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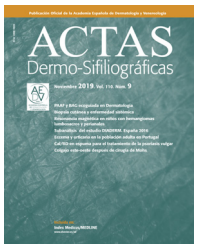

REVIEW

# Pollution, a Relevant Exposome Factor in Skin Aging and the Role of Multi-benefit Photoprotection

J. Santamaria[a], Y. Gilaberte[b], L. Prudkin[a,*], J. Piquero-Casals[c]

[a] *Innovation and Development, ISDIN, Barcelona, Spain*
[b] *Department of Dermatology, Miguel Servet University Hospital, IIS Aragón, Universidad de Zaragoza, 50009 Zaragoza, Spain*
[c] *Dermik, Multidisciplinary Dermatology Clinic, Barcelona, Spain*

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**KEYWORDS**
Skin aging;
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**Abstract** Skin aging is a complex, continuous, multifactorial process resulting from cumulative morphological and functional changes in the skin over time.

This happens because of two processes: intrinsic and extrinsic skin aging. Intrinsic skin aging occurs naturally over time and reflects each person's genetic makeup, or heredity. Extrinsic skin aging, on the other hand, is due to exposomal factors, such as solar radiation, air pollution, tobacco or nutrition, being the first two the most important of all. Exposure to air pollutants, primarily gases such as ground-level ozone and particulate matter, can accelerate the process via four key mechanisms: reactive oxygen species generation, inflammation, skin microbiome disruption, and aryl hydrocarbon receptor activation. Regarding solar radiation, all wavelengths reaching the Earth's surface have an impact on the skin, having a synergistic effect with air pollution (''photo-pollution''). Here, we discuss this phenomenon and mitigation strategies, including sunscreens, cosmetics with film-forming plus antioxidant ingredients, and oral supplementation.


**PALABRAS CLAVE**
Envejecimiento de la piel;
Exposoma;
Contaminación del aire;
Radiación solar;
Anticontaminación

## La contaminación, un factor relevante del exposoma en el envejecimiento cutáneo y el papel de la fotoprotección multibeneficio

**Resumen** El envejecimiento cutáneo es un proceso complejo, continuo y multifactorial que resulta de los cambios morfológicos y funcionales acumulados en la piel a lo largo del tiempo. Esto sucede debido a 2 procesos: el envejecimiento cutáneo intrínseco y el extrínseco. El envejecimiento cutáneo intrínseco ocurre de forma natural con el tiempo, y refleja el trasfondo genético o herencia de cada persona. El envejecimiento cutáneo extrínseco, por otro lado, es causado por factores del exposoma, como la radiación solar, la contaminación atmosférica, el tabaco o la nutrición, siendo los 2 primeros los más importantes. La exposición a contaminantes

* Corresponding author.
*E-mail address:* Ludmila.prudkin@isdin.com (L. Prudkin).

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atmosféricos, principalmente gases como el ozono troposférico y las partículas en suspensión, puede acelerar el proceso a través de 4 mecanismos clave: generación de especies reactivas de oxígeno, inflamación, alteración del microbioma cutáneo y activación del receptor de hidrocarburos arílicos. En cuanto a la radiación solar, todas las longitudes de onda que llegan a la superficie de la Tierra tienen un impacto en la piel, teniendo un efecto sinérgico con la contaminación atmosférica («fotocontaminación»). Aquí analizamos este fenómeno y las estrategias de mitigación, que incluyen protectores solares, cosméticos con ingredientes formadores de película, y antioxidantes y suplementos orales.


## Introduction

Aging is an unavoidable physiological phenomenon, characterized by a progressive decline in the biological function of cells and organs.[1] It is influenced by genetics (intrinsic aging) and the exposure to exposomal factors such as solar radiation, air pollution, nutrition, lifestyle, and others (extrinsic aging).[2] Molecular epidemiologist Christopher Wild coined the term ''exposome'' in 2005 to represent the totality of exposures an individual experiences from conception to death.[3] Miller and Jones further refined it in 2014, proposing that the exposome should be considered as the total of environmental factors that interact with an individual throughout life, and the biological response to these factors.[4]

The skin is the first defensive barrier of the body and is in continuous contact with the environment.[5] It undergoes significant changes due to intrinsic and extrinsic aging.[5] Intrinsic skin aging manifests as fine lines, xerosis, and laxity, whereas extrinsic aging skin shows as coarse wrinkles, irregular pigmentation, and lentigines.[2] The term photoaging has been used synonymously with extrinsic skin aging to indicate the high impact of solar radiation on the aging process.[2] However, many other factors contribute to extrinsic skin aging such as air pollution, climate, tobacco and nutrition.[5,6] Added to their individual effects, these environmental factors also interact with each other in a complex manner.[2] Air pollution and solar radiation are the main factors responsible for skin aging. They accelerate skin aging mainly via oxidative stress. This occurs when there is an imbalance between the production of reactive oxygen species (ROS) and the body's capacity to neutralize them, which ultimately results in ROS accumulation.[6–8] The best defense vs age-related changes in the skin is protection vs exposomal factors.[9] Urban life exposes people to heavy air pollution created by vehicles, industry, construction activities, and others. The main air pollutants that induce skin damage are particulate matter (PM) and gases such as ground-level ozone ($O_3$). The skin damage caused by these air pollutants is further augmented by solar radiation (''photo-pollution''). The combination of ultraviolet radiation (UVR) plus PM and ozone exposure has a synergistic effect increasing the oxidative stress and inflammation.[10] Their harmful effects can be mitigated by fighting them: passively by creating a physical barrier on the skin surface to reduce contact with air pollutants (film-forming ingredients) and actively by counteracting oxidative stress (antioxidants) and absorbing, reflecting and/or scattering solar radiation (sun filters).[11,12]

Therefore, the use of products that protect from solar radiation and air pollution has become important as a part of daily skincare.[13] This review focuses on the effects of air pollution and solar radiation on skin aging and how we can counter them with cosmetics and oral supplements.

## Methods

We conducted a literature narrative review. GoogleScholar and PubMed searches from November 1997 through June 2024 using the keywords ''exposome'', ''pollution'', ''air pollution'', ''solar radiation'', ''sunlight'', ''ultraviolet radiation'', ''visible light'', ''blue light'', ''infrared radiation'', ''sunscreens'', ''photoprotection'', ''oral photoprotection'', ''oral supplements'', ''skin aging'', ''hyperpigmentation'', ''skin cancer'', ''cosmetics'', ''dermocosmetics'', ''film-forming'' and ''antioxidant'', were performed. The search strategy, restricted to English and Spanish language articles, included meta-analyses, observational studies, clinical trials, and review articles.

## Results and discussion

### Air pollution and solar radiation effects on skin aging

#### Skin exposome

The skin exposome includes external and internal factors, their interactions, and the response of the human body to these factors leading to biological and clinical signs of skin aging.[6] However, studying the exposome in its entirety is challenging because it is highly variable and dynamic.[14] The exposome factors of skin aging can be broadly categorized as solar radiation: UVR, visible light (VL), and infrared (IR) radiation; air pollution; tobacco; nutrition, cosmetics, and other lesser-known factors.[6] Most factors of skin exposome are solar radiation and air pollution. Biological responses to exposome factors can cause physiological adaptations, such as metabolic changes, protein modifications, DNA mutations and others.[15] Most skin disorders are highly influenced by exposure to exposome factors.[14]

## Effects of air pollution on skin aging

Air pollutants that can cause extrinsic skin aging mostly include gases such as ground-level ozone, and PM, a complex mixture of solids and liquid particles suspended in the air. PM can be formed in two main ways: directly emitted from a source like vehicle exhaust, construction activities, wildfires (primary PM) or formed in the atmosphere via complex chemical reactions between gas precursors such as volatile organic compounds (VOCs) and the presence of solar radiation (secondary PM).[16,17] PMs are categorized based on its diameter: PM2.5 (fine particles; diameter $\leq$2.5 $\mu$m) and PM10 (coarse particles; diameter $\leq$10 $\mu$m). Air pollutants interact with the body, either via skin contact, inhalation or ingestion.[18] Air pollutants affect the human skin through four different ways: generating ROS, triggering inflammation, impacting skin microbiota, and activating hydrocarbon receptor (AhR).[19] The activation of AhR – a transcription factor – can lead to hyperpigmentation, wrinkles, skin cancer and worsening of several dermatoses such as acne, atopic dermatitis and psoriasis.[11]

Exposure to ozone causes changes in the stratum corneum (SC), the outermost layer of the epidermis. It reduces SC-associated antioxidants, leading to an oxidative stress response. This oxidative stress response reaches the deeper layers of the skin, including the dermis, affecting collagen metabolism, leading to wrinkle formation.[20]

Repeated exposure of the skin to PM even at non-toxic concentrations increases the production of ROS, which in turn leads to the secretion of cytokines and cellular dysfunction. This can break down the lipid barrier of the epidermis, decrease the number of cutaneous microbial species, trigger inflammatory skin diseases, and induce melanogenesis via AhR activation.[21] A study showed that one-unit increase in PMs was associated with a 20% increase in lentigines on the forehead and cheeks and in wrinkles of the nasolabial fold. The risk of lentigines was higher after increased exposure to PM2.5 than after increased exposure to PM10.[22] PM2.5 are highly lipophilic and penetrate the skin easily vs the PM10 particles that stay at the surface of the skin.[23] Regarding skin cancer, an epidemiological study shows that an increment of 10 $\mu g/m^3$ PM10 in the air increases 52% relative risk of developing non-melanoma skin cancers.[24] AhR may play a role in inducing skin cancer; AhR-deficient mice exposed to PM did not develop keratinocyte carcinomas whereas those AhR positive developed keratinocyte carcinomas via CYP1A1 expression.[25]

In addition to PM, other air pollutants have been shown to have an impact on skin health.[26] Studies indicate that high levels of environmental factors including polycyclic aromatic hydrocarbons (PAHs), VOCs, heavy metals, and gases such as CO, NOx, SO, and $O_3$, can impair the skin's barrier function. Both the concentration and duration of exposure are significant. These pollutants are linked to various skin issues, including aging, inflammatory diseases, acne, hair loss, and skin cancers, with responses varying by pollutant characteristics.[27]

The relationship between pollution and skin aging was evaluated in a cohort of 389 patients aged 30–74 who planned to undergo laser treatment. Researchers used the VISIA Complexion Analysis System to assess skin conditions alongside levels of various air pollutants, including CO, non-methane hydrocarbons (NMHC), nitrogen oxides (NO, $NO_2$, NOx), PM2.5 and PM10, $O_3$, and $SO_2$. Findings revealed a strong correlation between NMHC exposure and issues such as skin texture, enlarged pores, and brown spots. Conversely, exposure to ozone was associated with better skin texture and pore scores. Notably, brown spots were negatively associated with several pollutants, particularly in individuals older than 45 years.[28]

Moreover, we already know that increased $NO_2$ concentrations characterize traffic-related air pollution. Although the effects of $NO_2$ on skin health have not been previously explored, the relationship between environmentally induced lung and skin aging prompted an assessment of $NO_2$ exposure and lentigo development.[29] Data from the extended SALIA population and an independent Han Chinese cohort were analyzed. Results indicated a significant correlation between $NO_2$ exposure and increased lentigines on the cheeks in both cohorts. Specifically, a 10 $\mu g/m^3$ increase in $NO_2$ correlated with a 25% increase in lentigines in SALIA participants and a 24% increase in Chinese women >50 years.[26]

## The effects of solar radiation on aging

Solar radiation is the major external factor related to skin aging. Up to 80% of skin aging is caused by sun exposure.[30] Sun-exposed areas such as the face and neck appear prematurely aged vs unexposed skin. Clinical features of aging due to sun exposure include wrinkles, dullness, changes in pigmentation, laxity, roughness, and telangiectasia.[31] Solar radiation that raises earth's surface includes electromagnetic rays of different wavelengths. These include UVR (UVB and UVA), VL, and IR. They arrive at the earth's surface in different proportions and penetrate the skin to different levels. Skin aging occurs due to daily exposure to non-extreme, low doses of these solar waves. The most energetic radiation – UVB (290–315 nm) – only penetrates up to the epidermis. It mainly causes erythema, photoimmunosuppression and cutaneous cancer. Additionally, it increases the production of epidermal matrix metalloproteinase (MMP)-1, which disseminates into the dermis where it breaks down collagen, contributing to skin aging.[2] UVA (315–400 nm) is the main radiation responsible for photoaging. It penetrates up to the dermis and has direct effects on dermal fibroblasts.[32,33] Both UVB and UVA contribute to acquired skin pigmentation and skin cancer.[31] Regarding skin cancer, while UVB causes direct damage to DNA, UVA causes indirect damage to DNA by forming ROS.[34] UVR is a recognized carcinogen, responsible for more than 50% of all tumors. It causes almost 65% of malignant melanomas and 90% of keratinocyte carcinomas.[31] VL (400–700 nm) is the wavelength that can be detected by the human eye. One of the VL wavelengths with more biologic effects is the blue-violet light (BL) also known as high-energy visible light ($\approx$400–500 nm). It produces ROS and induces MMP-1 expression contributing to skin aging.[6,35] OPN3 receptors detect BL and increase the synthesis of tyrosinase and dopachrome tautomerase involved in melanogenesis and hyperpigmentation.

The impact of BL is higher in subjects with darker skin tones (ITA <28°); hence, protection vs BL is specially recommended in them.[36,37] IR (700 nm–1 mm) damages the skin; IR-A penetrates deeply, generating mitochondrial ROS,

increasing MMP-1, reducing collagen production, promoting angiogenesis, and raising mast cell numbers.[38]

### Synergies between solar radiation and air pollution

Humans are not exclusively exposed to a single exposome factor. While many studies examine the impact of solar radiation or air pollution on the skin of aging individually, few assess their combined effect.[30] In this regard, solar radiation converts volatile organic compounds (VOC), found in the air, into secondary organic aerosols that contribute to PM formation, particularly PM2.5.[19] Additionally, the combined effect of UVA radiation and ozone can synergistically induce more oxidative stress in human skin.[39]

In preclinical studies, the combination of UVA and diesel PMs (DPM) induced significant cytotoxic and genotoxic damage through the photoactive production of singlet oxygen, which was not observed with either UVA or DPM extracts alone.[40] Furthermore, other *in vitro* data have demonstrated that PAHs, found in PM, in combination with UVA significantly increases skin damage and aging in the skin.[41] UVA along with air pollutants considerably increases the risk of skin cancer.[34] Clinically, an analysis of 799 Caucasian women in Germany suggested that facial lentigines are the consequence of an interplay between UVR and PMs.[42] A recent study compared a similar population from two Chinese cities located at the same latitude (thus receiving approximately the same sun exposure) but exposed to different atmospheric pollution levels. It was found that people living in a higher polluted environment for many years had a higher prevalence of hyperpigmented lesions as well as higher severity of wrinkles.[43]

However, pollution could have in some circumstances a photoprotective effect reducing UV irradiance due to the presence of $O_3$, $NO_2$, $SO_2$ and scattering particulates in the troposphere.[44] More research is needed to elucidate the mechanisms of UV and pollution interaction.[45] However, all existing evidence leads to the conclusion that the combination of solar radiation plus air pollution can have synergistic effects increasing their detrimental cutaneous effects. Hence, combined anti-pollution and photoprotective strategies should be implemented.

## Anti-pollution ingredients

The first step to prevent the negative impact of air pollutants to the skin is to prevent their deposition and penetration, and the next step is to revert their effects once they have penetrated the skin.[46] The main approaches to counteract cutaneous negative effects of air pollution are to reinforce the skin's barrier function and increase its antioxidant stores.[21] Several anti-pollution ingredients have been proven to be effective in preventing and counteracting the skin damage caused by air pollutants. Some of these actives are added to sunscreens, topical cosmetics, while others can be taken as oral supplements.

### Anti-pollution cosmetic ingredients

Cosmetic ingredients can help protect the skin from air pollution mainly by forming a protective film (film-forming), neutralizing ROS (antioxidants) and decreasing AhR expression. Some active ingredients with scientific evidence are listed below:

1. *Film-forming agents*: One novel film-forming agent is *Alteromonas* ferment extract, an exopolysaccharide derived from marine microorganisms. It creates a protective film on the skin, reducing the adherence of PM2.5 and improving skin barrier function. A study showed that after 56 days of daily use, *Alteromonas* ferment extract significantly improved skin hydration, firmness, and elasticity.[47] Other film-forming agents are extracts from *Kappaphycus alvarezii* and *Caesalpinia spinosa*.[48,49]
2. *Antioxidant ingredients*: Several categories of ingredients can act as antioxidants including vitamins, plant-derived compounds, and microorganism-derived substances.
   - 2.1 *Vitamins*: Topical vitamin C is a potent antioxidant that increases collagen synthesis and reduces the expression of matrix metalloproteinases (MMPs), increasing collagen levels.[50] It can reduce pigmentation by inhibiting tyrosinase activity, prevent UV-induced erythema, and maintain skin hydration.[50] Vitamin E is another important antioxidant that decreases MMP-1 levels and reinforces skin barrier.[50] Topical niacinamide (vitamin B3) has been shown to improve the appearance of aging facial skin by reducing hyperpigmentation, pore size, and redness.[51,52] It also offers benefits in preventing photo-immunosuppression and photo-carcinogenesis. Niacinamide improves skin barrier function, decreases sebum production, and is well tolerated.[51,52] An *in vitro* study showed that continuous exposure for 3 days to 30 pmol/cm$^2$ of benzo(a)pyrene (BaP) and squalene monohydroperoxides, as surrogate environmental stressors, led to significant reductions in cell viability, increased inflammation, and rise in pigmentation in reconstructed human skin equivalents. Niacinamide pretreatment (5 mmol/L) effectively reduced these effects, likely by supporting NAD+-dependent detoxification pathways.[53] Medical literature does not contain studies specifically examining the protective effects of the other vitamins individually vs pollution-related skin aging. However, their capacity to mitigate oxidative stress – regardless of the source – suggests that such effects may be inferred. Future research should focus on this area of investigation.
   - 2.2 *Plant-derived compounds*: Ginger oil from *Zingiber officinale* possesses antioxidant and anti-inflammatory properties. It has been shown to reduce UVB-induced erythema and wrinkle formation.[54] In preclinical studies, *Zingiber montanum* has proven capable of inhibiting ROS formation, increase type I procollagen synthesis and decrease MMP (1, 3 and 9) expression and elastase activity.[55] Another plant-derived antioxidant active is *Polypodium leucotomos* (PL). An aqueous PL leaf extract reduced oxidative stress and inhibited melanogenic pathway activation in keratinocyte and melanocyte cells exposed to BaP pollutants and UVA.[56] In a study of cultured keratinocytes exposed

to PM2.5, PL reduced inflammation and generation of new melanocytes.[57]

2.3 *Microorganism-derived compounds*: Ectoine, a metabolite produced by a halophilic bacterium, reinforces the skin barrier and suppresses inflammatory processes.[58] In UVA-irradiated keratinocytes, it suppresses α-MSH-stimulated melanogenesis and activates the antioxidant Nrf2 pathways having a skin-whitening effect.[59] *Porphyridium cruentum*, a red microalga, produces a high amount of sulfated polysaccharides (SPs) that interfere with ROS formation and inhibit elastase activity, preserving elastin and collagen.[60] *K. alvarezii*, another seaweed extract, has demonstrated antioxidant, photoprotective, and anti-inflammatory properties.[61]

2.4 *Other anti-pollution ingredients*: Melatonin acts as an antioxidant by scavenging ROS (direct antioxidant) and increasing the levels of endogenous antioxidant enzymes (indirect antioxidant)[62]; additionally, it has been demonstrated that topical melatonin 12.5% protect vs UVB-induced erythema.[63] Coenzyme Q10 (Q10) is an important endogenous coenzyme whose levels decrease with age and exposomal factors exposure. Topical Q10 can penetrate the skin and exert antioxidant effects, benefiting both elderly individuals with Q10 deficiency and people of all ages seeking protection due to oxidative stress.[64] Moreover, Q10 decreases PM-induced inflammation by enhancing the cellular oxidative status, suppressing pro-inflammatory NF-kB, and improving the levels of the antioxidant and anti-inflammatory regulators Nrf2 and SIRT1 in human dermal fibroblasts.[65]

3. *Aryl-receptor inhibitors*: Another way to counteract the effect of pollution on the skin is through the blockade of the AhR. *Deschampsia antarctica* is a polyextremophile Gramineae native to Antarctica whose aqueous extract has shown to counteract the pollutant-induced AhR activation in the keratinocytes.[66] A night cream containing melatonin, carnosine and *Helichrysum italicum* extract reduced the expression levels of AhR by 96% in human skin explants exposed to a mixture of PAH and heavy metals for 1.5 h vs the control group.[67]

## Oral supplements that can counteract the effects of air pollution

In addition to cosmetics, oral supplements can also mitigate the harmful effects of exposome. Carotenoids reduce UVA-induced oxidative stress and pigmentation, and UVB-induced erythema.[7] However, humans cannot synthesize carotenoids on their own and dietary supplementation is necessary.[55,68,69] Ferulic acid found in tissues of plants has antioxidant and anti-inflammatory effects on the skin.[69] Green tea is rich in polyphenols which scavenge ROS, enhance immunity and decrease MMPs.[70] Another useful active ingredient is the extract of the Mesoamerican fern *P. leucotomos* (PL). It has been demonstrated that oral treatment with PL extracts reduced the harmful effects of UVB irradiation, including the appearance of sunburn cells, DNA damage, and inflammation.[71] It also protects vs VL, particularly from hyperpigmentation.[72–74] In a study with 22 individuals irradiated with UVB, UVA, and VL, oral PL extract showed suppressive effects on UVB-induced erythema within 2 h of administration.[75]

The mechanism of action and administration route of different anti-pollution ingredients are shown in Table 1.

## Multi-benefit photoprotection formulations

Sunscreen is a great tool to prevent and reduce premature skin aging. Given the increasing list of actives that may help counteract the effects of air pollution on the skin, the use of sunscreens enriched with such ingredients are becoming an appealing and useful strategy. Few studies show multi-benefit sunscreens with anti-pollution actives effectively counter solar and pollution damage. Narda et al. evaluated a water-based SPF50 facial anti-pollution and anti-aging sunscreen (WSC) containing hyaluronic acid, palmitoyl tripeptide-38, and pentapeptide-34 trifluoroacetate.[13] Preclinically, WSC protected vs sunburn cell formation and significantly reduced the adherence of PM to the skin (15.2% less than control; $p < 0.01$). Skin treated with WSC showed reduced levels of pro-inflammatory and oxidative stress markers. Clinically, daily use of the product during 28 days significantly decreased the area of brown spots, and count ($p < 0.01$) and increased firmness by 14.1% ($p < 0.01$).[13] A topical serum of 15% ascorbic acid, 0.5% ferulic acid, and 1% tocopherol prevented skin barrier damage, lipid peroxidation an inflammation induced by PM+UVR in 15 subjects confirming its utility to prevent pollution-induced skin damage.[76]

Oral photoprotection may help mitigate combined pollution and solar effects, but evidence is limited. Marini et al., investigated the efficacy of an oral supplement containing a combination of actives with mainly antioxidant properties (*P. leucotomos*, green tea, lycopene, lutein, and vitamin C, among others) in protecting the skin from sun damage (UVA/UVB) and air pollution particles.[77] Minimal erythemal dose and minimal persistent pigmentation dose were evaluated before and after supplementation in an *in vivo* double-blind placebo controlled study. Oral supplementation provided significant protection vs UVB-induced sunburn and UVA-induced pigmentation in air pollutant exposed skin. The observed reduction in air pollution-induced skin tanning responses is likely due to the antioxidant activity of the actives.[77] A double-blind randomized, parallel group trial conducted among 100 outdoors workers living in a polluted city showed that the intake of an oral supplement composed by four herbal extracts (*Olea europaea* leaf, *Lippia citriodora*, *Rosmarinus officinalis*, and *Sophora japonica*) reduced wrinkled depth, increased elasticity and firmness, improved skin moisturization and transepidermal water loss and reduced dark spots as early as 2 weeks after being used.[78]

These results suggest that multi-benefit photoprotection formulas, both topical and oral, might contribute to mitigate the negative effects of combined effects of air pollution and solar radiation.

A summary of air pollution and solar radiation cutaneous effects and non-pharmacologic strategies to counteract them is shown in Fig. 1.

**Table 1** Mechanism of action and administration route of different anti-pollution ingredients.

| Anti-pollution ingredient | Mechanism of action | Route of administration |
|---|---|---|
| *Alteromonas* ferment extract[47] | • Film-forming. Reduces adherence of PM2.5 to the skin<br>• Improves skin barrier function | Topical |
| Ginger oil (*Zingiber* spp.)[54] | • Antioxidant<br>• Anti-inflammatory | Topical |
| *Zingiber montanum*[55] | • Antioxidant<br>• Decreases the activity of elastase<br>• Decreases MMP expression<br>• Increases type I procollagen synthesis | Topical |
| Ectoine[52] | • Antioxidant<br>• Reinforce skin barrier<br>• Protects from UV radiation and environmental hazards<br>• Suppresses inflammatory processes: $\alpha$-MSH-stimulated melanogenesis<br>• Activates antioxidant Nrf2 pathways | Topical |
| *Porphyridium cruentum*[60] | • Antioxidant<br>• Reinforce skin barrier<br>• Inhibit elastase | Topical |
| *Kappaphycus alvarezii*[61] | • Antioxidant<br>• Photoprotective<br>• Anti-inflammatory | Topical |
| Coenzyme Q10[64] | • Antioxidant<br>• Anti-inflammatory | Topical |
| *Deschampsia antarctica*[66] | • AhR inhibitor | Topical |
| *Helichrysum italicum*[67] | • AhR inhibitor | Topical |
| Carotenoids[7] | • Antioxidant (reduces UVA-induced oxidative stress, pigmentation and UVB-induced erythema) | Oral |
| Ferulic acid[69] | • Antioxidant<br>• Anti-inflammatory | Oral |
| Green tea polyphenols (GTPP)[70] | • Antioxidant<br>• Enhance immunity<br>• Decrease MMPs | Oral |
| Vitamin C[50] | • Antioxidant<br>• Increases collagen synthesis<br>• Reduces MMP expression<br>• Inhibits tyrosinase | Topical/oral |
| Vitamin E[50] | • Antioxidant<br>• Decreases MMP-1 transcription levels | Topical/oral |
| Niacinamide (vitamin B3)[52] | • Antioxidant<br>• Prevents photo-immunosuppression and photo-carcinogen<br>• Prevents the loss of dermal collagen | Topical/oral |
| *Polypodium leucotomos* (PL)[71,72,75] | • Antioxidant<br>• Anti-inflammatory<br>• Prevents melanogenic signaling pathway activation | Topical/oral |

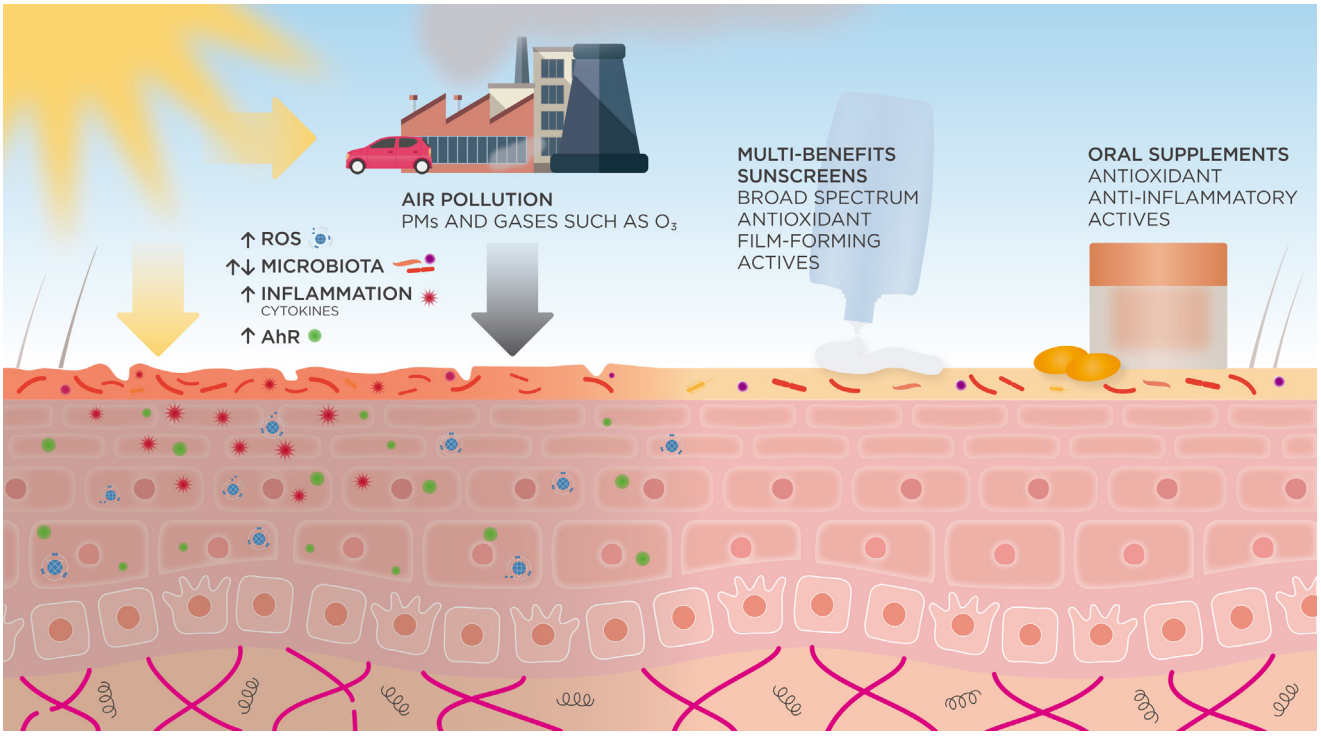


**Figure 1** Air pollution and solar radiation effects on skin and non-pharmacologic strategies to counteract them.

## Conclusions

The skin easily develops signs of aging, due to accumulating oxidative stress caused by various exposome factors. Among exposomal factors, the maximum damage occurs due to solar radiation and air pollution. We described the effect of air pollution and its synergistic effects with solar radiation on skin aging. It remains to be studied if pollution also interacts with other exposomal factors and whether these potential interactions induce premature aging of the skin. The use of multi-benefit photoprotection (both topical and oral) are promising strategies to counteract the negative effects of exposomal factors. Further investigation is crucial to understand how pollution interacts with other exposomal factors and how to best address this complex interplay for optimal skin health.

## CRediT authorship contribution statement

J. Santamaria and L. Prudkin equally contributed to the manuscript drafting and critical revision regarding significant intellectual content. All authors read and approved the manuscript final version.

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## Conflicts of interest

J. Santamaría and L. Prudkin are employees at ISDIN. J. Piquero-Casals is a consultant for ISDIN. Y. Gilaberte has received honoraria from ISDIN.

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## References

1. Misra BB. The chemical exposome of human aging. Front Genet. 2020;11, http://dx.doi.org/10.3389/fgene.2020.574936.
2. Krutmann J, Schikowski T, Morita A, Berneburg M. Environmentally-induced (extrinsic) skin aging: exposomal factors and underlying mechanisms. J Invest Dermatol. 2021;141:1096–103, http://dx.doi.org/10.1016/j.jid.2020.12.011.
3. Wild CP. Complementing the genome with an ''exposome'': the outstanding challenge of environmental exposure measurement in molecular epidemiology. Cancer Epidemiol Biomarkers Prev. 2005;14:1847–50, http://dx.doi.org/10.1158/1055-9965.EPI-05-0456.
4. Miller GW, Jones DP. The nature of nurture: refining the definition of the exposome. Toxicol Sci. 2014;137:1–2, http://dx.doi.org/10.1093/toxsci/kft251.

5. Parrado C, Mercado-Saenz S, Perez-Davo A, Gilaberte Y, Gonzalez S, Juarranz A. Environmental stressors on skin aging. Mechanistic insights. Front Pharmacol. 2019;10, http://dx.doi.org/10.3389/fphar.2019.00759.
6. Krutmann J, Bouloc A, Sore G, Bernard BA, Passeron T. The skin aging exposome. J Dermatol Sci. 2017;85:152–61, http://dx.doi.org/10.1016/j.jdermsci.2016.09.015.
7. Baswan SM, Klosner AE, Weir C, Salter-Venzon D, Gellenbeck KW, Leverett J, et al. Role of ingestible carotenoids in skin protection: a review of clinical evidence. Photodermatol Photoimmunol Photomed. 2021;37:490–504, http://dx.doi.org/10.1111/phpp.12690.
8. Pizzino G, Irrera N, Cucinotta M, Pallio G, Mannino F, Arcoraci V, et al. Oxidative stress: harms and benefits for human health. Oxid Med Cell Longev. 2017;2017:8416763, http://dx.doi.org/10.1155/2017/8416763.
9. Guan LL, Lim HW, Mohammad TF. Sunscreens and photoaging: a review of current literature. Am J Clin Dermatol. 2021;22:819–28, http://dx.doi.org/10.1007/s40257-021-00632-5.
10. Ferrara F, Woodby B, Pecorelli A, Schiavone ML, Pambianchi E, Messano N, et al. Additive effect of combined pollutants to UV induced skin OxInflammation damage. Evaluating the protective topical application of a cosmeceutical mixture formulation. Redox Biol. 2020;34, http://dx.doi.org/10.1016/j.redox.2020.101481.
11. Narda M, Bauza G, Valderas P, Granger C. Protective effects of a novel facial cream against environmental pollution: in vivo and in vitro assessment. Clin Cosmet Investig Dermatol. 2018;11:571–8, http://dx.doi.org/10.2147/CCID.S180575.
12. Geisler AN, Austin E, Nguyen J, Hamzavi I, Jagdeo J, Lim HW. Visible light. Part II: Photoprotection against visible and ultraviolet light. J Am Acad Dermatol. 2021;84:1233–44, http://dx.doi.org/10.1016/j.jaad.2020.11.074.
13. Narda M, Ramos-Lopez D, Bustos J, Trullàs C, Granger C. A novel water-based anti-aging suncare formulation provides multifaceted protection and repair against environmental aggressors: evidence from in vitro, ex vivo, and clinical studies. Clin Cosmet Investig Dermatol. 2019;12:533–44, http://dx.doi.org/10.2147/CCID.S209728.
14. Molina-García M, Granger C, Trullàs C, Puig S. Exposome and skin. Part 1: Bibliometric analysis and review of the impact of exposome approaches on dermatology. Dermatol Ther (Heidelb). 2022;12:345–59.
15. Niedzwiecki MM, Walker DI, Vermeulen R, Chadeau-Hyam M, Jones DP, Miller GW. The exposome: molecules to populations. Annu Rev Pharmacol Toxicol. 2019;59:107–27, http://dx.doi.org/10.1146/annurev-pharmtox-010818-021315.
16. Fuzzi S, Baltensperger U, Carslaw K, Decesari S, Denier van der Gon H, Facchini MC, et al. Particulate matter, air quality and climate: lessons learned and future needs. Atmos Chem Phys. 2015;15:8217–99, http://dx.doi.org/10.5194/acp-15-8217-2015.
17. Forster P, Ramaswamy V, Artaxo P, Bernsten T, Betts R, Fahey DW, et al. Changes in atmospheric constituents and in radiative forcing; 2007.
18. Araviiskaia E. The impact of airborne pollution on skin. J Eur Acad Dermatol Venereol. 2019;33:1496–505.
19. Ali A, Khan H, Bahadar R, Riaz A, Bin Asad MHH. The impact of airborne pollution and exposure to solar ultraviolet radiation on skin: mechanistic and physiological insight. Environ Sci Pollut Res. 2020;27:28730–6, http://dx.doi.org/10.1007/s11356-020-09280-4.
20. Fuks KB, Woodby B, Valacchi G. Skin damage by tropospheric ozone. Hautarzt. 2019, http://dx.doi.org/10.1007/s00105-018-4319-y. Jan 18. English.
21. Denisow-Pietrzyk M. Human skin reflects air pollution – a review of the mechanisms and clinical manifestations of environment-derived skin pathologies. Pol J Environ Stud. 2021;30:3433–44, http://dx.doi.org/10.15244/pjoes/130525.
22. Vierkötter A, Schikowski T, Ranft U, Sugiri D, Matsui M, Krämer U, et al. Airborne particle exposure and extrinsic skin aging. J Invest Dermatol. 2010;130:2719–26, http://dx.doi.org/10.1038/jid.2010.204.
23. Grether-Beck S, Marini A, Jaenicke T, Krutmann J. Photoprotection of human skin beyond ultraviolet radiation. Photodermatol Photoimmunol Photomed. 2014;30:167–74, http://dx.doi.org/10.1111/phpp.12111.
24. Datzmann T, Markevych I, Trautmann F, Heinrich J, Schmitt J, Tesch F. Outdoor air pollution, green space, and cancer incidence in Saxony: a semi-individual cohort study. BMC Public Health. 2018;18:715, http://dx.doi.org/10.1186/s12889-018-5615-2.
25. Kim KE, Cho D, Park HJ. Air pollution and skin diseases: adverse effects of airborne particulate matter on various skin diseases. Life Sci. 2016;152:126–34, http://dx.doi.org/10.1016/j.lfs.2016.03.039.
26. Hüls A, Vierkötter A, Gao W, Krämer U, Yang Y, Ding A, et al. Traffic-related air pollution contributes to development of facial lentigines: further epidemiological evidence from Caucasians and Asians. J Invest Dermatol. 2016;136:1053–6, http://dx.doi.org/10.1016/j.jid.2015.12.045.
27. Abolhasani R, Araghi F, Tabary M, Aryannejad A, Mashinchi B, Robati RM. The impact of air pollution on skin and related disorders: a comprehensive review. Dermatol Ther. 2021;34, http://dx.doi.org/10.1111/dth.14840.
28. Huang CH, Chen SC, Wang YC, Wang CF, Hung CH, Lee SS. Detrimental correlation between air pollution with skin aging in Taiwan population. Medicine. 2022;101:e29380, http://dx.doi.org/10.1097/MD.0000000000029380.
29. Fussell JC, Kelly FJ. Oxidative contribution of air pollution to extrinsic skin ageing. Free Radic Biol Med. 2020;151:111–22, http://dx.doi.org/10.1016/j.freeradbiomed.2019.11.038.
30. Buendía-Eisman A, Prieto L, Abarquero M, Arias-Santiago S. Study of the exposome ageing-related factors in the Spanish population. Acta Derm Venereol. 2020;100:1–8, http://dx.doi.org/10.2340/00015555-3500.
31. Passeron T, Krutmann J, Andersen ML, Katta R, Zouboulis CC. Clinical and biological impact of the exposome on the skin. J Eur Acad Dermatol Venereol. 2020;34(S4):4–25, http://dx.doi.org/10.1111/jdv.16614.
32. Marionnet C, Pierrard C, Golebiewski C, Bernerd F. Diversity of biological effects induced by longwave UVA rays (UVA1) in reconstructed skin. PLoS One. 2014;9:e105263, http://dx.doi.org/10.1371/JOURNAL.PONE.0105263.
33. Bernerd F, Passeron T, Castiel I, Marionnet C. The damaging effects of long UVA (UVA1) rays: a major challenge to preserve skin health and integrity. Int J Mol Sci. 2022;23, http://dx.doi.org/10.3390/ijms23158243.
34. Burke K, Wei H. Synergistic damage by UVA radiation and pollutants. Toxicol Ind Health. 2009;25:219–24, http://dx.doi.org/10.1177/0748233709106067.
35. Mann T, Eggers K, Rippke F, Tesch M, Buerger A, Darvin ME, et al. High-energy visible light at ambient doses and intensities induces oxidative stress of skin – protective effects of the antioxidant and Nrf2 inducer Licochalcone A in vitro and in vivo. Photodermatol Photoimmunol Photomed. 2020;36:135–44, http://dx.doi.org/10.1111/PHPP. 12523.
36. Lim HW, Kohli I, Granger C, Trullàs C, Piquero-Casals J, Narda M, et al. Photoprotection of the skin from visible light-induced pigmentation: current testing methods and proposed harmonization. J Invest Dermatol. 2021;141:2569–76, http://dx.doi.org/10.1016/j.jid.2021.03.012.

37. Krutmann J, Piquero-Casals J, Morgado-Carrasco D, Granger C, Trullàs C, Passeron T, et al. Photoprotection for people with skin of colour: needs and strategies. Br J Dermatol. 2023;188:168–75, http://dx.doi.org/10.1093/bjd/ljac046.
38. Wang SQ, Lim HW. In: Wang SQ, Lim HW, editors. Principles and practice of photoprotection; 2016.
39. Thiele J, Podda M, Packer L. Tropospheric ozone: an emerging environmental stress to skin. Biol Chem. 1997;378:1299–305.
40. Bao L, Xu A, Tong L, Chen S, Zhu L, Zhao Y, et al. Activated toxicity of diesel particulate extract by ultraviolet A radiation in mammalian cells: role of singlet oxygen. Environ Health Perspect. 2009;117:436–41, http://dx.doi.org/10.1289/ehp.0800029.
41. Soeur J, Belaïdi JP, Chollet C, Denat L, Dimitrov A, Jones C, et al. Photo-pollution stress in skin: traces of pollutants (PAH and particulate matter) impair redox homeostasis in keratinocytes exposed to UVA1. J Dermatol Sci. 2017;86:162–9, http://dx.doi.org/10.1016/j.jdermsci.2017.01.007.
42. Hüls A, Sugiri D, Fuks K, Krutmann J, Schikowski T. Lentigine formation in Caucasian women – interaction between particulate matter and solar UVR. J Invest Dermatol. 2019;139:974–6, http://dx.doi.org/10.1016/j.jid.2018.09.034.
43. Flament F, Bourokba N, Nouveau S, Li J, Charbonneau A. A severe chronic outdoor urban pollution alters some facial aging signs in Chinese women. A tale of two cities. Int J Cosmet Sci. 2018;40:467–81, http://dx.doi.org/10.1111/ics.12487.
44. Puri P, Nandar S, Kathuria S, Ramesh V. Effects of air pollution on the skin: a review. Indian J Dermatol Venereol Leprol. 2017;83:415, http://dx.doi.org/10.4103/0378-6323.199579.
45. Schikowski T, Hüls A. Air pollution and skin aging. Curr Environ Health Rep. 2020;7:58–64, http://dx.doi.org/10.1007/s40572-020-00262-9.
46. Mistry N. Guidelines for formulating anti-pollution products. Cosmetics. 2017;4:57, http://dx.doi.org/10.3390/cosmetics4040057.
47. Garre A, Martinez-Masana G, Piquero-Casals J, Granger C. Redefining face contour with a novel anti-aging cosmetic product: an open-label, prospective clinical study. Clin Cosmet Investig Dermatol. 2017;10:473–82.
48. Penachin B, Kakuda L, Maia Campos P. Evaluation of the protective and moisturizing effects of cosmetic formulations for the skin containing extracts with film-forming properties. J Biomed Biopharm Res. 2022;19:361–78, http://dx.doi.org/10.19277/bbr.19.2.293.
49. Melo MO, Maia Campos P. Application of biophysical and skin imaging techniques to evaluate the film-forming effect of cosmetic formulations. Int J Cosmet Sci. 2019;41:579–84, http://dx.doi.org/10.1111/ics.12577.
50. Chen L, Hu JY, Wang SQ. The role of antioxidants in photoprotection: a critical review. J Am Acad Dermatol. 2012;67:1013–24, http://dx.doi.org/10.1016/j.jaad.2012.02.009.
51. Bissett DL, Miyamoto K, Sun P, Li J, Berge CA. Topical niacinamide reduces yellowing, wrinkling, red blotchiness, and hyperpigmented spots in aging facial skin. Int J Cosmet Sci. 2004;26:231–8, http://dx.doi.org/10.1111/j.1467-2494.2004.00228.x.
52. Bissett DL, Oblong JE, Berge CA. Niacinamide: a B vitamin that improves aging facial skin appearance. Dermatol Surg. 2005;31 Pt 2:860–6, http://dx.doi.org/10.1111/J.1524-4725.2005.31732.
53. Mi T, Dong Y, Santhanam U, Huang N. Niacinamide and 12-hydroxystearic acid prevented benzo(a)pyrene and squalene peroxides induced hyperpigmentation in skin equivalent. Exp Dermatol. 2019;28:742–6, http://dx.doi.org/10.1111/exd.13811.
54. Feng J, Du Z, Zhang L, Luo W, Zheng Y, Chen D, et al. Chemical composition and skin protective effects of essential oil obtained from ginger (*Zingiber officinale* Roscoe). J Essent Oil Bear Plants. 2018;21:1542–9, http://dx.doi.org/10.1080/0972060X.2018.1533436.
55. Navabhatra A, Maniratanachote R, Yingngam B. Antiphotoaging properties of *Zingiber montanum* essential oil isolated by solvent-free microwave extraction against ultraviolet B-irradiated human dermal fibroblasts. Toxicol Res. 2022;38:235–48, http://dx.doi.org/10.1007/s43188-021-00107-z.
56. Gallego-Rentero M, Nicolás-Morala J, Alonso-Juarranz M, Carrasco E, Portillo-Esnaola M, Rodríguez-Luna A, et al. Protective effect of the hydrophilic extract of *Polypodium leucotomos* Fernblock®, against the synergistic action of UVA radiation and benzo[a]pyrene pollutant. Antioxidants. 2022;11:2185, http://dx.doi.org/10.3390/antiox11112185.
57. Delgado-Wicke P, Rodríguez-Luna A, Ikeyama Y, Honma Y, Kume T, Gutierrez M, et al. Fernblock® upregulates NRF2 antioxidant pathway and protects keratinocytes from $PM_{2.5}$-induced xenotoxic stress. Oxid Med Cell Longev. 2020;2020:1–12, http://dx.doi.org/10.1155/2020/2908108.
58. Kocherovets VI. Ectoine – a microbial metabolite with unique biotherapeutic properties. Pediatr Cons Med. 2019;1:108–15.
59. Hseu YC, Chen XZ, Vudhya Gowrisankar Y, Yen HR, Chuang JY, Yang HL. The skin-whitening effects of ectoine via the suppression of $\alpha$-MSH-stimulated melanogenesis and the activation of antioxidant Nrf2 pathways in UVA-irradiated keratinocytes. Antioxidants. 2020;9:63, http://dx.doi.org/10.3390/antiox9010063.
60. Díaz Bayona K, Navarro GS, Lara EA, Colorado RJ, Atehortúa GL, Martínez MA. Activity of sulfated polysaccharides from microalgae *Porphyridium cruentum* over degenerative mechanisms of the skin. Int J Sci Adv Technol. 2012;2:85–92.
61. Liang Y, Su W, Wang F. Skin ageing: a progressive, multi-factorial condition demanding an integrated, multilayer-targeted remedy. Clin Cosmet Investig Dermatol. 2023;16:1215–29, http://dx.doi.org/10.2147/CCID.S408765.
62. Rezzani R, Rodella LF, Favero G, Damiani G, Paganelli C, Reiter RJ. Attenuation of ultraviolet A-induced alterations in NIH3T3 dermal fibroblasts by melatonin. Br J Dermatol. 2014;170:382–91, http://dx.doi.org/10.1111/BJD.12622.
63. Scheuer C, Pommergaard HC, Rosenberg J, Gögenur I. Melatonin for prevention of erythema and oxidative stress in response to ultraviolet radiation. Dan Med J. 2017;27:488–94.
64. Knott A, Achterberg V, Smuda C, Mielke H, Sperling G, Dunckelmann K, et al. Topical treatment with coenzyme Q10-containing formulas improves skin's Q10 level and provides antioxidative effects. BioFactors. 2015;41:383–90, http://dx.doi.org/10.1002/biof.1239.
65. Chang TM, Yang TY, Huang HC. Nicotinamide mononucleotide and coenzyme Q10 protects fibroblast senescence induced by particulate matter preconditioned mast cells. Int J Mol Sci. 2022;23:7539, http://dx.doi.org/10.3390/ijms23147539.
66. Milani M, Hastroody B, Piacentini M, Celleno L. Skin protective effects of an antipollution, antioxidant serum containing *Deschampsia antartica* extract, ferulic acid and vitamin C: a controlled single-blind, prospective trial in women living in urbanized, high air pollution area. Clin Cosmet Investig Dermatol. 2019;12:393–9.
67. Granger C, Brown A, Aladren S, Narda M. Night cream containing melatonin carnosine and *Helichrysum italicum* extract helps reduce skin reactivity and signs of photodamage: ex vivo and clinical studies. Dermatol Ther (Heidelb). 2020;10:1315–29, http://dx.doi.org/10.1007/s13555-020-00443-2.
68. Maoka T. Carotenoids as natural functional pigments. J Nat Med. 2020;74:1–16, http://dx.doi.org/10.1007/s11418-019-01364-x.

69. Zduńska K, Dana A, Kolodziejczak A, Rotsztejn H. Antioxidant properties of ferulic acid and its possible application. Skin Pharmacol Physiol. 2018;31:332–6, http://dx.doi.org/10.1159/000491755.
70. González S, Aguilera J, Berman B, Calzavara-Pinton P, Gilaberte Y, Goh CL, et al. Expert recommendations on the evaluation of sunscreen efficacy and the beneficial role of non-filtering ingredients. Front Med (Lausanne). 2022;9, http://dx.doi.org/10.3389/fmed.2022.790207.
71. Middelkamp-Hup MA, Pathak MA, Parrado C, Garcia-Caballero T, Rius-Díaz F, Fitzpatrick TB, et al. Orally administered *Polypodium leucotomos* extract decreases psoralen-UVA-induced phototoxicity, pigmentation, and damage of human skin. J Am Acad Dermatol. 2004;50:41–9, http://dx.doi.org/10.1016/S0190-9622(03)02732-4.
72. Pourang A, Dourra M, Ezekwe N, Kohli I, Hamzavi I, Lim HW. The potential effect of *Polypodium leucotomos* extract on ultraviolet- and visible light-induced photoaging. Photochem Photobiol Sci. 2021;20:1229–38, http://dx.doi.org/10.1007/s43630-021-00087-x.
73. Aguilera J, Vicente-Manzanares M, de Gálvez MV, Herrera-Ceballos E, Rodríguez-Luna A, González S. Booster effect of a natural extract of *Polypodium leucotomos* (Fernblock®) that improves the UV barrier function and immune protection capability of sunscreen formulations. Front Med (Lausanne). 2021;8, http://dx.doi.org/10.3389/fmed.2021.684665.
74. Schalka S, Donato LC. Avaliação da eficácia de um protetor solar contendo extrato de Polypodium leucatomos na redução de danos ocasionados pela exposição à radiação solar. Surg Cosmet Dermatol. 2019;11, http://dx.doi.org/10.5935/scd1984-8773.201911408.
75. Kohli I, Shafi R, Isedeh P, Griffith JL, Al-Jamal MS, Silpa-archa N, et al. The impact of oral *Polypodium leucotomos* extract on ultraviolet B response: a human clinical study. J Am Acad Dermatol. 2017;77, http://dx.doi.org/10.1016/j.jaad.2017.01.044, 33–41.e1.
76. Ferrara F, Yan X, Pecorelli A, Guiotto A, Colella S, Pasqui A, et al. Combined exposure to UV and PM affect skin oxinflammatory responses and it is prevented by antioxidant mix topical application: evidences from clinical study. J Cosmet Dermatol. 2024;23:2644–56, http://dx.doi.org/10.1111/jocd.16321.
77. Marini A, Aue N, Jaenicke T, Grether-Beck S, Trullas C, Granger C, et al. Assessment of the protective effect against air pollution-induced skin pigmentation of an oral nutritional supplement containing antioxidants: a randomized, double-blinded, placebo-controlled study. J Eur Acad Dermatol Venereol. 2023;37, http://dx.doi.org/10.1111/jdv.19183.
78. Nobile V, Schiano I, Peral A, Giardina S, Spartà E, Caturla N. Antioxidant and reduced skin-ageing effects of a polyphenol-enriched dietary supplement in response to air pollution: a randomized, double-blind, placebo-controlled study. Food Nutr Res. 2021;65, http://dx.doi.org/10.29219/fnr.v65.5619.