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Systematic Review

Potential of Natural-Based Sun Protection Factor (SPF): A Systematic Review of Curcumin as Sunscreen

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Abstract: Exposure to ultraviolet (UV) radiation from the sun significantly damages the skin, leading to premature aging, hyperpigmentation, and oxidative stress that disrupts skin homeostasis. UV radiation increases the production of reactive oxygen species (ROS), accelerating skin deterioration. Although sunscreens remain the primary method for UV protection, chemical-based formulations are often associated with side effects, such as allergic reactions and acne. To address these concerns, the inclusion of natural ingredients in sunscreen formulations has gained attention. Curcumin, an active compound found in turmeric (*Curcuma longa*) and Java turmeric (*Curcuma xanthorrhiza*), is well-known for its antioxidant and anti-inflammatory properties. This review explores the potential of curcumin as a natural ingredient for enhancing the Sun Protection Factor (SPF) of sunscreen products. A systematic literature review was conducted, analyzing 200 articles sourced from Google Scholar and PubMed using keywords such as "Curcumin", "Curcuma", "Antioxidant", "Anti-Inflammatory", and "Sun Protection Factor". Studies unrelated to UV protection were excluded. The findings, presented in tabular form, indicate that curcumin and *Curcuma* exhibit significant potential to enhance SPF values due to their antioxidant, anti-inflammatory, and UV-absorbing properties. Additionally, curcumin may aid in skin repair following UV-induced damage. However, the specific concentration of curcumin in various *Curcuma* species remains unknown, and further research is necessary to determine its optimal use. Consideration of additional excipients in sunscreen formulations is also required to maximize efficacy. In conclusion, curcumin demonstrates considerable promise as a sustainable and effective natural ingredient for protecting the skin from UV radiation, offering a safer alternative to conventional chemical-based sunscreens.

Keywords: curcumin; sun protection factor; antioxidant; anti-inflammatory; UV protection

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1. Introduction

The exposure of human skin to solar ultraviolet radiation (UVR) significantly increases the production of reactive oxygen species (ROS), disrupting the natural redox balance and promoting a pro-oxidative state, which ultimately leads to oxidative stress [1–3]. The detrimental effects of oxidative stress manifest through various mechanisms, including

alterations in proteins and lipids, inflammation, immune suppression, DNA damage, and the activation of signaling pathways that regulate gene transcription, cell cycle control, proliferation, and apoptosis [1]. Consequently, maintaining ROS levels within a physiological range is critical for preserving normal skin homeostasis [1–7].

To mitigate the detrimental effects of oxidative stress, reactive oxygen species (ROS) can be regulated by various compounds, including antioxidants such as vitamin C, vitamin E, and glutathione, as well as enzymatic antioxidants like superoxide dismutase (SOD), catalase, and glutathione peroxidase, which play crucial roles in reducing ROS levels and maintaining cellular redox homeostasis [8–10]. In addition to these compounds, natural substances such as curcumin, kaempferol, ellagic acid, capsaicin, and anthocyanin have been shown to contribute significantly to ROS regulation [11–17]. Among these, curcumin, a bioactive compound derived from turmeric (*Curcuma longa*) and Java turmeric (*Curcuma xanthorrhiza*), stands out for its potent antioxidant properties [11–13]. Curcumin not only neutralizes free radicals but also modulates ROS-metabolizing enzymes, thereby offering protection against oxidative stress-induced skin damage [18,19].

Recent studies have highlighted the potential of curcumin in the cosmetic industry, particularly for maintaining skin homeostasis and regulating ROS levels. Curcumin has been shown to enhance cellular antioxidant defense mechanisms through the activation of the nuclear factor erythroid 2-related factor 2 (Nrf2) pathway, which plays a pivotal role in mitigating oxidative stress [20–23]. As a natural active ingredient, curcumin not only aids in repairing UV-damaged skin but also acts as an anti-aging agent due to its potent antioxidant and anti-inflammatory properties [24–27]. Its potential as a natural UV protector has garnered significant attention, as it can absorb UV radiation and prevent skin damage, including erythema, hyperpigmentation, and wrinkles [28–34]. Furthermore, curcumin has been found to inhibit UVB-induced tumor necrosis factor (TNF) mRNA expression and reduce matrix metalloproteinase-1 (MMP-1) expression in keratinocytes and fibroblasts, contributing to its protective effects against photoaging [35,36].

Given this potential, curcumin is increasingly being explored as an alternative ingredient in UV protection products. Its efficacy as a UV protectant lies in its ability to absorb UV rays and mitigate oxidative stress induced by sun exposure [37–40]. While studies have shown that curcumin can enhance Sun Protection Factor (SPF) values, further research is required to fully evaluate its potential as a standalone agent in effective sunscreen formulations [41–43].

Sunscreen has long been recognized as one of the primary methods for protecting the skin from ultraviolet (UV) radiation [44,45]. These products reduce the harmful effects of UV rays by absorbing, reflecting, or scattering radiation and are specifically formulated for topical application [46,47]. The effectiveness of sunscreen is often enhanced by incorporating antioxidants, which boost photoprotective properties [48,49]. The SPF value is a key metric for determining a sunscreen's efficacy in preventing sunburn; higher SPF values indicate greater protection [50,51]. However, traditional sunscreens frequently rely on chemical filters, which are a leading cause of photoallergic reactions and can trigger both acute and chronic allergic symptoms [52–54]. Additionally, inorganic filters may interfere with percutaneous absorption, disrupt endocrine function, clog pores, and contribute to acne. In response to these concerns, the pharmaceutical industry is increasingly focusing on the development of sunscreens made from safer and more cost-effective natural ingredients, such as curcumin [55,56].

Curcumin, a bioactive compound derived from plants of the *Curcuma* genus in the *Zingiberaceae* family, has been extensively utilized as a natural active ingredient in herbal cosmetics, including as a photoprotective agent [57–59]. Recent studies demonstrate that curcumin protects skin cells from UV radiation and prevents sunburn through its potent

antioxidant and anti-inflammatory properties [60–62]. Moreover, curcumin enhances cellular antioxidant defenses by activating the Nrf2 pathway, which plays a pivotal role in mitigating oxidative stress [63,64]. As a result, antioxidants such as curcumin are highly valuable in preventing various UV-induced skin conditions, including premature aging [49,65–67]. In sunscreen formulations, UV-absorbing ingredients are designed to absorb UV rays within the 290–400 nm wavelength range, effectively preventing skin damage such as erythema, hyperpigmentation, and premature aging [68,69].

Several studies on plants of the *Curcuma* genus have demonstrated their potential to enhance the SPF values of sunscreen formulations. Despite these promising findings, a comprehensive evaluation of curcumin as a standalone sunscreen agent remains unexplored. This review aims to summarize and analyze the potential of curcumin as a natural and effective ingredient for sunscreen products.

2. Materials and Methods

2.1. Focal Question

This systematic review is conducted to answer the following question: "Can curcumin be used as sun protector agent in sunscreen formulation?".

2.2. Literature Search

This systematic review was conducted using both national and international databases, specifically Google Scholar and PubMed. The search utilized keywords such as "curcumin", "Curcuma", "antioxidant", "anti-inflammation", and "sun protection factor".

2.3. Inclusion and Exclusion Criteria

The inclusion criteria for this systematic review encompassed in vitro and in vivo studies that reported the antioxidant or anti-inflammatory activities of curcumin and *Curcuma* and included their Sun Protection Factor (SPF) values. It is acknowledged that SPF values in formulations can be influenced by excipients. The exclusion criteria consisted of studies focusing on the activities of curcumin and *Curcuma* in relation to specific diseases.

2.4. Study Selection

This systematic review adhered to the guidelines of PRISMA (The Preferred Reporting Items for a Systematic Review and Meta-Analysis), with the corresponding flow diagram presented in Figure 1. The primary outcome considered in this review was the SPF value of curcumin.

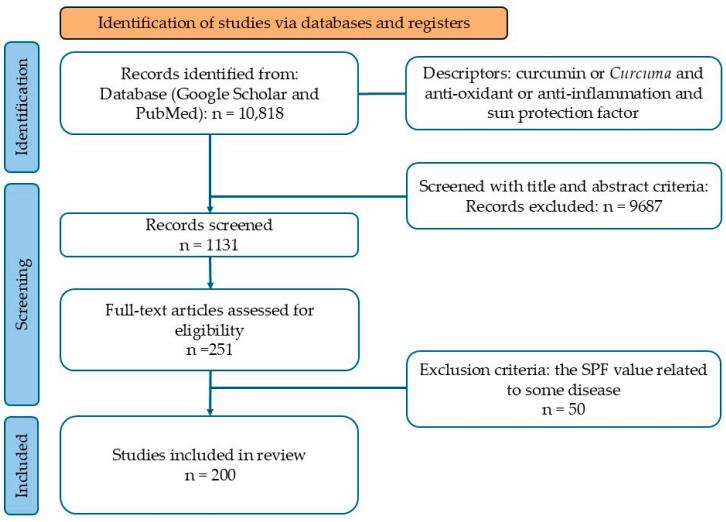

Figure 1. Flow diagram according to PRISMA guidelines.

2.5. Data Analysis

A qualitative assessment of the outcomes from the included studies is provided in this systematic review. No meta-analysis was performed. The results are presented descriptively and supplemented with tables that summarize the evidence.

3. Results

Based on the defined search terms, a total of 10,818 studies were identified. Following a full-text screening aligned with the inclusion criteria, 251 studies were selected. Among these, 50 were excluded as their SPF values were associated with specific diseases. Consequently, 200 studies were included in this review. The study selection process adhered to the PRISMA guidelines and is illustrated in Figure 1.

3.1. Physicochemical Characteristics of Curcumin

Curcumin is recognized as an effective natural sunscreen, largely attributable to its active components, particularly flavonoids. The chemical structure of curcumin is presented in Figure 2.

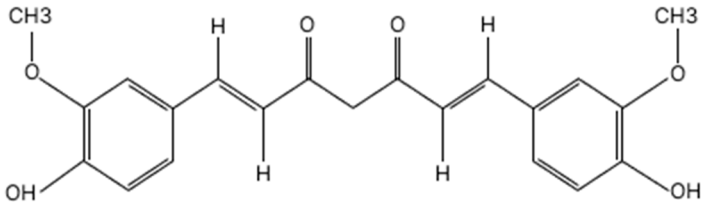

Figure 2. Chemical structure of curcumin.

Curcumin is a yellow–orange pigment derived from plants of the *Curcuma* genus, including *Curcuma longa*, *Curcuma xanthorrhiza*, *Curcuma zedoaria*, *Curcuma mangga*, and other species [70–74]. Curcumin extracted from different species exhibits unique physicochemical characteristics, as summarized in Table 1. These distinct properties are essential for the formulation and therapeutic applications of curcumin in sunscreen products [75,76].

Table 1. Physicochemical characteristics of curcumin.

Sources	Parameters	Specifications	References
Curcuma longa	Colour	Yellowish Orange	[70]
	Odour and taste	Characteristic	[70]
	Stability	Curcumin is prone to degradation when exposed to sunlight, remains heat-resistant at 140 °C for up to 15 min, and is unstable at pH levels above 6.5	[70]
	Solubility	Curcuma longa extract is poorly soluble in water and ether but demonstrates good solubility in organic solvents such as ethanol and glacial acetic acid	[71]
	Ash content	6.20%	[72]
	Water content	8.11%	[72]
Curcuma xanthorrhiza	Colour	Yellowish brown	[73]
	Odour and taste	Characteristic	[73]
	Stability	Curcumin is heat-stable but rapidly loses its colour when exposed to light	[73]
	Solubility	*Curcuma xanthorrhiza is readily soluble* in solvents such as dimethyl sulfoxide (DMSO), ethanol, and acetone but exhibits only sparing solubility in aqueous solutions	[73]
	Ash content	4.8%	[74]
	Water content	9.1%	[74]

3.2. Antioxidant Activity of Curcumin

Antioxidant activity can be evaluated using various methods, including the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay, oxygen radical absorption capacity (ORAC), reducing power assay (RPA), 2-deoxyribose degradation assay (2-DR), ferric reducing antioxidant power (FRAP), 2,2-azinobis(3-ethylbenzothiazoline)-6-sulfonic acid (ABTS), and cupric reducing antioxidant capacity (CUPRAC) [77–86]. The DPPH and 2-DR methods allow for the determination of free radical inhibition percentages and the inhibition concentration (IC_{50}) value, where a lower IC_{50} indicates higher antioxidant activity [77]. In several studies, antioxidant activity measured using the ORAC, ABTS, and CUPRAC methods is expressed as Trolox equivalents in micromoles per gram of extract (μmol TE/g). In contrast, the antioxidant activity in the RPA method is reported as absorbance [77–86]. Higher ORAC, ABTS, and CUPRAC values indicate greater antioxidant activity, while higher absorbance values in the RPA method reflect stronger reducing power and antioxidant activity [77]. Antioxidant activity in the FRAP assay is expressed as micromoles of ferrous equivalent (μM Fe[II] per 100 g), with higher FRAP values indicating stronger antioxidant potential [85]. Several studies have highlighted the antioxidant activity of curcumin, as summarized in Table 2.

Table 2. Antioxidant activity of curcumin.

Sources	Method	Result	References
Curcuma longa	DPPH	The IC_{50} values of *Curcuma longa* extracts with total flavonoid contents of 1089.5 ± 0.9 mg rutin/g extract and 620.7 ± 0.9 mg rutin/g extract were determined to be 26.4 ± 0.2 μg/mL and 291.3 ± 3.1 μg/mL, respectively.	[77]
		The IC_{50} value of *Curcuma longa* was determined to be 41.95 μg/mL.	[78]
		The IC_{50} values of *Curcuma longa* extracts obtained using water and ethanol were determined to be 5.31 μg/mL and 1.08 μg/mL, respectively.	[79]
		The free radical inhibition percentages of *Curcuma longa* ethanolic extracts at concentrations of 25, 50, 100, 250, and 500 μg/mL were determined to be 6.06 ± 0.27%, 7.76 ± 0.18%, 9.41 ± 0.27%, 19.64 ± 0.27%, and 32.51 ± 0.27%, respectively.	[80]
		The IC_{50} values of freshly grated and cut *Curcuma longa* were determined to be 114.7 μg/mL and 158.3 μg/mL, respectively.	[81]
		The IC_{50} value of the peel-off mask containing 10% *Curcuma longa* was determined to be 37.399 μg/mL.	[82]
		In serum formulations, the free radical inhibition percentages of 1.1% *Curcuma longa* extract combined with 2% collagen and 0.5% *Curcuma longa* extract combined with 2% collagen were determined to be 90.526 ± 1.87% and 36.594 ± 2.89%, respectively.	[83]
		The antioxidant activities of 2.8% and 0.9% *Curcuma longa* powder were determined to be 90.51 ± 0.24% and 81.76 ± 0.08%, respectively.	[84]
	ORAC	The antioxidant activity of *Curcuma longa* extracts with total flavonoid contents of 1089.5 ± 0.9 mg rutin/g extract and 620.7 ± 0.9 mg rutin/g extract were determined to be 14,090 ± 0.9 μmol TE/g and 4119.7 ± 0.7 μmol TE/g, respectively.	[77]
	RPA	The absorbances of *Curcuma longa* extracts with total flavonoid contents of 1089.5 ± 0.9 mg rutin/g extract and 620.7 ± 0.9 mg rutin/g extract were measured as 0.3 ± 0.0 and 0.1 ± 0.0, respectively.	[77]
	2-DR	The IC_{50} values of *Curcuma longa* extracts with total flavonoid contents of 1089.5 ± 0.9 mg rutin/g extract and 620.7 ± 0.9 mg rutin/g extract were determined to be 7.4 ± 1.3 μg/mL and 28.3 ± 2.3 μg/mL, respectively.	[77]
	FRAP	The FRAP values of *Curcuma longa* extracts obtained using water and ethanol were measured as 646.67 ± 2.48 μM Fe[II] per 100 g and 3475.36 ± 173.10 μM Fe[II] per 100 g, respectively.	[79]
Curcuma xanthorrhiza	DPPH	The IC_{50} value of *Curcuma xanthorrhiza* was determined to be 80.4 ± 0.7 μg/mL.	[77]
		The antioxidant activity of *Curcuma xanthorrhiza* from different regions ranged from 0.13 ± 0.02 μmol TE/g to 1.11 ± 0.02 μmol TE/g.	[85]
		The antioxidant activities of *Curcuma xanthorrhiza* acetone extracts from different varieties were 1.56 ± 0.04 μmol TE/g, 3.28 ± 0.03 μmol TE/g, and 2.44 ± 0.09 μmol TE/g, while the antioxidant activities of ethyl acetate extracts were 1.59 ± 0.05 μmol TE/g, 2.11 ± 0.04 μmol TE/g, and 2.04 ± 0.13 μmol TE/g.	[86]

Table 2. *Cont.*

Sources	Method	Result	References
		The IC_{50} value of *Curcuma xanthorrhiza* used in gel formulation was determined to be 1973.38 ± 219.93 μg/mL	[87]
		The antioxidant activity of *Curcuma xanthorrhiza* ranged from 5.265 μmol TE/g DW to 14.960 μmol TE/g DW.	[88]
	ORAC	The antioxidant activity of *Curcuma xanthorrhiza* was determined to be 6490.3 ± 0.7 μmol TE/g.	[77]
	2-DR	The IC_{50} value of *Curcuma xanthorrhiza* was determined to be 19.0 ± 1.7 μg/mL.	[77]
	ABTS	The antioxidant activity of *Curcuma xanthorrhiza* from different regions ranged from 0.72 ± 0.18 to 4.14 ± 0.06 μmol TE/g.	[85]
		The antioxidant activity of *Curcuma xanthorrhiza* acetone extracts from different varieties were determined to be 66.82 ± 4.22 μmol TE/g, 148.91 ± 6.10 μmol TE/g, and 92.86 ± 3.10 μmol TE/g, while the antioxidant activity of ethyl acetate extracts was 57.02 ± 4.30 μmol TE/g, 84.30 ± 5.10 μmol TE/g, and 90.38 ± 6.19 μmol TE/g.	[86]
		The IC_{50} value of *Curcuma xanthorrhiza* used in gel formulations was determined to be 700.65 ± 142.14 μg/mL.	[87]
	FRAP	The antioxidant activity of *Curcuma xanthorrhiza* from different regions ranged from 7.71 ± 1.29 μmol TE/g to 81.48 ± 4.43 μmol TE/g.	[85]
		The antioxidant activity of *Curcuma xanthorrhiza* acetone extracts from different varieties were determined to be 51.24 ± 1.32, 115.23 ± 2.30, and 82.68 ± 1.50 μmol TE/g, while the antioxidant activity of ethyl acetate extracts was 51.76 ± 1.25, 65.41 ± 2.11, and 71.88 ± 1.48 μmol TE/g.	[86]
	CUPRAC	The antioxidant activity of *Curcuma xanthorrhiza* from different regions ranged from 18.37 ± 4.30 μmol TE/g to 211.68 ± 1.53 μmol TE/g.	[85]
Curcuma zedoaria	DPPH	The IC_{50} value of *Curcuma zedoaria* was determined to be 228.4 ± 3.4 μg/mL.	[77]
		The IC_{50} values of *Curcuma zedoaria* extract in different solvents, temperatures, and extraction times ranged from 184.25 ± 6.35 μg/mL to 956.16 ± 20.27 μg/mL.	[89]
		The IC_{50} value of *Curcuma zedoaria* extracted with ethanol was determined to be 49.72 ± 0.32 μg/mL, while the IC_{50} value of 2% *Curcuma zedoaria* combined with 4% Sepigel 305 was 135.8 μg/mL.	[90]
		The IC_{50} values of *Curcuma zedoaria* extracted with methanol, ethyl acetate, and n-hexane were determined to be 185.77 ± 3.91 μg/mL, 153.49 ± 2.66 μg/mL, and 837.92 ± 5.32 μg/mL, respectively.	[91]
	ORAC	The antioxidant activity of *Curcuma zedoaria* was determined to be 1790.3 ± 0.7 μmol TE/g.	[77]
	2-DR	he IC_{50} value of *Curcuma zedoaria* was determined to be 20.2 ± 2.0 μg/mL.	[77]
Curcuma heyneana	DPPH	The IC_{50} values of *Curcuma heyneana* extracted with ethanol, n-hexane, methanol, and ethyl acetate were determined to be 338.38 μg/mL, greater than 500 μg/mL, and 363.26 μg/mL, respectively.	[92]
		The IC_{50} value of *Curcuma heyneana* was determined to be 37.75 μg/mL.	[93]
		The IC_{50} value of *Curcuma heyneana* extract in ethanol solvent was determined to be 102.15 μg/mL.	[94]
Curcuma aeruginosa	DPPH	The IC_{50} value of *Curcuma aeruginosa* was determined to be 158.50 μg/mL.	[93]
		The IC_{50}values of *Curcuma aeruginosa* extracted with methanol and n-hexane were determined to be 171 μg/mL and 1724 μg/mL, respectively.	[95]
		The IC_{50} values of *Curcuma aeruginosa* extract and its gel peel-off mask were determined to be 746.75 μg/mL and 5569.90 μg/mL, respectively.	[96]
		The IC_{50} value of *Curcuma aeruginosa* extracted with ethanol was determined to be 6.0313 μg/mL.	[97]
Curcuma mangga	DPPH	The IC_{50} values of *Curcuma mangga* extracted with 50%, 70%, and 96% ethanol were determined to be 95.05 μg/mL, 88.51 μg/mL, and 75.06 μg/mL, respectively.	[98]
		The IC_{50} values of *Curcuma mangga* from different regions ranged from 37.338 ± 1.851 μg/mL to 268.802 ± 43.573 μg/mL.	[99]

Research has shown that the flavonoids present in curcumin exhibit strong antioxidant properties, effectively preventing the formation of reactive oxygen species (ROS) and lipid peroxidation induced by UV exposure [79,100]. These processes are closely associated with conditions such as photoaging and skin cancer [101].

3.3. Anti-Inflammatory Properties of Curcumin

The anti-inflammatory activities of curcumin have been extensively investigated in numerous studies, both in vivo and in vitro, as summarized in Table 3.

Table 3. Anti-inflammatory properties of curcumin.

Sources	Method	Result	References
Curcuma longa	In Vivo (wound closure effect)	The result showed that the 10% *Curcuma longa* extract had the best wound closure effect (0 ± 0.00 cm^2) compared with the positive control (0.11 ± 0.01 cm^2) on day 14.	[102]
	In Vivo (wound closure effect)	The results showed that 10% *Curcuma longa* extract gel application could accelerate wound healing.	[103]
	In Vivo (wound closure effect)	The results showed that the mean wound healing areas in rabbits after application of 5% *Curcuma longa* extract gel at 3, 7, and 14 days were 1.02, 0.06, and 0 cm, respectively.	[104]
	In Vivo (wound closure effect)	The combination of *Curcuma longa* and $Ca(OH)_2$ (2:1) resulted in the highest value of wound healing decrease, with a value of 13.88 ± 0.10 mm compared with the combination of *Curcuma longa* and $Ca(OH)_2$ (1:2), which showed 10.97 ± 0.58 mm.	[105]
	In Vitro (HPLC analysis)	After treatment with the plant extracts, the production of both cytokines decreased as the concentration of the *Curcuma longa* extract increased. The production of IL-6 cytokines for the positive control and plant extracts at doses of 75, 150, and 300 µg were 629.3, 374, 184.3, and 140 pg/mL, respectively.	[106]
	In Vitro (ELISA kit)	The results showed that treatment with the *Curcuma longa* extract decreased pro-inflammatory cytokines, including IL-1β, IL-6, and TNF-α, with values of 110, 300, and 100 pg/mL; 62.5, 225, and 90 pg/mL; and 50, 150, and 80 pg/mL at doses of 50, 100, and 150 µg/mL, respectively.	[107]
	In Vivo (induced mice ear edema assay)	The results showed a percentage inhibition effect of *Curcuma longa* in ethanol extract on TPA(12-O-tetradecanoylphorbol-13-acetate) induced mice ear edema, with values of $2.28 \pm 0.32\%$, $4.43 \pm 1.19\%$, and $7.38 \pm 1.24\%$ at doses of 25, 50, and 100 mg/kg, respectively.	[108]
	In Vitro (BSA denaturation assay using spectrophotometry)	The results showed the percentages of anti-inflammatory activity in the BSA denaturation assay at concentrations of 125, 250, 500, and 1000 µg/mL *Curcuma longa*, with values ranging from $41.45 \pm 1.00\%$ to $70.55 \pm 0.77\%$, compared with salicylic acid (positive control), which ranged from $74.45 \pm 0.42\%$ to $96.85 \pm 0.83\%$.	[109]
	In Vivo (wound closure effect)	The results showed that *Curcuma longa* extract oily ointment at concentration 2.5% could heal the wound and improve collagen levels at wound area.	[110]
	In Vitro (qRT PCR method)	Studies showed that the hexane extract of *Curcuma longa* significantly downregulated inflammatory cytokines (TNF-α and IL-6), with an 80-fold decrease and a 1.5-fold decrease, respectively, compared with the positive control group.	[111]
	In Vivo (wound closure effect)	Curcumin-containing 5% and 10% ethanolic extract ointments showed significant wound healing, with wound contraction values of 100% after 28 and 26 days, respectively, while aspirin achieved 100% wound contraction after 30 days.	[112]
Curcuma domestica	In Vitro (human red blood cell)	The percentage inhibition of *Curcuma domestica* extract at 100 µg/mL was $89.39 \pm 2.04\%$, compared with the positive control, aspirin at 100 µg/mL, which showed 93.88%.	[113]
	In Vitro (inhibition of protein denaturation assay)	The percentage inhibition of the extract at 10 µg/mL was 38.38%, and at 50 µg/mL was 51.24%, with the IC_{50} calculation showing a value of 46.87 µg/mL. A percentage inhibition greater than 20% indicates that the extract can effectively inhibit protein denaturation.	[114]
	In Vitro (spectrophotometry)	The combination of *Curcuma domestica* Val. and *Phoenix dactylifera* L. extracts at 100 µg/mL yielded the highest percentage of inhibition, which was 65.64%.	[115]
	In Vivo (hydrogen peroxide induced ulcer on the labial mucosa)	The results showed that the treatment group with the *Curcuma domestica* extract, topically, had a higher number of macrophages (5.36) and a smaller ulcer diameter (0.26 mm) compared to the control group on day 10.	[116]

Table 3. *Cont.*

Sources	Method	Result	References
	In Vitro (Pearson test)	The results showed the most substantial differences in the treatment group with *Curcuma domestica* extract at concentrations of 125 µg/mL for cyclooxygenase-2 (COX-2) and 250 µg/mL for inducible nitric oxide synthase (iNOS), with values of 24.29 ± 5.88 and 29.24 ± 7.84, respectively, compared with the positive control group (82.29 ± 1.49 and 82.70 ± 1.67).	[117]
	In Vivo (wound closure effect)	The results showed that the most effective *Curcuma domestica* extract gel for wound healing was at a 100% concentration, with a wound diameter of 15 mm on day 21. The largest diameter was observed in the negative control group, with a diameter of 20 mm on day 21, while the positive control group had a diameter of 16 mm.	[118]
Curcuma xanthorrhiza	In Vitro (inhibition of protein denaturation assay)	The IC_{50} value of *Curcuma xanthorrhiza* extract was determined to be 521.67 ± 5.80 µg/mL, while the IC_{50} value of *Curcuma xanthorrhiza* extract nanoparticles was 398.02 ± 1.78 µg/mL. This result indicates that the anti-inflammatory activity of *Curcuma xanthorrhiza* extract nanoparticles is superior to that of *Curcuma xanthorrhiza* extract.	[119]
Curcuma zedoaria	In Vivo (wound closure effect)	The results showed that 0.75% and 1.5% nanoparticle gel of *Curcuma zedoaria* could accelerate wound healing. However, both concentrations did not give a significant difference of wound healing effect.	[120]
Curcuma aeruginosa	In Vitro (nitric oxide production using spectrophotometer)	This study revealed that the rhizome extract of *Curcuma aeruginosa* Roxb. inhibited inducible nitric oxide synthesis, with values of 84.426% at 25 µg/mL and 83.606% at 50 µg/mL.	[121]
Curcuma mangga	In Vitro (human dermal fibroblast cells viability)	The results showed that the cream containing 2%, 5%, and 10% w/w *Curcuma mangga* extract increased cell viability by over 100% before and after healing–cooling test at 3 µg/mL.	[122]
	In Vitro (protein denaturation inhibition method using spectrophotometer)	The result showed that the percentage inhibition of ethanol extract of *Curcuma mangga* increased from 38.38% at a concentration of 10 mg/mL to 51.24% at a concentration of 50 mg/mL.	[114]
Curcuma aromatica	In Vivo (induced mice ear edema assay)	The results showed the percentage inhibition effect of the ethanol extract on TPA-induced mice ear edema, with values of 14.26 ± 3.35%, 23.14 ± 3.83%, and 42.60 ± 4.23% at doses of 25, 50, and 100 mg/kg, respectively.	[108]
Curcuma elata	In Vivo (induced mice ear edema assay)	The results showed the percentage inhibition effect of the ethanol extract on TPA-induced mice ear edema, with values of 9.34 ± 2.3%, 18.64 ± 2.26%, and 36.61 ± 2.92% at doses of 25, 50, and 100 mg/kg, respectively.	[108]
Curcuma kwangsiensis	In Vivo (induced mice ear edema assay)	The results showed the percentage inhibition effect of the ethanol extract on TPA-induced mice ear edema, with values of 11.56 ± 2.16%, 22.19 ± 3.21%, and 39.23 ± 3.15% at doses of 25, 50, and 100 mg/kg, respectively.	[108]
Curcuma rubescens	In Vivo (induced mice ear edema assay)	The results showed the percentage inhibition effect of the ethanol extract on TPA-induced mice ear edema, with values of 6.14 ± 1.06%, 14.54 ± 1.68%, and 28.26 ± 1.58% at doses of 25, 50, and 100 mg/kg, respectively.	[108]
Curcumin	In Vivo (xylene-induced mice ear edema assay)	The effects of curcumin (95% purity) significantly decreased the relative weight of xylene-induced ears, with a value of 0.501% compared with the control group, which had a value of 0.617%.	[123]
	In Vivo (xylene-induced mice ear edema assay)	After topical administration to mice, curcumin showed anti-inflammatory activities by significantly reducing the ear edema in mice caused by xylene (extent of edema 17.9 ± 4.2 mg and 30.08% inhibition)	[124]
	In Vivo (streptozotocin-induced diabetic rats)	The mean percentage of wound contraction in the curcumin-treated (40%) group was significantly higher compared with the control (30%) and gel-treated (35%) groups on day 7, with this significant difference continuing until day 19 after wound creation.	[125]
	In Vivo (wound closure effect)	After 7 days, combination of nano-curcumin with CCS-OA (carboxymethyl chitosan and oxidized alginate) hydrogel could effectively improve the wound healing with decreasing wound area from 3 cm^2 to 1 cm^2.	[126]
	In Vivo (wound closure effect)	The result showed that after days 21 post wounding, the wound contraction present in rats treated with the curcumin nanoformulation was higher than sulfadiazine. Curcumin had best wound closure effect (1.222 ± 0.441 cm^2) compared with positive control (1.444 ± 0.726 cm^2).	[127]
	In Vivo (anti-inflammatory activity)	The result showed that curcumin-nanogel had a higher anti-inflammatory activity (61.8%) than free curcumin (33.2%). Diclofenac as a positive control had the highest anti-inflammatory activity (85.4%).	[128]
	In Vivo (wound closure effect)	The result showed that after topical application of curcumin, 65.0% of the wounds were closed on day 6 and 100% closed on day 12.	[129]

Table 3. *Cont.*

Sources	Method	Result	References
	In Vivo (experimental induced periodontitis)	The result showed a significant reduction in anti-inflammatory biomarkers after applying 12.5 µg/mL curcumin gels.	[130]
	In Vivo (wound closure effect)	The result showed that the mean wound healing area in mice after application of curcumin gel at 7, 9, and 12 days were 71.1 ± 8,7%, 86.1 ± 7.8%, and 97.9 ± 2.8%, respectively.	[131]
	In Vivo (carrageenan-induced rat paw edema)	The results showed that the pretreatment of gel and cream containing curcumin in rat showed the lower values in paw edema.	[132]

Recent research indicates that curcumin, a flavonoid compound, exhibits anti-inflammatory effects by suppressing the release of pro-inflammatory cytokines and scavenging free radicals, thereby protecting tissues and cells from damage [133,134].

3.4. Potential of Curcumin (Curcuma Spesies) as SPF Agent

Several studies have demonstrated that curcumin improves SPF values, as outlined in Table 4. Its ability to enhance the skin's defense against ultraviolet (UV) radiation is attributed to its antioxidant and UV-absorbing properties [60–62]. By neutralizing free radicals and reducing oxidative stress caused by UV exposure, curcumin enhances the photoprotective capacity of sunscreen formulations [48,49]. Due to these properties, curcumin holds potential as a valuable addition to sun care products, not only as an SPF-boosting agent but also for its broader skin-protective benefits, including preventing photoaging and reducing inflammation [55,56,101].

Table 4. Potential of curcumin (*Curcuma species*) as SPF agent.

Sources	Concentration	Method	Result	References
Curcuma longa	1% of *Curcuma longa* (concentration of curcumin is unknown)	Spectrophotometry	*Curcuma longa* exhibits significant absorbance values within the 290–320 nm range, correlating to an SPF value of 12.35 ± 4.44.	[135]
	0.1%, 0.2%, 0.3%, 0.4%, and 0.5% of *Curcuma longa* (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of 0.1% *Curcuma longa* is 1, which is significantly lower compared with 0.5% *Curcuma longa*, exhibiting an SPF value of 15.	[136]
	1% of *Curcuma longa* (concentration of curcumin is unknown)	Spectrophotometry	The SPF value calculated for the pure extract was 17.451, while the Curcuma longa hydrogel exhibited a significantly higher SPF of 22.586. Maximum cell viability was observed at the highest dose of 200 µg/mL for both the Curcuma longa extract (75.55 ± 2.38%) and the Curcuma longa hydrogel (65.03 ± 2.65%), indicating that both CE and CG demonstrate effective UV-protection properties.	[137]
	Combination of *Curcuma longa* and other excipients in sunscreen formulation (concentration of curcumin is unknown)	Spectrophotometry	The SPF values of the formula with the addition of Carbopol 934 and distilled water ranged from 0.30 to 7.32, whereas the SPF values of the formula without these components were 33.44 and 33.50.	[138]
	Combination of *Curcuma longa* and *Haematococus pluvialis* (3:1, 1:1, 1:3)	Spectrophotometry	The SPF values of the combination of *Curcuma longa* and *Haematococcus pluvialis* extracts at ratios of 3:1, 1:1, and 1:3 were 15.203, 15.997, and 31.513, respectively.	[139]
	500 and 1000 µg/mL of *Curcuma longa* (concentration of curcumin is unknown)	Spectrophotometry	The SPF values of 500 µg/mL and 1000 µg/mL *Curcuma longa* were 31.55 and 37.46, respectively.	[140]
	200 µg/mL solution of *Curcuma longa* extract (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of the *Curcuma longa* extract was found to be 0.330 ± 0.08.	[141]

Table 4. *Cont.*

Sources	Concentration	Method	Result	References
	10% of *Curcuma longa* extract (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of 10% *Curcuma longa* extract was lower than that of 10% pu'er tea extract, which had an SPF value of 0.36.	[142]
Curcuma domestica	1% of *Curcuma domestica* extract (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of 1% *Curcuma domestica* was 15.12 ± 1.55.	[56]
Curcuma xanthorrhiza	0.02% of *Curcuma xanthorrhiza* (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of 0.02% *Curcuma xanthorrhiza* loaded in gel was 16.77.	[143]
Curcuma zedoaria	0.5, 1, 1.5, 2, 2.5, and 3% of *Curcuma zedoaria* (concentration of curcumin is unknown)	Spectrophotometry	*Curcuma zedoaria* at 3% exhibited the highest SPF value of 20.24	[144]
Curcuma heyneana	5%, 7.5%, 10% of *Curcuma heyneana* in cream formulation (concentration of curcumin is unknown)	Spectrophotometry	The SPF values of 5%, 7.5%, and 10% *Curcuma heyneana* were 3.307 ± 0.12, 3.497 ± 0.18, and 4.965 ± 0.24, respectively	[145]
	15% of *Curcuma heyneana* (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of 15% *Curcuma heyneana* was 27.40, categorizing it as offering ultra protection.	[146]
	1, 2, 3, and 4% of *Curcuma heyneana* (concentration of curcumin is unknown)	Spectrophotometry	The SPF values of 1%, 2%, and 3% *Curcuma heyneana* fall under minimal protection, while the SPF value of 4% is categorized as medium protection.	[147]
	1%, 2.5%, and 4% of *Curcuma heyneana* in gel formulation (concentration of curcumin is unknown)	Spectrophotometry	The SPF values of 1%, 2.5%, and 5% *Curcuma heyneana* were 4.84, 8.76, and 18.86, respectively.	[148]
	1% and 2% of *Curucma heyneana* (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of 1% *Curcuma heyneana* combined with 1% zinc oxide was 13.24 ± 0.20, compared with 12.25 ± 0.27 for 2% zinc oxide alone and 6.77 ± 0.04 for 2% *Curcuma heyneana* alone.	[149]
Curcuma mangga	4 g of *Curcuma mangga* (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of 4 g of *Curcuma mangga* in a cream formulation was 8.99.	[150]
	2.5%, 5%, 7.5%, 10%, 12.5% of *Curcuma mangga* in lotion formulation (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of the ethanolic extract of *Curcuma mangga* at a concentration of 3% was 28.65. However, the ethanolic extract o/w lotion containing 12.5% *Curcuma mangga* exhibited an SPF value of 12.82 ± 0.16, providing only medium protection and was, therefore, not efficient in preventing erythema and pigmentation.	[151]
	5% *Curcuma mangga* (concentration of curcumin is unknown)	Spectrophotometry	The SPF value of 5% *Curcuma mangga* combined with 5% titanium dioxide was 2.799, compared with 2.050 for 5% titanium dioxide alone.	[152]
	500, 1000, and 1500 µg/mL of *Curcuma mangga*	Spectrophotometry	The SPF values of 500, 1000, and 1500 µg/mL *Curcuma mangga* were 1.82, 3.68, and 5.55, respectively.	[140]
Curcumin	4 mg/mL	Spectrophotometry	The SPF value of the formulation with a curcumin loading of 4 mg/mL was calculated to be 8.5.	[153]
	0.1% stock solution of pure Curcumin	Spectrophotometry	The SPF value of pure curcumin was determined to be 11.58.	[154]
	Initial stock solution was prepared by taking 1% *w*/*v* curcumin	Spectrophotometry	The SPF value of curcumin was 11.58.	[155]

The SPF values of different *Curcuma* species vary due to the differing curcumin concentrations among them. Even within the same species, variations in SPF values can occur due to differences in the material's origin and the processing methods employed.

3.5. Mechanism of Curcumin as a Sun Protector Agent

Curcumin has several mechanisms of action that make it an ideal ingredient for cosmetic formulations, particularly as an SPF booster [101]. These mechanisms include its anti-inflammatory, antioxidant, and sun-protective properties, as summarized in Table 5.

Table 5. Mechanism of curcumin as a sun protector agent.

Sources	Method	Result	References
Curcuma longa	Anti-inflammatory	Curcumin exerts its effects by reducing levels of inflammatory markers such as IL-1β, IL-6, and TNF-α.	[37]
		Curcumin reduces the release of arachidonic acid by decreasing the catalytic activity of phospholipase A2 and phospholipase C g1.	[156]
		Curcumin exhibits anti-inflammatory effects by inhibiting IL-6.	[106]
		Curcumin in *Curcuma longa* modulates the TLR4-MyD88-IRAK-MAPK-NFκB pathway in THP-1 cells and regulates the production of inflammatory cytokines.	[157]
		Curcumin enhances caspase-3 activity and inhibits the transcription factor NFκB. Additionally, it exhibits antiapoptotic properties and suppresses the paclitaxel-induced NFκB pathway in cancer cells.	[129]
	Antioxidant	Curcumin functions as an antioxidant by activating Nuclear Factor Erythroid 2–Related Factor 2 (Nrf2).	[158]
	Sun protector	The absorption spectrum of *Curcuma longa* exhibits a peak wavelength at 320 nm and maximum absorption at 420 nm (blue light), indicating that the curcumin content in *Curcuma longa* can protect human skin fibroblasts from damage caused by blue light.	[142]
		Curcumin decreases TNF-α expression and increases type I collagen expression in UVB-exposed skin.	[159]
Curcuma domestica	Anti-inflammatory	Curcumin reduces neutrophil infiltration in inflammatory conditions and inhibits platelet aggregation.	[160]
		Curcumin reduces the production of iNOS (inducible nitric oxide synthase) and COX-2 by suppressing NF-κB through the TLR4 pathway.	[120]
	Sun protector	*Curcuma domestica* protects skin tissues from radical photons that cause skin damage.	[135]
Curcuma xanthorrhiza	Anti-inflammatory	Curcumin reduces the activity and concentrations of pro-inflammatory cytokines IL-6 and IL-8, enabling its function as an anti-inflammatory agent.	[161]
		Curcumin suppresses pro-inflammatory cytokines by inhibiting COX-2, iNOS, and the lipoxygenase pathway.	[133]
	Antioxidant	Curcumin contains a hydrogen atom in its phenolic group that acts as a radical scavenger, helping to maintain the integrity of cell membranes by preventing oxidative degradation caused by oxygen radicals and other reactive species.	[162]
Curcuma zedoaria	Anti-inflammatory	Curcumin inhibits the synthesis of nitric oxide (NO), thereby preventing UVB-induced skin inflammation.	[163]
		Curcumin acts as an anti-inflammatory agent with glucocorticoid-like properties, stimulating prostaglandins and collagenase.	[164]
	Sun protector	*Curcuma zedoaria* inhibits repetitive UVB-induced wrinkle formation, as well as the expression of COX-2 and MMP-13. It also suppresses UVB-induced MMP-1 promoter activity, along with EGFR, Src, MAPKKs/MAPKs, and Akt phosphorylation.	[165]
Curcuma mangga	Anti-inflammatory	Curcumin exhibits activity in inhibiting lipoxygenase.	[166]
		Curcumin reduces reactive oxygen species stimulated by neutrophils, inhibits the activation of pro-inflammatory mediators, and suppresses the activity of the cyclooxygenase enzyme.	[167]
	Antioxidant	Curcumin acts as a catalyst for the formation of hydroxyl radicals and serves as an antidote to oxygen and nitrogen radicals generated by biological processes in the body.	[168]
	Sun protector	Curcumin absorbs UV light within the wavelength range of 200–400 nm, providing protection against both UVA and UVB rays.	[169]
Curcumin	Antioxidant	Curcumin can restore the activities and capacities of antioxidant enzymes.	[170]

Table 5. *Cont.*

Sources	Method	Result	References
	Sun protector	Curcumin inhibits UV-induced oxidative damage by promoting and regulating Nrf2 activation in HaCaT cells, thereby accelerating the accumulation of antioxidant regulators.	[37]
		Curcumin inhibits collagen degradation and enhances collagen synthesis, while also promoting fibroblast repair and reducing the accumulation of UVA-induced ROS.	[170]
		Curcumin scavenges free radicals and restores histopathological alterations, protecting the skin from excessive UV exposure.	[171]

The anti-inflammatory and antioxidant properties of curcumin are strongly correlated with its potential as a sun-protective agent [167,170]. Evidence from research highlights curcumin's ability to reduce inflammatory markers and alleviate oxidative damage, both of which are critical factors in skin damage induced by UV radiation [28–34]. Through its capacity to mitigate inflammation and oxidative stress, curcumin plays a pivotal role in shielding the skin from UV-related damage, thus serving as a multifunctional component in sun care formulations [55,56].

4. Discussion

Curcumin, the primary bioactive compound derived from *Curcuma longa*, has attracted considerable interest due to its broad spectrum of bioactive properties, notably its antioxidant, anti-inflammatory, and UV-protective effects [101,167,170]. The flavonoid components of curcumin demonstrate robust antioxidant capabilities, efficiently inhibiting the generation of oxygen free radicals and lipid peroxidation triggered by UV radiation [79,100,172]. These protective effects are crucial in mitigating conditions such as photoaging and skin cancer [24–27,101]. Additionally, curcumin alleviates UV-induced inflammatory responses by suppressing the activation of NF-κB and other pro-inflammatory transcription factors, ultimately reducing inflammation and safeguarding the skin against UV-induced damage [87].

As a UV protector, curcumin holds promise for inclusion in natural sunscreen formulations, offering a range of opportunities, advantages, and challenges [173–175]. Natural sunscreens present an opportunity to leverage plant-based compounds such as flavonoids, polyphenols, and other secondary metabolites, known for their strong antioxidant and UV-absorbing properties [176,177]. These compounds can shield the skin from oxidative damage caused by UV radiation while reducing inflammation and mitigating aging effects [176,178–180]. The integration of natural ingredients with nanotechnology, such as nanoparticles and liposomes, further expands the potential of natural sunscreens. These advanced delivery systems enhance the stability, bioavailability, and efficacy of the active compounds, improving protection against UV rays [181]. Research indicates that natural ingredients can significantly enhance the photoprotective capabilities of sunscreens, providing antioxidant benefits and addressing skin inflammation, barrier damage, and UV-induced aging [182–184]. However, natural sunscreens face notable challenges, including their relatively lower SPF and photostability compared with chemical-based sunscreens [185–187]. Stabilization techniques, such as incorporating natural compounds into nanoparticles, are often required to improve their performance and resilience under sun exposure [181]. For instance, a study by Sari and Susiloningrum (2022) demonstrated that combining *Curcuma mangga* with TiO2 in sunscreen formulations resulted in higher SPF values compared with TiO2-only formulations [152]. This suggests that natural ingredients can act as SPF boosters, potentially reducing the reliance on synthetic UV filters. The composition of natural sunscreens, which typically involves fewer synthetic UV filters, offers additional benefits, including safety, non-toxicity, and a lower risk of irritation or

side effects compared with formulations with chemical or synthetic ingredients [188,189]. This makes natural sunscreens an appealing choice for consumers seeking effective and safer alternatives for sun protection [188,189].

The physicochemical properties of curcumin, summarized in Table 1, play a significant role in its applicability within cosmetic formulations. This compound is recognized for its yellowish-orange hue, mild earthy aroma, and bitter taste, yet these characteristics pose challenges in product development [70,73]. Curcumin's limited solubility in water significantly restricts its bioavailability, though it is readily soluble in organic solvents such as ethanol, acetone, and dimethyl sulfoxide (DMSO) [71,73]. This poor solubility necessitates advanced formulation strategies to enhance both its stability and integration into cosmetic products. Furthermore, curcumin exhibits instability under specific conditions, degrading when exposed to sunlight and becoming unstable at pH levels exceeding 6.5 [70]. These issues must be meticulously managed during formulation to preserve its efficacy [75,76]. On the other hand, curcumin demonstrates favorable heat resistance, tolerating temperatures up to 140 °C for short durations, an attribute beneficial for certain manufacturing processes [70]. Additionally, the ash and water content of curcumin extracts, typically ranging between 4 and 6% and 8 and 9%, respectively, influence both its stability and shelf life [72,74]. Addressing these factors is crucial for optimizing its use in sustainable and effective cosmetic formulations.

Curcumin's antioxidant activity, as detailed in Table 2, has been evaluated using a range of assays, including DPPH radical scavenging, ORAC, FRAP, ABTS, and others. These studies highlight variations in antioxidant potential among different *Curcuma* species, primarily influenced by differences in curcumin content [77–99]. Furthermore, environmental factors such as geographic region, solvent selection, and extraction methodologies significantly impact the antioxidant properties of curcumin, as summarized in Table 2 [89,92,95,97]. The antioxidant activity of curcumin across various *Curcuma* species demonstrates notable variability, with values ranging from 291.3 ± 3.1 μg/mL to 1.08 μg/mL for *Curcuma longa*, 19.0 ± 1.7 μg/mL to 1973.38 ± 219.93 μg/mL for *Curcuma xanthorrhiza*, 20.2 ± 2.0 μg/mL to 956.16 ± 20.27 μg/mL for *Curcuma zedoaria*, 37.75 μg/mL to 500 μg/mL for *Curcuma heyneana*, 6.0313 μg/mL to 1724 μg/mL for *Curcuma aeruginosa*, and 37.338 ± 1.851 μg/mL to 268.802 ± 43.573 μg/mL for *Curcuma mangga* [77,79,87,89,92,95,97,99]. Notably, curcumin in its extract form demonstrates superior antioxidant activity compared with formulated products, likely due to the reduced bioavailability of the active compound in complex formulations [90,151]. The enhanced antioxidant activity of curcumin is closely linked to its photoprotective properties, including reductions in sunburn cell formation, erythema, and UV-induced immunosuppression [182,190,191]. Consequently, optimizing the concentration of curcumin in formulations is essential to ensure adequate antioxidant and photoprotective effects.

Curcumin's anti-inflammatory properties have been widely studied through both in vivo and in vitro approaches, as summarized in Table 3. In vivo experiments, such as those utilizing TPA-induced and xylene-induced ear edema models in mice, have demonstrated curcumin's efficacy in reducing inflammation by assessing changes in edema volume in the ears of the test subjects [108,129]. Additionally, the application of curcumin, topically, has been shown to accelerate wound contraction in streptozotocin-induced models, with higher concentrations of curcumin extracts correlating with improved wound healing outcomes [125]. In vitro studies, employing spectrophotometric methods and high-performance liquid chromatography (HPLC), further support curcumin's anti-inflammatory potential. These studies have demonstrated reductions in pro-inflammatory cytokines such as IL-1β, IL-6, and TNF-α, as detailed in Table 3. Variations in these effects are influenced by curcumin concentration and the extraction methods used [89,92,95,97]. For instance, research by Indriani et al. (2018) highlighted that curcumin extract exhibited

anti-inflammatory efficacy comparable to the positive control [113]. Similarly, Arisonya et al. (2018) reported a significant reduction in ulcers on the labial mucosa diameter in male white rats treated with curcumin extract topically, further validating its potent anti-inflammatory effects [116]. The anti-inflammatory properties of curcumin are closely associated with its photoprotective benefits. These include the inhibition of edema and erythema, as well as reductions in hyperplastic responses, inflammatory leukocyte infiltration, skin aging, and the risk of skin cancer formation [192–194]. These findings highlight curcumin's potential as a multifunctional agent in both therapeutic and cosmetic applications.

As a photoprotective agent, curcumin demonstrates considerable variability in SPF values, as outlined in Table 4. In vitro testing using UV–Vis spectroscopy, with ethanol as a blank, evaluated curcumin's absorbance within the 290–320 nm wavelength range [107]. These analyses revealed that curcumin's SPF values span from minimal protection (SPF 1–4) to ultra protection (SPF > 15) [135–155]. Table 4 highlights that SPF values of curcumin in *Curcuma* extracts are generally higher than those observed in formulated products, emphasizing the need to optimize curcumin concentrations in sunscreen formulations to enhance photoprotective efficacy [46,47]. Additionally, as shown in Table 4, *Curcuma* extracts at concentrations ranging from 0.1 to 15% exhibited SPF values between 1 and 27.40. Extracts with concentrations of 200–1500 ppm demonstrated SPF values ranging from approximately 0.33 to 37.46 [66–86]. These findings indicate a positive correlation between extract concentration and SPF value, suggesting that higher extract concentrations result in enhanced UV absorption and greater protection against UVB radiation [172,195]. This relationship highlights the potential for higher curcumin content to provide extended and more effective sun protection [196]. However, a notable limitation is the lack of detailed information regarding curcumin concentrations in different *Curcuma* species. This gap underscores the importance of further standardization and the quantification of curcumin content to maximize its potential as a photoprotective agent.

Several factors influence the SPF value generated by *Curcuma* extracts and curcumin, including the choice of solvent, extraction temperature, and formulation ingredients [89,92,95,97]. Research by Kanani et al. (2017) demonstrated that using ethyl acetate as a solvent at 30 °C resulted in higher SPF values compared with methanol at elevated temperatures [173]. This is attributed to ethyl acetate's ability to extract more potent antioxidant compounds, which are strongly associated with increased SPF values [173,197,198]. Antioxidant compounds extracted by ethyl acetate contain chromophores and aliphatic CH groups capable of absorbing UV rays, thereby enhancing photoprotective efficacy [199,200]. These findings underscore the importance of selecting an appropriate solvent and optimizing extraction temperature during the formulation process to maximize the efficacy of sunscreens derived from *Curcuma* extracts containing curcumin [89,92,95,97,173]. Such considerations are critical to ensuring the development of effective and stable photoprotective products.

Curcumin enhances the effectiveness of sunscreen formulations by complementing other SPF-active ingredients, as evidenced by its multifunctional properties [152]. Acting as a skin protector, curcumin's antioxidant and anti-inflammatory activities provide substantial benefits [60–62]. Specifically, its anti-inflammatory effects include the ability to reduce redness and tissue damage caused by inflammation following sunlight exposure [133,134]. Curcumin achieves this by inhibiting the production of pro-inflammatory cytokines, such as IL-β, IL-6, and TNF-α, while reducing arachidonic acid release through the suppression of phospholipase A2 and phospholipase C g1 activity [37,156]. Additionally, curcumin inhibits the synthesis of nitric oxide (NO), COX-2, and lipoxygenase, further mitigating inflammation [37,133]. As detailed in Table 5, plants containing curcumin protect skin cells from oxidative damage via their antioxidant properties, preserving cell membrane integrity and preventing oxidative degradation. The phenolic group in curcumin enables

the scavenging of free radicals, providing additional photoprotection by absorbing UV light, reducing UV-induced oxidative damage, and decreasing TNF-α expression [162]. In summary, curcumin's combined antioxidant, anti-inflammatory, and UV-protective effects make it a valuable ingredient in sunscreen formulations, as demonstrated in Figure 3. These attributes highlight its potential to improve the overall efficacy and multifunctionality of sun care products.

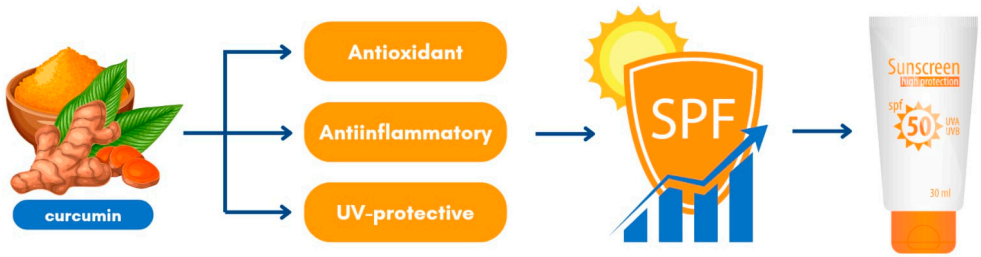

Figure 3. Curcumin could be used in sunscreen formulations.

Studies, such as those conducted by Arizona and Zulkarnain (2018), have shown that increasing curcumin concentrations in lotions significantly enhances SPF values [151]. However, the impact of other excipients included in the formulation must also be considered, as these components can influence SPF values and alter the overall sun protection efficacy. Consequently, optimizing both the concentration of curcumin and the selection of suitable excipients is crucial to maximizing its photoprotective potential in sunscreen formulations. This strategic approach ensures the development of effective and stable sunscreen products that fully leverage curcumin's properties.

5. Conclusions

Based on the reviewed literature, curcumin demonstrates significant potential as a sunscreen agent, primarily due to its ability to enhance SPF values through its synergistic antioxidant, anti-inflammatory, and UV-protective properties. These activities collectively strengthen curcumin's effectiveness as an SPF booster, providing dual protection against UV-induced damage. Increasing curcumin concentrations in sunscreen formulations has been shown to result in higher SPF values, further highlighting its potential utility. However, the inclusion of various excipients must be carefully considered, as they can influence SPF values and potentially affect the overall efficacy of the formulation. Therefore, further research is necessary to identify the optimal concentration of curcumin and to evaluate its interaction with excipients, ensuring the development of effective and stable sunscreen products.

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