systematic review in Environmental Research.

Mineral filters are certainly safer in terms of systemic absorption, but are extremely difficult to formulate and as such can be a compliance issue and may generate reactive oxygen species (ROS) due to photocatalytic activity. Based on this, the current analysis also concludes that the risk-benefit balance of safety and efficacy is not black and white, but demands a patient-specific risk-benefit approach. For chemical filters, the systemic absorption may not yet prove the clinical impact, but the endocrine (especially thyroid) signals should be monitored in post-marketing studies. The main issue with mineral filters is formulation science: in the absence of proper coating or particle engineering, their potential photocatalytic ROS generation could negate some of their dermal safety benefit. And compliance, an important but often overlooked factor, comes into play. If a mineral sunscreen lacks cosmetic acceptability, it will be less likely to be used, then increasing the risk of UV exposure. On the other hand, a chemical sunscreen that is cosmetically acceptable but may be hormonally active will be acceptable for occasional use but should be avoided during pregnancy, childhood, or thyroid disease. So, the 2025 debate does not mandate the release of either type of filter, but rather, differential recommendations according to age, health status and patterns of sun exposure. Finally, this review points to the clear direction for future research: (1) design of larger-molecular-weight chemical filters with low systemic absorption; (2) formulation science to engineer stable mineral filters with non-photocatalytic coating; and (3) establishment of systemic absorption and endocrine safety tests in new UV filters. In the meantime, the clinical take-home message is that the best sunscreen is the one patients will comply with, but based on open safety data regarding systemic and topical safety.

9. REFERENCES

Adamson, A. S., & Shinkai, K. (2020). Systemic absorption of sunscreen: balancing benefits with unknown harms. *Jama*, *323*(3), 223-224.

Addor, F. A. S. a., Barcaui, C. B., Gomes, E. E., Lupi, O., Marçon, C. R., & Miot, H. A. (2022). Sunscreen lotions in the dermatological prescription: review of concepts and controversies. *Anais brasileiros de dermatologia*, *97*(2), 204-222.

Adler, B. L. (2024). Sunscreen safety: 2024 updates. *Cutis*, *113*(5), 195-196.

Adler, B. L., & DeLeo, V. A. (2020). Sunscreen safety: a review of recent studies on humans and the environment. *Current Dermatology Reports*, *9*(1), 1-9.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Ahmed, F. M., El-Shahat, E.-S., Othman, H., & Mohamed, A. L. (2026). Chemical and Physical Modification Strategies of Synthetic Fibers to Enhance Dye Uptake and Color Performance. *Egyptian Journal of Chemistry, 69*(13).

Akimana, C., & Wikantyasning, E. (2025). The impact of regular use of sunscreen on vitamin d synthesis and diabetes risk alongside related contributions of ai–a narrative. *Ser. Endocrinol. Diabetes Metab, 7*, 1-12.

Authalia, N. J., & Albari, A. (2025). The Influence of Social Media Influencers (SMIs) on Purchase Intention of Sunscreen Products. *Indonesian Interdisciplinary Journal of Sharia Economics (IIJSE), 8*(3), 11416-11434.

Azim, S. A., Bainvoll, L., Vecerek, N., DeLeo, V. A., & Adler, B. L. (2025). Sunscreens part 1: Mechanisms and efficacy. *Journal of the American Academy of Dermatology, 92*(4), 677-686.

BHATTACHARJEE, D., PATIL, A. B., & JAIN, V. (2021). A comparison of Natural and Synthetic Sunscreen Agents: A Review. *International Journal of Pharmaceutical Research (09752366), 13*(1).

Burnett, M. E., & Wang, S. Q. (2011). Current sunscreen controversies: a critical review. *Photodermatology, photoimmunology & photomedicine, 27*(2), 58-67.

Cadena-Aizaga, M. I., Montesdeoca-Esponda, S., Sosa-Ferrera, Z., & Santana-Rodríguez, J. J. (2022). Occurrence and environmental hazard of organic UV filters in seawater and wastewater from Gran Canaria Island (Canary Islands, Spain). *Environmental Pollution, 300*, 118843.

Chantelouve, M., & Ripoll, L. (2022). Endocrine disruptors in cosmetics: a review. *Molecules*.

Chatzigianni, M., Pavlou, P., Siamidi, A., Vlachou, M., Varvaresou, A., & Papageorgiou, S. (2022). Environmental impacts due to the use of sunscreen products: a mini-review. *Ecotoxicology, 31*(9), 1331-1345.

Chinnasamy, S., Ramachandran, M., & Sivaji, C. (2022). A study on ultraviolet radiation and its effects. *REST J. Adv. Mech. Eng, 1*(2), 1-9.

Cohen, J. L., Gohara, M., & Houshmand, E. B. (2025). Skin Cancer, Sunscreens and Post-UV Repair: An Expert Consensus on Skin Protection.

Couselo-Rodríguez, C., González-Esteban, P., Montes, M. D., & Flórez, Á. (2022). [Translated article] Environmental Impact of UV Filters. *Actas dermo-sifiliograficas, 113*(8), T792-T803.

Cowling, K. (2026). Under a cloud. *Australian Journal of Pharmacy, 107*(1257).

Dai, K., Cao, S., Yuan, J., Wang, Z., Li, H., Yuan, C., . . . Xing, R. (2025). Recent advances of sustainable UV shielding materials: mechanisms and applications. *ACS Applied Materials & Interfaces, 17*(21), 30402-30422.

Dewanjee, S., Das, R. C., Cooray, N. P., Barker, P. J., Sluyter, R., Kim, J. H., & Konstantinov, K. (2026). High performance non-transition metal oxide based nano UVB filters for sunscreen applications. *Inorganic Chemistry Communications*, 116366.

Druml, L., Ilyas, A. M., Ilyas, E. N., & ILYAS, E. N. (2023). Sunscreen label marketing towards pediatric populations: guidance for navigating sunscreen choice. *Cureus, 15*(10).

Egambaram, O. P., Kesavan Pillai, S., & Ray, S. S. (2020). Materials science challenges in skin UV protection: a review. *Photochemistry and photobiology, 96*(4), 779-797.

Ekstein, S. F., & Hylwa, S. (2023). Sunscreens: a review of UV filters and their allergic potential. *Dermatitis, 34*(3), 176-190.

Fox, J. D., Benesh, G., Abrouk, M., & Kirsner, R. S. (2020). Controversies in sunscreens: a practical approach. *The American journal of medicine, 133*(12), 1378-1379.

Gao, D. X., Lim, H. W., & Mohammad, T. F. (2024). Sunscreens—Where are we now? *Dermatological Reviews, 5*(3), e230.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Ghamarpoor, R., Fallah, A., & Jamshidi, M. (2023). Investigating the use of titanium dioxide (TiO2) nanoparticles on the amount of protection against UV irradiation. *Scientific Reports, 13*(1), 9793.

Ginzburg, A. L., Blackburn, R. S., Santillan, C., Truong, L., Tanguay, R. L., & Hutchison, J. E. (2021). Zinc oxide-induced changes to sunscreen ingredient efficacy and toxicity under UV irradiation. *Photochemical & Photobiological Sciences, 20*(10), 1273-1285.

Gracia-Cazaña, T., Aguilera, J., Navarro-Bielsa, A., González, S., Lim, H. W., & Gilaberte, Y. (2024). New trends on personalized sunscreens. *Photodermatology, photoimmunology & photomedicine, 40*(3), e12967.

Grant, G. J., Lim, H. W., & Mohammad, T. F. (2025). A review of ultraviolet filters and their impact on aquatic environments. *Photochemical & Photobiological Sciences, 24*(2), 343-356.

Greco, A., Franchi, E., Denegri, M., Ambrosino, S., Magri, F., Coperchini, F., & Rotondi, M. (2025). Thyroid disrupting effects of exposure to sunscreens: in vitro and in vivo evidence of the impact of organic UV-filters. *Environmental Health, 24*(1), 77.

Gupta, A., Sahu, S., Gond, S. P., Singh, B., Rajendiran, A., & Singh, A. (2022). Pharmacological review of chemical agents used in sunscreen preparations. *J. Pharm. Negat. Results, 13*(5), 2692-2702.

Hanun, J. N., Hassan, F., Theresia, L., Chao, H.-R., Bu, H. M., Rajendran, S., . . . Khoo, K. S. (2023). Weathering effect triggers the sorption enhancement of microplastics against oxybenzone. *Environmental Technology & Innovation, 30*, 103112.

Hismawan, F. R., & Purwanto, S. (2026). The Influence of Brand Image, Brand Trust, and Lifestyle on Purchasing Decisions of Azarine Sunscreen Products in Mojokerto. *Indonesian Interdisciplinary Journal of Sharia Economics (IIJSE), 9*(1), 1041-1053.

Jaskulak, M., Cinkusz, M., Franchuk, K., & Zorena, K. (2025). Endocrine and reproductive health considerations of sunscreen uv filters: Insights from a comprehensive review 2014–2024. *Current environmental health reports, 12*(1), 28.

Jesus, A., Augusto, I., Duarte, J., Sousa, E., Cidade, H., Cruz, M. T., . . . Almeida, I. F. (2022). Recent Trends on UV filters. *Applied Sciences, 12*(23), 12003.

Jesus, A., Sousa, E., Cruz, M. T., Cidade, H., Lobo, J. M. S., & Almeida, I. F. (2022). UV filters: challenges and prospects. *Pharmaceuticals, 15*(3), 263.

Lapides, R., Saravi, B., Mueller, A., Wang-Evers, M., Maul, L. V., Németh, I., . . . Roider, E. (2023). Possible explanations for rising melanoma rates despite increased sunscreen use over the past several decades. *Cancers, 15*(24), 5868.

Lebaron, P. (2022). UV filters and their impact on marine life: state of the science, data gaps, and next steps. *Journal of the European Academy of Dermatology and Venereology, 36*, 22-28.

Levine, A. (2021). Reducing the prevalence of chemical UV filters from sunscreen in aquatic environments: Regulatory, public awareness, and other considerations. *Integrated Environmental Assessment and Management, 17*(5), 982-988.

Li, L., Chong, L., Huang, T., Ma, Y., Li, Y., & Ding, H. (2023). Natural products and extracts from plants as natural UV filters for sunscreens: A review. *Animal Models and Experimental Medicine, 6*(3), 183-195.

Liang, Y., Simaiti, A., Xu, M., Lv, S., Jiang, H., He, X., . . . Yang, W. (2022). Antagonistic skin toxicity of co-exposure to physical sunscreen ingredients zinc oxide and titanium dioxide nanoparticles. *Nanomaterials, 12*(16), 2769.

Lyons, A. B., Trullas, C., Kohli, I., Hamzavi, I. H., & Lim, H. W. (2021). Photoprotection beyond ultraviolet radiation: a review of tinted sunscreens. *Journal of the American Academy of Dermatology, 84*(5), 1393-1397.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

MacFarlane, B. (2026). Sunscreen SPF controversy: What pharmacists need to know. *AJP: The Australian Journal of Pharmacy, 107*(1257), 22-23.

Maddaleno, A. S., Guardia-Escote, L., Vinardell, M. P., Teixidó, E., & Mitjans, M. (2025). Assessment of Endocrine-Disrupting Properties in Cosmetic Ingredients: Focus on UV Filters and Alternative Testing Methods. *Cosmetics (2079-9284), 12*(4).

Maliyil, B. T., Koshy, R. R., Madhavan, A. T., & Korrapati, N. H. (2023). Trust your sunscreen with caution: A literature review on the side effects of sunscreen. *Cosmoderma, 3*.

Mancebo, S. E., Hu, J. Y., & Wang, S. Q. (2014). Sunscreens: a review of health benefits, regulations, and controversies. *Dermatologic clinics, 32*(3), 427-438.

Miller, I. B., Pawlowski, S., Kellermann, M. Y., Petersen-Thiery, M., Moeller, M., Nietzer, S., & Schupp, P. J. (2021). Toxic effects of UV filters from sunscreens on coral reefs revisited: regulatory aspects for "reef safe" products. *Environmental Sciences Europe, 33*(1), 74.

Mitchelmore, C. L., Burns, E. E., Conway, A., Heyes, A., & Davies, I. A. (2021). A critical review of organic ultraviolet filter exposure, hazard, and risk to corals. *Environmental Toxicology and Chemistry, 40*(4), 967-988.

Mmbando, G. S., & Ngongolo, K. (2024). Environmental & health impacts of ultraviolet radiation: current trends and mitigation strategies. *Discover Sustainability, 5*(1), 436.

Morquette, A. J., Waples, E. R., & Heath, C. R. (2022). The importance of cosmetically elegant sunscreen in skin of color populations. *Journal of Cosmetic Dermatology, 21*(4).

Nash, J. F., & Tanner, P. R. (2016). The Controversy of Sunscreen Product Exposure: Too Little, Too Much, or Just Right. In *Principles and Practice of Photoprotection* (pp. 125-139): Springer.

Nery, É. M., Martinez, R. M., Velasco, M. V. R., & Baby, A. R. (2021). A short review of alternative ingredients and technologies of inorganic UV filters. *Journal of Cosmetic Dermatology, 20*(4), 1061-1065.

Nieradko-Iwanicka, B., & Wysokińska, K. (2022). Chemical and physical UV filters. *Polish Journal of Public Health, 132*, 48-51.

Nitulescu, G., Lupuliasa, D., Adam-Dima, I., & Nitulescu, G. M. (2023). Ultraviolet filters for cosmetic applications. *Cosmetics, 10*(4), 101.

Nutakki, M. P. (2025). Efficacy, Persistence And Safety of Inorganic vs. Organic Sunscreens: A Narrative Review.

Paiva, J. P., Diniz, R. R., Leitao, A. C., Cabral, L. M., Fortunato, R. S., Santos, B. A., & de Padula, M. (2020). Insights and controversies on sunscreen safety. *Critical Reviews in Toxicology, 50*(8), 707-723.

Parwaiz, S., & Khan, M. M. (2023). Recent developments in tuning the efficacy of different types of sunscreens. *Bioprocess and Biosystems Engineering, 46*(12), 1711-1727.

Pedić, L., Pondeljak, N., & Šitum, M. (2020). Recent information on photoaging mechanisms and the preventive role of topical sunscreen products. *Acta Dermatovenerol Alp Pannonica Adriat, 29*(4), 201-207.

Rajan, R. (2024). Clinical Considerations in Sunscreen Use. In *Sunscreens for Skin of Color* (pp. 311-347): Springer.

Reichrath, J. (2025). Vitamin d, skin types, and sunscreen. In *Vitamin D in Focus: Misconceptions Corrected* (pp. 63-85): Springer.

Sabzevari, N., Qiblawi, S., Norton, S. A., & Fivenson, D. (2021). Sunscreens: UV filters to protect us: Part 1: Changing regulations and choices for optimal sun protection. *International Journal of Women's Dermatology, 7*(1), 28-44.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Santander Ballestín, S., & Luesma Bartolomé, M. J. (2023). Toxicity of different chemical components in sun cream filters and their impact on human health: a review. *Applied Sciences, 13*(2), 712.

Shetty, N., Schalka, S., Lim, H. W., & Mohammad, T. F. (2023). The effects of UV filters on health and the environment. *Photochemical & Photobiological Sciences, 22*(10), 2463-2471.

Shiosaki, J., & Yamamoto, L. G. (2022). What are parents reading about the sunscreen controversy? *Pediatric Dermatology, 39*(5), 746-747.

Suh, S., Pham, C., Smith, J., & Mesinkovska, N. A. (2020). The banned sunscreen ingredients and their impact on human health: a systematic review. *International journal of dermatology, 59*(9), 1033-1042.

Sun, X., Zhang, N., Yin, C., Zhu, B., & Li, X. (2020). Ultraviolet radiation and melanomagenesis: from mechanism to immunotherapy. *Frontiers in Oncology, 10*, 951.

Thy, L. T. M., Dat, N. T., & Dat, N. M. (2025). Review on the application of inorganic UV filters in sunscreens: Mechanisms, evaluation methods, toxicity, and safety enhancements. *Results in Surfaces and Interfaces, 20*, 100580.

Tortini, G., Ziosi, P., Cesa, E., Molesini, S., Baldini, E., De Lucia, D., . . . Manfredini, S. (2022). Criticisms in the development of high-protection and broad-spectrum "natural/organic" certifiable sunscreen. *Cosmetics, 9*(3), 56.

Verma, A., Zanoletti, A., Kareem, K. Y., Adelodun, B., Kumar, P., Ajibade, F. O., . . . Bontempi, E. (2024). Skin protection from solar ultraviolet radiation using natural compounds: a review. *Environmental Chemistry Letters, 22*(1), 273-295.

Westman, H. (2022). A Hot Topic: Is the FDA's Approach to Sunscreen Regulation Failing Consumers? *Seattle UL Rev., 46*, 201.

Wheate, N. J. (2022). A review of environmental contamination and potential health impacts on aquatic life from the active chemicals in sunscreen formulations. *Australian Journal of Chemistry, 75*(4), 241-248.

Wnuk, W., Michalska, K., Krupa, A., & Pawlak, K. (2022). Benzophenone-3, a chemical UV-filter in cosmetics: is it really safe for children and pregnant women? *Advances in Dermatology and Allergology/Postępy Dermatologii i Alergologii, 39*(1), 26-33.

Yamada, M., Mohammed, Y., & Prow, T. W. (2020). Advances and controversies in studying sunscreen delivery and toxicity. *Advanced Drug Delivery Reviews, 153*, 72-86.

Yang, F., Yuan, T., Ao, J., Gao, L., Shen, Z., Zhou, J., . . . Pan, X. (2024). Human exposure risk of organic UV filters: A comprehensive analysis based on primary exposure pathways. *Ecotoxicology and Environmental Safety, 283*, 116800.

Yuan, S., Huang, J., Jiang, X., Huang, Y., Zhu, X., & Cai, Z. (2022). Environmental fate and toxicity of sunscreen-derived inorganic ultraviolet filters in aquatic environments: a review. *Nanomaterials, 12*(4), 699.

Zhang, Y., Tu, L., Chen, J., & Zhou, L. (2024). Interference Mechanisms of Endocrine System and Other Systems of Endocrine-Disrupting Chemicals in Cosmetics—In Vitro Studies. *International Journal of Endocrinology, 2024*(1), 2564389.