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While the demand for products with higher SPF and UVA protection is rising, the regulatory landscape for UV filters is shifting towards stricter safety and environmental standards. Given the uncertain future of several UV filters due to regulations and the potential impact they may have on human and/or environmental health, sunscreen manufacturers are actively seeking new ways to maintain and even enhance UV protection. This trend holds true regardless of the region. Two principal levers are driving their efforts: maximizing the effectiveness of the UV absorbing system by combining different UV filter technologies, and leveraging specific formulation excipients and formulation properties. Regarding the UV filter system, a practical, high-impact approach rests on three core principles: ensuring a minimum level of UVA protection, prioritizing photostability, and exploiting synergistic combinations such as pairing water- and oil-dispersed UV filters and/or adding particulate filters. Excipients and formulation properties offer additional benefits: scattering particles increase the optical path length and thereby enhance filter efficacy, and film-formers improve the homogeneity and thereby the effectiveness of the applied sunscreen layer. This article outlines a synergistic approach to enhancing sunscreen performance by combining these two complementary strategies, enabling formulators to develop highly effective sun care products while limiting the overall UV filter concentrations to better meet evolving consumer expectations.

Introduction

Sunscreens play a critical role in protecting the skin from the harmful effects of UV radiation. Consumer demand for higher sun protection factors (SPF) combined with enhanced UVA protection (UVA-PF) is rising globally – a trend reflected in European market data showing 76% of sun care products claiming SPF 50 or above by 2025, up from 50% in 2010 [1]. The European Commission's 2006 recommendation already stipulates a minimum UVA-PF of 1/3 of the labeled SPF [2]. At the same time, manufacturers are trying to limit the UV filter concentrations for sensory, regulatory, ecological, and safety reasons – with the permitted number of filters varying significantly by region [3].

This paradox poses a serious challenge for formulators. Boosting strategies are designed to improve the ratio of UV performance to UV filter load. In this article we explain how maximizing the UV filter system's performance and optimizing excipients and formulation architecture are complementary approaches for achieving the best possible sunscreen performance. The following sections show that these two approaches are most effective when combined.

1. Maximizing UV filter systems for reliable and safe performance

1.1 UV spectral coverage

To achieve true spectral complementarity and higher overall sunscreen efficacy, the combination of UVB and UVA filters is essential. The primary measure of sunscreen performance is the SPF value, which evaluates protection against erythema, mainly linked to UVB. However, UVA protection is also a key contributor to high SPF performance. As demonstrated by Sayre and colleagues, SPF values plateau at a low 10 to 15 when protection is based solely on UVB filters, because unattenuated UVA radiation continues to contribute to erythema by approximately 20% [4]. The European Commission recommendation stipulates a minimum UVA-PF of one third of the SPF to ensure a minimum UVA protection. UVA radiation is known to be associated with long term skin damage, including indirect DNA damage linked to skin cancer, premature photoaging, and pigmentation disorders such as persistent hyperpigmentation, particularly in melanin rich skin. Accordingly, measurement of UVA protection relies on persistent pigment darkening (PPD), which correlates with the maximum biological response occurring in the UVA range **(Figure 1)**.

Figure 1 shows the erythemal and PPD effectiveness spectra, obtained by weighting the UV spectral irradiance with the corresponding action spectra, representing the wavelength dependent biological response.

Furthermore, the European Commission's 2006 recommendation is currently under revision [5], with the possibility of increased minimum UVA-PF requirements to achieve greater spectral balance [6].

1.2 Photostability and photocompatibility

Another important factor for reliable protection is photostability. Photounstable UV filters can generate by-products and/or free radicals upon irradiation; sunscreens containing photolabile UV filters therefore require higher concentrations of those filters to achieve equivalent levels of protection compared with photostable counterparts.

One typical example of a photounstable UVA filter is Butyl Methoxydibenzoylmethane (BMDBM). The mechanisms of its degradation have been well studied [7]. In brief, BMDBM is known to undergo two types of photoreactions: first, reversible enol-keto isomerization; and second, the more problematic, irreversible Norrish Type I cleavage of the keto form into benzoyl and phenacyl radicals, which then can undergo further reactions. Several additional photofragments have also been reported [8]. Additionally, oxygen quenching of the keto triplet state produces singlet oxygen, which can lead to further secondary reactions.

BMDBM can partly be photostabilized by quenching molecules; to be effective, the difference between the de-excitation energy of BMDBM and the energy required for the corresponding transition of the quencher must be small. This explains why suitable quenchers are generally other UV filters, such as octocrylene (OCR) and Bis-ethylhexyloxyphenol methoxyphenyl triazine (BEMT). **Figure 2** shows the recovery rate after UV irradiation of BMDBM alone and in combination either with OCR or BEMT compared to the photostable UV filter Diethylamino Hydroxybenzoyl Hexyl Benzoate (DHHB) in an O/W formulation using HPLC measurements.

As **Figure 2** shows, BMDBM is highly photounstable, exhibiting more than 80% loss. BMDBM can, however, be partially photostabilized by OCR and BEMT, but stabilization is not complete – losses still reach 30 to 40% and free radical formation can occur under prolonged UV exposure. These findings are consistent with previous studies by *Herzog et al.* and *Sohn et al.*, who have investigated the photokinetics of BMDBM with OCR and BEMT as quenchers using HPLC measurements and quantum-chemical calculations [9,10]. Additionally, OCR is increasingly being phased out of sunscreens for various reasons [11], and BEMT must be dissolved and therefore cannot technically replace OCR at equivalent concentrations – reinforcing the fact that a significant proportion of BMDBM will inevitably photodegrade. There are other molecules that were shown to quench BMDBM in excited state. However, although some share the same chemical structure as registered UV filters, they have not undergone official approval and safety evaluation. A characteristic example is Butyloctyl salicylate (non-approved UV absorbing molecule) vs Ethylhexyl Salicylate (approved UV filter) which both contain the same salicylic-acid chromophore. Described as hidden

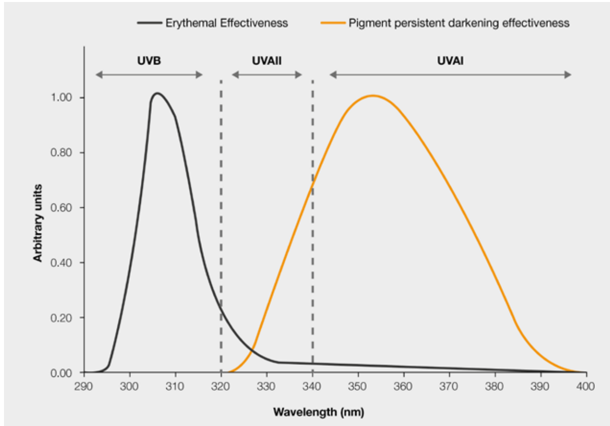


Fig. 1 Effectiveness spectra of erythema in black and PPD in orange.

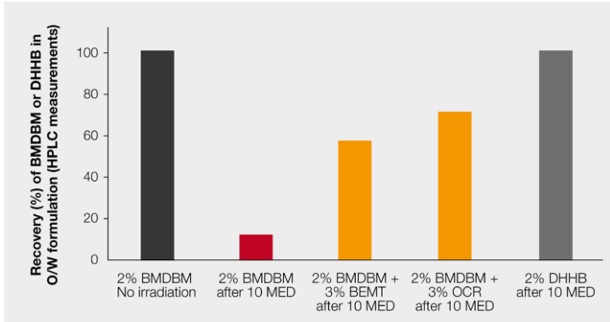


Fig. 2 Recovery of BMDBM alone and in combination with BEMT or OCR, and of DHHB after 10 MED UV irradiation.

or doping UV filters [12,13], they are not a viable option for responsible formulation.

Given these limitations, the most effective approach is to use inherently photostable UV filters such as Ethylhexyl Triazone (EHT), DHHB, and BEMT, which avoid adverse effects and secondary reactions altogether.

1.3 Oil-water filter distribution synergy to enhance performance

The use of water-soluble UV filters in combination with oil-soluble ones offers an additional means of enhancing UV protection. When only lipophilic filters are used [14], O/W emulsions can leave unprotected water pockets after spreading, making

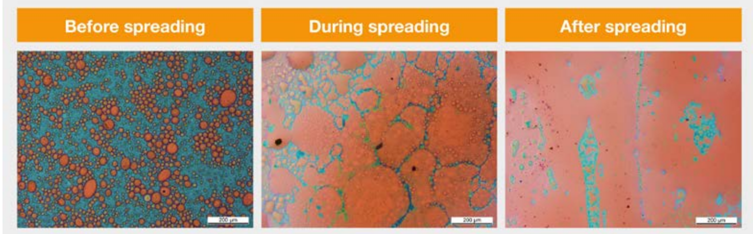


Fig. 3 Light microscopic pictures of an O/W emulsion containing oil-dispersed Sudan Red III pigment (CI 26100) and water-dispersed blue pigment (CI42090) before, during and after manual spreading on a glass plate.

the combination of water-soluble and oil-soluble UV filters essential for optimal coverage and improved SPF/UVA-PF performance. **Figure 3** illustrates this principle using color-differentiated light microscopy.

When only lipophilic UV filters are used, residual areas of the water phase after spreading (in blue) leave areas of the skin without UV protection. This is detrimental to the overall photoprotection performance of sunscreens. The most effective way to address this is to incorporate a water-soluble UV filter that improves not only SPF but also UVA-PF across both the UVB and UVA ranges. This is possible with the water-soluble Terephthalylidene Dicamphor Sulfonic Acid (TDSA) [14], primarily classified as a UVA filter (maximum absorption at 345 nm), whose absorption spectrum, however, extends into the UVB range, which enables it to contribute to both UVA protection and SPF **(Table 1)**.

In this formulation, the addition of TDSA increases the SPF by approximately 20%, while increasing the total filter content by less than 10%.

Phase	Trade name	INCI	% by weight	
			Reference	Reference + TDSA
A	Eumulgin Prisma	Disodium Cetearyl Sulfosuccinate	1.00	1.00
	Emulgade® PL 68/50	Cetearyl Glucoside (and) Cetearyl Alcohol	3.00	3.00
	Lanette® O	Cetearyl Alcohol	0.80	0.80
	Cetiol® ABV	C12-15 Alkyl Benzoate	7.00	7.00
	Cetiol® B	Dibutyl Adipate	15.00	15.00
	Cetiol® Sensoft	Propylheptyl Caprylate	5.00	5.00
		Preservative	qs	qs
	Uvinul® T 150	Ethylhexyl Triazone	3.00	3.00
	Tinosorb® S	Bis-Ethylhexyloxyphenol Methoxyphenyl Triazine	3.50	3.50
	Uvinul® A Plus	Diethylamino Hydroxybenzoyl Hexyl Benzoate	4.50	4.50
B	Water	Aqua	Qsp 100%	Qsp 100%
	Glycerin	Glycerin	5.00	5.00
	Verdessence® Xanthan	Xanthan gum	0.30	0.30
C	**Uvinul® TS Hydro ***	**Aqua (and) Terephthalylidene Dicamphor Sulfonic Acid**	**–**	**3.00**
	L-Arginine	Arginine	–	0.60
D	Cetiol® Ultimate	Undecane (and) Tridecane	3.00	3.00
Performance		**SPF *in vivo***	**28**	**33**
		UVA-PF *in vitro*	**12.7**	**14.7**

* Uvinul® TS Hydro is a 30% active solution; 3% Uvinul® TS Hydro corresponds to 1% active matter

Table 1: O/W formulation without and with 1% TDSA and corresponding SPF and UVA-PF.

1.4 Particulate UV filters' scattering properties

Particulate UV filters not only absorb UV but also scatter light, thereby increasing the optical path length through a sunscreen film and enhancing the likelihood that scattered light is absorbed by surrounding soluble UV filter molecules. This combined effect boosts the performance of the overall UV filter system [15]. The dual action of absorption and scattering applies to both inorganic and organic particulate UV filters, with absorption remaining the dominant mechanism and scattering accounting for approximately 10 to 20% of the total effect. **Figure 4** schematically illustrates these UV attenuation processes.

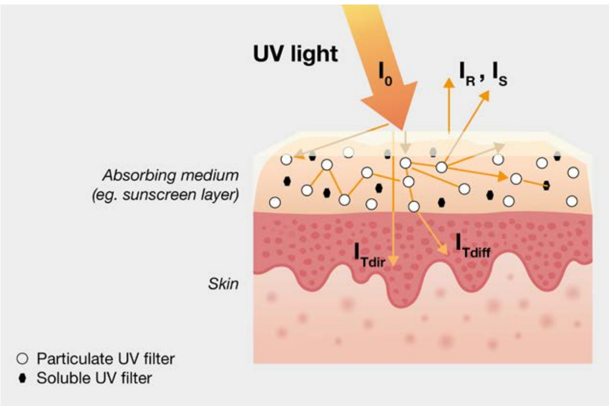


Fig. 4 UV attenuation processes of particulate UV filters, with I0 the intensity of the incident light; I_{Tdir} the intensity of the direct transmitted light; I_{Tdiff} the intensity of the diffused transmitted light; I_S and I_R the intensities of reflected and scattered light.

Compared to inorganic particulate filters, organic variants offer higher extinction properties and, therefore, the potential for lower use concentrations. The two commercially available options currently approved in Europe and freely available are the

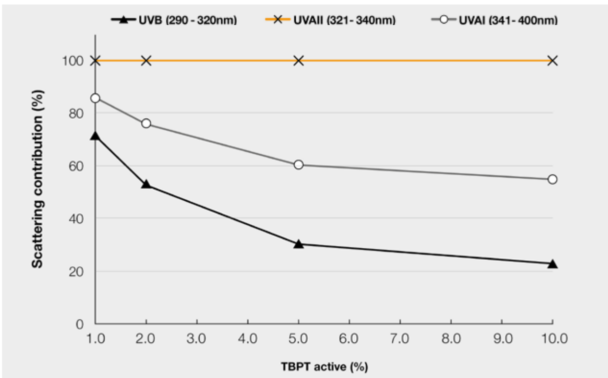


Fig. 5 Scattering contribution of varying concentrations of particulate TBPT filter in the UVB, UVAII and UVAI range..

UVB filter Tris-biphenyl Triazine (TBPT) (Tinosorb® A2B) and the broad-spectrum filter Methylene Bis-Benzotriazolyl Tetramethylbutylphenol (MBBT) (Tinosorb® M), both of which are supplied as aqueous dispersions.

Figure 5 displays the scattering contribution of increasing concentration of the particulate filter TBPT in the UVB, UVAII and UVAI range.

The scattering contribution varies with both wavelength range and filter concentration: It is higher where absorption of the filter is low and increases at lower particle concentrations, where particles are spaced further apart and scattered light is less likely to be re-absorbed. At higher concentrations, absorption becomes the dominant attenuation mechanism [16].

UV filter type	UV filter*	Formulation phase	UVA-PF/SPF ratio of 1/3	UVA-PF/SPF ratio of 1/2	UVA-PF/SPF ratio of 1/2
UVB	EHT	Oil soluble	3.5	2.5	3.5
	TBPT	Water dispersed	1.0	1.0	-
Broad-spectrum	BEMT	Oil soluble	2.0	2.0	3.0
	MBBT	Water dispersed	–	1.0	–
UVA	DHHB	Oil soluble	4.0	4.0	4.0
	TDSA	Water soluble	–	–	2.0

* EHT, Ethylhexyl Triazone; TBPT, Tris-Biphenyl Traizone; BEMT, Bis-Ethylhexyloxyphenol Methoxyphenyl Triazine; MBBT, Methylene Bis-Benzotriazolyl Tetramethylbutylphenol; DHHB; Diethylamino Hydroxybenzoyl Hexyl Benzoate; TDSA, Terephthalylidene Dicamphor Sulfonic Acid.

Table 2: UV filter combinations SPF 30 for a typical UVA-PF/SPF ratio of ⅓ and increased UVA-PF/SPF ratio of ½.

1.5 Showcase of exemplary UV filter systems as the ideal path

Using a filter matrix that incorporates multiple filters to cover the aspects described above is ideal for leveraging their specific benefits. **Table 2** presents illustrative UV filter combinations for SPF 30 formulations targeting a typical UVA-PF/SPF ratio of 1/3, and targeting an increased ratio of 1/2 – the latter being provided in two versions, with and without the particulate filter MBBT, as well as an alternative based on TDSA as UVA filter. The optimal filter matrix should include several filters to take advantage of the benefits from each, rather than minimizing the number of filters.

2. Optimizing excipients and formulation architecture to increase performance

The performance of sunscreen products is inseparable from the applied sunscreen film, which can be influenced by both excipients (light-scattering agents and film formers) and formulation chassis (type and viscosity).

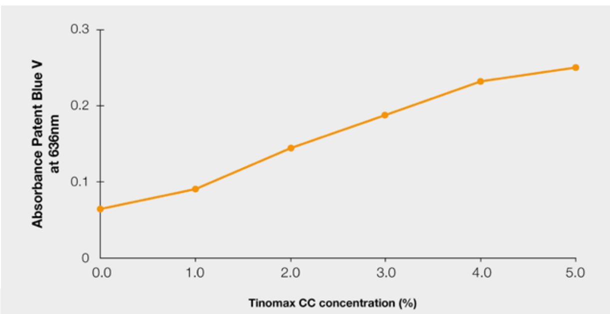


Fig. 6 Relationship of the dye absorbance at 636 nm and the concentration of Tinomax™ CC.

2.1 Light scattering agents

Light-scattering agents act like particulate UV filters by increasing the optical path length through the sunscreen film, but contain no chromophores and are therefore inactive in UV absorption. One example is Tinomax™ CC (INCI: Calcium Carbonate, Hydroxyapatite) – a natural-based functionalized calcium carbonate and hydroxyapatite particle (NATRUE- and COSMOS-approved). It is supplied as a highly porous powder with a D50 of 3-4 µm and is readily dispersible in the oil or water phase under high-speed homogenization. The pH of the final formulation should be at least 7 for maximized stability. The effect of this functional particle was assessed by measuring changes in absorbance of Patent Blue V dye, which has a maximum absorbance at 636 nm, with increasing concentrations of Tinomax™ CC, following a study design analogous to that of Herzog [15]. In this experimental set-up, the dye concentration was kept constant while the functional particle concentration varied from 0 to 5% (0, 1, 2, 3, 4, and 5%). The absorbance of the dye was measured using a UV/Vis spectrometer with an integration sphere and is shown in **Figure 6**.

The results in **Figure 6** demonstrate a clear dose-response relationship. This effect similarly applies to the influence Tinomax™ CC will have on soluble UV filters: It enhances the absorption of surrounding soluble UV filter molecules through scattering. In order not to compete with the scattering effect of particulate filters, it performs best in soluble UV filter systems, where a performance enhancement of 20 to 30% can be expected. For example, the addition of 3% Tinomax™ CC *in vivo* increased SPF from 44 to 54 in a filter system consisting of 2% EHT, 5% EHS, 3% BEMT, and 5% DHHB.

2.2 Film formers

Variations in film thickness distribution can lead to differences in SPF values even when UV filter concentrations are identical [17]. Film formers – typically waxes – are therefore employed to provide a more uniform film layer and improve SPF and water resistance (WR). However, some waxes recrystallize unevenly, thereby affecting formulation stability.

The film-forming wax Dicocoyl Pentaerythrityl Distearyl Citrate (Cutina® Shine) was found as an effective solution to overcome these issues [18]. In contrast to the typical Triacontanyl PVP, which is synthetic, Cutina® Shine is produced from RSPO-certified, sustainably sourced palm kernel oil and contains 75% renewable carbon. Its melting range of 45-50°C enables easy incorporation by melting into the oil phase during emulsion manufacture.

Table 3 presents *in vivo* SPF and WR results (ISO 24444; ISO 16217) comparing formulations with either Triacontanyl PVP or Dicocoyl Pentaerythrityl Distearyl Citrate wax-based film former compared to a placebo.

Adding Cutina® Shine markedly increased SPF and water resistance; these benefits were validated *in vivo* across various formulation platforms.

2.3 Formulation type & viscosity effects

Beyond the single excipients, the vehicle – including formulation type and viscosity – was also shown to contribute to film distribution and subsequently delivered photoprotection. We developed a qualitative assessment method using optical light microscopy to evaluate film homogeneity as a simple and fast technique, applying the tested formulation to a combined pig skin/PMMA substrate. The substrate consisted of mold-injected SPF Master PA01 (Shiseido Irica Technology) PMMA plates overlaid with the stratum corneum from pig ear. This combined substrate reproduces the surface pattern and roughness of human skin (from SPF Master PA01), while the trypsin-treated porcine *stratum corneum* provides surface properties comparable to those of human skin [19]. A test amount of 2 mg/cm² of the test formulation was applied to the combined pig skin/PMMA substrate plate, and subsequent optical light microscopy images were acquired. The *in vitro* SPF was determined from UV transmittance measurements obtained through the pig skin/PMMA substrate plate.

Formulations varying in emulsifier type and viscosity were assessed while keeping the UV filter system – EHMC, DHHB, and BEMT – and emollient concentration constant **(Table 4)**.

Trade name	INCI	% by weight		
		Placebo	Synthetic film former	Cutina® Shine film former
Part A – Oil phase				
Eumulgin® Prisma	Disodium Cetearyl Sulfosuccinate	0.20	0.20	0.20
Cutina® GMS-SE	Glyceryl Stearate SE	2.00	2.00	2.00
Lanette® O	Cetearyl Alcohol	1.50	1.50	1.50
	Triacontanyl PVP	–	3.00	–
Cutina® Shine	Dicocoyl Pentaerythrityl Distearyl Citrate	–	–	3.00
Cetiol® B	Dibutyl Adipate	12.00	12.00	12.00
Cetiol® CC	Dicaprylyl Carbonate	5.00	5.00	5.00
Eutanol® G	Octyldodecanol	3.00	3.00	3.00
Cetiol® Sensoft	Propylheptyl Caprylate	2.00	2.00	2.00
Cetiol® OE	Dicaprylyl Ether	2.00	2.00	2.00
Verdessence® Xanthan	Xanthan Gum	0.50	0.50	0.50
	Preservative	qs	qs	qs
Uvinul® T 150	Ethylhexyl Triazone	3.00	3.00	3.00
Tinosorb® S	Bis-Ethylhexyloxyphenol Methoxyphenyl Triazine	2.00	2.00	2.00
Uvinul® A Plus	Diethylamino Hydroxybenzoyl Hexyl Benzoate	6.00	6.00	6.00
Part B – Water phase				
Water	Aqua	Qsp 100%	Qsp 100%	Qsp 100%
Glycerin	Glycerin	3.00	3.00	3.00
Part C – After emulsification				
Water	Water	10.00	10.00	10.00
	Phenylbenzimidazole Sulfonic Acid	0.70	0.70	0.70
	Tromethamine	qs	qs	qs
Part D – After emulsification				
Tinosorb® A2B	Tris-Biphenyl Triazine (nano), Aqua, Decyl Glucoside, Disodium Phosphate, Butylene Glycol, Xanthan Gum	4.00	4.00	4.00
Performance	**SPF *in vivo***	**37**	**44**	**60**
	WR *in vivo* (%)	**27%**	**61%**	**57%**

Table 3: Sunscreen compositions with and without film formers and their SPF and WR *in vivo*.

Poor film distribution was identified by localized packing of the formulation on the pig skin/PMMA substrate after spreading; these packed regions appeared as discrete droplet like beads.

The results showed that the formulation with microscopic visible discrete packing of sunscreen film exhibited the significantly smaller SPF value of 14 compared to greater than 31 for the two others. Further, the study revealed that the dual emulsifiers/thickeners highly impacted the SPF *in vitro* values.

A previous study examining five formulation bases – O/W cream, O/W fluid, gel, W/O, and clear lipo-alcoholic spray

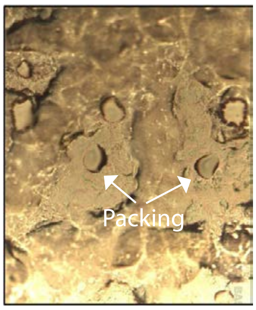
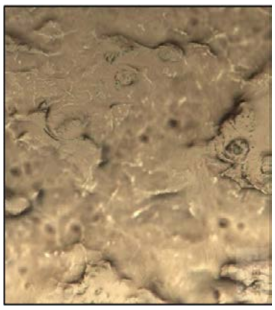
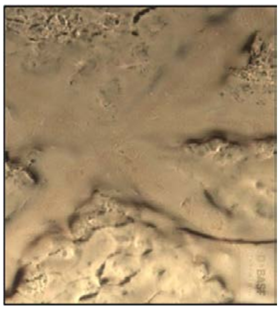
AQUARICH®-MAX	Lotion (ref. 14123-7-1)	Lotion (ref. 14123-1-2)	Lotion (ref. 14123-1-1)
Emulsifier 1	Sucrose Palmitate (and) Glyceryl Stearate (and) Glyceryl Stearate Citrate (and) Sucrose (and) Mannan (and) Xanthan Gum	Lauryl Glucoside (and) Polyglyceryl-2 Dipolyhydroxystearate (and) Glycerin	Lauryl Glucoside (and) Polyglyceryl-2 Dipolyhydroxystearate (and) Glycerin
Emulsifier 2	–	Glyceryl Stearate (and) Peg-100 Stearate	Glyceryl Stearate (and) Peg-100 Stearate
Thickener	Polymeric thickener	–	Polymeric thickener
Microscopic picture X200			
Film aspect	Packing of film	No packing	No packing
SPF *in vitro*	14	31	43

Table 4: Microscopic film appearance and in vitro SPF of formulations varying in emulsifier/thickener and viscosity while maintaining a constant UV filter blend.

(CAS) – found that the two lowest-viscosity vehicles (O/W fluid and CAS) produced the thinnest films and the lowest SPF values, leaving broad ridges virtually uncovered while accumulating in skin furrows. These effects resulted in lower SPF values compared to the formulations containing thickener in the same study. This suggests that the presence of thickeners is an essential requirement for adequate photoprotection [17].

The previous analysis shows that UV protection depends primarily on the UV filters used, which are the active ingredients in sunscreens. However, the overall performance can be maximized by the selection of excipients and vehicle, as summarized in **Figure 7**.

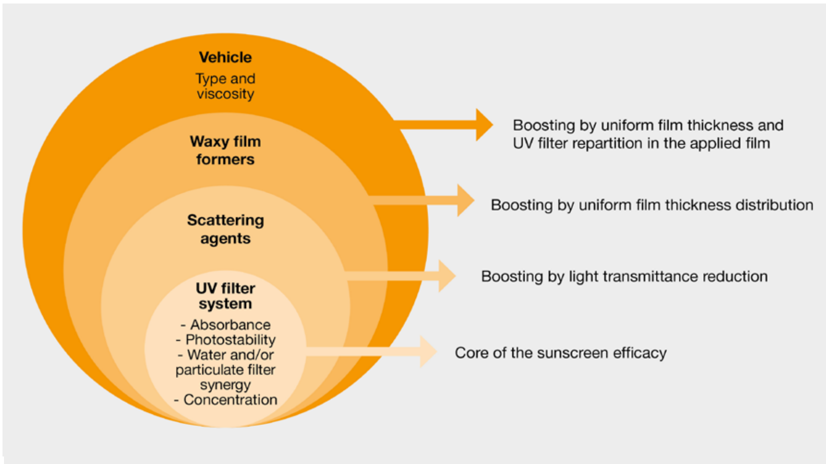


Fig. 7 Summary of levers to maximize UV performance.

Conclusion

The article showed how optimal sunscreen design combines a maximized UV filter system with well-chosen excipients and formulation architecture. The data confirms that this holistic approach delivers substantial gains in SPF and UVA-PF while meeting today's demands for safety, sensorial elegance, and environmental responsibility without relying on unapproved "hidden" UV filters. In light of ongoing ecotoxicity concerns and European regulatory discussions, future sunscreen innovation will increasingly rely on smart formulation engineering rather than on ever-higher filter concentrations.

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