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Natural Antioxidants as Sunscreen SPF Boosters: Mechanisms, Benefits and Challenges

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Abstract

Prolonged exposure to ultraviolet (UV) rays is a major extrinsic factor causing sunburn, oxidative stress, inflammation, photoaging, and carcinogenesis of the skin. Although traditional sunscreen materials have been shown to provide a powerful protective effect against UV-induced damage to the skin, there is still a need to address the shortcomings of such sunscreen materials, which are: the photo-instability of the absorbing materials, skin irritation, environmental impacts, and inadequate protection against long-wavelength UVA rays. These limitations have created a growing interest in natural antioxidants as supplementary sunscreen materials. Natural antioxidants successfully demonstrated considerable potential to reinforce their photoprotective efficacy through different mechanisms. These antioxidants neutralize the free oxygen produced due to the effects of UV radiation, help in stabilizing the chemical antioxidants against photodegradation, reduce erythema and inflammation, and show their ability to reinforce the barrier function. Along with improving their biological protection, antioxidant supplementation possesses the ability to show enhanced sunscreen efficacy without increasing the amount of conventional chemical filters. The review critically addresses the mechanisms by which natural antioxidants can be effective in the improvement of the efficacy of sunscreens, as well as the significant benefits, along with the formulation-related challenges, limitations in regulations, recent experimental evidence, and prospects.

Keywords: Antioxidants; Sunscreens; SPF Boosters; Photoprotection; Polyphenols; Phycocyanin

1. Introduction

Ultraviolet (UV) radiation is one of the most important exogenous agents causing acute and chronic skin injury. Chronic exposure to UV radiation leads to erythema, inflammation, DNA damage, oxidative stress, and finally photo carcinogenesis, making photoprotection a crucial part of skin health management [1]. UVB radiation, with a wavelength of 280-320 nm, has a direct effect on the epidermal layer of the skin and is primarily responsible for sunburn, epidermal DNA damage, and the initiation of mutagenic processes. On the other hand, UVA radiation, with a wavelength of 320-400 nm, penetrates deeper into the skin and reaches the dermal layer. UVA radiation is a major contributor to the production of ROS (reactive oxygen species) which causes oxidative stress, collagen breakdown, photoaging, and chronic damage to the skin [2].

Naturally occurring antioxidants have become versatile thespians in the world of sunscreens. Think polyphenols, flavonoids, vitamins, carotenoids, and microalgal pigments-their role is much more than adding color and flavor but real might, scavenging reactive oxygen species and soothing inflammation to tackle the UV-induced oxidative damage. In addition to these functions, antioxidants work in synergy with traditional UV filters to reinforce the photoprotective properties of sunscreens and thus improve the skin's resistance to UV stress. It is this additional protective mechanism that has contributed to antioxidants being increasingly viewed as effective SPF boosters [3,4,5].

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2. UV-induced oxidative damage and rationale for antioxidant use

2.1. Mechanisms of UV-induced skin damage.

Ultraviolet (UV) radiation exposure causes the overproduction of reactive oxygen species (ROS), such as singlet oxygen, superoxide anions, and hydroxyl radicals, in both the epidermal and dermal layers of the skin. ROS trigger the oxidative damage of vital cellular components like DNA, lipids, and proteins, causing mutagenesis, cell membrane damage, and disruption of cellular functions [1,7].

UV radiation also triggers the activation of inflammatory pathways and the production of pro-inflammatory mediators, which contribute to erythema and chronic inflammation. In addition, ROS trigger the activation of matrix metalloproteinases (MMPs), which break down structural proteins such as collagen and elastin in the dermal extracellular matrix. This results in loss of elasticity, wrinkle formation, and other clinical manifestations of photoaging [2,6,7].

2.2. Limitations of conventional UV filters.

Photodegradation of Chemical UV filters (e.g., Avobenzone and Octocrylene) due to exposure to UV radiation leads to lower effectiveness of protection from UV radiation and can result in skin irritation [3]. In contrast, Mineral filters like Zinc Oxide (ZnO) and Titanium Dioxide (TiO_2) can provide broad-spectrum UV protection but may have aesthetic limitations like whitening effect or agglomeration of particles. The use of natural antioxidants can mitigate some of the limitations associated with both chemical and mineral filters. Antioxidants help to preserve the stability of chemical UV filters, decrease the inflammation caused by UV radiation, and improve the SPF performance of chemical and mineral UV filters without increasing their concentrations [8].

3. Natural antioxidants as SPF boosters

3.1. Polyphenols and flavonoids.

Polyphenols like quercetin, catechins, and epigallocatechin gallate (EGCG) are well-known natural antioxidants with high free radical-scavenging and UV-absorbing activities. These agents contribute to the mitigation of UV-induced reactive oxygen species and play a role in photoprotection by preventing oxidative damage at the cellular level [4]. Green tea polyphenols have been demonstrated to reduce UVB-induced erythema and sunburn cells effectively, confirming their ability to prevent acute UV damage [9]. Moreover, flavonoids prevent lipid peroxidation and work towards improving the stability of UV filters, thus increasing the overall efficacy and stability of sunscreen products [10].

3.2. Carotenoids (β-carotene, lutein, astaxanthin, lycopene).

Carotenoids also play a significant role as "key players" in photoprotection, particularly in quenching the activity of singlet oxygen and the inactivation of free radicals generated from UV exposure, thus preventing damage to different skin components. This has also been observed to elevate the resistance level in the skin to UV-induced damage [11,12]. Among the different carotenoids, astaxanthin has been observed to have high antioxidant activity and has been documented to cause a significant inhibition in wrinkle formation, Erythema, and inflammatory responses, thus providing further evidence for the photoprotective activity in both in vitro (laboratory) and in vivo (animals and clinical) studies [13].

3.3. Vitamins C and E

Vitamin C, also called ascorbic acid is a very potent water-loving antioxidant that can effectively protect DNA from oxidative impacts. At the same time, vitamin C minimizes sun-related redness with the help of its capacity to neutralize causative free radicals. On the contrary, vitamin E, also called α-tocopherol, is the fat-loving antioxidant that mainly targets the prevention of lipid peroxidation to sustain the integrity of the cellular membrane [14,15]. Their use in combination was demonstrated to provide synergistic photoprotection and enhance UV filter stability [16].

3.4. Microalgal pigments Phycocyanin, chlorophylls, carotenoids.

The microalgae-based pigments have progressively emerged as natural partners that protect the human body from the adverse effects of the sun. Among all these pigments, phycocyanin, especially that extracted from spirulina, emerges as the key player that possesses powerful antioxidant, anti-inflammatory, and photoprotective properties, which make the compound the perfect option for addition to sunscreen products [17]. Further, the nano-encapsulation technology raises the stability and solubility, coupled with the controlled release of phycocyanin pigment, to maximize the compound's SPF-boosting capacity [18].

3.5. Botanical oils and extracts.

Botanical oils and extracts like raspberry seed oil, carrot seed oil, turmeric extract, and aloe vera, which contain phenolics and carotenoids, have some intrinsic sun protection, as well as antioxidant and anti-inflammatory properties. They can be used as complementary sunscreens that offer additional sun protection to the formulation. They can also help in making versatile natural sunscreens [19,20].

4. Mechanisms by which antioxidants boost SPF

4.1. Reactive oxygen species neutralization.

Due to the overproduction of reactive oxygen species (ROS) in the epidermal and dermal layers of the skin, ROS trigger the oxidation of cellular lipids, proteins, and DNA, causing erythema, inflammation, and photodamage. Antioxidants work as antidotes to this process by neutralizing ROS and stopping the oxidative chain reaction. Antioxidants help to reduce oxidative stress at the cellular level, thus inhibiting UV-induced tissue damage and erythema, and hence indirectly increasing the overall photoprotective potential of sunscreen products [7,14].

4.2. Photo stabilization of UV filters.

Most employed chemical UV filters, especially avobenzone, are inherently unstable under the influence of ultraviolet radiation and tend to undergo photodegradation, thus impairing their ability to protect against UVA radiation. Antioxidants like vitamins C and E, polyphenols, and carotenoids act as protective agents for UV filters by scavenging free radicals formed during UV irradiation, thus inhibiting oxidative degradation. This property of antioxidants helps to maintain the stability of UV filters by preventing a decrease in their SPF values during exposure to sunlight [15,16].

4.3. Skin Barrier Function Enhancement.

Antioxidants play an important role in maintaining and restoring the skin barrier function following exposure to ultraviolet rays. By stimulating the growth and multiplication of keratinocytes, increasing the amount of collagen produced in the dermis, and repairing biomolecules that have been damaged by oxidation, they help improve the properties of the skin's barrier. These improvements result in an overall decrease in the amount of water lost from the skin through transepidermal means as well as making the skin tougher against both UV radiation and other types of environmental trauma. As a result, the enhancement of the skin barrier property due to antioxidants will also enhance and extend the photo protective benefits provided by sunscreens that contain antioxidants through their inhibition of oxidative stress [4,7].

4.4. Anti-inflammatory effects.

The activation of several inflammatory signal transduction pathways as a result of U/V-induced oxidative stress can lead to an increase in pro-inflammatory cytokine. Polyphenolic antioxidants can negatively impact these pathways by down-regulating cytokine expression and inhibiting the release of inflammatory mediators. In turn, this diminished activity will alleviate the potential for erythema, edema, and damage to tissues caused by sun exposure and therefore increase the efficacy of the biological protection of sunscreen products in improving skin tolerance after prolonged exposure to UV radiation [10].

4.5. Direct UV absorption

In addition to their indirect protective mechanisms, certain flavonoids and polyphenols possess inherent UV-absorbing properties due to the presence of their aromatic rings and conjugated double bonds. These compounds have a tendency to absorb the UV radiation in the approximate range of 260-350 nm, which overlaps the regions of both UVB and UVA radiation. Although their sunscreen properties are not as potent as those of conventional sunscreen chemicals, they can contribute to a slight increase in SPF values [10, 11].

5. Benefits of antioxidant-enriched sunscreens

Antioxidant-enriched sunscreens make it possible to use lower concentrations of UV filters because they complement the photoprotective effect of physical and chemical UV filters. Antioxidants counteract UV-induced reactive oxygen species that are not completely blocked by sunscreens, thus ensuring continued protection while minimizing the risk of irritation and safety issues posed by high loads of UV filters [8].

These sunscreens also have skin repairing, anti-aging, antioxidant properties, and prolonged protection. Antioxidants work by protecting cell components such as DNA, lipids, and proteins from free radicals, thus inhibiting collagen breakdown, improving skin barrier function, and delaying the appearance of signs of photoaging, such as wrinkles and pigmentation [8].

Adding antioxidants to sunscreen products can be helpful in enhancing the photostability and shelf life of the protective effect of creams. Antioxidants can be used to stabilize UV filters by protecting them from photodegradation when they come into contact with sunlight. This will ensure that the SPF values are stable and the photoprotective effect of the skin is not compromised.

Antioxidant-rich sunscreens also reduce inflammation and erythema induced by sun exposure. By blocking the oxidative stress-mediated inflammatory response, antioxidants reduce erythema, calm irritated skin, and prevent immune system suppression induced by UV radiation, making them ideal for use on sensitive skin types [10].

Furthermore, the use of natural antioxidants is also helpful in the development of eco-friendly and clean-label cosmetic products. Plant-based antioxidants are biodegradable and environmentally friendly, and they are also gaining popularity as consumers increasingly demand safer and more environmentally responsible skincare products [20].

6. Challenges and limitations

Problems of stability and oxidation – Most natural antioxidants are highly light, heat, and oxygen-sensitive and thus tend to be unstable during formulation and storage. Stabilization techniques such as encapsulation, use of protective carriers, or addition of stabilizers may be necessary to ensure stability, which may pose formulation problems [18,21].

Problems of compatibility during formulation – Some antioxidants may be incompatible with emulsifiers, preservatives, or UV stabilizers used in sunscreen formulations. Such incompatibilities may result in phase separation, loss of antioxidant activity, or overall instability of the final product, which may pose formulation problems [22].

Pigmentation- Highly colorful antioxidants such as carotenoids, phycocyanin, and turmeric may impact the appearance of the final products [17].

Limited Intrinsic SPF- Antioxidants have a propensity to increase SPF rather than being used as an alternate to UV filters [20].

Regulatory Restrictions- Botanical extracts would only be considered sunscreens if the extracts contain recognized UV blockers. The extracts can only be characterized as antioxidant or SPF-booster ingredients [23].

7. Future prospects

By utilizing advanced medication delivery techniques including liposomes, nano emulsions, solid lipid nanoparticles, and polymeric nanoparticles, more magnificent natural antioxidants can be incorporated into sunscreens to increase stability, penetration, and released control together with enhancing photoprotection overall through increasing bioavailability at skin level and extending the antioxidant longevity overall [21, 24].

There has been a great deal of interest in recent years regarding the utilization of natural antioxidants and pigmentation derived from marine sources (especially microalgae) such as phycocyanin and carotenoids due to their significant antioxidant and anti-inflammatory activity and the potential of these compounds as broad-spectrum UV protectors, thus providing an excellent basis for developing next-generation sunscreen products [17].

However, to confirm the safety and SPF-enhancing potential of antioxidant-enriched sunscreen formulations, well-designed clinical trials and in vivo studies are necessary. These studies will help confirm the laboratory results and pave the way for the approval of these formulations.

The use of natural antioxidants makes it possible to create eco-friendly and biodegradable sunscreen formulations that can decrease the negative impact of conventional sunscreen ingredients on the environment.

8. Conclusion

Natural antioxidants are promising physical and chemical SPF boosters that enhance the effectiveness of sunscreens through multi-mechanisms such as neutralizing ROS, stabilizing filters, and anti-inflammatory activity, besides their intrinsic UV absorption. Though there are challenges like instability, compatibility issues, and regulatory limits, advancing encapsulation technologies and improved formulation strategies support their incorporation into next-generation sunscreens.

Compliance with ethical standards

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No conflict of interest to be disclosed.

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