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REVIEW ARTICLE

Skin protection from solar ultraviolet radiation using natural compounds: a review

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Abstract

Skin exposure to solar ultraviolet radiation and pollutants causes several skin disorders, calling for protection methods such as sunscreen application. However, common sunscreen contains chemicals that have displayed toxicity when exposed to ultraviolet radiation. Therefore, alternatives approaches have been recently developed, such as the use of natural phytochemicals as active ingredients in photoprotection preparations. Here, we review skin protection with focus on the physics of ultraviolet radiation and photoprotection by ultraviolet filters. We present sensors for measuring ultraviolet radiation and ultraviolet radiation in ecosystems. We discuss the phototoxicity of drugs, preservatives, personal care products, and pollutants. Photocarcinogenesis, photoallergy, photostability, and toxicity of sunscreen ingredients and their impacts on human health and skin, are also reviewed. We observed that phytochemicals are promising for photoprotection due to their ability to absorb photon energy, and thus act as antioxidants.

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Introduction

The use of personal care products, especially protective ultraviolet agents, has witnessed an unprecedented global rise in protecting the human skin from various health risk concerns due to increasing climate change. However, the ecological and environmental consequences of using these agents are often overlooked, which could indirectly cause harmful threats to the ecosystem, especially marine life (Anand et al. 2022a). A general understanding of the measure of the lifetime exposure of human beings as it relates to human health from birth to death is defined by the exposome (Ajibade et al. 2021). Interestingly, the most significant kind of exposure from a list of diet, lifestyle, and occupational hazards is the exposure to ultraviolet radiation emanating mainly from the sun and a few other less significant artificial sources such as tanning beds, halogen and incandescent lights, lasers, and mercury vapor lightings predominant in stadia and school gymnasia. Excessive anthropogenic pollution has enhanced the continuous depletion of the stratospheric ozone layer globally, thereby subjecting all biotic and abiotic elements to harmful ultraviolet radiation in the ecosystem (Ali and Khan 2017).

Among other radiations, sunlight emits ultraviolet, corresponding to the wavelength range of 100–400 nm, visible light, with a wavelength from 400 to 700 nm, and infrared radiation, falling in the wavelength range of 700 nm to 1 mm. Based on their biological effects, the ultraviolet component of the electromagnetic spectrum is split into three categories: UV-A radiation corresponding to long wave 320–400 nm, UV-B radiation falling in the mid-wave 290–320 nm and UV-C radiation the short wave 200–290 nm (Katiyar 2016). UV-A and UV-B have photobiologic characteristics that change over time. Even though the sun produces a lot of ultraviolet radiation, only 5% of it reaches the earth's surface in the ultraviolet spectrum, corresponding to 96.65% UV-A and 3.35% UV-B, with UV-C virtually undetectable (Rünger et al. 2012). Indeed, the stratospheric ozone layer generally filters high-energy UV-C light. Terrestrial organisms constantly face exposure not only to natural environmental factors like ultraviolet radiation but also to pollutants originating from human activities. The skin is the body's largest organ and plays a crucial role as the primary interface with the external environment. It is responsible for protecting us from physical and chemical influences that could potentially impact the body's various functions. The skin acts as a metabolic defensive barrier, preventing ultraviolet radiation from penetrating deeper tissues (Patel et al. 2021). However, chronic exposure to solar ultraviolet radiation, especially UV-A and UV-B, generates oxidative stress and induces skin damage. UV-B radiation has the ability to traverse the entire epidermis layer and reach the dermis compartment of the human skin, as represented in Fig. 1 (Romanhole et al. 2015; WHO Newsroom 2016).

This photooxidative stress leads to sunburn, erythema, edema, and phototoxic reactions, such as photoallergy, photosensitivity, photoaging, and photocarcinogenesis, via numerous pathways (Sardoiwala et al. 2018). On the other hand, it is well documented that the effects of ultraviolet radiation on the skin can indirectly affect the skin microbiota

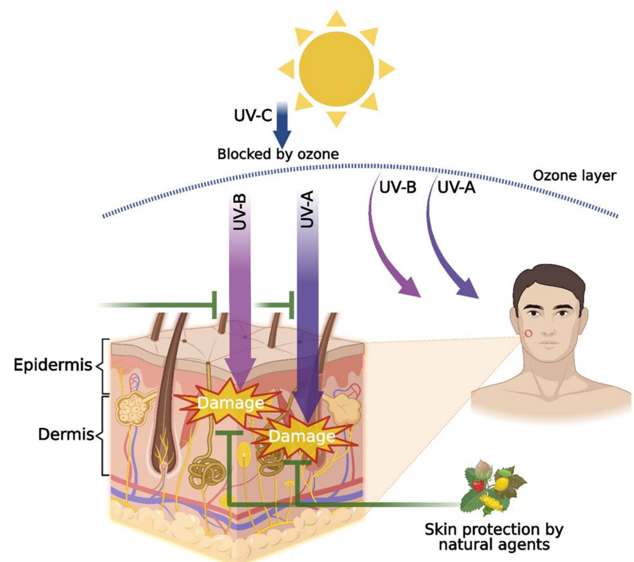

Fig. 1 Penetration of the skin by ultraviolet radiation of different wavelengths. The ultraviolet radiation spectrum that reaches the earth's surface is categorized into medium wavelength (UV-B) and long wavelength (UV-A); 95% of this total ultraviolet radiation is UV-A. The biological activity of UV categories, i.e., the damaging effect on the skin is largely based on their wavelength such that the shorter the wavelength, the more harmful the radiation on the skin. Despite its high level of biological activity, the UV-B does not penetrate beyond the superficial skin layers (epidermal cell components, e.g., proteins or DNA), thus responsible for the delayed tanning and burning effects. Besides, most UV-B is filtered or absorbed by the ozone and other components of the atmosphere as sunlight passes through the atmosphere. The UV-A, however, has the capability to penetrate deeper into the skin, reaching the basal layer of the epidermis and even extending to the dermal fibroblasts, thus responsible for the immediate tanning effect while contributing to skin aging and wrinkling. Additionally, natural substances (phytochemicals) protect the skin from the damaging effects of ultraviolet radiation (green arrow). The image was formed with the assistance of https://biorender.com

(Farghali et al. 2022). Ultraviolet radiation has been shown to alter the composition and activity of the microbiota, as well as modulate cellular response and immunological function (Patra et al. 2019).

Moreover, photoprotection is a biological mechanism that aids organisms in coping with the cellular and molecular damage induced by sun radiation. Physical ultraviolet filters, such as sunglasses and sun clothing, and chemical ultraviolet filters, such as sunscreen lotions, are both useful, but they do not offer comprehensive protection (D'Orazio et al. 2013; Ruszkiewicz et al. 2017; Garnacho Saucedo et al. 2020; Sabzevari et al. 2021). Sunscreen, often known as a sun blocker, protects against sunburn by absorbing or reflecting some of the sun's ultraviolet radiation. However, several studies reported that several sunscreen ingredients become photosensitive and unstable under exposure to ultraviolet radiation. Photosensitized sunscreen agents lose their protection efficacy, trigger phototoxic reactions and induce skin cell damage (Gonçalo 2011; Amar et al. 2015). As a result, physical and chemical measures of photoprotection are insufficient, and an alternative is necessary.

To emphasize the importance of the knowledge of ultraviolet radiation's effect on the environment and human skin, Krutmann et al. (2017) and Passeron et al. (2020) identified several factors such as solar radiation, ultraviolet, infrared and visible light, air pollution, weather condition, personal life attributes like stress, tobacco use, sleeping habits, among others that influence human health and skin conditions. The highlighted factors serve as a connecting pathway for diseases in humans, especially skin cancer, thermal discomfort, and untimely skin aging (Ivanov et al. 2018). Sunlight exposure could accelerate skin-related damage regardless of the time or season of the year, especially in the tropics (Correa et al. 2021). Skin cancer development is multifactorial (it can be caused by working with chemicals, the human papillomavirus or a weakened immune system). Still, ultraviolet radiation is the most important risk factor for skin cancer.

Recently, photoprotection findings have been solely focused on sunscreen technologies for avoiding exposure to the ultraviolet spectral range of 200–400 nm while failing to identify the ultraviolet range that offers beneficial gains to humans and the environment at large (de Assis et al. 2021). Sunscreen technologies attempt to reduce ultraviolet-induced skin cancer by absorbing, scattering or reflecting radiation (Tosato et al. 2016). Sadly, most sunscreen formulations contain organic and inorganic ultraviolet filters that are non-biodegradable in marine and terrestrial ecosystems. Epidemiological studies have reported reinvigoration of skin cells during sunbathing, vitamin D therapy, and

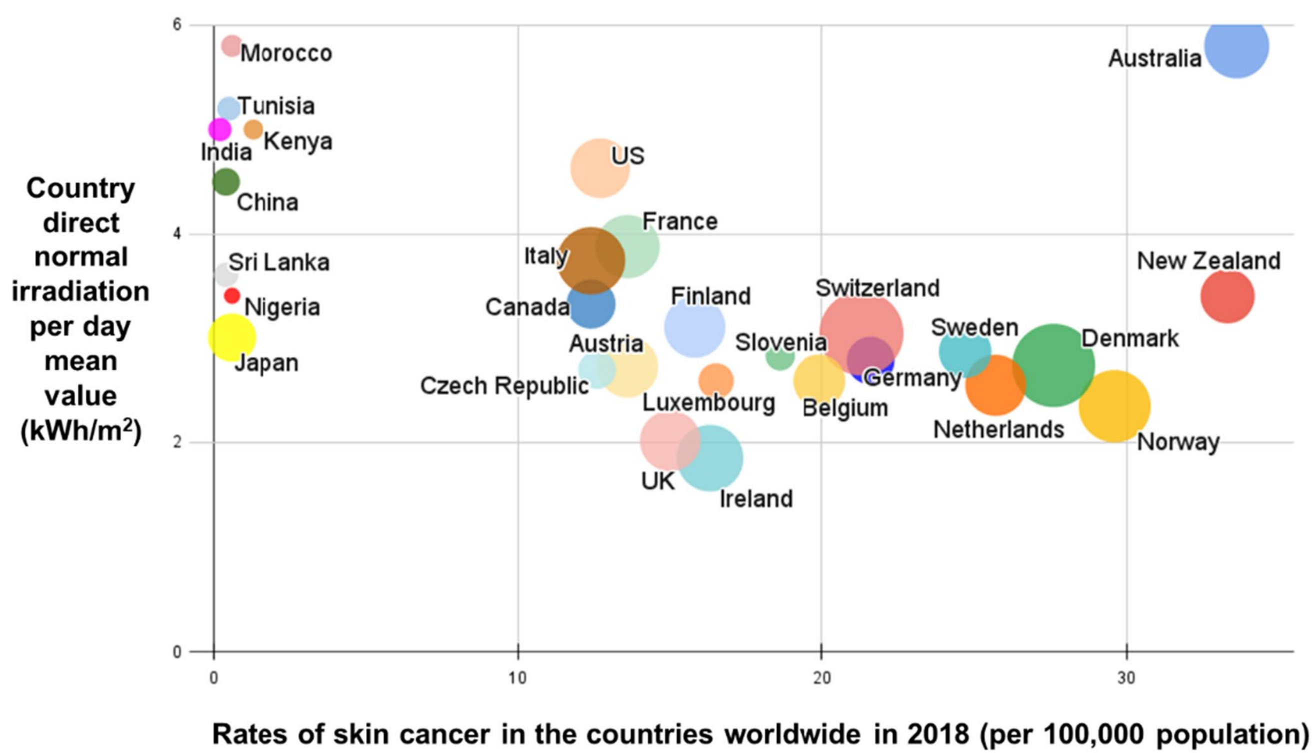

Fig. 2 Country direct normal irradiation per day mean value (kWh/m^2) versus rates of skin cancer in the countries worldwide in 2018 (per 100,000 population) (source: WCRF International 2018). The point dimensions represent the average revenue per capita in the sun protection market ($) for different world countries

moderate solar exposure for prolonged youthful look treatment (Arnold et al. 2018; Cohen et al. 2020).

Figure 2 shows the relation between the rates of skin cancer in the countries worldwide in 2018 (per 100,000 population) and the country irradiation per day mean (KWh/m^2). The points dimension represents the average revenue per capita in the sun protection market ($). Australia has the highest irradiation per day mean and the highest rate skin of cancer. The Nordic countries (such as Norway, Denmark and Sweden) have a higher rate of skin cancer (ranging from 25 to 34 per 100,000 population), despite an average radiation level (2.3–3.4 KWh/m^2) and a consistent use of sun protection products. This is probably due to skin that is more sensitive to solar radiation. On the contrary, Asian and African countries have a lower rate of skin cancer.

Sunscreen users have become increasingly interested in its composition and have found it made of synthetic materials, which pose a threat to aquatic life, eco-friendliness, eco-sustainability, and human health at large (Milito et al. 2021). Evidence is found in the ban of some ultraviolet synthetic filter sunscreens containing octyl methoxycinnamate (octinoxate) and benzophenone-3 (oxybenzone) from distribution and sale in Hawaii in January 2021 and other parts of Mexico, Palau, and the Caribbeans (Zen Life and Travel, 2022). Early pioneers in photochemistry have also verified that harm committed by visible light in other wavelengths is quite enormous, and protection against visible light must not be handled with levity (Halliday et al. 2005; Niida and Nakanishi 2006).

Although people with darker skin complexion experience less noticeable erythema symptoms manifest as redness of the skin or sunburn upon longer sunlight exposure, it is appropriate to say that carcinogenic threats and DNA damage can appear as malignant as those affecting people of lighter skin tones.

Abundant melanin pigmentation and thicker dermis layer might help to shroud wrinkles, but indirect DNA lesions and oxidative stress are catalyzed by the availability of more melanin pigments (Lee 2021). Inadequate sunlight exposure induces the prevalence of cardio-metabolic diseases, resulting in low vitamin D synthesis in Africans and Asians residing in temperate regions (Davis

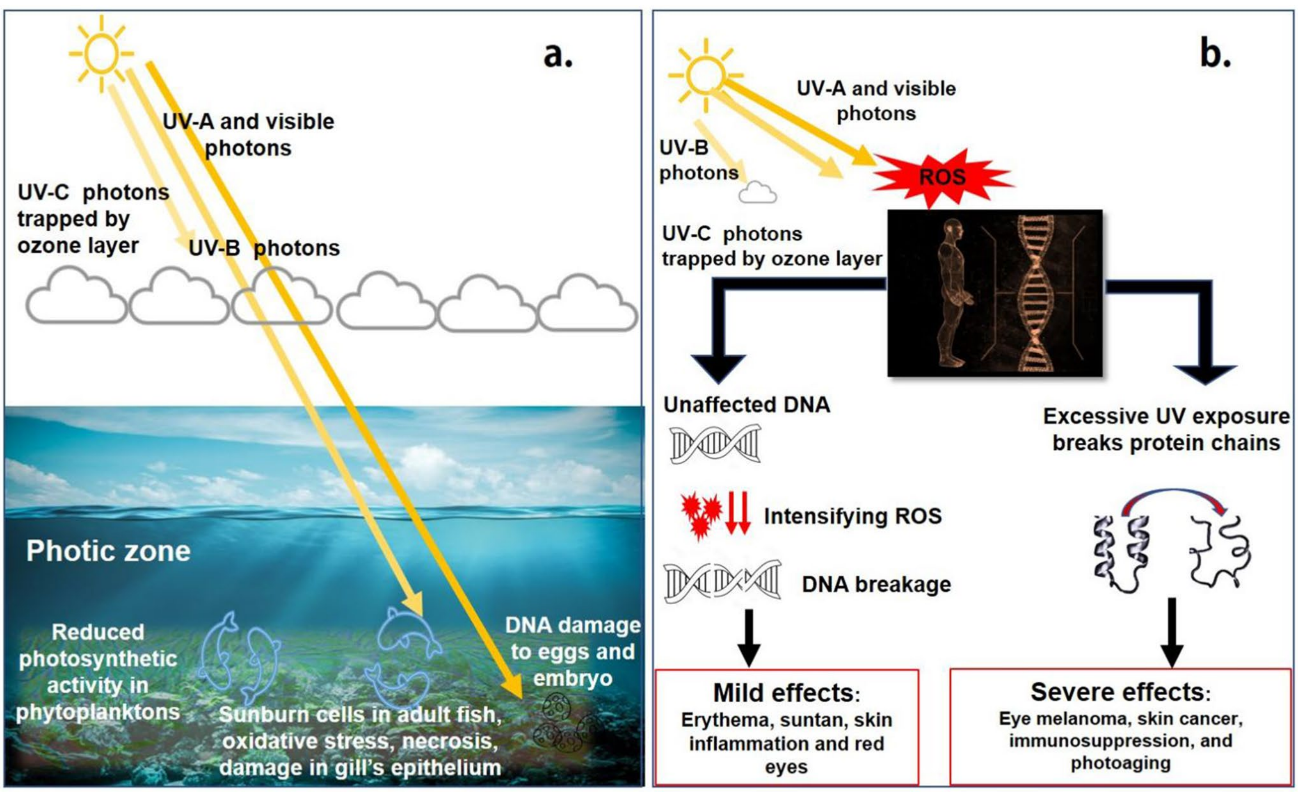

Fig. 3 Multispectral effect of ultraviolet radiation on receptor organisms such as **a** fish and phytoplankton, and **b** humans in both aquatic and terrestrial habitats, respectively. Both figures show an interception of UV-C photons by cloud formation while the UV-A and UV-B spectrums penetrate beyond the photic zone in the river and ocean beds to induce DNA damage to eggs and embryos and obstruct photosynthetic pathways in phytoplankton's metabolic activities. In humans, a dramatic increase in reactive oxygen species (ROS) during ultraviolet radiation exposure could break the DNA and cause skin erythema in mammals. Further exposure could also enhance photoaging and skin cancer while an accumulation of intense ultraviolet radiation within the 280–320 nm range could cause necrosis in humans and oxidative stress and gill damage in adult fish (Artyukhov et al. 2014; Shokrollahi Barough et al. 2015)

2011). Therefore, to maintain a tradeoff, there is a need to enjoin people with darker skin tones to enjoy some considerable sunlight exposure and embrace other photoprotection approaches to reduce the deleterious effects of solar radiation on human health and the environment. A great emphasis is laid on exploring the photoprotective potentials of natural agents and plant materials to achieve better performance than conventional sunscreens (Anand et al. 2022b). Figure 3 shows an overview of the effect of ultraviolet radiation on the environment, human health, and ecosystem.

Considering the increasing danger posed by the use of photoprotection that contains synthetic chemicals as sunscreens on both the ecosystem and human health, the paradigm shift toward the use of natural agents and plant materials as phytochemical alternatives to sunscreens is currently gaining momentum globally (Anand et al. 2022b). The adoption of these new materials forms the hypothesis of our research. External aggressors attacking the human body, particularly the human skin and the environment, can be mitigated significantly using efficient natural phytochemicals as active ingredients for photoprotection. To our knowledge, there are limited comprehensive review studies that specifically investigated the alternative materials as well as new approaches to overcome the negative effects of using photoprotection, including protective ultraviolet agents made from synthetic materials on human health and the ecosystem. This study aims to explore the applicability of several natural agents and plant materials as photoprotectants and their effects on human health and the environment. A systematic literature review was adopted to comprehensively assess and synthesize the available literature regarding photoprotection and associated impacts on human health and the environment. This work presents state-of-the-art knowledge on photoprotection to fill the information gap on this important topic and set the tone for future research on the use of alternative materials.

Physics of ultraviolet radiation

High-energy UV-C radiation gets absorbed by the stratospheric ozone layer. However, the characteristics of solar ultraviolet radiation depend on various factors, with the solar zenith angle being particularly significant. This angle varies with the time of day, season, stratospheric ozone concentration, pollution, cloud cover, as well as latitude and altitude. The measurement of ambient solar ultraviolet radiation has been conducted worldwide for many years. Furthermore, specialized ultraviolet radiation detectors have been developed for research purposes or individual use. For instance, a microprocessor-controlled ultraviolet radiometer has been created, equipped with short, mid- and long wave ultraviolet sensors, enabling precise measurement of solar irradiance. The intensity of ultraviolet radiation refers to the ultraviolet intensity and is measured in mW/cm^2 (Goyal et al. 2015; Verma et al. 2017). The dose of light is defined as the quantity of ultraviolet or visible radiation incident on a surface, measured in Joules per centimeter square or Joules per meter square.

Advances in sensor technology for ultraviolet radiation measurement

Recent advances in the field of remote sensing and sensor development for environmental protection and health studies have extensively focused on integrating artificial intelligence with sensor technology for combating erythema, cardiovascular diseases, skin cancer, ultraviolet-induced eye defects and premature aging. Commendable recent evolution of nano- and miniaturized electronics has spurred further development of portable sensors embedded in textiles, fabrics, wearables, patches and implants to serve as either photosensitive film-based sensing devices or electronic integrated sensors (Huang and Chalmers 2021). Photosensitive film sensors are photodegradable by incident photon energy while electronic integrated sensors create an electrical current. Typical examples of these two categories are dosimeters and radiometers. Ultraviolet dosimeter or radiometer sensors are always coupled with auxiliary electronics on a printed circuit board to generate spectral responses enough to repeal ultraviolet radiation and their applicability may be enhanced by including filters to trap infrared and visible light (Grandahl et al. 2017). Skin-mounted patches and electronic sensors are quite prevalent in modern sensor markets. While the former is relatively cheaper and sunscreen-compatible, the latter is quite durable.

As a public tool for sunlight protection, ultraviolet sensors are integrated with mobile phone apps to serve as a graphical user interface for monitoring erythema dangers. It is insightful to incorporate thin ultraviolet filter films to produce several color rate changes in photosensitive film-based sensing devices. In another study, Park et al. (2019) developed a portable ultraviolet sensor with the erythemally weighted UV-B ratio using natural light. With a combination of an ultraviolet index sensor, microcontroller unit and Bluetooth module, sunburn intensity was measured, calibrated and transmitted. Validated outputs from a standard spectrometer showed promising results and indicated that the technology is adequate to quantify potential risk and damage due to ultraviolet exposure. As the field of nanotechnology expands and new knowledge is being discovered, there is a very interesting prospect for ultraviolet sensor technology.

Ultraviolet radiation in ecosystems

About 52% of the reviewed articles, as shown in the Supplementary Material, addressed the impacts of ultraviolet radiation on biotic and abiotic environments, with major reports bordering on marine/aquatic life responses to the ultraviolet effect. Generally, ultraviolet radiation in form of UV-A and UV-B penetrates beyond the stratospheric ozone layer and delivers both beneficial and adverse effects on human health, plants, air quality, biogeochemical systems, and aquatic and terrestrial ecosystems. These effects are consequential returns brought about by anthropogenic activities inducing devastating climate change effects due to ozone layer depletion. Numerous countries are embracing policies aimed at interdicting the use of chemicals and substances that deplete the ozone layer while consistently manufacturing biodegradable radiation absorbents. A typical example of such act is the Montreal Protocol signed by over ninety-seven countries of the world, with a significant reduction in trichloromethane emissions in member countries (Montzka et al. 2018).

Bernhard et al. (2020) reported that changes in ultraviolet radiation during the last twenty years have been generally minimal, resulting in less than 4% in a decade. The authors substantiated this by reporting that trend estimates of ultraviolet irradiance showed no significant difference during study periods (Chubarova et al. 2018; Zhang et al. 2019; Aun et al. 2019). Other relevant findings from Bernhard et al. (2020) revealed that atmospheric aerosol particles are projected to cause millions of premature mortalities each year globally and opined that biodegradable polymers like polylactic acid are potentially environmentally friendly options to conventional plastics for ultraviolet radiation protection. Microplastics generated by natural weathering activities driven by ultraviolet in the marine environment can be replaced by such biodegradable polymers to ensure a lesser effect of this radiation (Dhaka et al. 2022).

Chatzigianni et al. (2022) explored the effects of sunscreen products in different ecosystem biota under the deleterious effect of ultraviolet radiation. Wastewater sewers and treatment plants form the main pathway of ultraviolet filters to the environment. Domestic effluents from washing, bathing and kitchen wastes do not get properly treated and eventually get discharged into open water bodies and marine ecosystems. Indirect photolysis in an aquatic environment thereby generates toxins, like cyclodimers and benzoic acids, from the untreated effluents, with the consequence that aquatic life is greatly hampered. Direct photolysis ensures that ultraviolet filters are disintegrated into harmful products in the aquatic environment (Chatzigianni et al. 2022). Every aquatic organism responds to ultraviolet radiation differently as was reported in algae reproduction, arthropods' synthesis of exogenous estrogen, molluscs and deformity in the tails of marine vertebrates. Also, time of sunlight exposure is a relative phenomenon across countries due to regional and meteorological variability (Correa 2015). Also, lignin—an emerging polymer used as a low-value product—can be modified by different routes to open the opportunity for its use as a high-value nanocarrier for agrochemical delivery, adsorbent for pollutants, drug delivery and natural sunscreens (Mondal et al. 2023). To provide a better understanding of the effects of ultraviolet radiation on the environment, we have summarized the findings of articles addressing ultraviolet radiation effect on the environment in Table 1.

Photoprotection by ultraviolet filters

Encouraging photoprotection is the leading preventative health strategy involved in skin care. The natural skin protection mechanism is not effective after a short period of a few minutes, which also depends on the skin type and the intensity of ultraviolet radiation coming into that area. However, protective agents are required against solar radiation, which absorbs or reflects light and thus helps protect against sunburn. Some synthetic procedures help to protect against the ultraviolet radiation consequences (More et al. 2021). As previously stated, sunscreen lotion is used to provide photoprotection. Sunscreen contains inorganic and organic ingredients acting as filters.

Inorganic ultraviolet filters contain ingredients like titanium dioxide and zinc oxide nanoparticles, which scatter or reflect ultraviolet radiation and prevent it from reaching the skin (Saka and Chella 2021). Nevertheless, its limitation in cosmetics applications is an uneven distribution on the skin due to lumping; thus, the uncovered areas are exposed to sunlight, not resistant to water, and easily washed off by sweating and water contact giving the skin a comparatively whiter than normal shade. Moreover, organic ultraviolet filters absorbed high-intensity ultraviolet rays and are released in the form of light or heat. They are the most widely used sunscreen agents in the current scenario. It contains para-amino benzoates, cinnamates, benzophenones, salicylates and dibenzoylmethanes. Usually, these chemical filters penetrate the skin, reach the circulatory system and can have a systemic action on the body and filters undergo changes and degradation (Saka and Chella 2021).

Drugs and preservatives

The drugs, which are used for medicinal purposes, may have some side effects. Drug phototoxicity, or photosensitivity, is one such detrimental effect that has received much attention (Monisha et al. 2022). Not all but few drugs have this property of the phototoxic response. Drug-induced phototoxic

Table 1 Effect of ultraviolet radiation exposure to aquatic environment, abiotic and biotic ecosystems. These data were extracted by the results of bibliographic analysis (see Supplementary Material)

References	Type of ultraviolet data or device used	Application	Findings
Reis et al. (2022)	Ground-based ultraviolet radiation data and cloud cover meteorological aerodrome report data	Short-term temporal variability assessment of ultraviolet radiation in Brazil	Cloud cover affects UV variability in a 2-year short-term analysis in Santarem, Brazil
Gonzalez et al. (2022)	2-phenylbenzimidazole-5-sulfonic acid	Toxicity evaluation of sunscreens on marine plankton	Exposure of planktons to sunscreen's leachates showed divergent toxicity results
Chatzigianni et al. (2022)	Not applicable	Effects of UV agents on marine biota and the environment	Harmful accumulation of sunscreens in marine biota affects marine ecosystem
Gonzalez-Rodriguez et al. (2021)	Ultraviolet erythemal radiation tropospheric ozone	Direct and indirect impacts of ultraviolet erythemal radiation on public health in Chile	Ozone photochemistry is greatly influenced by changes in UV erythemal radiation levels than nitrogen dioxide
Addas et al. (2021)	Ozone monitoring instruments—NASA satellite products	Satellite-based UV analysis for development of UV Index for Saudi Arabia	Satellite UV data revealed a significantly increasing UV heat wave exposure for 15 years
Parisi et al. (2021)	Ozone monitoring instruments and Global Ozone Monitoring Experiment (GOME-2) satellite products	Monitoring terrestrial UV-A using ozone monitoring instruments and GOME-2	Comparison of ground-based UV irradiance and satellite-based data showed 30% mean absolute error more on cloudy days
de Paula Corrêa et al. (2021)	Erythemal UV doses phototype V	Environmental exposure during routine daily activities in Brazil	Cyclists revealed that high UV levels are recorded in tropical areas on cloudy days and winter
Caloni et al. (2021)	Not applicable	Toxicological and ecotoxicological effects of common UV filters in different coastal regions	New conservation approaches are needed to compare UV data
Milito et al. (2021)	Not applicable	A study on molecular techniques adopted by marine organisms to combat negative effects of ultraviolet radiation in the marine environment	Identified several UV filters like polyphenols, carotenoids, scytonemin as photoprotectants
Knight et al. (2021)	Not applicable	Effectiveness of green urban areas in UV exposure reduction	It was found that urban green areas are cooler than urban non-green areas for UV monitoring
de Assis et al. (2021)	Photosensors like opsins and chromophores	Skin responses to sun exposure by considering light sensing opsins	The human skin is a complex light-detecting organ that can differentiate between ultraviolet radiation and light photons
Overholt et al. (2020)	UV phototron at biologically relevant UV-B, UV-A and visible light	Sensitivity of pathogen to light	Pathogen light sensitivity and infectivity of *Pasteuria ramose* reduced drastically at increasing UV intensity
Grandi & D'Ovidio (2020)	Not applicable	Risk assessment and management of outdoor workers exposed to solar radiation	Proposed a balance approach to managing adverse and beneficial effects of UV in the whole solar spectrum
Bernhard et al. (2020)	Not applicable	UV effect interaction withclimate on humans and material damage	Future changes in UV depend on rate of ozone recovery, air pollution control and effects of climate change on land cover
Wolinski et al. (2020)	Black light, b-ultraviolet radiation treatment	Effect of prolong UV exposure on molting and growth of zooplankton	UV affected molting process of mother and egg zooplanktons negatively
Park et al. (2019)	UV index sensor, Bluetooth low-energy module, microcontroller unit	Application of a UV index sensor-based device to evaluate potential exposure damage	A UV sensor-based portable device was developed, calibrated and performed optimally for outdoor exposure risk mitigation

Table 1 (continued)

References	Type of ultraviolet data or device used	Application	Findings
Bais et al. (2019)	Not applicable	Effects of ozone depletion on ozone recovery due to UV intensity	No UV detector can match the biological response of vitamin D synthesis. Therefore, UV exposure's risk–benefit indices must be re-evaluated accordingly
Vingerhoets et al. (2019)	EXFO Omnicure S2000 lamp	Determination of impacts of UV irradiation on solar concentrators	UV treatment revealed that perylene-doped luminescent solar concentrators must be exposed to ambient conditions before performance evaluation
Derebe et al. (2019)	Skye UV-A and UV-B sensors	Exclusion of UV-B spectrum from solar radiation for growth and yield assessment of taro (*Colocasia esculenta*)	Physiological parameters of taro (*Colocasia esculenta*) responded to UV treatment than its vegetative growth
Sahu et al. (2019)	Fluorescent lamps	UV effect on thermal properties of carbon/high-density polyethylene	No thermal degradation in polymer after UV light exposure of polymer–carbon composites
Correa (2015)	Not applicable	Assessment of relevant information on ultraviolet radiation in Brazil and South America	Time of sunlight exposure is a relative phenomenon across countries due to regional and meteorological variability
Ramos et al. (2015)	UV filters from crylene and benzophenone derivatives	Analysis of presence of organic filters in the environment	UV filters were found in wastewater, aquatic biota, tap and groundwater and called for more study
Zhang et al. (2012)	2-phenylbenzimidazole-5-sulfonic acid	Degradation treatment of sunscreen UV filter 2-phenylbenzimidazole-5-sulfonic acid with humic acids	Low concentrations of detected humic acids in continental waters and sea accelerate the photodegradation of sunscreen UV filter 2-phenylbenzimidazole-5-sulfonic acid (PBSA) while high concentration prevents timely photodegradation
Lucas et al. (2015)	Not applicable	UV and environmental factors effect due to ozone depletion	Quantification and integration of several climate parameters complicates assessment of UV effects on health and environment
Na et al. (2014)	Scanning imaging absorption spectrometer for Atmospheric CHartographY-based UV data	Human UV exposure reduction potential of trees	Tree covers mathematical model shows optimal ultraviolet reductions and will be integrated in the i-Tree analysis for Seoul and other cities
Baczynska et al. (2011)	Bentham DMc-150f monochromator	Temperature correction of UV spectroradiometric data	Temperature-corrected UV indices data showed 5% agreement with those from ground observatory
Hansen et al. (2002)	USDA UV-B monitoring program Optronics 754 spectroradiometer	Effects of solar UV on toxicity of Arsenic in the crustacean—*Ceriodaphnia dubia*	A positive correlation exists between arsenic composition and UV exposure in aquatic habitats

refers to drug reactions triggered by ultraviolet radiation exposure to the skin. They have absorption maxima in the range of ultraviolet radiation and visible light and become photosensitive.

There are several antibiotics, anti-inflammatory, antimalarial and antifungal drugs, used to treat various diseases, but they are inducing phototoxicity. For example, ciprofloxacin and levofloxacin are broad-spectrum antibiotics. Following UV-A, UV-B and sunlight exposure, they exhibited phototoxicity and formed toxic photoproducts, potentially posing significant health risks to drug users (Dwivedi et al. 2012; Loupa 2017). Anti-inflammatory drugs such as ketoprofen, naproxen showed phototoxic products and induce dermatological complications like photoallergic responses (Liu et al. 2007; Ray et al. 2013). According to a recent study, nabumetone, which is used as anti-inflammatory medicine, loses its function when exposed to UV-A and UV-B, and rises inflammatory markers (Qureshi et al. 2021).

On the other hand, antimalarial drugs being used for the prevention and cure of malaria disease showed photosensitivity responses. The researcher reported that antimalarial drugs like quinine and mefloquine may be associated with the induction of skin diseases and cancer by altering various biological processes due to phototoxicity as well as the formation of photoproducts (Yadav et al. 2013, 2014). Furthermore, fungicidal medications are used to treat and prevent fungal infections such as dermatophytosis and candidiasis. Voriconazole and itraconazole are antifungal drugs that have been linked to liver damage, phototoxicity and cutaneous squamous cell cancer. Voriconazole therapy showed phototoxicity in children and caused immense concern (Mujtaba et al. 2018). All of these studies suggest that patients using photosensitive drugs should avoid direct or indirect sunlight exposure and be cautioned by clinicians about its potentially harmful consequences.

Moreover, the preservative is a substance or chemical, i.e., applied to things including food, beverages, pharmaceutical products, cosmetics and many other products to keep them from decomposing due to microbial development or unwanted chemical changes. However, according to recent studies, several preservatives are susceptible to ultraviolet radiation and transform their characteristics to phototoxic. The preservatives methyl paraben and triclosan are frequently utilized in pharmaceutical and cosmetic products. Photosensitized methyl paraben and triclosan showed cytotoxicity, genotoxicity, arrest the cell cycle of skin cells and triggered apoptosis as well as plate sensitivity test showed a reduction in antibacterial activity (Dubey et al. 2017).

Personal care products

Most cosmetics are chemical ingredients that are applied body's skin surface to improve a person's appearance. Now it has been investigated that personal care products become activated followed by solar ultraviolet radiation exposures mostly UV-A and UV-B. Hair dyes are the most common personal care products in the cosmetics sector. As per the European Commission Scientific Committee on Consumer Safety, 46 hair dye ingredients act as a sensitizer (Mujtaba et al. 2018). Paraphenylenediamine and 2-Amino-3-hydroxypyridine are important ingredients used in the formulation of hair dye. According to studies, after ultraviolet radiation exposure, these ingredients become photosensitized and form toxic photoproducts, which causes genetic damage and apoptosis in skin cells (Goyal et al. 2015; Yadav and Banerjee 2018). Sunscreen is one of the personal care products that is extensively used as a safeguard for skin, but studies have reported that components of sunscreens fail to protect users (Sardoiwala et al. 2018). Sunscreen ingredients absorb sunlight to get photosensitized. For instance, benzophenone is an ingredient for sunscreen, and photosensitized benzophenone induced cell death of skin keratinocytes (Amar et al. 2015). Furthermore, lipsticks and facial creams are widely used as cosmetics. Therefore, the paper suggests that sunlight exposure should be avoided after the use of photosensitive personal care products (Yadav and Banerjee 2018).

Environmental pollutants

When coal, oil, gas, wood, waste and tobacco are burned, polycyclic aromatic hydrocarbons are generated. They are severe environmental contaminants, having the ability to bind to or create tiny particles in the air. Occupational exposure to polycyclic aromatic hydrocarbons can induce breathing problems, chest pain and vexing coughing, as well as cancer (Srivastav et al. 2018). This study reported that they can induce phototoxicity under the environmental intensity of UV-B irradiation. It also observed that UV-B activation of chrysene enhances the intercellular oxidative stress and causes apoptosis by activating caspases-3 and phosphatidylserine translocation in skin cells. Literature also reported that DNA damage as photogenotoxicity can be found under UV-B irradiation (Ali et al. 2011). Photoirradiation of polycyclic aromatic hydrocarbons has also been linked to human skin cancer due to exposure to terrestrial light (Yu 2002). For example, coal tar is used to treat psoriasis, which contains polycyclic aromatic hydrocarbons: It is applied topically to the skin followed by ultraviolet radiation exposure. This treatment has been implicated in the pathogenesis of acquiring skin cancer (Fu et al. 2012).

Furthermore, other polycyclic aromatic hydrocarbons like anthracene, benzanthracene received environmental intensities of sunlight and ultraviolet radiation (UV-A and UV-B) and produced toxic products. These polycyclic aromatic hydrocarbons go through a series of photochemical processes that result in the production of reactive oxygen species and photoproducts, which can damage cell membranes and DNA, and cause cell death (Mujtaba et al. 2018; Yadav and Banerjee 2018). Recently a study reported that polycyclic aromatic hydrocarbons like carbazole, which is found in coal, eye kohl and tattoo ink, induced photodynamic reactions and causes phototoxicity in the human keratinocyte cells (Srivastav et al. 2020). Because human skin is exposed to solar radiation, it is essential to understand the human health risks associated with polycyclic aromatic hydrocarbons and sunlight exposure (Srivastav et al. 2018).

Photocarcinogenesis

Epidemiological studies and experimental models indicate that chronic exposure to solar ultraviolet radiation that damages the skin's biomolecules leading to skin cancer. The epidermal cells, the skin's outermost layer, become sensitized. Epidermal cells, the skin's outermost layer, become sensitized, leading to skin cancer (Agarwal 2018). UV-A causes genetic damage to cells, photoaging and immunosuppression when it penetrates deep into the dermis of the skin. UV-B, on the other hand, only penetrates the epidermis and damages cells. Sunburn is caused mostly by UV-B, which is a substantial risk factor for skin cancer, particularly melanoma.

Photocarcinogenesis is the result of a series of simultaneous and sequential biochemical reactions that eventually result in skin cancer (Subhadarshani et al. 2020). The development of carcinoma depends on the UV-A and UV-B absorption by the superficial skin layers and is mainly responsible for oxidative damage to cellular DNA, proteins and lipids, via photosensitized reactions, which can lead to mutations in key cancer genes (D'Orazio et al. 2013). The production of DNA photoproducts, like cyclic pyrimidine dimers and 6–4 photoproducts, the mutation of proto-oncogenes and the tumor suppressor genes, and the production of radical species are triggered by ultraviolet radiation. DNA photoproducts are considered as a molecular trigger for the induction of immunosuppression and initiation of photocarcinogenesis (Bosch et al. 2015; Srivastav et al. 2018).

Moreover, non-melanoma and malignant melanoma are the two main types of skin cancer that can be caused by photocarcinogenesis. Basal cell carcinoma and squamous cell carcinoma are two types of non-melanoma skin cancer (Moan et al. 2015; Bosch et al. 2015). Nearly 80% of all occurrences of non-melanoma skin cancer are caused by basal cell carcinoma. It is most frequent in Caucasian populations and uncommon among Asians and African black races (Chu et al. 2007). Squamous cell carcinoma is the second most common type of non-melanoma skin cancer. It is responsible for roughly 20% of all skin cancer cases discovered (Prasad et al. 2014). However, photocarcinogenesis is dependent on a few factors, for example age, gender and the thickness of the skin. For example, because men's bodies have thicker skin than women's, elderly people are more likely to develop photocarcinogenesis. With increasing overall lifetime exposure to sunlight/solar radiation, the risk of photocarcinogenesis in the head, neck, trunk and limbs rises.

Sunscreen ingredients

Photostability denotes the capacity of a molecule to endure irradiation without undergoing significant changes. This characteristic becomes a potential concern for all ultraviolet filters since they are deliberately chosen for their ability to absorb ultraviolet radiation. Among the ultraviolet blockers utilized, para-aminobenzoic acid, benzophenone and avobenzone are commonly employed. Shaw et al. (1992) have studied the photochemistry of para-aminobenzoic acid, and they found two photoproducts were formed, 4-(4'-aminophenyl) aminobenzoic acid (I) and 4-(2'-amino-5'-carboxy-phenyl) aminobenzoic acid (II) after exposure to ultraviolet radiation. Photochemical and cytological studies suggested that para-aminobenzoic acid interacts with DNA following ultraviolet radiation and might potentiate photocarcinogenesis. On the other hand, Amar et al. (2015) reported that benzophenone was unstable under sunlight and ultraviolet radiation exposure. This change has also been observed in various ingredients. Thus, sunscreens alone may provide insufficient protection from ultraviolet radiation. Other ingredients may be added to the sunscreen formulation to provide photostability or raise protection.

Photoallergy

The absorption of light by the endogenous/exogenous photosensitizer in the presence of oxygen in a live creature can produce photooxidation, which can lead to chemical and biological consequences (Gonçalo 2011; Fuentes-Lemus and López-Alarcón 2020). The photochemical production of reactive oxygen species and reactive nitrogen species is the principal mechanism by which ultraviolet radiation can induce molecular reactions in human skin. Phototoxicity is a toxic reaction caused by the interaction of photons and substances. It is a chemically generated skin irritation, defined as photoirritation or photosensitivity that needs to be treated with light (Ray et al. 2018; Stein and Scheinfeld 2007).

The word "photosensitization" refers to a phototoxic reaction induced by photons with chemicals followed by exposure to light (Vassileva et al. 1998). Ultraviolet light can photolyze chemical bonds because of energy absorption by molecules/substances. There are two types of photosensitization reactions: type 1 and type 2. The electron transport mechanism is type 1, while the energy transfer method is type 2, as shown in Fig. 4. Many dyes, for example methylene blue, rose Bengal and eosin, pigments, for example

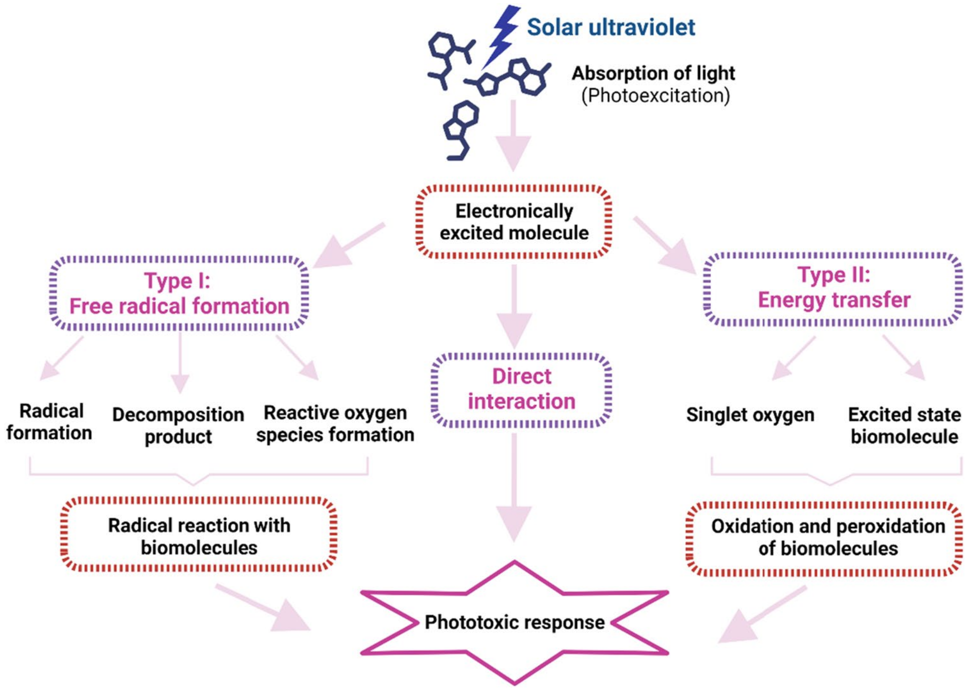

Fig. 4 Molecular mechanisms of phototoxicity. Reversible light absorption by pharmacological chromophores is possible. Phototoxic reactions, such as those caused by active chemicals in sunscreen, are avoided by spontaneous, rapid relaxation by fluorescence or thermal decay. Three key following reactions are responsible for phototoxic responses: Typically, radicals or their breakdown products are involved in Type I reactions. Energy transfer from drug triplet states, on the other hand, can result in singlet oxygen or biomolecule excitation (no radicals involved, type II reactions). Type III encompasses a wide range of covalent reactions that do not include radicals. Excited state medicines' electronic arrangement and high energy typically allow for non-specific interactions with biomolecules. All of these processes can result in cytotoxic damage, which can cause phototoxic tissue consequences. Created with BioRender.com

chlorophyll, hematoporphyrin and flavins, and aromatic hydrocarbons are effective photosensitizers because these molecules may reach a long-lived triplet state in high quantum yield (Ormond and Freeman 2013; Xiao et al. 2018). A triplet state may subsequently react with other biomolecules and trigger adverse reactions. All biological molecules exist in a singlet ground state. Photoexcited substances lead to the generation of reactive oxygen species, RNS and hydroxy radicals through type 1 and type 2 photosensitized reactions. However, phototoxicity reactions have been found quite variable in a population exposed to the same agent. Individual responses to phototoxic chemicals are influenced by several parameters, including absorption, metabolism and light penetration into the skin (Korzeniowska et al. 2019).

Effect of ultraviolet radiation on human health and skin

Thirty-four of the articles reviewed for this work presented findings on the beneficial and adverse effects of ultraviolet radiation on human health. Generally, there is abundant evidence that ultraviolet radiation is carcinogenic to humans, and it forms the major driver of other underlying medical conditions ranging from eye defects, sunburn, skin disorder and hair damage (Grandi & D'Ovidio 2020; Kim & Giovannucci 2020; Moan et al. 2012). According to Wnuk et al. (2022), benzophenone-3, an organic sunscreen formulation commonly used in cosmetic products to minimize damaging effect by ultraviolet radiation has been reported to disrupt functioning of organs, endocrine systems and fetal development in humans. Interestingly, previous epidemiological studies have established that there is a link between human's exposure experience to harmful environmental radiation during childhood and consequential neurodisorders in adulthood; however, there has not been sufficient convincing literature to assert that benzophenone-3 exerts such. It might be harmful to fetuses and children because it can be transmitted during suckling. Consumers of cosmetics are admonished to observe caution when products with primary benzophenone-3 while we await a landslide breakthrough in benzophenone-3 assessment research.

In many ultraviolet-related studies, researchers and policymakers have always been engrossed in elaborately identifying the demerits of ultraviolet radiation while ignoring its numerous benefits. With the most common benefit known to be vitamin D synthesis, one wonders if there are more beneficial prospects of ultraviolet radiation. Meanwhile, a balanced diet and a healthy lifestyle are not adequate to supply vitamin D requirements without a considerable amount of sunlight exposure. Indeed, the concept of ultraviolet radiation is a double-edged sword, whose pros and cons seem to maintain a balance. Umar and Tasduq (2022) highlighted the positive impacts of ultraviolet radiation on human skin which ranges from the enhancement of melanogenesis that acts as natural sunscreen inherent in dark-skinned people, to ultraviolet radiation phototherapeutic treatment of inflamed cutaneous conditions. Another benefit is mood enhancement when enough sunlight time is expended. In South Korea, it is common practice to behold old nationals enjoying a brief sunlight shower to revitalize dead cells and rekindle youthful feelings. Other health effects are presented in Table 2.

The skin plays a vital role as the first line of defense against oxidative damage caused by environmental factors, including ultraviolet radiation. Human skin contains various chromophores, such as urocanic acid, melanin, bilirubin and proteins containing aromatic amino acids, which act as protective agents against ultraviolet stress. Among these, melanin is the most crucial physiological mechanism in countering ultraviolet radiation as it acts as a radical scavenger. Melanin is responsible for determining the skin color in humans and is also present in hair. In mammals, there are two types of melanin: brownish-black eumelanin and reddish-yellow pheomelanin. These pigments are produced within specialized cells called melanocytes. The protective effect of melanin, particularly eumelanin, is attributed to its ability to act as a physical barrier that scatters ultraviolet radiation and as an absorbent filter that reduces the penetration of ultraviolet rays through the epidermis (Brenner and Hearing 2008). Melanin's effectiveness as a sunscreen has been estimated to provide approximately 1.5–2.0 sun protection factor (SPF), with some suggestions of up to 4 SPF. This implies that melanin can absorb around 50% to 75% of ultraviolet radiation. A sun protection factor of 2 indicates that the skin's protection against sunburn is doubled. The basal layers of the epidermis in dark skin, particularly in individuals with Black ethnicity, contain higher levels of melanin, making it more efficient in sun protection compared to Asian or White skin. The abundance of eumelanin in dark skin offers superior defense against UV-induced damage, with eumelanin being considered more effective in its photoprotective properties than pheomelanin (Gloster and Neal 2006). On the other hand, the imbalance between excessive oxidative stress generation and insufficient antioxidant defense was created by prolonged ultraviolet radiation exposure. Consequently, photooxidative reactions are initiated, and high amounts of oxidative stress overwhelm the natural protection of skin cells causing damage to biomolecules and affecting the integrity of cells as well as tissues (Fernández-García 2014). So, active ultraviolet blockers or ultraviolet filters are required to limit the harmful effects of solar radiation on the skin.

Challenges

Photosensitivity, phototoxicity, immunosuppression, and photocarcinogenesis are all caused by solar ultraviolet radiation exposure; thus, photoprotection is an important issue. For the prevention of overexposure to ultraviolet radiation, several measures including wearing sun-protective clothes such as hats and sunglasses, avoiding exposure to the direct sunlight, and using sunscreens with their sun protection factor are being explored. Sunscreens are chemicals that can absorb or reflect ultraviolet light efficiently, are applied topically and protected from the adverse effects of sunlight, mainly erythema. The sun protection factor is a measurement of how much solar ultraviolet energy is protected of skin against sunburn. For example, sun protection factors 15, 30, 45 and 50 block/absorb the UV-B light 93.3%, 96.7%, 97.8% and 98.0%, respectively (Wilson et al. 2012). Most commercial formulations contain several active ingredients for a broad sun protection factor of 280 to 400 nm, corresponding to UV-B and UV-A. The application of sunscreen before exposure to ultraviolet radiation, prevents sunburn, skin damage as well as skin cancer (Medeiros and Lim 2010; Mancebo et al. 2014).

On the other hand, there are several photoprotective agents are using in the present scenario, but various agents become photosensitized and showed adverse effects (Baptista et al. 2021). Sunscreens can induce side effects such as irritation, allergy and phototoxic reactions, affect the synthesis of vitamin D, generate reactive oxygen species and act as photosensitizers (DiNardo and Downs 2018; Ngoc et al. 2019; Neale et al. 2019; Passeron et al. 2019; Narla and Lim 2020; Suh et al. 2020). Furthermore, finding a sunscreen that can offer complete protection across the full spectrum of ultraviolet light is challenging. Additionally, some sunscreen ingredients may transform into free radicals when exposed to ultraviolet irradiation, and certain chemicals in sunscreens have the potential to be absorbed into the skin, raising concerns about possible adverse effects. As primary prevention approaches, sunscreen usage has shown limited success in fully preventing skin disorders. Therefore, it is crucial to explore and implement additional efforts to effectively safeguard against skin-related issues.

Cross talk between skin microflora and ultraviolet radiation

The human skin is known to harbor a wide variety of microbes including bacteria, fungi, archaea, mites and viruses. Many studies performed in the last decade have shown that microbiota plays a key role in skin homeostasis. The majority of these microorganisms are commensals or transients that coexist with the skin's immune system in a

Table 2 Effect of ultraviolet (UV) exposure to human health and skin treatment

References	Type of UV filter or device used	Application	Findings
Wnuk et al. (2022)	Benzophenone-3	Harmful effects of application of organic sunscreens	Benzophenone-3, a chemical UV filter might be harmful to fetuses and children because it can be transmitted during suckling
Umar and Tasduq (2022)	Not applicable	Epidemiological effects of ultraviolet radiation on public health and ozone depletion	Vitamin D deficiency due to inadequate UV-B exposure can be supplemented with fortification food and new biotechnology ideas
Santiesteban-Romero et al. (2022)	Carotenoids, polyamines, scytonemin, mycosporine-like amino acids	Application of microalgae as natural photoprotectants for skin care	Microalgae enhanced DNA repair and antioxidant synthesis to combat UV skin damage
Henderson et al. (2022)	Not applicable	Optimal approaches for sunscreen application in Australia	Primary sunscreens are superior to cosmetic sunscreens due to the former's high sun protection factor Further research on impacts of sunscreen on vitamin D synthesis is highly important
Huang and Chalmers (2021)	Ultraviolet radiometer, dosimeter	Tracking personal UV exposure using wearable and portable sensors	Monitoring daily UV exposure by wearable sensor devices creates checks for harnessing sunlight benefits and avoiding the harm
Kim and Giovannucci (2020)	Not applicable	Interaction among vitamin D synthesis, cancer incidence, eventual mortality and ultraviolet radiation	Potential benefit of vitamin D on cancer mortality can be only effective during prediagnostic stages
Miligi (2020)	Artificial ultraviolet radiation from welding arc, solar ultraviolet radiation	Cancer risk and primary prevention approaches due to ultraviolet radiation exposure in Italy	Outdoor workers' risk increases with increasing ambient solar radiation and using artificial sunbeds
Khan et al. (2020)	Inorganic: talc, calamine, kaolin, zinc oxide Organic: octocrylene, ensulizole, triazine derivatives	Fabrics and textiles as ultraviolet radiation photoprotectants	Ultraviolet-absorbing textile can be enhanced with integration of inorganic and organic UV filters through doping or coating during fiber formation
Lan (2019)	Not applicable	Photoaging and skin cancer caused by combined effects of increased temperature and ultraviolet radiation	Exposure to increased temperature before UV-B treatment reduces UV-B-induced skin tumor formation and had similar effects on dermal fibroblasts by activating distinct pathways
Sondenheimer and Krutmann (2018)	Iron oxide sunscreen, keratinocyte-derived cytokines	Prevention of skin damage at specific ultraviolet wavelengths through a novel approach	Photoprotection of damaged skin can be performed by enhancing DNA repair through supply of biological enzymes in absorbable formulation
Lerche et al. (2017)	Not applicable	Impacts of ultraviolet radiation exposure on vitamin D and non-vitamin D pathways	Skin-thickening can be a preventive mechanism against UV erythemic effect
Moan et al. (2012)	Sunbeds and solar ultraviolet	Health benefits of sunbeds, solar radiation and vitamin D intake	Overall health benefit of improved vitamin D status is more important to human health than cutaneous malignant melanoma risks
Wright et al. (2012)	Not applicable	Assessment of solar ultraviolet radiation impacts on human health in sub-Saharan Africa	Adoption of best global practices for UV protection is ongoing in sub-Saharan Africa, but data on prevalence of ultraviolet-related diseases are deficient
Afaq and Katiyar (2011)	Polyphenols: grape seed, silymarin, genistein, green tea, pomegranate fruit extract	Application of polyphenols as photoprotectants to prevent skin and DNA damage	Clinical trials are needed to validate antiphotocarcinogenic potential of new plantpolyphenols

Table 2 (continued)

References	Type of UV filter or device used	Application	Findings
Hu et al. (2010)	Solar UV sensors (SUB-T Toray Industries, Tokyo)	Diurnal variations of ultraviolet radiation at different anatomical sites	Diurnal variations in ultraviolet radiation at defined anatomical points (eye and cheeks) of study mannequin were significantly different at different solar elevation angles. Protection must extend beyond noon periods
Norval et al. (2011)	Zinc oxide, titanium oxide, cinnamate and salicylate having SPFs of 30	Climate change and human health effects due to ozone depletion	A few UV-B filters have weak estrogenic activity and may have adverse effects on reproductivity in humans
Terenetskaya (2003)	D-dosimeter, Xenon arc lamp	Vitamin D synthesis and proper dosimetry to combat erythema	Quantification of lowest healthy UV doses to sustain vitamin D synthesis is deficient globally

mutualistic relationship (Patra et al. 2018, 2019). According to current research, skin microorganisms have an impact on gene expression in the skin and are responsible for training and adjusting its immunological response (Belkaid and Segre 2014; Meisel et al. 2018). Despite the challenges posed by numerous external environmental conditions like ultraviolet radiation, skin cells and the immune system constantly interact with bacteria to preserve cutaneous homeostasis. Ultraviolet radiation has been shown to cause significant changes in the skin as well as modify immunological responses (Shen et al. 2016).

A study found that the skin microflora plays an important role in differential gene expression regulation in the skin, particularly for genes encoding Toll-like receptors and antimicrobial peptides, as well as genes associated with the interleukin (IL)-1 family (Meisel et al. 2018). Ultraviolet radiation can also encourage or inhibit microbial growth on the skin, as well as alter the immune system, which can be beneficial or harmful. Furthermore, a recent study on mice model of contact hypersensitivity and germ-free reported that the skin microbiome inhibited ultraviolet-induced immune suppression (Patra et al. 2019). On the other hand, direct ultraviolet-induced DNA and membrane damage to the skin microbiome may result in pathogen-associated molecular patterns that interfere with ultraviolet-induced immune suppression (Patra et al. 2018). After ultraviolet exposure, DNA damage, potent phospholipid activator formation factor and isomerization of inactive trans- to active cis-urocanic acid, are the primary key events in immunosuppression (Bernard et al. 2019). The *Micrococcus luteus* strain has the unique ability to counteract the negative effects of ultraviolet on the immune system by converting the cis-urocanic acid produced by ultraviolet radiation during skin exposure (Patra et al. 2018).

In addition, a study demonstrated that UV-A and UV-B exposure has an impact on the composition of the skin microbiota. This finding was based on the 16S rDNA sequencing and reveals a decrease in the family Lactobacillaceae and Pseudomonadaceae while the phylum Cyanobacteria increased following ultraviolet radiation exposure (Burns et al. 2019). Cyanobacteria contain a variety of defense mechanisms, including the production of UV-absorbing compounds such as mycosporine-like amino acids and enzymes such as superoxide dismutases, which help to minimize the effects of oxidative stress (Lawrence et al. 2018). Porphyrins play a vital role in the function of hemoglobin, ultraviolet rays also directly affect cutaneous propionibacteria such as *Propionibacterium acnes* by reducing their porphyrin production (Wang et al. 2012).

A study showed that the skin commensal bacterium, *Propionibacterium acnes*, was able to secrete an antioxidant enzyme like RoxP for radical oxygenase of

Propionibacterium acnes (Allhorn et al. 2016). This protein positively influences the viability of monocytes and keratinocytes exposed to oxidative stress (Andersson et al. 2019). This enzyme possesses intriguing features that may be useful in lowering oxidative damage caused by ultraviolet exposure (Souak et al. 2021). All these studies show that ultraviolet radiation has significant qualitative and quantitative effects on the skin microbiota, potentially affecting skin pathology where ultraviolet radiation is a factor.

Natural agents and phytochemicals for photoprotection

Currently, existing natural agents are prepared to supplement the inadequacies of conventional sunscreens in ultraviolet radiation protection. Also, oral photoprotectants do not offer full skin protection, but they provide a boost to set photoprotection in motion in living organisms (Torres-Contreras et al. 2022). So, people are clamoring for natural solutions to this problem. As the revenue generated by skin care products skyrocket globally, there is a yearning need to explore natural and botanical sources of ultraviolet protection. When plants are irradiated by sunlight, they can easily synthesize certain molecules that resist ultraviolet radiation damage, and prevent photoaging and skin cancer. Common secondary plant compounds used as alternative photoprotectants include carotenoids, polyphenols, natural botanicals agents, phytochemicals, antioxidants, alkaloids and phenolic compounds as illustrated in Fig. 5 (Nunes et al. 2018; Fardiyah et al. 2020; Bendjedid et al. 2021). Carotenoids (lycopene) attack the singlet oxygen radical generated by reactive oxygen stress upon sunlight exposure. Caffeine and theobromine are good examples of alkaloids (Wnuk et al. 2022). Phytochemicals may operate in a variety of ways, including being capable of absorbing the ultraviolet and act as filters, stimulating the immune system, triggering gene suppression, stopping oxidative DNA damage, detoxifying carcinogens and initiating specific signaling pathways (Vanhaelewyn et al. 2020).

Polyphenols are natural compounds widely distributed in plant foods, including fruits, vegetables, nuts, seeds and flowers. Some important dietary sources of polyphenols are epigallocatechin-3-gallate, grape seed proanthocyanidins, apples, green tea, flavonols and catechins, flavanones, anthocyanidins and isoflavones (Rasouli et al. 2017; Williamson 2017; Cory et al. 2018). These polyphenols play a potent role in antioxidant as well as anticarcinogenic and have

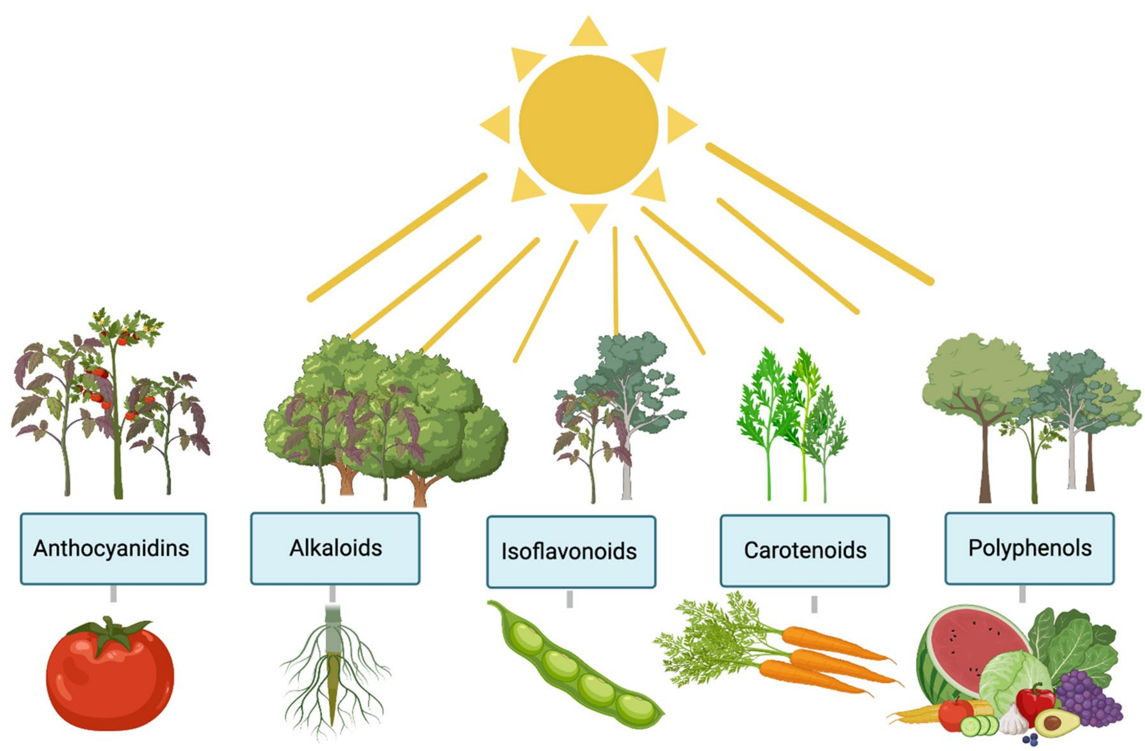

Fig. 5 Plant photoprotectants. Plants, constantly irradiated by sunlight, can synthesized molecules that resist ultraviolet radiation damage, prevent photoaging and skin cancer. The most common plant secondary metabolism compounds are carotenoids, polyphenols, anthocyanidins, isoflavonoids and alkaloids. Created with BioRender.com

been reported to possess substantial skin protective effects of ultraviolet radiation including the risk of skin cancers.

Epigallocatechin-3-gallate has the ability to prevent UV-B-induced leukocyte infiltration in both mouse and human skin. As a result, it may effectively inhibit the production of reactive oxygen species by these infiltrating leukocytes upon UV-B exposure (Nichols and Katiyar 2010). Furthermore, research studies have indicated that when human fibroblasts were treated with epigallocatechin-3-gallate in culture, it effectively prevented the UV-induced rise in collagen secretion and collagenase mRNA levels. Additionally, it demonstrated the ability to inhibit the binding activities of nuclear transcription factors NF-κB (nuclear factor kappa light chain enhancer of activated B cells) and activated protein (AP)-1, both induced by UV exposure. Moreover, epigallocatechin-3-gallate was found to regulate mitogen-activated protein kinase signaling pathways (Kim et al. 2001). Upon topical application to mouse skin, green tea polyphenols demonstrated a significant inhibitory effect on UV-B-induced DNA damage, as assessed through a 32P-postlabeling technique. Similarly, when human skin was topically treated with green tea polyphenols before exposure to ultraviolet radiation, a dose-dependent inhibition of cyclobutane pyrimidine dimer formation was observed (Katiyar 2016).

Grape seed proanthocyanidins belong to a class of phenolic compounds renowned for their potent antioxidant properties, safeguarding the body against premature aging, diseases and deterioration (Sharma et al. 2007). It has anti-mutagenic, anti-inflammatory and anticarcinogenic (Nandakumar et al. 2008) properties. In SKH-1 hairless mice, the addition of grape seed proanthocyanidins to a standard diet effectively inhibited photocarcinogenesis, as evidenced by reduced tumor incidence, decreased tumor multiplicity and smaller tumor sizes (Katiyar 2016). Grape seed proanthocyanidins also resulted in the prevention of the malignant progression of UV-B-induced papillomas to carcinomas. In the skin, grape seed proanthocyanidins were observed to inhibit the UV-B-induced infiltration of proinflammatory leukocytes. Furthermore, the levels of myeloperoxidase, cyclooxygenase-2, prostaglandin E2, cyclin D1 and proliferating cell nuclear antigen were also reduced by the presence of grape seed proanthocyanidins (Sharma and Katiyar 2010).

Teas, honey, wines, fruits, vegetables, nuts, olive oil, cocoa and grains all contain anthocyanins, which belong to the flavonoid group of phytochemicals (Nguyen et al. 2022). The anthocyanin biosynthesis in plants is regulated by light and light quality, such as UV-A, UV-B, blue and red lights (Li et al. 2020). The use of anthocyanin pigments as therapeutic agents has long been accepted orthodoxy in folk medicine around the world, and these pigments have been connected to a staggering array of health advantages (Lila 2004). A study reported that treatment of anthocyanins inhibited the production of hydrogen peroxide (H_2O_2) and lipid peroxide in human dermal fibroblast cells caused by UV-A irradiation. A recent study showed that anthocyanins against UV-B induced oxidative damage in keratinocyte cells and the activation of Nrf 2 (nuclear factor E2-related factor 2) signaling. Similarly, anthocyanins reduced UV-B-induced oxidative stress and cell death in BALB/c mouse skin tissues when applied topically (Li et al. 2019). These findings suggest that anthocyanin could be a promising choice for the creation of photoprotective agents.

Isoflavonoids are dietary antioxidants that may protect against oxidative stress connected to inflammation and damaging the macromolecule by free radicals and other oxygen and nitrogen oxidizers (Miadoková 2009). Genistein, the most prevalent isoflavone of the phytoestrogen chemicals generated from soy and it is a well-known potent antioxidant. In a human reconstituted skin model, the isoflavone genistein was found to be photoprotective against UV-B induced pyrimidine dimer production and proliferating cell nuclear antigen expression. It has also been suggested that genistein could be used as a potent inhibitor for photocarcinogenesis (Moore et al. 2006). Another study investigated that oral administration of soy isoflavone extract in a hairless mouse model protects UV-B-induced skin aging (Kim et al. 2004). Moreover, the pig skin model was treated with a cocktail of five isoflavone compounds, which are genistein, equol, daidzein, biochanin A and formononetin, followed by solar-simulated ultraviolet radiation exposure. They observed that this cocktail protects pig skin from photodamage as evaluated by sunburn cell development and erythema (Lin et al. 2008). All these findings support that Isoflavones provide effective photoprotection against ultraviolet radiation damage.

Carotenoids are a group of over 600 fat-soluble plant pigments that make up the carotene family. Carotenoids like lycopene, beta-carotene and lutein are abundant in fruits and vegetables (Fernández-García 2014). These carotenoids have a wide range of biological effects. They play a role in light harvesting and photoprotection as well as provitamin and antioxidant properties, in humans and animals. Carotenoids' photoprotective qualities are linked to their antioxidant activities, which effectively scavenge reactive oxygen species, such as superoxide anions, singlet molecular oxygen, hydroxyl radicals and hydrogen peroxide (Sies and Stahl 2004). Most studies have found that increasing carotene consumption reduces the severity of ultraviolet-induced erythema (Stahl and Sies 2012).

Alkaloids are nitrogenous compounds with a low molecular weight that are found in nature. Plants use it to defend themselves against herbivores and disease pathogens. It has anti-inflammatory, anticancer, local anesthetic and pain-relieving effects, as well as neuropharmacological and other activities (Anand et al. 2022a; Khare et al. 2021). Various studies have found that alkaloids such as sanguinarine, piperine and caffeine act as defenders against ultraviolet radiation damage (Dinkova-Kostova 2008; Verma et al. 2017; Gherardini et al. 2019).

Sanguinarine is generated from the root of *Sanguinaria canadensis* and other poppy Fumaria species. According to an in vitro study, UV-B irradiation increased the number of human keratinocyte (HaCaT) cells in the gap 2-mitosis phase of the cell cycle, but pretreatment with sanguinarine dramatically shifted cells toward the synthesis phase. On the other hand, it protected the cell from apoptosis via modulating the tumor suppressor protein p53 and pro-apoptotic BAX (BCL-2-associated X protein), BAK (BCL-2 antagonist killer 1), BID (BCL-2-interacting domain death agonist) and BCL-2 (B-cell lymphoma-2) pathways (Reagan-Shaw et al. 2006). Moreover, in vivo findings on SKH-1 hairless mice reported that pretreatment with sanguinarine significantly decreased the UV-B-mediated skin edema, skin hyperplasia and infiltration of leukocytes. Further, they also observed that sanguinarine prevented UV-B-mediated elevations in ornithine decarboxylase, proliferating cell nuclear antigen and Kiel antigen-67, all of which are indicators of cellular proliferation (Ahsan et al. 2007; Dinkova-Kostova 2008).

Piperine, which is found in black pepper (*Piper nigrum*), is another plant alkaloid with a long list of medical uses (Ahmad et al. 2012). It is known to improve the bioavailability of other substances and plays a crucial function in maintaining cellular homeostasis (Johnson et al. 2011). A recent study revealed that piperine was stable under UV-A/UV-B exposure viz it was not degraded under ultraviolet radiation. Piperine was also observed to lower ultraviolet radiation-mediated DNA damage, micronuclei creation and the sub-Gap 1 phase of the cell cycle, all of which helped to protect against photogenotoxicity. Further, they found that piperine protects human keratinocytes from ultraviolet radiation-induced cell damage via the NF-κB (nuclear factor kappa light chain enhancer of activated B cells), BAX/BCL-2 pathway in keratinocytes cells (Verma et al. 2017).

The outcome of several experimental studies strongly suggests that these phytochemicals could be employed in therapeutic applications like cosmetics or medicine formulations to prevent ultraviolet-induced skin damage (Nguyen et al. 2022). One of the constraints of plant photoprotectants is that biotic and abiotic factors such as crop management plans, latitude, climate and soil, affect phytochemical profiles of such plant extracts. It is quite challenging to quantify or predict the essential active ingredients in the right proportion after harvest. However, this seems to be a trivial problem as the photoprotective prospects outweigh this uncertainty. Ongoing research activities may proffer solutions to this problem in the near future. In textile manufacturing, polysorbate improved ultraviolet exposure protection and the esthetics of polyester fabric (Sk et al. 2022). Some other studies reveal that cotton-based fabrics have excellent properties for ultraviolet protection (Kocić et al. 2019). Rabiei et al. showed that ultraviolet protection of workwear fabrics can be improved by coating titania nanoparticles (Rabiei et al. 2022).

A summary of natural agents for photoprotection is presented in Table 3. The use of sunscreens, to prevent damage from sun radiation, has been largely adopted. Sunscreen formulation is characterized by synthetic materials that are a threat to aquatic life, eco-sustainability and human health. Natural agents are prepared to supplement the inadequacies of conventional sunscreens in ultraviolet radiation protection.

Table 3 Natural agents as photoprotectant alternatives to sunscreens

References	Location	Type	Ultraviolet photoprotective activity
Torres-Contreras et al. (2022)	Mexico	Extracts of cocoa, tomato, pigweed	Absorption of UV-B and antioxidant agent
Kreft et al. (2022)	Slovenia	Flavonoids rutin and quercetin found in buckwheat	UV-B metabolites found in buckwheat prevent cardiovascular ailments and resist UV-B effect
Sk et al. (2022)	Bangladesh	Polysorbate	Polysorbate improved UV exposure protection and esthetics of polyester fabric
Pambianchi et al. (2021)	USA	Alaska bog blueberry extract	Restoration of skin barrier proteins lost during UV exposure
Jiao et al. (2021)	China	Afforestation	Optimizing spatial pattern of trees and buildings increased shade efficiency and could reduce UV exposure damage
Lawrence et al. (2018)	UK	Palythine from red algae	Palythine can serve as a natural and biocompatible option to current UV filters
Cefali et al. (2016)	Brazil	Phytocosmetic compounds	Plant extracts of phytocosmetic compounds help to prevent skin aging
Torres-Contreras et al. (2022)	Mexico	Mexican plant extracts, e.g., *Echinacea spp.*, wild sunflower, flor de oregano, hog plum	Anti-inflammatory, anticarcinogenic and antioxidants

Conclusion

Several concerted efforts have been made toward proffering environmentally friendly alternatives to conventional sunscreens for ultraviolet radiation protection. Also, a series of biochemical events occur when skin is exposed to UV-A and UV-B radiation from the sun. These events are the photooxidative reactions that cause skin damage. Modification of gene expression, activation or inactivation of regulatory pathways, immunological and inflammatory processes, and induction of apoptosis are all examples of photooxidative reactions that disrupt the function of cellular responses. These include, for example, sunburn, phototoxicity, photoallergy, and photoimmunosuppression. Various strategies are used to protect the skin against ultraviolet-dependent damage, but photoprotection from phytochemicals or natural agents is widely investigated. Natural agents and secondary plant extracts have been elaborately discussed and presented to offer future prospects as sustainable options for sunscreen technology. All these findings should help researchers better understand how to treat ultraviolet-induced skin damage and other skin illnesses connected to microbiome changes or ultraviolet radiation exposure. In current molecules/compounds development practice, photosafety testing remains to be an important component for natural agents. Several potential future studies would probe the question of the protective nature of phytochemicals for healthy skin. Further study about other potential photoprotectants is recommended, and a repository can be created to ensure easy retrieval of information and data for further research. Clinical trials of identified photoprotectants should be replicated to eradicate uncertainties and scaled up for mass production in cosmetic, textile and other related industries. This could pave the path for natural agents to be used in dermatologic health management while ensuring a safer environment.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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