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# Next-Generation Sunscreen Science: Advances in UV Filters, Photoprotection and Formulation Strategies - Insights from Lacto Calamine®

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## Abstract

Sunscreens play an important role in providing photoprotection, by minimizing adverse effects of ultraviolet (UV) radiation on the skin. This review focuses on the analysis of sunscreens and their categorization as chemical, physical, new generation, and encapsulated according to the mechanism of photoprotection that each of these groups have. Detailed information is provided about the design of skin type-specific sunscreens, including recommendations for oily, combination, dry and sensitive, Sun protection factor (SPF), persistent pigment darkening (PPD), critical wavelength, and photostability as key physicochemical properties of sunscreens and global regulations on these products are reviewed. This article also provides an overview of the Lacto Calamine® sunscreen formulation's consumer-centric approach to photoprotection by integrating scientifically selected UV filters with elegant formulation design to cater to the evolving needs of Indian consumers, particularly those with oily and combination skin.

**Conclusion:** The review explains how sunscreens are essential for protecting against UV-induced damage, including sunburn, tanning, photoaging and skin cancer. Advances in UV filters and formulation technologies have improved efficacy and user experience, while SPF, UVA-PF, critical wavelength, and photostability support performance evaluation. Lacto Calamine® Sunscreen is well positioned to deliver lightweight, effective everyday photoprotection for Indian consumers, with future innovation focused on multifunctional, sustainable and personalized solutions.

**Keywords:** Sunscreen; Photoprotection; SPF; Ultraviolet radiation; Skin type; Formulation; Organic filters; Inorganic filters; Encapsulation; PPD; Exposome; Lacto Calamine®

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## 1. Introduction

The skin serves as the primary interface between the human body and its external environment, rendering it susceptible to a wide array of physical, chemical, and biological stressors. One of the most common and damaging of these is the ultraviolet (UV) radiation produced by the sun. Prolonged and unshielded exposure to this radiation has been proven to induce a variety of skin diseases, including sunburns, skin aging, immunosuppression, and even the formation of various skin tumors such as basal cell carcinoma, squamous cell carcinoma, and melanoma. (1,2) In the arsenal of any dermatologist, sunscreens are the indispensable means for protection against photodamage since they act to absorb, reflect and disperse UV radiation before it enters the skin. (3)

Skin cancer has become increasingly prevalent among people all over the globe. According to the World Health Organization, annually there are estimated to be 2 to 3 million new cases of non-melanoma skin cancer and around 132,000 new cases of melanoma. (4) However, although sunscreens have proven their effectiveness in preventing skin diseases, there still is poor compliance due to aesthetic preferences and false beliefs regarding skin tanning and vitamin D production. (5) There have been major developments in the science behind formulation of sunscreens in the last decade, through major improvements in filter technology, delivery technology and regulation. (6)

The purpose of the current review paper is to analyze the scientific concepts behind formulation of sunscreens in a systematic manner starting from the characteristics of UV rays and their effect of UV exposure on skin, categorization of sunscreen agents, formulation of sunscreen suitable for different types of skins, assessment methods, and new technologies. It is hoped that the review paper will become a useful source of information for specialists working in the field of photoprotection.

### 1.1 The Invisible Threat: Understanding the Ultraviolet Spectrum

The solar radiation striking the earth's surface has an extensive electromagnetic spectrum, where the UV radiation has a wavelength range of 100 to 400 nm. In terms of photoprotection purposes, the UV radiation can be divided into three major ranges of wavelengths: UVC (100-280 nm), UVB (280-315 nm), and UVA (315-400 nm). UVC radiation has the highest photon energy and highest genotoxicity; however, it is fully absorbed by the stratospheric ozone layer and does not reach the earth's surface. (7) Hence, photoprotection is mainly aimed at protection from UVB and UVA radiation.

The UVB radiation accounts for only 5% of the UV radiation that strikes the earth's surface, and it penetrates the epidermis and is absorbed by DNA, inducing the formation of cyclobutane pyrimidine dimers (CPDs) and pyrimidine(6-4)pyrimidone photoproducts (64PPs). (8) When DNA damage is not repaired by body’s repair mechanism, it can cause mutations that may further lead to the development of cancer. UVB is the main agent causing erythema and dominates in the formation of squamous cell carcinoma. On the other hand, UVA radiation, which makes up the remaining 95% of UV radiation, affects the dermis more profoundly by causing photoaging due to the formation of reactive oxygen species, breaking down collagen and elastin proteins, and activating matrix metalloproteinases. (9) It is important to mention that UVA radiation is further classified into UVA-I (340-400 nm) and UVA-II (315-340 nm); UVA-I causes more profound penetration into skin layers and has more potent potential for inducing indirect DNA damage by using oxidative mechanisms. (10)

The effect of UV radiation on the biological body is subject to regulation through different environmental and constitutional factors. These include altitude, latitude, season, hour of the day, presence of clouds, and surface reflectivity such as snow, sand, and water, which together affect the UV Index the standard scale of UV radiation intensity in a specific place and moment. (11) The constitutional factors that affect the sensitivity to UV radiation are Fitzpatrick phototype, melanin concentration, and stratum corneum thickness. Lighter phototypes (I and II) have a higher predisposition to sunburn, DNA damage, and consequently to skin cancers compared to darker phototypes (V and VI). Nevertheless, the latter are still predisposed to the development of UV immunosuppression. Infrared-A (IRA) rays (760-1440 nm) have recently been attracting attention as contributors to photoaging due to their ability to induce mitochondrial ROS production, resulting in increased expression of MMP-1. Photoprotection, thus, needs to take into consideration protection against UV and visible light (400-700 nm) and IRA as well, especially when dealing with patients suffering from melasma and post-inflammatory hyperpigmentation. (12, 13)

### 1.2 Effect of Ultraviolet Radiation on Skin: Why Sunscreen Matters

Ultraviolet (UV) radiation exerts both beneficial and harmful effects on the skin. Controlled UV exposure is essential for vitamin D synthesis, however, excessive exposure can lead to a range of harmful effects on the skin, such as tanning and sunburn (erythema), or chronic skin effects, including photoaging, immunosuppression, and skin cancer. (14)

Tanning refers to visible darkening of the skin occurring following UV exposure. It mainly results from increased melanin synthesis and its distribution within the epidermis, as a protection mechanism against UV exposure. Sunburn is an acute inflammatory condition of the skin caused by excessive exposure to UV radiation, particularly UVB. It is characterized by erythema resulting from the dilation of superficial dermal blood vessels. Severe UV exposure may lead to painful, oedematous, and sometimes blistered skin, depending on the intensity and duration of exposure. (15) Continued episodes of sunburn contribute to cumulative skin damage and increase the risk of premature skin ageing and skin cancer.

The significant etiological factor considered for most forms of skin cancer is UV exposure. The burden of UV-induced skin diseases is considerable and is still on the rise worldwide. In many countries, skin cancer is the most frequently occurring cancer. Commonly occurring forms of skin cancer are; basal cell carcinoma, squamous cell carcinoma, and cutaneous malignant melanoma. The first two forms are grouped as non-melanomas and are associated with higher morbidity and causing more extensive aesthetic changes on the skin whereas higher mortality occurs in the cutaneous malignant melanoma. (16)

Photoaging involves irreversible changes to the skin resulting from chronic exposure to the sun. It is mainly manifested by fine and coarse wrinkles, irregular pigmentation, dry skin, rugged furrows, sagging and loss of skin elasticity. (17)

Flament et. al reported that approx.. 80% of visible aging in Caucasian women’s faces is attributed to UV & sun exposure. (18, 19)

Using sunscreens is advantageous because of the ability to maintain outdoor activity without a substantial decrease in protection from UV radiation. Based on a clinical study conducted on 1621 Australian residents, Green A.C. et al., reported that regular sunscreen use prevents not only cutaneous squamous cell carcinoma but melanoma as well (20), suggesting importance of sunscreen in providing photoprotection. However, it should be considered that the effectiveness of sunscreens in daily practice is significantly decreased due to insufficient quantities of product application, lack of repeated application and coverage of all exposed skin surfaces. (21)

## 2. Classification of Sunscreens and the Mechanism of Photoprotection

Sunscreens are classified based on their mechanism of action, chemical nature, and physical form. Broadly, they fall into two major categories: organic (chemical) sunscreens, which absorb UV radiation, and inorganic (physical) sunscreens, which reflect and scatter UV radiation. Beyond these conventional categories, newer classifications encompass new-generation sunscreens incorporating novel filter molecules, and encapsulated sunscreen systems designed to enhance stability and minimize cutaneous penetration. Combination formulations incorporating both organic and inorganic filters are increasingly common in commercial products to achieve broad-spectrum protection with optimal cosmetic acceptability. (22)

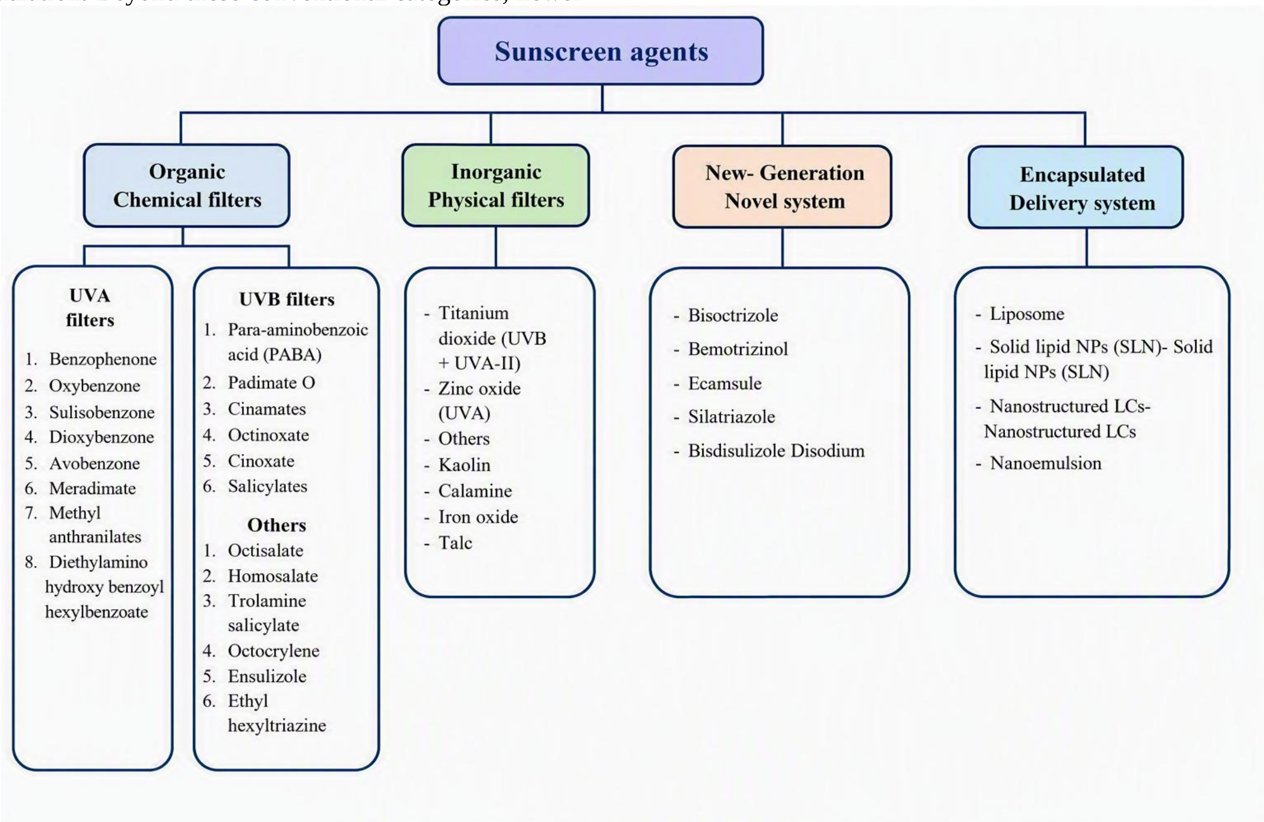


**Figure 2: The classification tree of sunscreen types**

*NPs = nanoparticles; LCs = lipid carriers;*

### 2.1 Organic Sunscreens

Organic sunscreens, commonly known as chemical sunscreens, are aromatic molecules that can absorb UV photons and dissipate energy through molecular excitations followed by relaxation. The chemistry behind their effectiveness is based on the existence of conjugated pi-bonded electrons that transition electronically following UV radiation, after which the molecule relaxes to its ground state either via radiative or non-radiative processes. (23) The wavelength at which the molecule absorbs UV light (lambda max) depends on its molecular structure, especially conjugation and substituent group type.

Commonly used organic absorbers of UVB light are para-aminobenzoic acid (PABA) and its derivatives, cinnamates and salicylates. PABA, the earliest sunscreen, has now become outdated due to its property of causing contact dermatitis and fabric staining. Octinoxate (ethylhexyl methoxycinnamate) has become one of the most commonly used UVB blockers worldwide due to its efficient UVB absorption (lambda max ~ 311 nm), with good cosmetics elegance, although it has come under some scrutiny due to photostability and endocrine disruption. (24) Although octocrylene acts as a poor absorber of UVB when isolated, it is often utilized as a photostabilizer because of its ability to quench the triplet excited states of the other filter compounds and reduce photodegradation. (25)

UVA organic filters are composed of benzophenones, anthranilates, and, more importantly, dibenzoyl-methanes. Avobenzone (butyl methoxydibenzoyl-methane) offers broad absorption in the range of UVA-I with the maximum lambda at 357 nm and is one of the few organic filters that give some sort of protection from long wavelengths of UVA. The problem is that this compound is quite photo-labile and experiences photoisomerization and photodegradation under the influence of UV radiation, so it needs to be combined with photostabilizers like octocrylene, bemotrizinol, or ethylhexyl triazone. (26) Benzophenone-3 (oxybenzone) is a compound providing both UVB and UVA-II protection and one of the most popular sunscreens. (27)

### 2.2 Inorganic Sunscreens

Physical sunscreen most commonly used are titanium dioxide ($TiO_2$) and zinc oxide (ZnO). In addition, another physical sunscreen agent contains kaolin, iron oxide, calamine, talc and ichthammol have also been reported to provide photoprotection by providing physical barriers. (28) In contrast to organic filters that absorb UV rays, inorganic filters protect the skin through reflection, scattering, and absorption of UV rays, with the ratio of each process depending on the particle size of the filter. (28)

Titanium dioxide exists in three crystalline forms namely: rutile, anatase, and brookite. Amongst these forms rutile form is the most stable and widely used form in sunscreens. TiO2 provides efficient protection in UVB and UVA II region compared to UVA I (340 – 400 nm). The high refractive index of rutile titanium dioxide (~2.6) enables strong visible light scattering, resulting in the characteristic white appearance (white cast) observed with the use of older $TiO_2$-based sunscreen formulations. (29) ZnO gives much more spectrum coverage than TiO2, giving protection in both the UVA range (315–400 nm) and the UVB range. Due to its greater spectrum coverage, ZnO is the ideal inorganic sunscreen that gives real broad-spectrum protection and is therefore becoming more popular in sunscreens that focus on giving protection from the UVA. (29)

From the regulatory perspective, TiO2 and ZnO are classified as Generally Recognized as Safe and Effective (GRASE) by the United States Food and Drug Administration (FDA), which makes them stand out from other organic filters that are still being evaluated from the safety perspective. (30) These filters are especially popular in sunscreens that target sensitive skin, children and individuals who have allergic reactions to the organic filters. Inorganic filters are also getting much interest due to their environmental safety characteristics in contrast to the damage that can be caused to the coral reefs by Oxybenzone. (31)

The Lacto Calamine® sunscreen formulation demonstrates a scientifically optimized approach to broad-spectrum photoprotection through the strategic selection of organic & inorganic UV filters and compatible formulation excipients which are suitable for Indian consumers.

### 2.3 New Generation Sunscreens

"The new generation sunscreens" is a broad description of various innovations regarding chemical structures of filters, addition of antioxidants to sunscreens, and photoprotection strategies going beyond traditional UV filters and addressing the problem of solar damage in a more holistic way. They include novel organic filter molecules, photostable combinations, DNA repair enzymes, antioxidants, and immunomodulating agents present in topical preparations. (32)

Among the novel filter molecules, Bemotrizinol (Bis-Ethylhexyloxyphenol Methoxyphenyl Triazine) and Bisoctrizole(Methylene Bis-Benzotriazolyl Tetramethylbutylphenol) are the most important. Bemotrizinol is an oil-soluble triazine compound having dual capabilities of UVB and UVA absorption (maximum at 310 and 343 nm wavelengths), high molar absorptivity, and outstanding photostability. Bisoctrizole is a water-dispersible solid particle sunscreen agent possessing both organic UV absorption and physical scattering properties. It has low risk of systemic absorption owing to its large molecule size and particulate form. (33) Another interesting photostable broad-spectrum filter is Drometrizole trisiloxane.

Antioxidant-rich sunscreens can be considered a major breakthrough because there is evidence that UV-induced reactive oxygen species (ROS) can cause significant damage to skin even under sub-erythematous conditions. Various vitamins (such as C and E), niacinamide, resveratrol, ferulic acid, coenzyme Q10, and polyphenols (green tea catechins and pomegranate extract) have been used in sunscreens to neutralize ROS and overcome oxidative stress beyond the capabilities of UV filters. (34) Research has shown that antioxidant-enriched sunscreens offer better protection against oxidative DNA damage and photoaging than UV filters alone. (35)

Furthermore, the concept of 'sunscreen supplementation' has expanded to include systemic photoprotective agents such as nicotinamide (niacinamide), which has demonstrated clinical efficacy in reducing actinic keratoses and non-melanoma skin cancer incidence in high-risk populations. (36)

### 2.4 Encapsulated Sunscreen

Encapsulation technology has been found to be a viable option to enhance the efficiency of sunscreens by increasing photostability, decreasing skin permeation, and making them more consumer friendly. Sunscreen active ingredients can be encapsulated using various carrier systems, such as liposomes, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), polymer nanoparticles, and cyclodextrins. (37) Encapsulation increases the stability of photolabile filters like avobenzone and decreases the risks associated with their systemic penetration into the body.

Various safety concerns were raised for sunscreen nanoparticulate systems containing inorganic UV filters such as zinc oxide (ZnO) and titanium dioxide (TiO2) for systemic absorption and ROS generation, which could further induce cellular damage. A recent review by the Australian Therapeutic Goods Administration (TGA, 2017) concluded that nanoparticles of ZnO and TiO2 do not significantly penetrate the stratum corneum, the outermost layer of the skin, suggesting that these nanoparticles are unlikely to cause systemic harm. (38)

### 2.5 Mechanism of Photoprotection

Sunscreens provide photoprotection through a complex mechanism which is highly dependent on the physical chemical properties of the sunscreen filters. First, sunscreens act as a barrier against harmful radiation by minimizing the number of photons that reach live epidermis and dermis cells. Organic filters use the method of UV absorption. In other words, photons interact with chromophores and excite their valence electrons to a higher energy state. Then, the excitation energy is dissipated through internal conversion, intersystem crossing, and fluorescence. Therefore, less energy is available for photochemical reactions with skin substances. (39)

On the contrary, inorganic filters decrease the harmful effect of the radiation by reflecting and scattering it. The reflection takes place at the surface of pigment particles because it happens where there is an interaction of light rays with interfaces of materials that have different refractive indexes. On the other hand, the scattering occurs in accordance with Mie theory. It means that the particles that are equal to the wavelengths of incident light scatter it in various directions. (40) Quantum confinement effects for nanoparticles cause an increased energy of the band gap of $TiO_2$ and ZnO and allow UV absorption and production of electron hole pairs-a photocatalytic mechanism that needs to be inhibited by the surface coating (silica or alumina) to avoid ROS generation. (41)

Photostability plays a crucial role in the prolonged efficiency of sunscreens in UV radiation conditions. Photodecomposition of organic filters leads to the creation of photo products with the reduced or lost ability to absorb UV radiation; thus, decreasing the SPF of the product. Photostabilization of unstable filters, like avobenzone, is achieved by adding photostabilizers, choosing a synergistic combination of filters, or by encapsulation, as was mentioned above. Energy transfer from the excited state of avobenzone to quenchers can occur via two different ways (triplet-triplet annihilation of octocrylene and electron transfer mechanism of Bemotrizinol. (42)

The idea of substantivity, the capability of the sunscreen to remain adhered to the skin through water immersion, sweating, and physical activities, is also important in the protection process. The water resistance property of the sunscreen is attributed to the incorporation of film-forming polymers, hydrophobic emollients, and use of solid lipid nanoparticles or wax matrix that are not affected by water exposure. 'Water resistant' is defined in terms of 40 minutes of water immersion, while 'very water resistant' is 80 minutes. This test is conducted by immersion of a volunteer subject in a pool or spa for 40 min with a five-minute rest in between (20-5-20) and for 80 min with two cycles of 20-5-20. The procedure is done immediately after SPF determination. The sunscreen product is considered water resistant if it retains no less than 50% of its SPF after the respective immersion. (43)

## 3. Skin-Type-Specific Formulation Architecture

Modern sunscreen formulas go far beyond the simple choice of filters for UV protection. Successful product design entails consideration of the physical chemical properties of the active compounds along with the physiological features of the skin type of the intended consumer, the climate conditions under which it will be used, and the expectations of the consumer. The structure of skin-type specific formulations is based on the information on the rates of secretion of sebum, skin barrier function, hydration, and skin sensitivity. (44-46)

### 3.1 Selection of Sunscreen Formulations Based on Skin Type

The selection of an appropriate sunscreen formulation should be tailored to an individual's skin characteristics and needs to ensure optimal photoprotection while maintaining skin safety, tolerability, and user comfort. Selection of appropriate sunscreens has been based on such classifications. Table 1 describes recommended sunscreen formats & key ingredients based on skin type.

#### *3.1.1 Oily and Acne-Prone Skin*

Oily and acne-prone skin requires non-comedogenic, oil-free, and lightweight sunscreen formulations to minimize breakouts and shine while ensuring adequate photoprotection. Gel-based, fluid, and water-based formulations containing sebum-absorbing agents such as silica, kaolin, and modified starches help control excess oil and provide a matte finish. Non-comedogenic emollients improve spreadability without clogging pores, while micronized ZnO offers additional anti-inflammatory, antimicrobial, and sebum-regulating benefits.

#### *3.1.2 Combination Skin*

Combination skin requires balanced formulations that control oil in the T-zone while maintaining hydration in drier areas. Lightweight emulsions containing sebum-absorbing agents and humectants such as glycerin and hyaluronic acid provide effective oil control and moisturization. Niacinamide further supports sebum regulation and skin barrier function, making it a valuable ingredient for combination skin.

#### *3.1.3 Dry Skin*

Dry skin is characterized by impaired barrier function and increased transepidermal water loss, making photoprotection and moisturization equally important. Sunscreens for dry skin should contain humectants, emollients, and occlusives to enhance hydration and barrier repair. Rich cream-based formulations enriched with ceramides, cholesterol, fatty acids, and hyaluronic acid help restore barrier function, reduce water loss, and improve skin hydration.

#### *3.1.4 Sensitive Skin*

Sensitive skin requires highly tolerable sunscreen formulations with minimal irritant potential. Mineral-based sunscreens containing ZnO and $TiO_2$ are preferred due to their superior safety profile and low allergenic potential. Fragrance-free, dye-free, and preservative-minimized formulations supplemented with soothing agents such as panthenol, allantoin, aloe vera, centella asiatica, and green tea extract help reduce skin irritation and UV-induced inflammation.

#### *3.1.5 Post-Procedure Skin*

**Table 1.** Recommended sunscreen formats & key ingredients based on skin type

| Skin Type | Recommended Vehicle | Key Ingredients |
|---|---|---|
| **Normal skin** | Lotion, cream, or fluid | Broad-spectrum UV filters, antioxidants (Vitamin E), glycerin |
| **Oily/Acne-prone skin** | Gel, aqua gel, silicone gel, fluid | Broad-spectrum UV filters, Niacinamide, silica, Kaolin |
| **Dry skin** | Cream, lotion, balm | Broad-spectrum UV filters, Ceramides, hyaluronic acid, emollients |
| **Sensitive skin** | Mineral cream, lotion | Zinc oxide, titanium dioxide, ceramides |
| **Combination skin** | Fluid lotion, light cream, gel-cream | Balanced moisturizers, non-greasy emollients, broad-spectrum UV filters |

### 3.4 Formulation Types

Sunscreens are available in various formulations, including creams, lotions, gels, sprays, sticks, and powders, each offering specific advantages in terms of UV protection, application, and user preference. Emulsions (O/W and W/O) are the most common, providing balanced photoprotection, moisturization, and water resistance. Gel formulations are lightweight and suitable for oily skin, while sprays offer convenient application over large body areas, although facial application requires caution due to inhalation risks. Sunscreen sticks provide targeted, water-resistant protection, whereas powder sunscreens are mainly used for touch-ups and oil control, offering limited SPF enhancement. (46)

### 3.5 Evaluation of the Final Product: Physicochemical Parameters

Quality, safety, and efficacy of the sunscreen's compositions are determined by different physicochemical parameters, according to international regulatory standards. Among them are organoleptic characteristics, pH, viscosity, rheology, and stability test, which allow to evaluate consistency and stability of the products. Photostability test allows to determine SPF persistence during UV irradiation, while in vitro UV absorbance test can be applied to evaluate SPF and assess broad spectrum protection with the critical wavelength of ≥370 nm. (47)

### 3.6 Measurement of the Effectiveness of a Sunscreen

#### *3.6.1 Sun Protection Factor (SPF)*

Sun Protection Factor (SPF) is the most widely known performance indicator of sunscreen efficacy providing quantitative measures of the efficiency of a product to protect the skin from erythema formation due to UV-radiation. SPF is the ratio of minimal erythema dose (MED) of sunscreen protected skin and minimal erythema dose (MED) of unprotected skin; whereby minimal erythema dose (MED) is the lowest dose of UV-radiation which causes noticeable erythema 16-24 hours post irradiation. (48) Since erythema is a consequence of the action of UVB, SPF represents the index reflecting UVB protection and, in addition, can be affected by UVA-II filters.

ISO 24444:2019 involves in vivo SPF evaluation and prescribes the use of a solar simulator to apply a sunscreen test sample in the amount of 2 mg per cm² onto the back of the test individuals specifically areas that have not had previous exposure to sunscreens. (49) Detailed guidelines for the in-vivo SPF determination is outlined in the international sun protection Test Method ISO 24444:2019. SPF is expressed as the ratio of the minimal erythemal dose (MED) required to induce erythema on the protected skin divided by dose required to induce the same erythema on unprotected skin on the same individual.

It is mathematically expressed as:

SPF = MED (protected skin)/MED (unprotected skin)

In vitro approach for SPF determination has been developed and validated. It involves measurement of absorption or the transmission of UV radiation through sunscreen product films in quartz plates or membranes and methods. (50) In vitro techniques have the advantage of being fast, repeatable, ethical-free, and having less intra- and inter-subject variability than human subjects' tests.

The SPF only measures the protection against UVB light. SPF grading system ranges from low to high: Low: (SPF 2-15), Medium: (SPF 15–30) High: (SPF 30–50), Highest: (SPF > 50).

The relationship between SPF and UVB radiation blocked is not linear but logarithmic: SPF 15 blocks 93.3% of UVB, SPF 30 blocks 96.7%, SPF 50 blocks 98.0%, SPF 100 blocks 99.0%. The logarithmic nature of the relationship is often misunderstood by consumers, and they believe that SPF 100 is two times more effective than SPF 50. (51)

#### *3.6.2 Persistent Pigment Darkening (PPD)*

PPD is the key in-vivo testing of UVA protection effectiveness, recognized by the European Commission, and used all around the world (ISO 24442:2022). PPD is the term for the persistent pigment darkening after UVA radiation, which lasts more than 2 hours after the exposure; this reaction takes place due to the photo-oxidation of pre-existing melanin in the melanocytes and melanosomes; it results in the gray-brown discoloration and differs from delayed tanning effect (newly synthesized melanin formation) seen 72 hours after the UVA exposure. (52)

For the determination of the PPD, the irradiation of the defined skin areas (located on the buttocks of volunteers with phototypes III–IV) using increasing amounts of UVA radiation both on the skin without any product and with the tested sunscreen applied at 2 mg/cm² is performed. The UVA-PF (UVA protection factor) is estimated by dividing the amount of UVA radiation needed to induce PPD on the skin with the sunscreen and on the bare skin; this is similar to SPF estimation for UVB radiation. (52)

Labeling regulations for UVA vary around the world. For instance, in Europe, the recommended Cosmetics Europe UVA-PF should be equal or higher than one-third of the SPF (1:3 UVA:SPF ratio rule), while the critical wavelength must be ≥370 nm for 'broad-spectrum' labeling. In the United States, the FDA requirement for the broad-spectrum label is that the sun screen passes the critical wavelength test (≥370 nm) using in vitro spectrophotometric method; however, there is no requirement for a minimum UVA-PF value. In Japan, the PA (Protection Grade of UVA) rating is used and this method is based on PPD testing and it divides UVA protection into four grades (PA+, PA++, PA+++, PA++++) with corresponding ranges of UVA-PF of 2–4, 4–8, 8–16, and >16. (53)

***3.6.3. Boots Star Rating:*** Another type of rating system was developed in the United Kingdom, which allows in vitro evaluation of UVA protection based on the ratio of UVA (320-400) over UVB absorbance (290-320).

The star system ranges from one to five stars where 1=minimum sun protection, 2=moderate, 3=good, 4=superior, and 5=ultra.

Although it is consumer friendly approach of communication about the ratio of UVA and UVB protection, it gives no information about absolute level of UVA protection intensity and became outdated by PPD-based approaches. (53)

## 4. Lacto Calamine® Sunscreen portfolio in India based on Indian Consumer needs and Climatic Conditions:

India experiences high ultraviolet (UV) radiation throughout the year due to its tropical geographical location. Prolonged exposure to UVA and UVB radiation as discussed earlier contributes to sunburn, tanning, pigmentation, premature skin aging, and an increased risk of skin cancer. The Indian sunscreen market is evolving rapidly not only to provide effective broad-spectrum UV protection but also deliver superior aesthetics and comfort considering Indian climatic conditions, to encourage daily use.

Lacto Calamine® has expanded its sunscreen portfolio to cater to the evolving needs of Indian consumers, particularly those with oily and combination skin. The Lacto Calamine® sunscreen portfolio is positioned around three core Indian consumer needs:

- **High sun protection:** SPF 50 PA+++ variants provide broad-spectrum UVA and UVB protection suitable for everyday use.
- **Superior sensory experience:** Lightweight, fast-absorbing formulations with no white cast and a non-greasy finish improve user compliance.
- **Suitability for Indian climate:** Formulations are designed to perform under high temperatures and humidity, with variants offering sweat resistance, oil control, and comfortable all-day wear.

Available Lacto Calamine® sunscreen variants include:

**Table 2.** Lacto Calamine® sunscreen portfolio considering Indian consumer skin needs & Indian climatic conditions (Temperature & humidity)

| Product | Key Features | Target Consumer |
|---|---|---|
| **Lacto Calamine® Light weight Sunscreen SPF 50 \| PA ++++ With Kaolin Clay and Lemon Extracts** | • Broad spectrum sunscreen<br>• No white cast<br>• Non-sticky<br>• Provides 98% protection against harmful rays and protects the skin from tanning, sunburns and premature skin ageing<br>• For face & body<br>• Unique water-based sunscreen lotion, that is light weight and quick absorbing and very water resistant<br>• Enriched with kaolin clay & lemon extract - gives a clear matte look<br>• In vitro tested & In vivo tested SPF 50<br>• *Marksmen Daily Most Trusted Brand of India 6th edition 2026-2027* | All skin types<br>Made for Oily or Acne prone skin |
| **Lacto Calamine® Dewy Glow Lightweight Sunscreen SPF 50 PA +++ Brightens, hydrates & primes** | • Dual-purpose sunscreen Dewy Sunscreen + Primer SPF 50 PA +++ UVA & UVB Protection.<br>• Hydrates, brightens & primes<br>• Blue light protection<br>• Leaves no white cast<br>• Non-sticky formula<br>• Rich in Watermelon, Acai berries & Seaweed extract<br>• 3% Niacinamide: helps lighten & even skin tone & protection against blue light<br>• Acai berries: Anti-oxidant rich, promotes collagen synthesis | For Oily<br>Acne prone skin<br>All skin types |

| | | |
|---|---|---|
| | • Watermelon: Hydrates deeply & adds dewy radiance<br>• In vitro tested & In vivo tested SPF 50<br>• ***Marksmen Daily Most Trusted Brand of India 6th edition 2026-2027*** | |
| **Lacto Calamine® Sunscreen Lotion SPF 30 & PA+++** | • Daily Face Moisturizer<br>• Sun protection: UVA/UVB<br>• Flawless primer<br>• Lightweight comfort<br>• Face & Body lotion<br>• Kaolin clay: Absorbs excess oil<br>• Zinc oxide: Anti-Germ properties & Mineral sunscreen<br>• Fights Oily Skin problems like Pimples, Patchy skin, Dark spots & Clogged pores | Suitable for Oily & Combination skin |

The inclusion of ingredients such as Kaolin Clay helps absorb excess sebum, making the sunscreen particularly suitable for oily and combination skin, while Vitamin E and moisturizing components contribute to skin conditioning. This consumer-centric approach differentiates the Lacto Calamine® sunscreen range by combining effective photoprotection with aesthetics tailored to Indian skin types and environmental condition.

## 5. Emerging Trends in Modern Sunscreen Science

### 5.1 Exposome and Modern Photoprotection

The concept of exposome refers to the cumulative environmental exposures encountered throughout an individual's lifetime that influence health and disease. In dermatology, the skin exposome encompasses solar ultraviolet (UV) radiation, visible light, infrared radiation (IR), air pollution, tobacco smoke, temperature fluctuations, humidity, nutrition, psychological stress, and lifestyle factors. These exposures interact synergistically to accelerate skin aging, impair barrier function, induce pigmentation disorders, and increase the risk of photo carcinogenesis. Traditional sunscreen formulations were primarily designed to protect against UVB-induced erythema and, more recently, UVA-mediated photoaging. However, growing evidence suggests that UV radiation is only one component of the complex environmental stressors contributing to skin damage. Consequently, modern photoprotection has evolved from simple UV filtering toward multifunctional exposome-oriented protection, incorporating antioxidants, anti-inflammatory agents, DNA repair enzymes, and barrier-supportive ingredients that mitigate oxidative stress and environmental damage.

Current formulations increasingly include niacinamide, vitamin C, vitamin E, ferulic acid, coenzyme Q10, ectoin, and botanical polyphenols to neutralize reactive oxygen species (ROS) generated by UV radiation and pollution. These multifunctional systems not only improve photoprotection but also enhance skin barrier integrity and reduce chronic inflammation associated with environmental exposure. As understanding of the skin exposome continues to expand, future sunscreen development is expected to integrate personalized photoprotection strategies tailored to individual environmental exposure profiles and skin characteristics. (54,55)

### 5.2 Blue Light and Infrared Protection

Although ultraviolet radiation remains the principal target of sunscreen formulations, increasing attention has been directed toward the biological effects of high-energy visible (HEV) blue light (400–500 nm) and infrared-A (IRA, 760–1440 nm) radiation. Blue light penetrates deeper into the skin than UVB and has been shown to induce oxidative stress, persistent pigmentation, mitochondrial dysfunction, and disruption of circadian skin physiology. These effects are particularly significant in individuals with darker Fitzpatrick skin phototypes, who exhibit a greater propensity for visible light-induced hyperpigmentation. Similarly, infrared-A radiation contributes to photoaging by stimulating mitochondrial ROS production, activating matrix metalloproteinases (MMPs), and promoting collagen degradation. Unlike UV radiation, neither blue light nor infrared radiation is adequately addressed by conventional SPF measurements, highlighting the need for broader definitions of photoprotection.

Recent formulations employ iron oxides to attenuate visible light, particularly in tinted sunscreens designed for melasma and post-inflammatory hyperpigmentation. In addition, antioxidants such as lutein, carotenoids, niacinamide, vitamin C, and botanical extracts are incorporated to counteract oxidative stress generated by visible and infrared radiation. Future evaluation systems may therefore extend beyond SPF and UVA-PF to include standardized assessment of protection against visible and infrared wavelengths. (56-58)

### 5.3 Skin Microbiome-Friendly Sunscreens

The human skin microbiome plays an essential role in maintaining epidermal homeostasis, immune regulation, and barrier integrity. Emerging evidence suggests that environmental stressors, including ultraviolet radiation and certain topical formulations, may alter microbial diversity, leading to dysbiosis that contributes to inflammatory skin disorders such as acne, rosacea, and atopic dermatitis.

Modern sunscreen research increasingly recognizes the importance of preserving microbiome balance while providing effective photoprotection. Formulation strategies include minimizing harsh preservatives, avoiding unnecessary antimicrobial ingredients, optimizing formulation pH, and incorporating microbiome-supportive compounds such as prebiotics, postbiotics, and fermented bioactive ingredients. Barrier-repair lipids including ceramides, cholesterol, and fatty acids further contribute to maintaining a healthy skin ecosystem.

Although microbiome-friendly sunscreens remain an emerging field, future products are expected to combine broad-spectrum UV protection with targeted modulation of the skin microbiota to improve both photoprotection and long-term skin health. (59,60)

### 5.4 Artificial Intelligence in Sunscreen Formulation

Artificial intelligence (AI) is transforming pharmaceutical and cosmetic product development by accelerating ingredient selection, formulation optimization, predictive stability assessment, and consumer personalization. Machine learning algorithms can analyze extensive formulation databases to predict interactions between UV filters, emulsifiers, antioxidants, polymers, and delivery systems, thereby reducing formulation development time and experimental workload.

AI-driven predictive models are increasingly used to estimate SPF, photostability, rheological behavior, and formulation compatibility before laboratory validation. Furthermore, digital skin analysis technologies integrated with mobile applications enable personalized sunscreen recommendations based on skin type, pigmentation, geographic location, UV index, lifestyle, and environmental exposure.

The integration of AI with computational chemistry and high-throughput formulation screening may facilitate the discovery of next-generation UV filters exhibiting improved efficacy, enhanced photostability, and superior environmental safety. Although widespread industrial implementation remains in its early stages, AI is expected to become an integral component of intelligent sunscreen research and development. (61,62)

### 5.5 Sustainability and Environmental Considerations

Growing environmental awareness has shifted sunscreen development toward sustainable and environmentally responsible formulations. Several organic UV filters, including oxybenzone and octinoxate, have been implicated in coral bleaching and marine ecosystem toxicity, leading to regulatory restrictions in several geographical regions. Consequently, research efforts are focused on identifying environmentally benign UV filters while maintaining high levels of photoprotection.

Sustainable sunscreen development extends beyond filter selection to encompass biodegradable ingredients, renewable raw materials, reduced microplastic content, water-conscious manufacturing, recyclable packaging, and life-cycle assessment of products. Mineral UV filters such as zinc oxide and titanium dioxide remain important alternatives; however, concerns regarding nanoparticle environmental fate continue to warrant investigation.

Future formulation strategies will likely balance human safety, product efficacy, regulatory compliance, and ecological sustainability through green chemistry principles and environmentally conscious innovation. (63,64)

### 5.6 Future Intelligent Photoprotective Systems

The next generation of sunscreen technologies is expected to extend beyond passive UV shielding toward intelligent photoprotective systems capable of responding dynamically to environmental stimuli and individual skin physiology. Advances in nanotechnology, biomaterials, and controlled-release delivery platforms have enabled the development of UV-responsive nanoparticles, encapsulated antioxidants, smart polymers, and biomimetic delivery systems that release active ingredients upon exposure to sunlight or oxidative stress.

Personalized photoprotection is anticipated to integrate wearable UV sensors, mobile health technologies, artificial intelligence, and digital dermatology platforms capable of providing real-time recommendations for sunscreen application and reapplication based on UV index, geographic location, perspiration, and individual skin characteristics. Future formulations may additionally incorporate DNA repair enzymes, microbiome-modulating ingredients, circadian rhythm regulators, and adaptive delivery systems that respond to environmental conditions. Collectively, these innovations represent a paradigm shift from conventional sunscreens toward comprehensive skin health management systems that combine prevention, monitoring, and therapeutic support within a single multifunctional formulation. (63-65)

## 6. Conclusion

Sunscreens are essential photoprotective products that play a critical role in preventing sunburns, tanning, photoaging, skin cancer, and other UV-induced skin disorders. Advances in UV filters, antioxidant-enriched formulations, encapsulation technologies, and skin-specific sunscreen designs have significantly improved sunscreen efficacy and user acceptance. Standardised evaluation methods such as SPF, PPD/UVA-PF, critical wavelength, and photostability testing provide the scientific basis for product performance and regulatory approval. Despite these advances, inadequate application and reapplication remain major barriers to achieving optimal protection. Lacto Calamine® is one of the most trusted skincare brands in India, with strong recognition in the oil-control category, positioned to address the needs of Indian consumers by combining effective UV protection with lightweight aesthetics and everyday usability. Future sunscreen development is expected to focus on multifunctional, photostable, microbiome-friendly, sustainable, and personalised photoprotection systems, ensuring safer and more effective sun protection for diverse populations.

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**Conflict of Interest**

The author declares that there is no conflict of interest regarding the publication of this article.

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