AMERICAN JOURNAL OF BIOSCIENCE AND CLINICAL INTEGRITY
https://biojournals.us/index.php/AJBCI
ISSN: 2997-7347

Article

Sunscreen Formulations: A Comprehensive Review of UV Filters, Safety, and Environmental Impact

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Abstract: Typically, a sunscreen formulation consists of a number of UV filters, which may be either organic or inorganic. Organic UV filters are chemical compounds termed as UV-absorbers, which when applied to skin absorb the UV radiation and convert it into heat that is subsequently released by the skin to the atmosphere. Organics offer broader UV protection, a relatively large selection of UV filters is available today, and little information is available about their acute or chronic health effects on humans. The main types of organic UV filters include benzophenones, which are used for their ability to absorb a wide range of UV radiation few are approved with regard to the concern for endocrine disruption, another type is cinnamates, which absorb UV radiation by a different mechanism and are generally considered less efficient blockers, the last type is salicylates, they provide UV absorbing ability but are not used alone as they can be irritating to skin. Inorganic UV filters have proven to have less potential for sun-induced skin damage. They differ significantly from organics as they do not absorb UV radiation, but physically scatter and reflect it. Despite the lack of relevant data, studies have proven that they possess little to no systemic absorption when applied topically and are generally recognized as safe. The inorganic filters are either zinc oxide, a white but non-staining powder that scatters UV radiation efficiently or titanium dioxide, which is generally present in either a white or clear form depending on the degree of surface treatment that would help to inhibit scattering properties while retaining UV absorption. Concerns surrounding these inorganic filters are regarding their inhalation on spray compositions and their interaction with other active ingredients on sensitive skin. Most compositions use a combination of organic and inorganic UV filters to eliminate the disadvantages that each pose on their own while enhancing the benefits they contribute to the sunscreen product. However, their safety profiles and potential impact on willing consumers and aquatic ecosystems is of utmost importance. As such regulatory restrictions are currently imposed on the use of organic UV filters such as oxybenzone and octinoxate. Furthermore, research Vis-a-vis potential alternative sunscreen formulations continues to be relied on to promote optimal skin protection against the hazards of UV radiation without compromising on the quality of sun protection products being offered and its effects later down the line.

Keywords: UV filters; sunscreen; organic filters; inorganic filters; nanoparticles; endocrine disruption; environmental toxicity; photoprotection

Citation: Shamaya, A. N. S, Al-timimi, M. S & Rabea, M. j. Sunscreen Formulations: A Comprehensive Review of UV Filters, Safety, and Environmental Impact. American Journal Of Bioscience And Clinical Integrity 2026, 3(8), 1-15

Received: 10th May 2026
Revised: 27st Jun 2026
Accepted: 08th Jul 2026
Published: 05th Aug 2026

Introduction

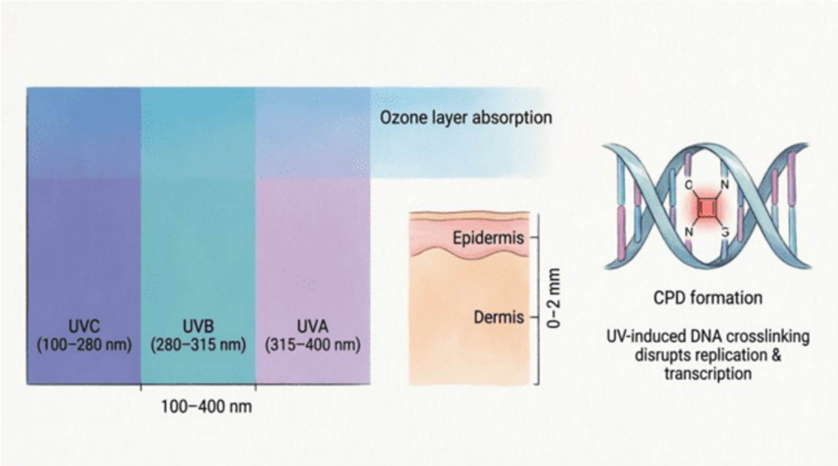

Figure 1. Classification of organic and inorganic UV filters used in sunscreen formulations.

Ultraviolet (UV) radiation is an unseen spectrum of light emitted from the sun. With a considerable part of the population globally exposed to UV radiation from sunlight on a daily basis, it can have significant harmful effects on the human body. There are two types of UV radiation: UV-B, which is responsible for sunlight-derived burns and cancer, and UV-A, which causes dermal photoaging and immunosuppression. Exposure to both forms of radiation can have severe results on the surface of the skin over time, forming sunspots, irregular pigmentation, and a greater risk of skin cancer. Sunscreen helps to protect against this damage by acting as an ultraviolet-absorbing molecule that scatters UV radiation away from the skin [1].The sunscreen market is currently estimated to be valued at USD 628 million in 2024, growing to an estimated USD 986 million by 2034 with a compound annual growth rate (CAGR) of 6.8%. With rising disposable incomes in mature markets, there is a higher willingness to pay for the best UV coverage, as well as a rising population concerned about the potential hazards of prolonged UV radiation exposure. However, sunscreen is an extremely competitive market that relies heavily on consumer perception of how good the product works and its effect on their skin. Consumers are unreasonable: they desire and expect their sunscreen to not only protect them from UV rays but also allow them to soak up the sun when it suits them without getting burned [2]. Various types of UV filters have been studied to be effective at achieving these goals in sunlight protection; however, as of late, some of these UV filters are coming under fire due to susceptibility to be absorbed into the bloodstream, resulting in outside regulatory scrutiny that the UV filter may not be safe or as beneficial.UV filters have also raised concerns regarding their safety profiles and environmental impact [3], [4]. Some common concerns include:

a. Environmental aspects of novel sunscreen filters and their ecological toxicity;
b. Endocrine disruption as a result of systemic absorption of some UV filters;
c. Safety concerns of common sunscreen filters in over-the-counter cosmetics and topically applied formulations.

Materials and Methods

As consumer demand for sun protection products continues to rise, environmental concerns have shifted the focus to the ingredients that deliver the promised protection. Of particular concern are the UV filters used in sunscreens, which many citizens and health organizations believe either damage the environment or are unsafe for human use. For the first time, we systematically analyzed the scientific literature on the safety and toxicity of UV filters marketed for use in sunscreens.

The goal of this review is to reassess the safety and toxicity of current UV filters based on a systematic literature search of recent data and discussions. Using established databases including PubMed, Scopus, Web of Science and Google Scholar, we performed a systematic search for the terms "UV filters," "sunscreen," "endocrine disruption," and "environmental toxicity." We extracted data on safety from the EWG Sunscreen Guide and regulatory assessments from the FDA, SCCS, TGA and IARC. We verified the chemicals through IUPAC and CAS. We referenced the manufacturers' specifications for the particles size. We referenced marine toxicology and studies of UV filter removal in wastewater studies for environmental impact. As we have learned from recent surveys, sunscreen consumers mistakenly believe that a higher SPF equals better protection despite scientific studies proving that the protection against UV damage does not scale with SPF. Moreover, it is believed that a 'waterproof' label means that avobenzone is protected and remains effective, which is incorrect. These prevailing misconceptions underscore the need for clear and honest product descriptions including chemical filters including their registration numbers, and their characteristics such as particle size (in the case of physical filters). In addition to these recommendations, we propose a standardization of the in vitro tests for the endocrine disrupting potential of chemicals. Using the same chemical parameters as discussed above, we expect to obtain reproducible and comparable results across laboratories. This should help ascertain the safety of chemicals and if needed implement a registration process focused on risk assessment. Taking these steps not only helps protect the environment, but also the safety of consumers.

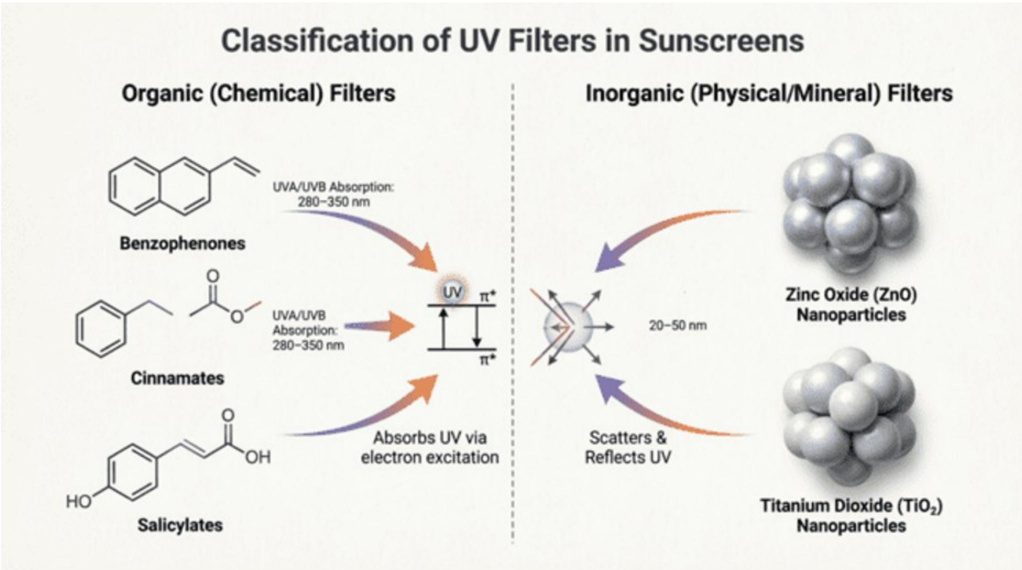

Figure 2. Chemical structures of common organic UV filters, including oxybenzone, octinoxate, avobenzone, octocrylene, and homosalate.

In the global UV filter market, organic UV filters (52.3%), characterized by their aromatic ring structures, and capable of conjugated π-electron systems, are by far predominant (Pérez-Gallego et al., 2021). These compounds absorb UV photons and do not reflect, as metallic or inorganic UV filters, but rather undergo an internal conversion process, which results in thermal dissipation of the absorbed energy. The efficacy of organic UV filters is mainly determined by several factors, such as their molar extinction coefficients, their absorption maxima and their photostability. Molar extinction coefficients are calculated using mathematical equations that derive from Beer-Lambert law and provide a measure of the intensity of the absorption of light by a certain molar concentration of the organic UV filter in a solution. High molar extinction coefficients are desired for the selection of efficient chemical UV filters.

Ultraviolet (UV) filters absorb UV radiation of solar spectrum or UV electromagnetic radiation of 280–315 nm by two compounds: organic compound and inorganic compound. Because of their ability of such light absorption, they are widely used in UV blocker for skin cosmetic product, especially for sunscreen skin protection cosmetic. UV filter chemical properties are crucial especially for organic compound, as they generally absorb UV electromagnetic radiation by outer shell electron movement which excited by the electromagnetic radiation. UVB filter commonly used in sunscreen are p-aminobenzoic acid (PABA) and derivatives, octyl methoxycinnamate (OMC), and ethylhexyl salicylate. PABA was one of the first topical skin sunblocks which used as a sunscreen. Nevertheless, PABA might cause allergic reaction in some people, making it less popular and its use is limited. OMC, widely used as a sunscreen, is an endocrine disruptor and environmental pollutant as it was detected in human fluids, surface water, and sediment. Ethylhexyl salicylate as a UVB filter has low absorption through skin, with the ability to enhance SPF of sunscreen and may have potential for increased dermal absorption in stable formulation.

Over the years, several UV filters (Table 1) have been developed, modified, and tested for cosmetic or dermatological applications, as well as regulations. Traditionally, UVB filters were synthesized and researched first, with the most well-known filter being Octyl methoxycinnamate (OMC), which has been part of several regulations since its development. The market then shifted to the development of UVA filters, prompted by the need for broad-spectrum photoprotection as the understanding of the harmful effects of UV radiation on human skin improved. To develop a broad-spectrum photoprotective formula, producers and formulators are increasingly interested in developing new-generation solar filters.

Octocrylene (CAS 6197-30-4) is a filter that was synthesized via Knoevenagel condensation, which gave rise to a compound that exhibited high photostability. As previously pointed out, an additional advantage of Octocrylene is that on diluting it with ethyl 4-(dimethylamino) benzoate (also known as Ethylhexyl methoxycinnamate), the photostability is increased along with protection for both UVB and short UVA spectra. Octocrylene is a global UV filter, meaning it is regulated for use by countries worldwide. However, the substance is also a potential endocrine disruptor, so it has been detected in human urine and even blood and breast milk. More recently, it was detected in the urine of human infants, for possibly coming from the mother's breast milk.

Interestingly, this water-soluble filter has also been implicated in the generation of reactive oxygen species and DNA alkylating properties in the skin, further explaining its potential as an endocrine disruptor as well as skin sensitizer.

Ensulizole is actually another water-soluble UVB filter that is small in molecular weight and can penetrate further into the dermis when compared to OMC. However, upon prolonged exposure, Ensulizole has also been shown to generate reactive oxygen species which induce changes in the skin, leading to ageing and the development of skin cancer, but that will only happen if it's in exposure to a UV radiation source. This property may also enable it to generate free radicals of its own and hence its purported skin sensitizing ability. However, Ensulizole remains one of the few UVB filters regulated by certain countries and is not approved in the United States.

4-Methylbenzylidene camphor (4-MBC; CAS 36861-47-9) is a chemical filter with strong absorption properties for short and long wavelength UVB. It is not regulated for use in the United States due to its association with estrogenic activity. While they are much older generation filters, they are essential in the production of a stable, efficacious, and broad-spectrum formula.

Both new generation and older generation UVA filters are essential in gradually producing photoprotective cosmetic formulations due to their high photostability and lack of reactive oxygen species generation, meaning they do not lead to skin damage. However, they are also associated with health and environmental concerns and are not only photoreactive, generating harmful species that lead to skin damage, but they do so in the absence of exposure to UV radiation.

For those who wish to avoid sun exposure while engaged in outdoor activities, sunscreen is not an option. Further, some think the only solution consists of sunblock formulations, pasty mixtures which are visible on the skin. As it turns out an another alternative exists, the use of physical sunblock in conjunction with broad-spectrum UV protection.

In this post I will present what is likely the most comprehensive examination of the advantages and disadvantages of chemical sunblock known to mankind. It is my hope that the information to be presented will assist you in making an informed decision as to what is the best approach to protecting your skin from UV rays today.

Benzophenone-3 (BP-3, CAS 131-57-7) was one of the first substances used in chemical sunscreen formulations. This ingredient is marketed under a variety of trade names and offers broad-spectrum UV protection, in particular UVB protection.

Of recent concern are suggested side effects associated with the use of benzophenone-3, or BP-3. These mainly relate to both endocrine disruption (mimicking estrogen) and environmental toxicity, especially as it relates to coral reefs. As a result, to their credit the state of Hawaii and territories Palau and the U.S. Virgin Islands have banned the use of sunscreen formulations which contain benzophenone-3. These regulations have logic and science to back them, with environmental concerns over coral reef degradation possibly trumping the need for sunblock.

Commonly, BP-3 is combined with other ingredients to attain a broader UV protection effectiveness. Such ingredients include octocrylene in those formulations which seek to counteract any photo-instability that BP-3 may cause. The combination of octocrylene is said to result in both improved UVB protection (of BP-3) and photostability, the tendency of both benzophenone-3 and octocrylene. In fact, the October 2019 publication "Colloids and Surfaces A: Physicochemical and Engineering Aspects" discusses how co-formulation with octocrylene counteracts BP-3's photounstable behavior (no definitive evidence is presented to support this, per se). The disadvantage of this particular combination is its overall environmental toxicity.

More recent replacements for other benzophenones - BP-3 and its derivatives - are anthranilates. This class of compounds is weak UVB absorbers and together cover the spectrum of UVA and UVB protection. Only one anthranilate is commercially available, Mexoryl SX (CAS 90457-82-2). This photostable UVA filter is currently marketed in the European Union (EU) and Canada, but not in the United States (though it has been approved by the FDA for use in formulations available for sale in the country).

For those with sensitive skin, this ingredient is the least irritating of those utilized in chemical sunscreen formulations. Further, its relatively low toxicity results in minimal skin penetration along with photostability.

Results

Table 1. Summary of organic UV filters: chemical classification, absorption characteristics, EWG hazard ratings, and key safety concerns.

UV Filter	Chemical Class	Absorption Range (nm)	EWG Hazard Rating	Key Safety Concerns
PABA	Aminobenzoic acid	280-315	7-10	Allergic contact dermatitis, photounstable
Octinoxate (OMC)	Cinnamate	280-320	7-10	Endocrine disruption, systemic absorption, ecotoxicity
Homosalate	Salicylate	295-315	7-9	Weak endocrine disruption, photodegradation to ROS
Octisalate	Salicylate	280-320	7-9	Enhances absorption of co-formulated filters
Octocrylene	Cyanoacrylate	280-320 (UVB), 290-375 (UVA2)	3-6	Photoallergen, endocrine disruption, generates benzophenone
Ensulizole	Benzimidazole	280-320	3-6	ROS generation, potential genotoxicity
4-MBC	Camphor derivative	280-320	7-10	Estrogenic activity, restricted

UV Filter	Chemical Class	Absorption Range (nm)	EWG Hazard Rating	Key Safety Concerns
				in several countries
Oxybenzone (BP-3)	Benzophenone	280-325 (UVB), 320-360 (UVA)	7-10	Endocrine disruption, coral bleaching, bioaccumulation
Avobenzone	Dibenzoylmethane	310-400	3-6	Photounstable, skin irritation, free radical generation
Mexoryl SX	Camphor sulfonic acid	320-360	1-2	Minimal concerns; not FDA-approved
Anthranilates	Aminobenzoate	320-340	3-6	Weak UVA protection

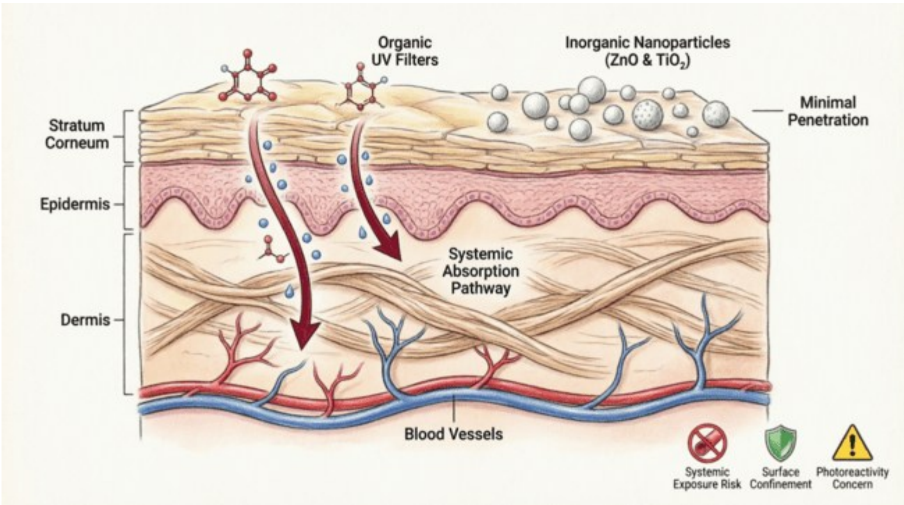

Figure 3. Schematic illustration of skin penetration pathways for organic UV filters compared with inorganic nanoparticles (ZnO and TiO_2).

Inorganic UV filters refer to compounds containing metals (e.g., zinc oxide, titanium dioxide), which work by reflecting, scattering, and absorbing UV radiation. This is the reason behind their preferred usage over organic filters due to their physical photoprotective property. They are considered safer than organic filters [5]. The inorganic UV filters contributes 38.1% of the total global UV filter market and they are gaining popularity due to growing consumer preference for mineral/physical sunscreens.

ZnO is an inorganic compound with the formula ZnO. It is a white, odorless powder. It can be in powder form (bulk zinc oxide, CAS 1314-13-2).

Zinc oxide is photostable, meaning it does not change chemically when exposed to the UV rays. It is a UV filter for UVB (280–315 nm) and UVA (315–400 nm). The efficacy of zinc oxide as a UV filter is affected by the particle size. For example, bulk ZnO (200–400 nm) to some extent scatters visible light, which gives it a white tint and thus may make sunscreens aesthetically less appealing (leaving a white film on the skin). There, however, a need for a higher density of ZnO particles in smaller sizes (many times less than what you need in bigger sizes) in order to achieve sufficient effectiveness [6]. The cosmetic industry's answer to this is to employ ZnO nanoparticles (20–50 nm), because they are smaller in size and thus cause less scattering of visible light.

Widespread use of ZnO NPs in the cosmetic industry started when the US Food and Drug Administration (FDA) classified it in 2012 as generally recognised as safe and effective (GRASE) for use as topical sunscreens and creams. According to the FDA, products containing up to 25% zinc oxide as the active ingredient are safe and effective.

All cosmetic manufacturers are required to conduct safety assessments to demonstrate the safety of the use of a cosmetic product, so some studies are available on ZnO NP safety. It was found in a number of studies that ZnO nanoparticles remain in the stratum corneum, meaning they do not penetrate through the skin. A review released on behalf of the Therapeutic Goods Administration (TGA) in Australia on the safety of ZnO and titanium dioxide (TiO_2) NPs used in sunscreens found that the NPs would need to be absorbed into the body to cause harm and therefore concluded that there is no evidence of harm from TiO_2 or ZnO NPs in sunscreens [7]. Concerns regarding the potential generation of reactive oxidative species (ROS) by ZnO NPs were also raised, which may cause oxidative stress; however, this risk is being actively mitigated through the use of surface coatings on the ZnO NPs to prevent the access of UV light to the NPs in addition to the use of antioxidants in topical products.

Titanium dioxide (CAS 13463-67-7) exists in three crystalline polymorphs: rutile, anatase, and brookite. Rutile is the most thermodynamically stable form and is predominantly used in sunscreen formulations, either as pure rutile or as a rutile-anatase mixture [8], [9], [10]. TiO_2 has a bandgap of 3.0 eV (rutile) or 3.2 eV (anatase), enabling absorption of UVB and UVA2 radiation. The anatase form is significantly more photocatalytically active, generating up to six times more reactive oxygen species than rutile upon UV exposure, and is therefore rarely used alone in cosmetic applications [11].

Similar to ZnO, TiO_2 nanoparticles (typically 20–50 nm primary particle size) are used to create transparent sunscreen formulations. The SCCS has concluded that nanosized TiO_2 at concentrations up to 25% "can be considered to not pose any risk of adverse effects to humans after application on healthy, intact or sunburnt skin" [12]. However, the International Agency for Research on Cancer (IARC) has classified TiO_2 as possibly carcinogenic to humans (Group 2B) when inhaled in occupational settings, primarily based on evidence of respiratory tract cancer in rats exposed to high concentrations of ultrafine TiO_2 dust [13]. This classification does not apply to dermal exposure from sunscreen use.

While predecessor tanning agents and chemical (organic) filters are effective in providing effective sun protection for the skin, their biggest drawback is that they undergo chemical transformation after absorption of UV radiation and that there is a time lag between UV absorption and skin protection. Therefore, physical (inorganic) filters like titanium dioxide and zinc oxides have become available in sunscreen formulations [14]. Since physical filters preferentially scatter UV photons in different angles, this effect is very informative in the formulation of sunscreens containing both active agents. This fact was shown through the synergy effect of organic and inorganic filters within sunscreens and through the Monte Carlo Simulation and modified fluorescence spectroscopy by Lademann. This synergistic mechanism between both types of filters increases the absorption efficiency of organic filters, which greatly increases their UV protection potential against UV radiation, especially against UVB in terms of higher SPF values than calculated under simplistic additive models [15]. This effect was recently confirmed by Ezekwe and colleagues who showed that tinted inorganic sunscreens containing iron oxides could provide better protection against UVA1 radiation and visible light than ordinary physical sunscreens alon High utilization of sunscreen led to safety concerns on both health and the environment. Concerns about the health impact of UV filters arise from the continuous rise of their systemic absorption, potentially interacting with endocrine system, thus raised their endocrine-disrupting potential. Environmental toxicity of these UV filters in various aquatic organisms arises from their continuous and increased usage, entering the aquatic ecosystem without treatment and filtration, thus led to their accumulation [16]. Some may also have potential to be photodegraded into other substances. Initial studies indicated that organic UV filters are more toxic than inorganic UV filters. However, other studies indicated otherwise. Studies also showed that the toxicity of organic UV filters are strongly influenced by their phototransformation products (products formed as a result of chemical changes on UV filters when they are exposed to sunlight [17]. It is important to note that organic and inorganic UV filters significantly differ in terms of their properties.

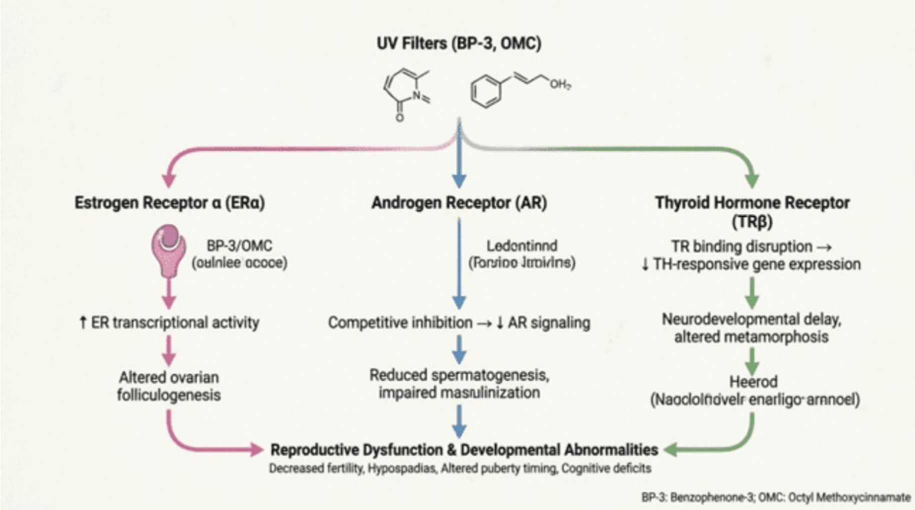

Figure 4. Proposed endocrine-disrupting mechanisms of selected organic UV filters involving estrogen, androgen, and thyroid hormone receptors.

Recent studies have contributed to a better understanding of the endocrine-disrupting potential of some organic UV filters. The best studied, benzophenone-3 (oxybenzone), was shown to have estrogenic, anti-androgenic, and thyroid-disrupting activities [18]. The compound also has the potential to induce cytotoxicity in estrogen-responsive MCF-7 breast cancer cells and to stimulate proliferation of this cell line [19]. Other UV filters are likewise suspected of disturbing human hormone homeostasis, e.g., octocrylene and octinoxate. To date, a limited number of studies have investigated the impact of UV filters on human reproduction and fertility, although the results were alarming. Disruption of human sperm function in vitro was observed for octocrylene and benzophenone-3 [20]. Currently, the fate of organic UV filters in human body has not been extensively studied. The increased potential for dermal penetration indicates that organic UV filters may be absorbed and enter the systemic circulation. Indeed, these compounds have been detected in urine, blood, and breast milk [21].

The issue of organic UV filters' effects on skin cells is even more troubling. Many of these compounds – including ensulizole, BP-3, and octocrylene – create reactive oxygen species (ROS), which cause photodegradation, creating 'free radicals'. Their mechanisms enable them to penetrate skin layers, where they continue to cause damage. For example, octocrylene leaves the skin and is phototransformed into benzophenone, which is also a known carcinogen (as well as an endocrine disruptor).

Another source of ROS is uncoated anatase TiO_2, which is commonly used in modern sunscreens. These particles create ROS when exposed to UV rays, leading to cell damage or cell death. Because of this, most modern formulations use additional coatings (often silica, alumina, or dimethicone) and antioxidants to mitigate modern formulations' potential dangers [22].

However, the TGA (Therapeutic Goods Administration, Australia) recently released a review on managing the use of coated nanoparticles. In very clear terms, this review states that the amount of ROS these nanoparticles generate is negligible enough to be neutralised under normal circumstances – ie: under use [23]. This effectively means that the use of coated nanoparticles is recommended, as they have no risk and provide the additional benefit of light scattering.

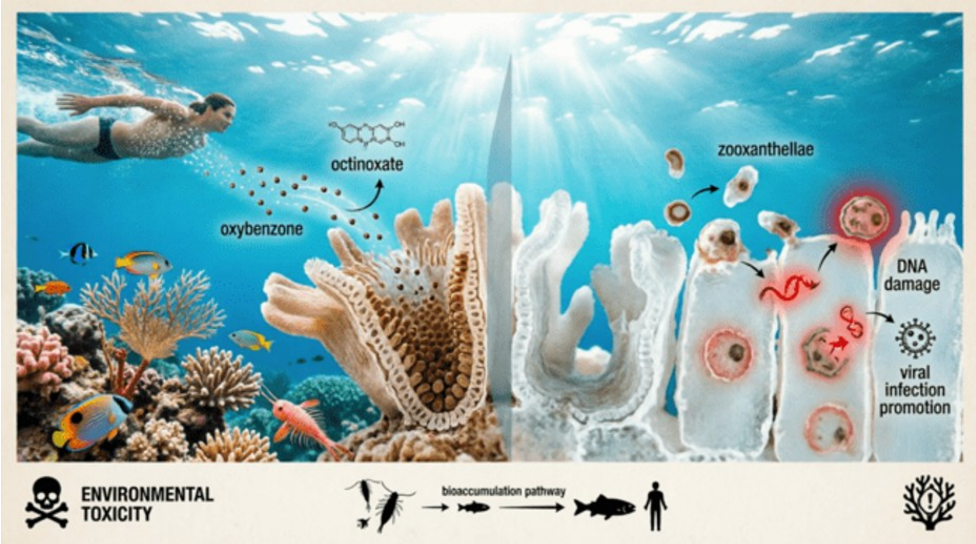

Figure 5. Environmental impact of organic UV filters on coral reefs and marine ecosystems, including bioaccumulation and DNA damage.

About 25% of the sunscreen applied onto the skin of human body is washed off into the seas during sea bathing [24]. Hence, even with an estimated sunscreen use of 0.8g/(m^2.body), daily from 1,000 visitors, an excess of 35 kilograms of sunscreen are deposited naturally from human into the delicate marine ecosystems. Hence, even minute concentrations of chemicals utilized in sunscreen products can significantly affect animal species in the oceans [25]. Indeed, organic UV filters have been detected in marine and freshwater systems and even in trophic levels of marine environments [26]. Such organic filters include benzophenone-3 (BP-3), which has been proposed as a potential promotor of viral infections in coral reefs and is on the watch-list of European Chemical Agency (ECHA) due to its suspected endocrine-disrupting properties and the damage it inflicts upon human ecosystems [27]. As a result, many nations have imposed bans on UV filters in the product they sell, including Octinoxate, due to their suspected disruptor effects on marine fish populations [28]. Some resorts have also imposed bans on as a result of their negative impact on the marine ecosystems [29]. Organic filters are more commonly used in sunscreen products, as they are seen as more efficient for sunscreening purposes than inorganic ones, such as ZnO and TiO_2 [30]. While the latter has been shown to have lower toxicity and thus less risk for the environment, other characteristics of these compounds, including that in nanoparticle formulations may pose significant risks to marine ecosystems [31], [32], [33], [34], [35], [36], [37].

5.4 Allergic and Photoallergic Reactions

Meyer et al. reported on contact dermatitis associated with organic UV filters (compound group). Both Scheuer and Warshaw and Warshaw et al. document cases of sunscreen allergy (originally to PABA, now to benzophenones, cinnamates, and octocrylene) in the literature [38], [39]. Warshaw et al. reported allergy in 219 of 23,908 participants (0.9%). It is possible to explain the incidence of allergic reactions to organic UV filters as follows: 1. Previously, PABA would have given rise to allergic reactions, but modern formulations exclude this chemical. 2. At the time, people might have been more inclined to seek medical advice about sunscreen use, but nowadays, organic UV filter deliver everyday products [40], [41], [42], [43].

Zinc oxide and titanium dioxide nanoparticles are not known to be harmful when they are applied to the skin. However, there is concern about the health risks of inhaling these ingredients when they are in powdered or spray formulations. This may be particularly concerning for people who work with powdered sunscreen (the ingredients are often in the form of powders). The concern stems from the limited lung clearance of particles less than 100 nm in size [44], [45], [46]. The International Agency for Research on Cancer (IARC) classifies TiO_2 as possibly carcinogenic in humans (Group 2B), making others raise additional concerns about inhalation exposure. Both the SCCS and EWG have warned against the use of powdered and aerosol formulations and recommend the use of lotion or cream formulations instead [47], [48], [49], [50].

Discussion

Currently, the paradigm of preventing skin damage and preserving biodiversity requires re-evaluation on several fronts. Sunscreens are one of several consumer cosmetics that offer pharmacological protection against UV but potentially at a considerably high cost for both the individual and the environment [51]. Importantly, the risk-benefit profile of UV filters should consider health and environmental implications before regulatory decisions.

The systemic absorption and health impact of organic UV filters has been studied extensively but remains heavily contested and poorly understood [52]. Some claims of endocrine disruption have not held in clinical prospective studies and "sunscreen mammalian carcass" analysis of organic filters as estrogen mimics in vivo raises questions on their real systemic dangers [53]. Environmental toxicity of some organic UV filters has also been established in the literature; however, the concentration of filters released through topical application is likely to be overestimated compared to commercial formulations with inbuilt safety data.

Interspecies estimation is fraught with uncertainty and sunscreen studies tend to target reef-building corals as these are already considered susceptible. Together with stressors such as excessive light and elevated temperature from climate change, the threat of UV filters may prove too great [54], [55]. Depending on management, these reefs may not be therefore protected from the dangers of constituents in sunscreen.

That said, systemic exposure and ecological risk should not be entirely dismissed. The very real potential for the former will intensify as climate change deteriorates global health. This will put even more challenge on the safety classification of these compounds for personal and environmental health. The rise of "reef-safe" sunscreens, biodegradable options and encapsulation technologies to eliminate ecotoxicity underscore the very real compromise of sustainability with environment and health [56], [57], [58]. Last but not least, the need for ecotoxicology studies will be made necessary by regulatory actions (e.g., bans in Hawaii, Palau) to ensure that an environmentally-conscious market does not landscape with dubious ingredients instead. In comparison, many inorganic filters such as ZnO and TiO_2 currently remain solubilised in sunscreens and generate a higher likelihood of photodegradation via free radicals, hence being considered safer with respect of dermal retention by stratum corneum [59], [60].

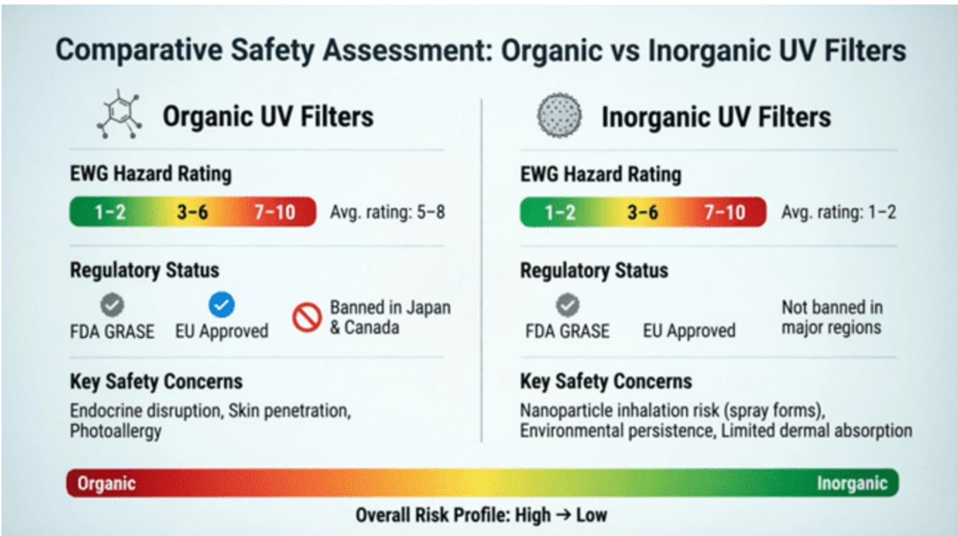

Figure 6. Comparative safety assessment of organic and inorganic UV filters based on hazard ratings, regulatory status, and key safety concerns

Table 2. Comparative toxicity assessment of UV filters based on EWG hazard ratings, regulatory status, and primary safety concerns.

UV Filter	EWG Hazard Rating	Regulatory Status	Primary Concerns
Oxybenzone (BP-3)	7–10 (High Danger)	Banned in HI, Palau, USVI; EU limit 2.2%	Endocrine disruption, coral bleaching, bioaccumulation
Octinoxate (OMC)	7–10 (High Danger)	Banned in HI, Palau, Key West	Systemic absorption, ecotoxicity, breast milk detection
Homosalate	7–9 (High Danger)	Under EU SCCS review	Weak endocrine disruption, photodegradation
Octisalate	7–9 (High Danger)	FDA-approved; under review	Enhances absorption of other filters
Octocrylene	3–6 (Medium Danger)	FDA-approved	Photoallergen, generates benzophenone upon degradation
Ensulizole	3–6 (Medium Danger)	FDA-approved	ROS generation, potential genotoxicity
Avobenzone	3–6 (Medium Danger)	FDA-approved	Photounstable, requires stabilizers
Mexoryl SX	1–2 (Low Danger)	EU/Canada approved; not FDA-approved	Limited availability in US market
Titanium Dioxide (nano)	1–2 (Low Danger)	FDA GRASE; EU SCCS approved up to 25%	Inhalation risk (occupational); IARC Group 2B
Zinc Oxide (nano)	1–2 (Low Danger)	FDA GRASE; EU SCCS approved up to 25%	Minimal concerns; inhalation risk for spray products

Conclusion

It is well-established that sunscreens can help protect skin from damaging UVA and UVB rays associated with skin cancer, photoaging, and other skin conditions. But these products can also contain chemical UV filters posing health and environmental risks that cannot be ignored. In recent years, the safety of these ingredients is garnering increasing scientific scrutiny and regulatory actions worldwide. For consumers, the choice should be clear: protect your skin with safe, effective sunscreens containing non-toxic, biodegradable ingredients. Many sunscreen formulas contain organic filters like oxybenzone, octinoxate, homosalate, and octisalate. When used on the skin, each of these UV filters may cause adverse health effects including hormonal effects like endocrine disruption, which can lead to adverse systemic effects from absorbance through the skin, photodegradation into toxic components upon UV exposure, and ecotoxicity from leaching into aquatic ecosystems after use. Not only are organic filters potentially harmful, but they also endanger the health of unborn children and infants. Various authorities, such as the U.S. Food and Drug Administration (FDA), the Scientific Committee on Consumer Safety (SCCS), and the Australian Department of Health Therapeutic Goods Administration (TGA) have labeled sunscreens containing these minerals as Generally Recognized As Safe And Effective (Other exemptions exist for certain countries, but these minerals remain fine to use in effective mineral sunscreens.) Low-dose exposure during pregnancy and childhood can have a significant effect on the health of future generations and should therefore be investigated with more vigilance. To accomplish these goals, standardized methods to assess cellular uptake and bioavailability of nanoparticles will need to be devised, and the safety of these nanoparticles should be carefully evaluated prior to use in humans.While screening for proper safety standards has become the norm, the field of environmental science has yet to develop prevailing methods to ascertain the safety of nanoparticles in wastewater systems. As such, attempts to properly characterize the specific environmental fate, persistence, and resulting ecotoxicity of these nanoparticles will be necessary not only for the continued protection of marine ecosystems but also in minimizing the unintended effects on freshwater ecosystems, both of which are crucial to public health. As more individuals become aware of the risks associated with UV exposure, the rate of public health campaigns promoting photoprotection will undoubtedly continue to increase. Improvements in the safety profiles for UV filters, particularly with regards to systemic absorption, and the provision of consumer education and further elucidation of the mechanisms by which these UV filters exert their adverse effects will serve to bolster the growing public health campaigns. By doing so, the industry will not only satisfy consumer demand for safer alternatives, but it will also enable the long-term viability of UV filters and the ever-growing market of photoprotection.

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