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TOPICAL GEL SUNSCREENS: FORMULATION STRATEGIES AND PHOTOPROTECTIVE EFFICIENCY – A COMPREHENSIVE REVIEW

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ABSTRACT

Cosmetics constitute an integral component of dermatological care, serving both aesthetic and protective functions. Among these, sunscreens play a critical role in safeguarding the skin against the deleterious effects of ultraviolet (UV) radiation, including erythema, photoaging, and photocarcinogenesis. Recent advancements in formulation science have led to the development of gel-based sunscreen systems, which offer distinct advantages such as non-greasy texture, improved spreadability, enhanced patient compliance, and suitability for diverse skin types. This review systematically discusses the classification and purpose of cosmetics, along with emerging trends in cosmetic science. It further elaborates on the fundamental aspects of sunscreens, including their definition, mechanism of action, and the impact of UV radiation. Special emphasis is placed on gel-based sunscreen formulations, encompassing their definition, formulation methodologies, and relevant regulatory standards, including International Organization for Standardization (ISO) guidelines and their applicability in India. Additionally, the review highlights critical quality attributes such as photostability, along with comprehensive evaluation techniques, including both *in vitro* and *in vivo* methods. The merits and limitations, packaging considerations, and practical applications of gel-based sunscreens are also examined. Overall, this article provides an in-depth and structured overview of gel-based sunscreen formulations, underscoring their growing significance in contemporary pharmaceutical and cosmetic research.

KEYWORDS: Gel-based drug delivery system, Sunscreen formulations, Ultraviolet (UV) radiation protection, Sun Protection Factor (SPF), Photostability evaluation.

INTRODUCTION

Cosmetics are preparations intended to be applied externally to various parts of the human body such as the skin, hair and nails with the primary purpose of cleansing, beautifying, enhancing appearance, and protecting or maintaining these body surfaces.[1] Unlike medicinal products, cosmetics do not alter the physiological functions of the body but improve aesthetics and personal hygiene through topical use.[2] Cosmetic products are generally classified into skin-care, hair-care, oral-care, decorative cosmetics, and personal hygiene preparations.[3] Among these, sunscreens are categorized as skin-care products due to their function in protecting the skin from ultraviolet radiation.[4] Today, cosmetics use is influenced by lifestyle changes, social media trends, and increasing awareness about skin care and personal grooming.[5] Currently, sunscreen stands out as a leading cosmetic product due to its dual role in beautification and prevention of UV-induced skin damage.[6] Sunscreen is a topical product that protects the skin by blocking or absorbing harmful UVA and UVB radiation, thus minimizing sunburn and other harmful effects associated with UV exposure.[7] UV rays from the sun can penetrate the skin and cause harmful effects such as sunburn, pigmentation, photoaging, and even skin cancer.[8]

Sunscreen provides protection from ultraviolet (UV) radiation emitted by the sun, which is categorized into three bands: UVA (315–400 nm), UVB (280–315 nm), and UVC (100–280 nm).[9] The ozone layer blocks most UVC radiation and absorbs much of the UVB before it reaches the Earth's surface, allowing primarily UVA and a small fraction of UVB to contact the ground, contributing about 3–4% of the solar spectrum.[10] While excessive exposure to UV can be harmful, it also plays essential roles in biological processes, particularly in photosynthesis, where UV photons excite specific molecules, driving reactions that convert solar energy into biochemical energy essential for life. Ultraviolet (UV) exposure is vital for vitamin D synthesis, important for bone, muscle health, and immune support. However, it also poses risks like sunburn, photoaging, and skin cancer.[11,12] To mitigate these risks, minimizing UV exposure through protective measures, particularly sunscreen use, is crucial. Sun Protection Factor (SPF) gauges a product's ability to prevent sunburn and is often associated with protection against long-term skin damage. Despite the lack of practical methods to assess long-term UV effects, regular sunscreen use is believed to reduce the risk of photoaging and skin cancer, as natural melanin protection is insufficient alone. Artificial photoprotection, primarily through sunscreens, is necessary to enhance skin safety.[13]

Sun protection is a crucial part of skincare since it shields the skin from sun-induced aging and carcinogenic effects in addition to preventing sunburn.[14] Sunscreens come in a variety of forms, including creams, lotions, sprays, and gels, each with special benefits.[15] Of these, gel-based sunscreens have drawn more interest because of their non-greasy finish, quick absorption, and lightweight texture.[16] Gels are typically water- or silicone-based, which makes them more appropriate for oily and combination skin types than standard cream-based sunscreens.[17] When applied, gel sunscreens have a cooling and revitalizing effect while giving broad-spectrum protection against UVA and UVB rays. Because they are translucent, there is little to no white residue, which increases user compliance, particularly in hot and muggy regions.[18, 19] Moreover, gel formulations are frequently chosen for outdoor activities or beneath makeup due to their non-sticky texture and ease of layering. In order to improve protection and skin compatibility, new UV filters, antioxidants, and moisturizing chemicals have been added to gel sunscreen formulas in response to the increased demand for these products. The purpose of this review is to provide an overview of the current developments, formulation techniques, and effectiveness of gel-based sunscreens, emphasizing their benefits, drawbacks, and potential applications in photoprotection.[20]

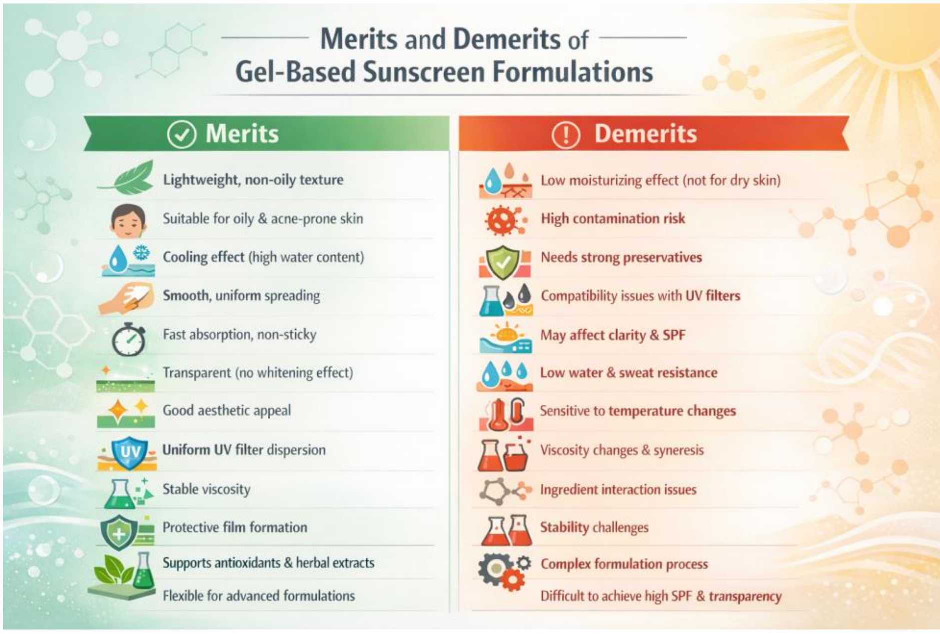

Fig. 1: Merits and Demerits of Gel Based Sunscreen.

ISO AND SUNSCREEN

The International Organization for Standardization (ISO) is an independent, non-governmental international body that develops globally accepted standards to ensure quality, safety, efficiency, and reliability across products, services, and systems. ISO brings together national standardization bodies from over 170 countries to create uniform guidelines that support international trade and technological development.[20]

ISO About sunscreen: Sunscreen products are mainly evaluated for safety, performance, UV protection efficiency, packaging, and labelling.[21] ISO provides several important standards used worldwide.

ISO 24444:2019 is the internationally standardized method used to determine the Sun Protection Factor (SPF) of sunscreen products.[21] It is an *in vivo* method, meaning the testing is performed on human volunteers to measure how effectively a sunscreen protects the skin from UVB radiation, which is responsible for sunburn.

ISO 24443:2021 is an *in vitro* (laboratory-based) international standard used to determine the UVA protection of sunscreen products. Unlike SPF testing, which is done on humans, this method measures how much UVA radiation passes through a sunscreen-coated substrate (usually a PMMA plate) when exposed to controlled UV light.[22]

ISO 24442:2011 is an *in vivo* (human-based) international standard used to measure the UVA Protection Factor (UVA-PF) of sunscreen products. This method complements SPF testing by evaluating how effectively a sunscreen protects the skin from UVA radiation, which is responsible for premature ageing, tanning, pigmentation, and deeper skin damage.

ISO 16217:2020 is an international *in vitro* test method used to evaluate the water-resistance of sunscreen products. This standard describes the water-immersion procedure, which determines whether a sunscreen can maintain its UV protection after the skin (or test substrate) is exposed to water for a specified time.

ISO 18861:2020 is an international standard that provides a method for evaluating the water resistance of sunscreen products. It is generally used in combination with ISO 16217, which defines the water-immersion procedure.

ISO 29621:2017 is an international guideline titled “Guidelines for the risk assessment and identification of low-risk cosmetic products.” It is used to determine when a cosmetic product—such as sunscreen, lotion, cream, gel, or other topical formulation—is considered to have low microbiological risk.

Regulation of Sunscreen in India

The regulation of sunscreen products in India has gained increasing attention as awareness of UV-induced skin disorders continues to rise. To ensure the safety and reliability of these products, India has strengthened its regulatory framework through the Cosmetic Rules, 2020 and updated standards issued by the Bureau of Indian Standards (BIS). These guidelines outline uniform procedures for evaluating SPF and UVA protection, drawing from globally accepted ISO methods to bring greater accuracy and consistency to sunscreen testing.[23] In a country exposed to intense sunlight throughout the year, these evolving guidelines are critical for ensuring widespread access to sunscreens that offer dependable and clinically validated photo protection.[24, 25]

CLASSIFICATION OF SUNSCREENS

Broad Spectrum Sunscreen

Broad spectrum” is the most crucial term to look for on any sunscreen label. It signifies that the product provides protection against both types of harmful ultraviolet radiation: UVA and UVB rays. A sunscreen is only considered “broad spectrum” if it protects the skin from the entire range of UV radiation.

Water Resistant Sunscreen

The term “water resistant” is the only claim manufacturers are legally allowed to make regarding a sunscreen’s ability to remain effective in wet conditions, replacing older, misleading terms like “waterproof” or “sweat proof.” Water resistance means that the sunscreen has been tested and proven to maintain its stated Sun Protection Factor (SPF) level for a specific duration after the skin has been exposed to water or heavy sweating.[26]

Very Water- Resistant Sunscreen

A sunscreen is labelled “Very Water-Resistant” when its SPF (Sun Protection Factor) remains effective after 80 minutes of water immersion

Water Resistant → SPF remains after 40 minutes water immersion.

Very Water Resistant → SPF remains after 80 minutes water immersion.

FORMULATION METHODS OF SUNSCREEN

Simple Dispersion Method

In this method, the gelling powder like Carbopol or HPMC is slowly added into water and mixed until it becomes smooth and fully swollen.[27] The sunscreen ingredients (UV filters) are dissolved or mixed separately, and then added into this gel base slowly with stirring. After everything mixes well, the pH is adjusted if needed, and the gel becomes thick and ready.

Heating (fusion) Method

Here, the oil-soluble sunscreen ingredients are dissolved in an oil and heated (70-80°c).[28] At the same time, the gelling agent is mixed in water and also heated to the same temperature. The hot oil mixture is then poured into the hot water mixture while stirring. After this, the mixture is cooled while stirring until it becomes a gel.

Solvent Evaporation Method
In this method, the sunscreen ingredients are first dissolved in a solvent like alcohol. This solution is then mixed into a pre-made gel base. The alcohol slowly evaporates on its own, leaving the sunscreen ingredients evenly spread throughout the gel.

Cold Method
In the cold method, the gelling agent is added to water at 4-10°c and allowed to swell naturally without heating. The sunscreen ingredients are dissolved in water or another mild solvent and then mixed into this gel gently. After mixing, the gel becomes smooth and ready without using heat.

High-Shear or Ultrasonic Method
This method is used mainly for mineral sunscreens like zinc oxide or titanium dioxide.[29] These powders are mixed into the gel and then broken into very fine particles using a high-speed mixer or ultrasonicator. This makes the gel smooth and prevents clumping.

Emulsification method
In the emulsion–gel (emulgel) method, an oil phase containing oil-soluble UV filters is first prepared as an emulsion and then incorporated into a gel base, which helps in delivering lipophilic sunscreens in a non-greasy gel form.

CRITICAL PARAMETERS OF SUNSCREEN
COLIPA (European Union)
COLIPA is a name historically and significantly associated with the development of standardized testing methods for sunscreens, particularly in Europe. COLIPA played a crucial role in establishing pan European, standardized, and reproducible test methods for sunscreens, which were influential globally.

Sun Protection Factor (SPF) Method
***(i) In vivo* Sunburn Protection Factor (SPF)**
It is the gold standard and most accepted method for determining a sunscreen's efficacy against the UVB radiation that causes sunburn. It is a biological assessment performed directly on human volunteers under controlled conditions.[30] The SPF value is a ratio that quantifies the amount of UV radiation required to cause minimal sunburn (erythema) on skin protected with sunscreen, compared to the amount of UV radiation required to cause the same minimal sunburn on unprotected skin.

$$SPFi = \frac{MEDp}{MEDu}$$

Where,
MEDp = Minimal Erythema Dose (MED) for Protected skin
MEDu = Minimal Erythema Dose (MED) for Unprotected skin

***(ii) In Vitro* Sunburn Protection Factor**
It is a laboratory measure of a sunscreen's effectiveness in protecting against the ultraviolet (UV) radiation that causes sunburn, primarily UVB rays (290–320 nm).[31] The fundamental principle of *in vitro* SPF testing is to measure the amount of UV radiation that is transmitted through a film of sunscreen applied to a non-biological substrate. The calculation involves weighting the measured transmittance values by the erythemal action spectrum (Eλ), which describes the relative effectiveness of different wavelengths of UV light in causing sunburn, and the solar spectral irradiance (Iλ), which represents the intensity of sunlight at each wavelength.[41]

$$SPF_{in-vitro} = \frac{\sum_{290}^{400} E\lambda . I\lambda . d\lambda}{\sum_{290}^{400} E\lambda . I\lambda . A\lambda . d\lambda}$$

Where,
E(λ) is the relative effectiveness of UVR
I(λ) is the spectral irradiance received from the UV source at wavelength λ
A(λ) is the monochromatic absorbance of the sunscreen layer at wavelength λ; A(λ) = -log [T(λ)]
d(λ) is the wavelength step.

UVA-PF (UVA Protection Factor)
The method is based on measuring UV transmission through a thin film of sunscreen on a substrate. The resulting data is convoluted with the action spectrum for the *in vivo* Persistent Pigment Darkening (PPD) endpoint to provide an *in vitro* UVA Protection Factor (UVA-PF).

***(i) In-Vitro* UVA Protection Factor (UVAPF)**
It is a laboratory-based measurement used to quantify a sunscreen's ability to protect the skin against Ultraviolet-A (UVA) radiation. It is a critical metric for determining a product's "broad-spectrum" efficacy, as UVA rays penetrate deeper into the skin and are associated with long-term damage like photo aging and certain skin cancers. The *in vitro* method is a more ethical, cost-effective, and reproducible lab test that aims to correlate closely with the PPD value. The international standard for this is ISO 24443:2021 (formerly COLIPA).[32] The final UVA-PF is calculated using the post-irradiation transmittance data, weighted with a specific Persistent Pigment Darkening (PPD) action spectrum and the output spectrum of the solar simulator. The formula is complex and involves integrating the protection across the entire UVA range (320-400 nm).

$$UVA - PF = \frac{\sum_{320}^{400} E\lambda . P\lambda . d\lambda}{\sum_{320}^{400} E\lambda . P\lambda . T\lambda . d\lambda}$$

Where,
E(λ) is the spectral irradiance of the UV source

P(λ) PPD action spectrum
T(λ) Post-irradiation transmittance of the sunscreen film at wavelength.

UVA-UVB Ratio
The UVA–UVB Ratio is a measure of how balanced a sunscreen's protection is across UVA (320–400 nm) and UVB (290–320 nm) wavelengths. It shows how much UVA protection a sunscreen offers relative to UVB protection. It is the ratio of the area under the absorbance curve (AUC) in the UVA region to the area under the absorbance curve in the UVB region.

$$UVA - UVB\ Ratio = \frac{Area\ under\ absrobance\ curve\ (UVA\ 320 - 400\ nm)}{Area\ under\ absrobance\ curve\ (UVB\ 290 - 320\ nm)}$$

Boots Star Rating System
The Boots Star Rating System is a popular, proprietary method developed in the UK (by the retailer Boots) to measure the level of UVA protection provided by a sunscreen product, relative to its UVB protection (SPF). It is an optional standard that many manufacturers in the UK and some other regions adopt alongside the mandatory SPF and {UVA} circle logo. The Boots Star Rating System does not measure the absolute strength of UVA protection (like the COLIPA/PPD method does). Instead, it measures the ratio of a product's UVA absorbance to its UVB absorbance.

Immune Protection Factor (IPF)
The term Immune Protection Factor (IPF) refers to a concept and measurement designed to assess a sunscreen's ability to prevent UV-induced immunosuppression (suppression of the skin's immune system by UV radiation).[33] While, Sun Protection Factor (SPF) measures protection against sunburn (erythema) caused primarily by UVB rays, IPF aims to capture a much broader and biologically significant protective effect. IPF is not a simple number seen on packaging like SPF. It is determined through complex, *in vivo* (on human skin) biological assays performed in research settings. The IPF is the ratio of the UV dose required to cause a specific level of immunosuppression on sunscreen-protected skin, compared to the unprotected skin.

STABILITY STUDIES OF GEL SUNSCREENS
Photostability Studies
Photostability refers to the ability of a gel sunscreen formulation to retain its ultraviolet (UV) protective efficacy after exposure to UV radiation. Since sunscreens are directly exposed to sunlight during use, photostability is a critical parameter to ensure continuous protection against UV-induced skin damage. Photostability testing is generally performed in accordance with ICH Q1B guidelines, where the gel sunscreen is uniformly applied on suitable substrates such as quartz or polymethylmethacrylate (PMMA) plates and exposed to controlled UV and visible light sources. After irradiation, changes in sun protection factor (SPF), UV absorbance, color, and physical appearance are evaluated. A photostable gel sunscreen exhibits minimal loss of SPF and UV absorbance following light exposure. Gel formulations often demonstrate enhanced photostability due to their ability to form a uniform film on the skin surface. Additionally, the incorporation of antioxidants and photostabilizing agents reduces UV-induced degradation of organic UV filters, thereby improving long-term efficacy and safety.[34]

Physical Stability
Physical stability studies are conducted to assess changes in appearance, color, clarity, homogeneity, viscosity, and phase separation of gel sunscreen formulations during storage. A physically stable gel should remain uniform without precipitation, liquefaction, or separation throughout the study period.

Chemical Stability
Chemical stability studies evaluate the integrity of UV filters and other active ingredients present in the formulation. Degradation of these components may lead to reduced sun protection efficacy and is assessed by monitoring changes in UV absorbance, assay values, or degradation products over time.

Thermal Stability
Thermal stability testing is performed by storing gel sunscreens at different temperature conditions, including refrigerated, room temperature, and accelerated temperatures. These studies help determine the effect of heat on formulation stability and predict product behavior during storage and transportation.

Storage Stability
Storage stability studies involve long-term evaluation of gel sunscreen formulations under recommended storage conditions. Periodic assessment of physical parameters, pH, viscosity, and UV protection efficacy helps establish the shelf life of the product.

pH Stability
pH stability studies ensure that the gel sunscreen maintains a consistent and skin-compatible pH throughout its shelf life. Significant variations in pH may indicate chemical degradation or formulation instability.

Rheological Stability
Rheological stability studies assess changes in flow behavior and viscosity of gel sunscreens over time. Stable rheological properties indicate good consistency, spreadability and consumer acceptability.

Centrifugation and Freeze–Thaw Studies
Centrifugation tests are performed as an accelerated method to detect early signs of physical instability, such as phase separation. Freeze–thaw studies evaluate formulation stability under repeated temperature fluctuations, simulating real-time storage and transportation conditions.

Microbial and Packaging Stability
Microbial stability studies are essential for gel sunscreens due to their high moisture content. Packaging compatibility studies assess possible interactions between the formulation and container, ensuring product integrity during storage.

Stability Testing as per ICH Guidelines
According to ICH Q1A (R2), stability studies for gel-based formulations are commonly performed under the following conditions, especially relevant for climatic Zone IVb (India). Long-term stability: 30°C ± 2°C / 75% RH ± 5% RH Accelerated stability: 40°C ± 2°C / 75% RH ± 5% RH. ICH Q1B guidelines are followed for photostability testing, where formulations are exposed to defined levels of UV and visible light to assess light-induced degradation.[35, 36]

Parameters Measured in Stability Studies
(i) Percentage SPF Retention (Photostability)

$$\% \, SPF \, Retention = \left(\frac{SPF \, after \, sun \, exposure}{Initial \, SPF}\right) \times 100$$

(ii) Percentage Degradation of UV Filters

$$\% \, Degradation = \left(\frac{C_o - C_t}{C_o}\right) \times 100$$

DOSAGE OF GEL BASED SUNSCREEN
Gel sunscreens demand accurate application at a rate of 2 milligrams per square centimeter to achieve the full UV-blocking power indicated by their SPF rating. Proper dosing delivers comprehensive defense from both UVB and UVA radiation. Many people underestimate the amount needed, which greatly diminishes the product's protective benefits. Proper Usage Amount Regulatory standards mandate a 2 mg/cm² film thickness for lab evaluations, roughly matching two finger-length strips (from palm base to tips of index and middle fingers) for each 9% body zone via the rule-of-nines method. Examples include the head/neck area or a single limb. Using only half that volume cuts protection to around 50% of the label claim, so experts recommend reapplying soon after, ideally within half an hour of exposure. Key Ingredient Levels These formulations generally feature UV blockers or absorbers at 2-20% of total weight, combined with gelling agents such as 2-20% chitosan for firmness and 5-25% glycerophosphate for durability.

Optimal blends often refine to 5-15% chitosan, 5-20% glycerophosphate, and 5-15% active sun protectors in a 50-70% aqueous foundation. Plant-derived versions might add 1-2.5% botanicals like mangiferin from Phaleria macrocarpa or turmeric extracts to boost sun protection factor.[37] Gelling Agents and Protectors Gelling components improve ease of rubbing in, skin moisture retention, and adhesion of UV agents while avoiding oily residue, typically dosed at 5-12.5% to fine-tune thickness.[38] Advanced nano-encapsulated versions optimize low levels like 1% Venuceane for better skin penetration through follicles and outer layer pores. Surface-altered titanium dioxide in gels enhances clarity and wide-range UV shielding without white cast.[39] Testing and Stability Ideal gels hold a skin-friendly pH of 5.8-6.0, spread smoothly without clumping, and remain consistent for extended periods. Sun protection ratings assess absorbance from 290 to 400 nanometers across the UV spectrum. For best results, dab product in spots first, then blend evenly; a common face/neck guideline is one teaspoon total.

PACKAGING OF GEL SUNSCREENS
Packaging is a vital component in the development of gel sunscreen formulations, as it plays a major role in preserving product stability, safety, and performance. Gel-based sunscreens usually contain a high proportion of water or alcohol, making them vulnerable to oxidative degradation, microbial contamination, light exposure, and solvent evaporation. Hence, the choice of packaging must ensure adequate protection of the formulation throughout its shelf life.

Commonly used packaging systems for gel sunscreens include squeezable tubes, pump dispensers, and airless containers, as these formats support hygienic use and formulation compatibility.[40] Plastic tubes, typically manufactured from polyethylene-based materials, are widely used due to their ease of handling, portability, and ability to dispense the required amount of gel with minimal product exposure to the external environment.

Pump-based packaging is often selected for dermatological and high-end gel sunscreens because it enables consistent dose delivery and limits direct contact between the formulation and the user. This reduces the chances of contamination and improves patient compliance. Airless packaging systems provide enhanced protection by restricting the entry of air into the container during dispensing, thereby minimizing oxidation, microbial growth, and degradation of UV-active ingredients.[41]

CONCLUSION
Gel-based sunscreens represent an important advancement in topical photoprotective formulations due to their favorable aesthetic properties and effective sun protection capability. Compared to conventional creams and lotions, gel formulations offer advantages such as non-greasy texture, rapid absorption, better spreadability, and improved patient compliance, making them particularly suitable for oily and acne-prone skin. The incorporation of appropriate UV filters, gelling agents, and stabilizers plays a crucial role in ensuring adequate photostability and broad-spectrum protection against harmful ultraviolet radiation. Both *in vitro* and *in vivo* evaluation methods are essential to assess the safety, efficacy, and performance of gel-based sunscreens. Parameters such as sun protection factor (SPF), photostability, skin compatibility, and water resistance

determine the overall quality of the formulation. In addition, proper packaging and recommended dosage are vital to maintain product stability and ensure optimal protection during use. With increasing awareness of sun-induced skin damage and the rising demand for cosmetically elegant products, gel-based sunscreens have gained significant acceptance in modern skincare. Continuous research and formulation improvements can further enhance their protective efficacy and user acceptability, contributing to better prevention of UV-related skin disorders.

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