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GREEN NANOTECHNOLOGY IN HERBAL SUNSCREEN FORMULATIONS: A MODERN REVIEW

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ABSTRACT

Sunscreen spray formulations have gained significant attention due to their ease of application, uniform spreading and improved user compliance compared to conventional lotions and creams. These formulations are designed to provide broad-spectrum protection against UVA and UVB radiation while ensuring a lightweight, non-greasy skin feel. Modern sunscreen sprays incorporate advanced carriers such as nanoemulsions, liposomes and polymeric systems to enhance photostability, skin penetration and water resistance. They also improve the dispersion of UV filters, resulting in increased Sun Protection Factor (SPF) and reduced white cast. The evaluation of sunscreen sprays involves assessing physicochemical properties, droplet size distribution, spray pattern, SPF value (*in vitro* or *in vivo*), rheology and stability under different environmental conditions. However, challenges such as aerosol safety, propellant selection, potential inhalation risks and regulatory limitations must be addressed to ensure product efficacy and consumer safety. Overall, sunscreen spray formulations represent a promising, consumer-friendly approach for effective photoprotection, supported by advancements in formulation science and nanotechnology.

KEYWORDS

Sunscreen spray, Photoprotection, UV filters, SPF, Nanoemulsion, Skin penetration and Nanotechnology.

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INTRODUCTION

The sun releases infrared, visible and ultraviolet (UV) radiation, among which UV rays are the most dangerous because of their high energy. UVA (320-400nm) and UVB (290-320nm) penetrate the Earth's atmosphere and contribute to tanning, sunburn and DNA damage by generating reactive oxygen species (ROS). Continuous exposure to these rays accelerates skin ageing, causes eye

problems, and increases the risk of skin cancers such as melanoma and nonmelanoma types. While sunlight is beneficial for vitamin D production, antimicrobial activity, and cardiovascular health, excessive exposure can be harmful. Therefore, the World Health Organisation advises using sunscreen daily and adopting protective measures like shade, clothing, hats and sunglasses regardless of skin colour.

SUNSCREEN UV-FILTERS

Sunscreens are topical formulations designed to protect the skin against the harmful effects of ultraviolet (UV) radiation by means of active ingredients capable of absorbing, scattering, or reflecting UV rays. Presently, sunscreens play a crucial role in photoprotection and are primarily composed of organic and inorganic UV filters.

Organic UV filters are classified based on their absorption characteristics into UVA, UVB, or broad-spectrum filters, depending on whether they absorb specific or multiple wavelength ranges of UV radiation. Inorganic UV filters, mainly titanium dioxide (TiO_2) and zinc oxide (ZnO), act primarily by reflecting and scattering UV radiation. These filters are widely preferred due to their limited skin penetration and reduced potential for allergic reactions. However, their major limitation is the formation of a whitish film on the skin, which can be minimized through nanotechnology or tinted formulations. Regulatory agencies worldwide have approved various UV filters for sunscreen formulations - for instance, the U.S. FDA has approved 16, Health Canada 22, European Commission 29, Australian TGA 31, and China's NMPA 27. The advent of nanotechnology has significantly enhanced the performance and aesthetic properties of inorganic UV filters, particularly those based on nano-TiO_2 and nano-ZnO, although safety evaluations are ongoing.

In addition to synthetic filters, the incorporation of naturally derived UV filters has gained prominence due to their biocompatibility, antioxidant potential and skin-nourishing properties. Bioactive compounds such as carotenoids, phenolic compounds, flavonoids, vitamins C and E and other plant or marine-derived molecules exhibit various photoprotective mechanisms.

Lignin nanoparticles enhance SPF and antioxidant activity.

Rosmarinic acid, extracted from *Plectranthus amboinicus*, shows broad-spectrum UV absorption with an SPF of 12.63.

Marine sources, including red algae (*Hydropuntia cornea* and *Gracilariopsis longissimi*) and marine fungi (*Aspergillus nidulans*), provide mycosporine-like amino acids and melanin-related compounds with antioxidant and UV-protective properties.

Rutin, a citrus flavonoid, significantly enhances antioxidant (by 40%) and photoprotective activity (by 70%), increasing SPF from 7.3 to 12.4.

Ferulic acid improves SPF and enhances formulation stability through its functional groups responsible for antioxidant activity.

Caffeine, when combined with physical and chemical UV filters, raises SPF by approximately 25% and reduces erythema.

Grape pomace extract increases UVA protection by about 18% and minimizes phototoxicity and irritation.

Bamboo extracts, rich in phenolics and flavonoids, demonstrate broad-spectrum and photostable sunscreen properties after UV exposure.

In conclusion, natural molecules exhibit significant potential as alternative or complementary UV filters owing to their antioxidant, photoprotective and skin-compatible characteristics. Their combination with conventional or nanotechnology-based systems can lead to safer, more effective and multifunctional sunscreen formulations, aligning with current trends toward eco-friendly and biologically active photoprotection strategies.

NANOCOSMECEUTICALS

The cosmetic industry is one of the fastest-growing sectors globally, driven by lifestyle changes, pollution, and climatic variations. The global cosmetics market was projected to reach USD 805.61 billion by 2023; however, the COVID-19 pandemic caused a temporary decline in 2020. After

recovery in 2021, the market value rose to USD 287.94 billion and is expected to grow at a 5% compound annual growth rate (CAGR), reaching USD 415.29 billion by 2028. According to the U.S. FDA, cosmetics are products that enhance appearance without altering body structure or function. Major market leaders include L'Oréal, P&G, Johnson and Johnson, Estee Lauder and Unilever. Although the terms cosmetics and cosmeceuticals are often used interchangeably, they differ in function-cosmetics beautify externally, while cosmeceuticals contain active ingredients that penetrate the skin to improve or treat underlying conditions. Coined by Dr.Albert Kligman in the late 1970s, "cosmeceuticals" are designed to address dryness, wrinkles, pigmentation, uneven tone, photoaging and UV damage.

Incorporating nanomaterials into formulations gives rise to nanocosmetics or nanocosmeceuticals, which enhance product stability, bioavailability and longevity. Nanoparticles, typically 1-100nm in size, exhibit unique physicochemical properties applied across medicine, engineering, and food sciences. Nanotechnology-based systems such as liposomes, nanoemulsions, niosomes, nanocapsules, solid lipid nanoparticles, and nanosponges significantly improve formulation performance, penetration, and dispersibility. In sunscreen formulations, nanosized particles offer superior UV protection and sensory appeal. Unlike traditional sunscreens, nanosunscreens are lightweight, non-greasy, odorless, and do not leave a white residue on the skin. Common nanoparticles used include 4-aminobenzoic acid, titanium dioxide (TiO_2) and zinc oxide (ZnO), which enhance sun protection efficiency while improving overall product aesthetics.

ADVANCED NANOTECHNOLOGY-BASED SUNSCREEN FORMULATIONS

NANOEMULSION

Nanoemulsions are colloidal systems composed of nanosized droplets dispersed within two immiscible liquid phases, offering high kinetic stability through the use of surfactants or cosurfactants to balance interfacial tension. The droplet size typically ranges from 100 to 500nm and these systems can be biphasic (water-in-oil or oil-in-water) or triphasic (water-in-oil-in-water or oil-in-water-in-oil). The ratio of aqueous and oil phases, along with the type of surfactant used-commonly Poloxamer 188-influences the formulation's structure, stability, and ability to encapsulate hydrophilic or lipophilic molecules. Although nanoemulsions are usually liquid, they can be modified into gel-like forms by adjusting preparation techniques such as high-pressure homogenization, spontaneous emulsification, and phase inversion methods. Smaller droplet sizes improve system stability and active ingredient loading, though homogenization requires high pressure. Nanoemulsions provide controlled release, enhanced skin penetration, reduced transepidermal water loss and a smooth, pleasant texture. They are biodegradable, composed of U.S. FDA-recognized safe (GRAS) ingredients, and non-toxic. Due to their high solubilization capacity for lipophilic molecules, easy absorption, low surfactant requirement and excellent stability, nanoemulsions are increasingly used in cosmetic formulations for effective and aesthetically appealing skin care applications.

SUNSPHERE

The concept of *sunsphere* was introduced in 1994 by Rohm and Haas Company as a novel photoprotective material to enhance the SPF of sunscreen formulations. Sunspheres are hollow microspheres (~325nm) made of acrylate or styrene copolymers. Developed by emulsion polymerization, they initially contain water, which is replaced by air when applied on the skin. This creates multiple layers with varying refractive indices - copolymer (1.6), sunscreen film (1.4-1.5) and air/vacuum (1.0) - resulting in effective scattering and refraction of UV rays.

Unlike UV filters, sunspheres do not absorb UV radiation but enhance SPF by amplifying the scattering and reflection of UV rays, allowing UV filters to absorb more efficiently. They are non-toxic, water-compatible and stable with various

sunscreen ingredients. Studies have shown that sunspheres alone have SPF < 2, confirming their non-absorptive nature. However, when combined with UV filters such as octyl methoxycinnamate (OMC), the SPF significantly increases-e.g., 4% sunspheres with 1% OMC enhanced SPF 12-fold compared to 7.5% OMC alone. Long-term tests also revealed SPF enhancement of up to 70%, proving sunspheres as efficient SPF boosters in sunscreen formulations.

TRANSFERSOMES

Transfersomes (TFs) are ultradeformable vesicles derived from liposomes by adding surfactants such as dipotassium glycyrrhizinate, sodium cholate, Tween 20, Span 60, or sodium deoxycholate. They are 100-150nm in size and are more flexible and deformable than conventional liposomes. Commonly prepared by vortexing–sonication or thin-film hydration, transfersomes can easily penetrate the stratum corneum through narrow intercellular spaces due to their elasticity. The osmotic gradient created during water evaporation further enhances the permeation of active ingredients into deeper skin layers.

Transfersomes can carry both hydrophilic and lipophilic compounds, although their flexibility decreases with hydrophobic drugs. They are effective under nonocclusive conditions. Studies combining hyaluronic acid (HA) and epigallocatechin gallate (EGCG) in transfersomes demonstrated strong antioxidant, antiaging and UV-protective effects by reducing reactive oxygen species (ROS) in skin cells. Another study using *Curcuma longa* (turmeric) extract in different vesicular systems found transfersome-based creams most effective, providing superior moisturizing and photoprotective effects due to the combined action of vesicle lipids and antioxidant curcuminoids.

ETHOSOMES

Ethosomes are ultradeformable vesicles composed of water, ethanol (20–45%), and phospholipids (0.5-10%), such as phosphatidylcholine, phosphatidylethanolamine, or phosphatidylinositol. They are modified liposomes containing ethanol, which enhances membrane fluidity and deformability. Ethosomes are typically prepared by dissolving lipids and active ingredients in ethanol, followed by the gradual addition of water using methods like reverse evaporation (REV) or film hydration.

Ethanol interacts with the lipids of the stratum corneum, lowering their melting point and increasing permeability, allowing ethosomes to deliver both hydrophilic and lipophilic drugs effectively. Ethanol also promotes the solubility of lipophilic compounds, resulting in higher entrapment efficiency. The mechanism of skin penetration involves ethanol-induced lipid disruption and vesicle elasticity working synergistically.

In sunscreen formulations, ethosomes are mainly used to enhance the skin delivery of vitamin E, an antioxidant that prevents sunlight-induced oxidative damage and malignancies. Studies by Godin and Touitou showed that vitamin E-loaded ethosomes achieved about 3.5 times greater skin penetration compared to conventional liposomes, proving ethosomes as superior carriers for deep dermal delivery.

TRANSETHOSOMES

Transethosomes are newly developed ultra-deformable vesicles (UDVs) that combine the properties of transfersomes and ethosomes. They consist of water, phospholipids, surfactants (edge activators), and ethanol (up to 30%), giving them high flexibility, elasticity and superior skin permeation. Their structure is irregular and spherical, with ethanol and surfactant enhancing lipid bilayer rearrangement. Prepared using the film hydration technique, transethosomes are suitable for large-scale industrial production. They exhibit greater deformability and skin penetration than ethosomes or transfersomes, with studies showing excellent results-especially in vitamin E formulations and high entrapment efficiency determined by HPLC analysis.

LIPOSOMES

Liposomes are spherical nanocarriers made of a phospholipid bilayer enclosing a hydrophilic core, with sizes ranging from 20-100nm. They can encapsulate both hydrophilic and hydrophobic drugs, enhancing their skin permeation and minimizing side effects. Being biodegradable and biocompatible, liposomes allow effective and controlled drug delivery with reduced skin irritation. The lipid bilayer, composed mainly of phospholipids and cholesterol, prevents drug leakage and improves stability. Depending on the number of layers, liposomes are classified as small unilamellar, large unilamellar, or multilamellar vesicles. Common preparation methods include the Bangham method, solvent injection, and reversed-phase evaporation. In sunscreen formulations, liposomes act as a drug reservoir in the subcutaneous layer, enabling controlled release. Studies show that incorporating UV filters like octyl methoxycinnamate (OMC) into liposomes increases SPF, enhances water resistance, and prevents systemic absorption. Overall, liposomal sunscreens provide superior photoprotection and safety compared to conventional formulations.

NIOSOMES

In cosmeceuticals, various advanced formulations have shown significant effects on skin applications. To address challenges like poor skin permeability and limited sunscreen efficacy, novel systems such as niosome-based formulations have been developed. Niosomes act as carriers that enhance the delivery and effectiveness of drugs that struggle to penetrate the skin barrier. They are vesicular structures made of nonionic surfactants, cholesterol, polyethylene glycol, and the active drug, with sizes ranging from 100nm to 2μm. The nonionic surfactants improve their stability, biodegradability, and skin compatibility. Niosomes are biocompatible, nontoxic and highly effective in enhancing skin absorption. In one study, Cristal Cerqueira *et al*. formulated a niosome-based sunscreen that achieved over 45% entrapment efficiency and an SPF above 34. Moreover, it was found to be non-toxic to macrophages, demonstrating good safety. Overall, niosomes show strong potential as effective carriers in sunscreen formulations for better protection and skin performance.

HYDROGELS

Hydrogels are innovative carriers in cosmetic and sunscreen formulations, offering cooling effects and UV protection. They have a cross-linked network structure that holds large amounts of water and drug molecules. Hydrogel sunscreens containing tannic acid and hyaluronic acid provide broad-spectrum UVA and UVB protection. Their water content gives a soothing, cooling sensation on the skin. Studies show that combining multiple ingredients enhances adhesion, antioxidant activity and overall sun protection.

NANOSPONGES

Nanosponges are advanced carrier systems used in cosmeceuticals and sunscreen formulations. They have nanosized porous cavities that can encapsulate both hydrophilic and lipophilic drugs. Their main advantages include high entrapment efficiency and controlled drug release, enhancing overall effectiveness. Structurally, they are three-dimensional, mesh-like networks made of biodegradable polyesters with cross-linkers. They can be prepared using methods like quasi-emulsion solvent diffusion and liquid–liquid suspension polymerization.

SOLID LIPID NANOPARTICLES

Solid lipid nanoparticles (SLNs), developed in the 1990s, are spherical carriers (40-1000nm) with a solid lipid core and outer lipid layer made from biocompatible materials like waxes, ceramides, and glycerides. They are ideal for delivering lipophilic and hydrophilic substances using surfactants for stabilization. SLNs provide controlled release, improved stability of active ingredients, and reduced toxicity due to their physiological lipid composition. Their strong crystalline structure offers UV-blocking and photoprotective properties,

making them suitable for sunscreen formulations. When UV filters are incorporated, SLNs enhance protection while reducing required doses and side effects. They also form a smooth, occlusive film on the skin, improving UV resistance. However, stability issues may arise due to crystallization during storage. Studies with silymarin-loaded SLNs showed excellent photoprotection and stability, suggesting potential as natural UV filters. Research combining organic (OCR) and inorganic (ZnO) UV filters in SLNs demonstrated synergistic UV protection, with OCR-SLNs effective in UVB and ZnO-SLNs in UVA absorption, confirming SLNs as promising carriers in sunscreens.

POLYMERIC NANOPARTICLES

Polymeric nanoparticles (PNs) are nanocarriers made from natural or synthetic biodegradable polymers like PLGA and poly(ε-caprolactone), typically below 1000nm in size. They can encapsulate both hydrophilic and lipophilic drugs, improving stability, solubility, and controlled release. PNs are prepared by methods such as spray drying, emulsion solvent evaporation, and nanoprecipitation. Based on structure, they are classified as nanospheres (solid polymer matrix) or nanocapsules (polymer shell with oily or aqueous core), with nanocapsules offering better loading capacity for lipophilic compounds. PNs enhance drug adhesion, prolong skin retention, and improve UV filter delivery in sunscreens. Naringenin-loaded PLGA nanoparticles showed higher SPF, antioxidant protection, and safety compared to pure naringenin, with no cytotoxicity or systemic absorption. Bioadhesive polymeric nanoparticles (BNPs) were developed to prevent UV filters from penetrating deeper layers, reducing DNA damage and ROS formation. In studies, padimate-O-loaded BNPs remained on the skin surface, offering effective UV protection with reduced dosage and high-water resistance.

MESOPOROUS SILICA NANOPARTICLES

Mesoporous silica nanoparticles (MSNs) are honeycomb-shaped structures with high surface area, tunable pore size, stability and biocompatibility, making them ideal for sunscreen formulations. Initially used to coat TiO_2 to reduce ROS generation, MSNs are now used to encapsulate UV filters, improving photostability and reducing toxicity. Studies by Knezevic *et al*. showed that surface-functionalized MSNs enhanced SPF, while benzene-based PMOBTB nanoparticles exhibited the highest UV absorption due to benzene bridges. Ambrogi *et al*, demonstrated that OMC-loaded MCM-41 coated with lipids improved photostability and provided controlled release without affecting storage stability. Daneluti *et al*, found that SBA-15-incorporated UV filters (OMC, OXY, AVO) significantly reduced skin penetration and increased SPF by 94%. Further studies showed SBA-15-based sunscreen sticks achieved SPF values close to marketed products with lower UV filter content. UVA protection was below EU-recommended levels but still notable. Additionally, Marcelino *et al*. developed TiO_2-loaded SBA-15 sunscreen lipstick with enhanced SPF, reduced aggregation, and improved photostability, proving MSNs' strong potential for safer, long-lasting sun protection formulations.

NANOCRYSTALS

Nanocrystals are nanoparticles (<1000nm) used in sunscreen formulations to enhance drug solubility, stability and penetration. They can exist in spherical (amorphous) or cuboidal (crystalline) forms and require stabilizers for stability. Among various solubility enhancement methods, nanocrystallization is preferred for its high drug-loading capacity and biodegradable stabilizers. Nanocrystals are prepared by top-down, bottom-up, or combined methods, with the top-down approach being most cost-effective and scalable. Advanced nanocrystals under 100 nm, introduced in 2001, improved stability and manufacturability, while patented "smart crystals" in 2006 enhanced solubilization. Their small size allows efficient skin penetration and better bioavailability. Studies show that nanocrystal-based formulations, such as rutin or apigenin nanocrystals, exhibit higher antioxidant

and bioactive effects. Cellulose nanocrystals, especially cinnamate-functionalized ones, demonstrate strong UV protection, safety and biodegradability. Overall, nanocrystals significantly enhance sunscreen efficacy with minimal side effects, suggesting further exploration of liquid crystal-based systems.

GELATIN-BASED NANOPARTICLES (GNPS)

Gelatin nanoparticles (GNPs) are biodegradable, FDA-approved (GRAS) polymers with inherent antioxidant properties due to their peptide structure. Although mainly used in drug delivery, their cosmetic use is emerging. Camila Areias de Oliveira et al. developed rutin-loaded gelatin nanoparticles (R-GNPs) combined with synthetic UV filters to enhance sunscreen efficacy. The alkaline preparation improved rutin entrapment efficiency (≈52%) and stability. R-GNPs showed a 74% increase in antioxidant activity and a 48% rise in SPF compared to free rutin formulations.

CRITICAL SUNSCREEN FACTORS

SUNSCREEN VEHICLE, APPLICATION, AND REMOVAL

Sunscreens are available in various emulsion forms like gels, creams, and lotions, mainly as water-in-oil (W/O) or oil-in-water (O/W) types, which influence their skin absorption and protection. Studies show that W/O emulsions maintain efficacy even after water exposure due to their low HLB and water-insoluble emulsifiers, while O/W emulsions lose effectiveness. W/O types also show higher SPF and non-comedogenic properties, though O/W is often preferred for its lighter feel. The U.S. FDA recommends applying 2mg/cm² sunscreen, but people usually apply only half; hence, SPF 30+ is advised. Sunscreen should be applied 15 minutes before sun exposure and reapplied every 2 hours or after sweating/swimming. Improper removal can harm skin; cleansing oil is most effective, especially for water-resistant types. Studies show non-water-resistant sunscreens wash off easily with cleansers, while water-resistant types need oil cleansers. Water temperature has minimal effect on most sunscreens, though some lose resistance at higher temperatures. Inorganic filters like zinc oxide and titanium dioxide often leave a white cast, which reduces consumer appeal.

SKIN PHOTOTYPES

Skin pigmentation and phototypes are commonly assessed using the Individual Typology Angle (ITA) and Fitzpatrick classification, with ITA being more precise as it relies on colorimetry. Different skin phototypes require varied sun protection levels. Light-skinned individuals have less melanin and a lower eumelanin/pheomelanin ratio, making them more vulnerable to UVB-induced DNA damage in both upper and basal epidermal layers. In contrast, dark-skinned individuals have better DNA repair and are mainly affected by UVA and visible light, leading to hyperpigmentation. Hence, sunscreens for light skin should focus on UVB protection, while those for dark skin should emphasize UVA and visible light defense. Tinted sunscreens containing iron oxides or titanium dioxide are ideal for dark skin as they match complexion and offer protection. Overall, SPF 50+ is advised for light skin, and SPF 30+ for dark skin.

AGE-RELATED FACTORS

UV radiation is a major cause of skin aging as it damages collagen and elastin fibers, reducing the skin's strength, flexibility, and repair ability. Continuous exposure leads to wrinkles, sagging and dullness. Protection methods like clothing, sunglasses and especially sunscreen are essential to prevent UV-induced damage. Sunscreens help protect against tanning, sunburn, premature aging and skin cancer. Dermatologists recommend using sunscreen daily for all age groups. According to the American Academy of Dermatology, SPF 30 or higher is ideal. Specific recommendations vary by age, generally ranging from SPF 40 to 50, with mineral-based and antioxidant-enriched formulas for older adults.

LONG-TERM EFFECTS OF SUNSCREEN

Sunscreens effectively prevent skin cancer and melanoma but may cause side effects with long-term use. Prolonged application can lead to skin issues like dermatitis, lichen planus, or allergic reactions. People with sensitive skin or eczema are more prone to irritant contact dermatitis from certain sunscreen ingredients. Allergic reactions may occur due to preservatives or fragrances, causing rashes or blisters. In rare cases, photo contact dermatitis can develop when sunscreen ingredients react with UV light.

TESTING METHODS FOR SUNSCREEN EFFICACY

Sunscreen performance is mainly tested on human volunteers because such products interact directly with the skin. In in vivo testing**,** selected participants apply the product, and their skin is then exposed to controlled UVA or UVB radiation to determine how long it takes for sunburn or tanning to appear.

As an alternative, *in vitro* tests use instruments like spectrophotometers to measure UV protection without involving people. Many such lab-based methods have been developed and standardized, but they are still not accepted for official SPF determination since they do not reliably match real human results. Therefore, regulatory agencies do not approve them for SPF labelling.

Official evaluation of sunscreens usually includes three major tests: SPF assessment, overall UV protection and water-resistance testing (details presented in Table No.6). In addition to these, several ex vivo methods-tests performed on isolated skin samples-are also used during research to study the product's effectiveness and stability, as summarized in Table No.2.

SUNSCREEN WITH ADDITIONAL PROPERTIES (COMBINATION SUNSCREEN FORMULATION)

SUNSCREEN AGAINST BLUE LIGHT

Blue light, which falls within the 380-500nm wavelength range, is emitted not only by sunlight but also by digital screens like phones, tablets and computers. Although this type of radiation is useful in medical treatments-such as photodynamic therapy for cancer when paired with specific drugs-it can also reach deeper layers of the skin and cause harm. Its negative effects include weakening the skin's protective barrier, generating reactive oxygen species (ROS) and speeding up aging by damaging the extracellular matrix.

Because of these risks, protecting the skin from blue light is important. Research shows that some traditional UV filters can also absorb or block blue light, offering broader protection. Modern sunscreens such as Murad's City Skin Age Defense (SPF 50, PA+++) and SKEYDOR's Sun Expertise (SPF 50+) are examples designed to shield the skin from blue light exposure.

Additionally, exosome-based formulations, which have recently shown strong potential in cancer therapy, are now being investigated for use in advanced sunscreen technologies.

SUNSCREEN AGAINST ENVIRONMENTAL POLLUTANTS

Air contains harmful pollutants like NOx, SO_2, PAHs and particulate matter that negatively impact the skin. These pollutants trigger inflammation, hyperpigmentation and collagen damage, leading to wrinkles, acne flare-ups, dryness and dark spots. To counter these effects, sunscreens often include antioxidants. These ingredients help by boosting collagen/elastin production and removing pollutant particles from the skin to reduce irritation.

SUNSCREEN COMBINED WITH DNA REPAIR ENZYMES

Sunlight can reach deep skin layers where cancer-prone cells exist and early signs of damage include wrinkles, uneven tone, and pigmentation changes. If the resulting DNA damage is not corrected, long-term exposure can lead to skin cancer. Traditional sunscreens only offer passive protection and cannot repair the harm already caused. Therefore, advanced unscreens with active protection are needed. This is possible through formulations containing DNA

repair enzyme-loaded liposomes and antioxidants. These enzymes help fix UV-induced DNA damage, lower mutation rates and boost immune defenses against tumor formation. Common DNA repair enzymes used include 8-oxoguanine glycosylase, photolyase, T4 endonuclease**,** and a photolyase-T4N5 combination**.** 8-Oxoguanine glycosylase is plant-derived, photolyase comes from cyanobacteria and T4N5 is sourced from UV-resistant Micrococcus luteus. Studies show that sunscreens enriched with the photolyase–T4N5 blend significantly reduce UV-induced DNA lesions and field cancerization. They also help prevent premature aging by reducing c-FOS overexpression and limiting telomere shortening, highlighting their strong protective benefits.

SUNSCREEN AGAINST THERMAL IR

Conventional sunscreens are designed mainly to protect against UVA and UVB rays, but they often fail to address infrared (IR) radiation, which makes up about 54.3% of sunlight. IR rays can activate enzymes such as MMP-1 and MMP-9 and increase the formation of reactive oxygen species, all of which speed up collagen breakdown and contribute to skin aging. To counter these harmful effects, sunscreens should ideally include antioxidants or similar protective agents. An *in vivo* study by Kim et al., conducted on 155 Korean volunteers using a reflectance probe and an IR source, confirmed that sunscreen offered significantly higher infrared protection factor (IPF) compared to unprotected skin. The study also showed a positive correlation between inorganic filters and IR protection. Since prolonged IR exposure is associated with premature aging, several modern sunscreens now provide IR defense, such as SkinMedica's "Total Defense and Repair SPF 34," which contains an antioxidant complex to help minimize fine lines and wrinkles.

SUNSCREEN WITH ANTIOXIDANTS AND ANTI-AGING

Conventional sunscreens rely on organic and inorganic filters that may cause unwanted side effects, prompting interest in natural alternatives. Natural ingredients not only reduce reliance on these filters but also offer added antioxidant and anti-aging benefits. A patented water-soluble sunscreen (US Patent 8,337,820B2) was created for sensitive skin, including rosacea, using N-acetyl-tyrosine, histidine, 5-hydroxytryptophan from *Griffonia simplicifolia* and TiO_2, which prevented redness and irritation by avoiding organic filters. Other examples include a tomato-lycopene-based sunscreen with SPF 20 that helps prevent wrinkles and a formulation by Blossom Kochhar Aroma Magic containing cucumber extract, providing UV protection, skin-soothing effects, anti-aging benefits, and a non-greasy feel.

SAFETY AND REGULATORY ASPECTS OF SUNSCREEN FORMULATIONS

Sunscreens require strict safety and regulatory oversight because certain ingredients can cause dermatitis, photoallergic reactions, hormonal disturbances and even interfere with vitamin D synthesis during long-term use. Since many countries allow sunscreens to be sold as OTC products, improper labeling and limited consumer knowledge can lead to misuse, whereas in the U.S., the FDA regulates sunscreens more closely to reduce such risks. Concerns also exist regarding organic filters like oxybenzone and PABA, which may trigger allergic reactions, and nanoparticle-based ingredients such as TiO_2, whose skin penetration and safety profiles are still under evaluation. To address these issues, the OECD introduced a program to test nanomaterials under 100nm, recognizing that smaller particles pose higher toxicity risks. Different regions have established varied regulatory guidelines: the U.S. FDA requires evidence of safety and UV filter effectiveness, including UVA and UVB testing and a critical wavelength of at least 370nm for broad-spectrum claims; the EU enforces strict criteria such as an SPF/UVA-PF ratio ≤ 3 and a critical wavelength over 370 nm, with SPF 6 as the minimum allowable value. Australia's TGA classifies sunscreens as primary (SPF >15) or

secondary (SPF ≤15) and does not require nanoparticle size labeling, while South Africa mandates UVA photostability testing and ISO 24443 compliance. Collectively, these regulations aim to ensure that sunscreen products maintain high safety standards, minimize toxicity, and provide effective protection.

CHALLENGES

This article highlights the effects of UV rays on the skin, available solutions, and regulatory considerations, while also addressing the various challenges faced in sunscreen use. Difficulties arise both from manufacturers-who must meet regulatory demands for safety, efficacy testing and proper labeling, as well as overcome ethical concerns related to testing carcinogenic UV exposure on human subjects-and from consumers, who often lack adequate knowledge about correct application, leading to insufficient protection and reduced trust in the product. Additional hurdles include the high cost and long development time of sunscreens, varying regulatory standards across countries and limited resources in developing regions, all of which complicate production, labelling and consistent effectiveness. Despite advancements in nanotechnology, few clinical trials have evaluated nano-based sunscreens; however, one study using bioadhesive nanoparticle formulations demonstrated enhanced UV protection through improved photostability, reduced ROS generation and longer skin adherence, suggesting potential for safer and more effective future sunscreen technologies.

Table No.1: Nanoemulsion

S.No	Nanoparticle	Production Method(s)	Advantages (The Good Stuff)	Disadvantages (The Trade-offs)
1	Polymeric Nanoparticles	Interfacial polymerization, Nano-precipitation, Dialysis, Solvent evaporation, Emulsion polymerization, etc.	Easily utilized in tissue engineering. Higher effectiveness over conventional oral delivery. Very useful for volatile substances delivery.	Potential toxicity due to the non-biodegradable nature of some polymers.
2	Nanoemulsion	Hydrogel method, Microfluidization, Ultrasonication, High-pressure homogenization, Phase inversion temperature, Phase inversion point, etc.	Avoids stability problems like coalescence and flocculation. Non-irritant and non-toxic for enhanced topical use. Useful in toxicity studies for oil-soluble substances. Higher skin penetration due to small size.	Stability can be affected by pH and temperature. Requires a higher amount of surfactant to maintain stability.
3	Nanocrystals	Combinational technology, Bottom-up and Top-down methods, High-pressure homogenization techniques, etc.	Most suitable for hydrophobic substances. Enhances drug solubility and permeation.	Not suitable for hydrophilic (water-loving) substances.
4	Mesoporous Silica Particles	Sol-gel method, Evaporation through self-induced assembly.	Excellent biodegradable and nontoxic nature.	Can potentially be linked to melanoma (requires further study/context from the source).
5	Solid Lipid Nanoparticles (SLN)	Double emulsion, Cold/Hot homogenization, Ultrasonication, Microemulsion, Melt dispersion, etc.	Excellent biodegradable property. Easy to produce. Higher bioavailability due to better skin permeation.	Low drug encapsulation property. Solution state stability issues.
6	Nanostructure Lipid Carriers (NLC)	Membrane contactor, Microfluidization, Phase inversion, Solvent injection, Cold/Hot homogenization, Solvent emulsification diffusion, etc.	Higher physical stability. Easy to formulate. Higher drug loading capacity. Higher penetration. Excellent benefit/risk ratio. Controlled drug delivery.	Surfactant-induced irritancy. Potential cytotoxic effect from the lipid portion.
7	Liposomes	Extrusion, Sonication, Solvent injection, Supercritical fluid, Heating, Bubble, Film hydration, etc.	Act as a nanocarrier for both hydrophilic and hydrophobic drugs. Excellent biodegradable property. Can produce sustained release (longer action).	May be allergic in some cases. Lesser stability.
8	Niosomes	Microfluidization, Ether injection, Sonication, Bubble, Handjani-Vila, Handshaking, Enzymatic, Lipid injection, Single pass, etc.	Higher bioavailability due to better penetration. Higher drug loading capacity. Higher physical stability.	More complex and time-consuming preparation. Highly costly in terms of production.

Table No.2: Study the product's effectiveness and stability

S.No	*Ex vivo* methods	Description
1	Radical skin protection factor (RSF)	The principle of RSF is based on the determination of the number of free radicals generated on protected skin to unprotected skin through electron spin spectroscopy (ESR). The number of free radicals produced is measured through their reaction with nitroxyl substrate 2, 2, 5, 5 tetramethylpyrrolidine-N-oxyl-oxyl PCA, which is a probe for detection through ESR.
2	TBARS assay (Thiobarbituric acid reactive species)	It is an assay used to determine both the direct activity of sunscreen to prevent ROS generation and its photostability. The assay is based on the principle of reaction between malondialdehyde (a predominant secondary product of lipid peroxidation) and TBA to form an adduct of MDA-TBA2 that produces a red-pink colour. The absorbance of this product is measured at 532nm and compared with the standard calibration curve of MDA.
3	HPLC-TBARS-EVSC assay (High-Pressure LiquidChromatography-Thiobarbituric acid reactive species-*ex vivo* stratum corneum)	A newer approach focused on measuring lipid peroxidation value on an *ex vivo* stratum corneum obtained through tape stripping

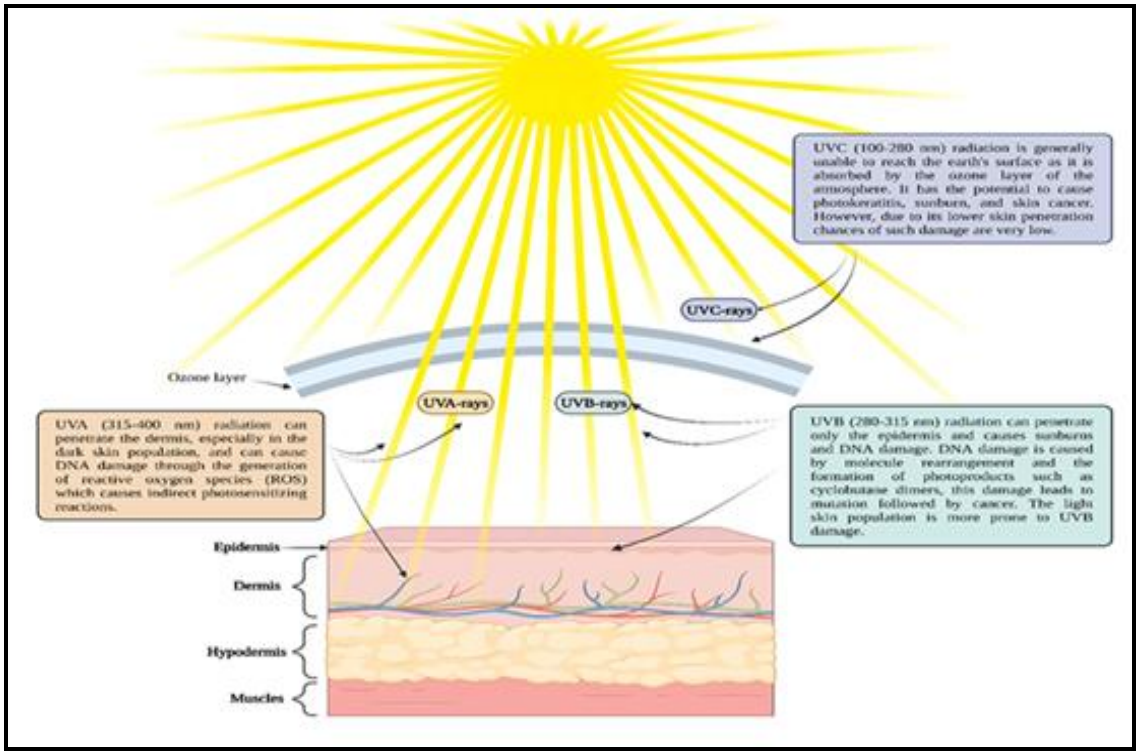

Figure No.1: Types of UV radiation along with their penetration power into the skin and associated diseases

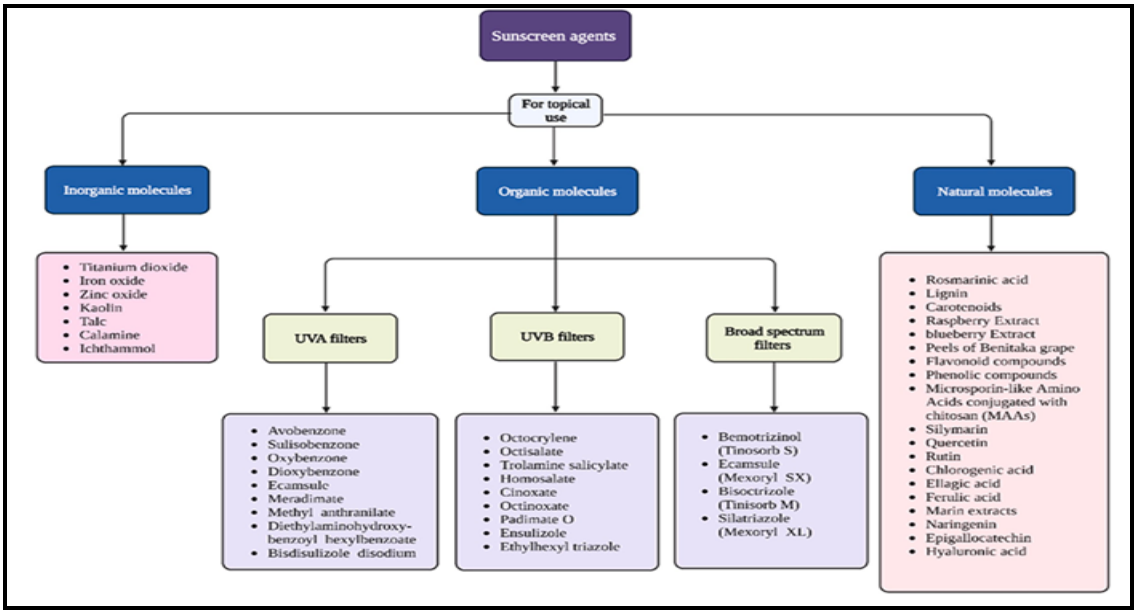

Figure No.2: The classification of various molecules used in the sunscreen formulation as UV filters

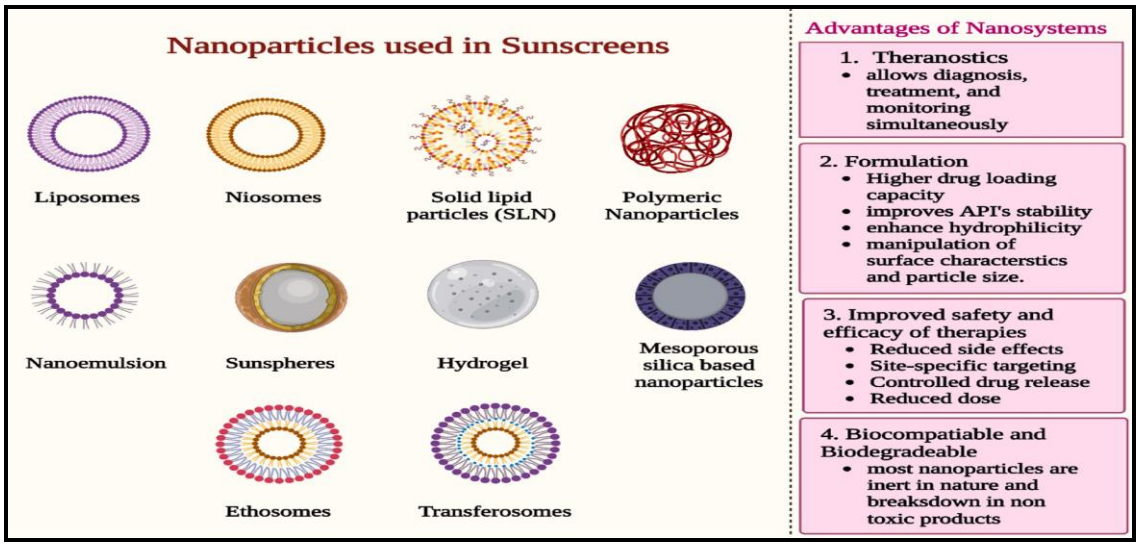

Figure No.3: Various nanocarriers useful in sunscreen formulations

FUTURE LANDSCAPES AND CONCLUSION

The growing rate of UV-related skin disorders makes sunscreen use increasingly essential, and while nanotechnology-based formulations offer enhanced protection, their safety and toxicity still require further investigation. As testing methods and sunscreen types evolve-with rising interest in natural ingredients and cosmetic benefits like tinted products-a unified global regulatory guideline is needed to standardize testing, labelling, and usage instructions, ultimately improving consumer confidence and reducing manufacturing costs. With continued research and greater public awareness about proper application and label interpretation, nanosystem-based sunscreens have strong potential to become safer, more effective, and more widely used in the future.

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CONFLICT OF INTEREST

We declare that we have no conflict of interest.

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