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Development, Optimization and Evaluation of Solid Lipid Nanoparticle-based Broad-Spectrum Sunscreen Hydrogel using a Quality by Design Approach

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ABSTRACT:

Background: Ultraviolet (UV) radiation is an important environmental factor associated with erythema, hyperpigmentation, premature skin aging and photocarcinogenesis. Conventional sunscreen formulations may exhibit limitations such as inadequate photostability, poor skin retention, greasy texture and the need for frequent reapplication.

Objective: The present study aimed to develop and optimize a broad-spectrum sunscreen hydrogel incorporating UV-filter-loaded solid lipid nanoparticles (SLNs) using a Quality by Design (QbD) approach.

Materials and Methods: The SLNs incorporated Uvinul® T150 and Uvasorb® HEB as organic UV filters and zinc oxide as an inorganic UV filter. Glyceryl monostearate, Cetiol® CC, C12–C15 alkyl benzoate and lecithin were used as the lipid components. A 2³ full factorial design was employed using glyceryl monostearate, Cetiol® CC and lecithin as formulation variables. Particle size, viscosity and entrapment efficiencies of Uvinul T150 and Uvasorb HEB were selected as critical responses. The optimized formulation was further characterized for physicochemical properties, drug content, SPF, in-vitro release and stability.

Results and Discussion: Eight formulations (F1–F8) were prepared according to the factorial design. Particle size ranged from 132.1 to 210.5 nm, viscosity from 2150 to 3400 cP, while entrapment efficiencies ranged from 86.1–96.2% for Uvinul T150 and 88.5–97.8% for Uvasorb HEB. F6 was selected as the optimized formulation with a particle size of 174.6 nm, PDI of 0.225, zeta potential of –27.9 mV and SPF of 36.37. F6 showed pH 5.9, viscosity of 3400 cP, spreadability of 462.96 ± 17.14 g·cm/sec and drug contents of 97.7 ± 0.2% and 97.9 ± 0.2% for Uvinul T150 and Uvasorb HEB, respectively. The formulation exhibited sustained UV-filter release over 10 h and remained physically stable during three months of storage.

Conclusion: The optimized F6 formulation demonstrated desirable physicochemical

properties, high entrapment efficiency, satisfactory SPF, sustained release and stability, indicating its potential as a broad-spectrum sunscreen formulation.

INTRODUCTION

Exposure to solar ultraviolet (UV) rays is among the leading factors in skin damage due to the occurrence of erythema, photodamage, immune system suppression, hyperpigmentation, and development of skin cancer (Diffey 2002). Solar UV radiation is made up of UV-A (320-400 nm) and UV-B (290-320 nm). Each of them has different biological actions. UV-A affects the dermal tissue and causes oxidative damage and early aging of the skin while UV-B has a significant effect on epidermal tissue that results in sunburn, DNA damage, and carcinogenesis (Narayanan et al., 2010). Chronic UV exposure causes the production of reactive oxygen species that lead to collagen breakdown and other damages. Therefore, the creation of effective sunscreen products is now of great importance (Gonzalez et al., 2020; Yaar et al., 2007).

Topical sunscreens are still the best option to protect skin from the damaging UV radiation. The typical components of sunscreen products include both organic and inorganic absorbers that absorb, reflect, or scatter the harmful rays (Mancebo et al., 2014; Osterwalder et al., 2009). The effectiveness of these products is often estimated by their Sun Protection Factor (SPF), meaning that SPF shows protection against erythema caused by UVB. While the existing sunscreen creams and lotions offer sufficient protection, there are several drawbacks to them, such as photostability of UV absorbers, poor skin retention, poor water resistance, need for re-application, greasiness, whitening effect, and poor patient compliance. Moreover, penetration of some chemical absorbers beyond the skin surface can increase the risk of irritation and systemic exposure (Sala et al., 2018; Souto et al., 2022).

There has been increasing interest in the application of nanotechnological approaches in formulating delivery systems capable of addressing the shortcomings of conventional topical products (Gupta et al., 2011). All the various systems, solid lipid nanoparticles (SLNs) have received much attention due to their favorable attributes such as biocompatibility, sustained release of drugs, high physical stability, and their capacity to enhance localization of lipophilic agents (Rajasekar et al., 2024; Khobragade et al., 2025). These nanoparticles are submicron colloidal systems that are made of physiological lipids which exist in solid state both at room temperature and body temperature. The special lipid system ensures protection of the active components from photodegradation while enhancing the physical stability and decreasing the contact between the UV absorbers and living skin tissues (Wong et al., 2021; Garibyan et al., 2010).

Numerous researchers have found out that encapsulation of sunscreen active substances in lipid nanoparticles provides higher SPF values, photostability, controlled delivery, as well as decreased skin irritation (Lavker et al., 1995; Afaq et al., 2005). Besides acting as nanovehicles, SLNs have an occlusive property that allows improving the hydration level of skin and increasing the duration of its presence on the skin surface (Lacatusu et al., 2021). Nevertheless, aqueous suspensions of SLNs usually have a low viscosity and spreadability. Thus, it is impossible to apply them directly for the formulation of the topical drug product. That is why hydrogel formulations are a good solution to combine both technologies (Gaspar et al., 2018; Müller et al., 2000). Hydrogels are three-dimensional polymeric matrices that can absorb large amounts of water while still retaining their structure. There are many benefits offered by hydrogels such as non-oily consistency, cooling effect, easy application, increased patient compliance, and prolonged stay on the skin (Sharma et al., 2022). SLNs incorporated in hydrogel formulation result in the development of a combination of the two types of nanocarriers, which is able to increase stability of the formulations, controlled delivery of UV filters, increased retention on skin, and improved cosmetic elegance of formulations (Gokce et al., 2022; Montgomery, 2017).

While there are many studies focused on the use of lipid nanoparticles for drug delivery via the topical route, not much work has been reported in terms of the optimization of broad-spectrum SLN-based sunscreen hydrogels using Quality by Design (QbD) approach (Patel et al., 2022; Lacatusu et al., 2021). Using the optimization process through Design of Experiments (DoE) will enable gaining knowledge about the effect of formulation variables on critical quality attributes such as particle size, entrapment efficiency, and stability of formulations. The application of QbD approach can therefore lead to the development of robust, reproducible and scalable sunscreen formulations (Kaur et al., 2020; Sharma et al., 2023).

In light of the above, the objective of this study was to develop, optimize and evaluate a broad-spectrum sunscreen hydrogel consisting of Uvinul® T150 and Uvasorb® HEB loaded solid lipid nanoparticles using 2³ full factorial designs. The optimal

formulation was analyzed in terms of particle size, polydispersity index, zeta potential, entrapment efficiency, FTIR, DSC, rheology, spreadability, SPF, drug release and stability. The novel SLN-based hydrogel sunscreen formulation developed will offer better photoprotection, physicochemical stability, sustained release and cosmetic appeal (Souto et al., 2022; El-Houssiny et al., 2022).

MATERIALS AND METHODS

Materials

Glyceryl monostearate (GMS) was used as the solid lipid and Cetiol® CC (dicaprylyl carbonate) as the liquid lipid. C12–C15 alkyl benzoate was used as the solvent for the UV filters, while lecithin was used as a lipid stabilizer.

Uvinul® T150 (ethylhexyl triazone) and Uvasorb® HEB (diethylhexyl butamido triazone) were selected as organic UV filters. Zinc oxide was incorporated as the inorganic UV filter. Sepinov™ EMT 10/acrylate polymer was used as the gelling agent. Propanediol was used as humectant, disodium EDTA as chelating agent and Euxyl® PE 9010 as preservative. Purified water was used as the aqueous phase.

Methods:

Drug–Excipient Compatibility Study

Physical compatibility of Uvinul T150 and Uvasorb HEB with the selected excipients was evaluated. The UV filters and selected excipients were combined in a 1:1 (w/w) ratio and stored at $40 \pm 2^\circ\text{C}/75 \pm 5\% \text{ RH}$ for four weeks. Samples were examined visually for changes such as discoloration, phase separation, liquefaction, aggregation and caking (Akombaetwa et al, 2023).

Fourier Transform Infrared Spectroscopy

FTIR analysis was performed to investigate the compatibility of the UV filters with the selected formulation excipients. Spectra of Uvinul T150, Uvasorb HEB, individual excipients, physical mixtures and the optimized formulation were recorded using a Shimadzu IR Affinity-1S spectrophotometer over $4000\text{--}400 \text{ cm}^{-1}$ using the KBr pellet method (Shahare et al., 2026).

Differential Scanning Calorimetry

Thermal behavior and compatibility of the UV filters and formulation components were examined using differential scanning calorimetry (Shimadzu DSC-60 Plus). Samples were analyzed in aluminum pans over a temperature range of $25\text{--}300^\circ\text{C}$ at a heating rate of $10^\circ\text{C}/\text{min}$ under nitrogen flow. An empty aluminum pan was used as reference (Daga et al., 2026).

Preparation of Solid Lipid Nanoparticles

The lipid phase was prepared by melting GMS, Cetiol® CC, C12–C15 alkyl benzoate and lecithin at $75\text{--}80^\circ\text{C}$. Uvinul T150 and Uvasorb HEB were subsequently dissolved in the lipid phase, followed by incorporation of zinc oxide with continuous stirring (Baste et al., 202; Shahare et al., 2026).

The aqueous phase was heated to the same temperature as the lipid phase and subsequently combined with the lipid phase. The mixture was homogenized at 10,000–15,000 rpm for 5–8 min and probe-sonicated three times for 30 s using an ice bath to obtain the SLN dispersion.

Preparation of SLN-Based Sunscreen Hydrogel

Disodium EDTA was dissolved in purified water followed by addition of propanediol and mixing for 5 min. The acrylate polymer was slowly incorporated into water with continuous stirring at 800–1000 rpm for 20–30 min to obtain the aqueous gel base (Pawar et al., 2024; Shahare et al., 2026).

The prepared SLN dispersion was gradually incorporated into the aqueous base under gentle stirring at approximately 500 rpm and 45°C . Preservative and fragrance were incorporated below 40°C and 35°C , respectively. The final formulation pH was maintained within 5.0–6.5.

Quality by Design and Factorial Experimental Design

A 2^3 full factorial design was employed to investigate the influence of three formulation variables:

- **Factor A:** GMS concentration
- **Factor B:** Cetiol® CC concentration
- **Factor C:** Lecithin concentration

Eight experimental batches (F1–F8) were prepared according to the factorial design.

The selected critical responses were:

- **Y1:** Particle size
- **Y2:** Viscosity
- **Y3:** Entrapment efficiency of Uvinul T150
- **Y4:** Entrapment efficiency of Uvasorb HEB

Linear, two-factor interaction (2FI), quadratic and cubic models were evaluated using Design-Expert® software version 13.0 (Stat-Ease). The formulation variables and response data were analyzed to identify the optimized formulation (Verma et al., 2026).

Physical Appearance

The formulations were visually examined for color, homogeneity, consistency, grittiness, aggregation, sedimentation and phase separation under normal daylight conditions. A small quantity was spread on a clean glass slide to assess uniformity and smoothness.

Determination of pH

The pH of each formulation was measured using a calibrated digital pH meter. The instrument was calibrated using standard buffer solutions before measurement. Measurements were performed at room temperature in triplicate.

Viscosity

Viscosity was determined using a Brookfield viscometer. Samples were equilibrated at $25 \pm 1^\circ\text{C}$ before analysis. An appropriate spindle was immersed to the specified level, and readings were recorded at different rotational speeds after stabilization. Measurements were performed in triplicate.

Spreadability

Spreadability of the optimized formulation was determined by the glass-slide method. Approximately 0.5–1 g of hydrogel was placed between two glass slides and subjected to a 500-g weight for 5 min. The upper slide was subsequently moved over a fixed distance of 7.5 cm, and the time required was recorded.

Spreadability was calculated using:

$$S = M \times L / T$$

Where S is spreadability, M is the applied weight, L is the distance travelled and T is the time required.

Drug Content

An accurately weighed quantity of formulation was dissolved in ethanol or methanol and sonicated to ensure complete extraction. The volume was adjusted to 100 mL. The solution was filtered through a 0.45- μm membrane filter and appropriately diluted.

The concentrations of Uvinul T150 and Uvasorb HEB were determined using UV-visible spectrophotometry at their respective analytical wavelengths. Drug-content analysis was performed in triplicate.

SPF Determination

SPF was determined using the UV-visible spectrophotometric method based on the Mansur equation. One gram of formulation was extracted using ethanol, followed by stirring and sonication. The extract was filtered through a 0.45- μ m membrane filter and appropriately diluted.

Absorbance was recorded between 290 and 320 nm at 5-nm intervals using ethanol as blank.

The SPF was calculated using:

$$\text{SPF} = \text{CF} \times \sum [\text{EE}(\lambda) \times \text{I}(\lambda) \times \text{Abs}(\lambda)]$$

Where CF is the correction factor, EE(λ) is the erythral effect spectrum, I(λ) is the solar intensity spectrum and Abs(λ) is the absorbance at the corresponding wavelength.

In-vitro Drug Release

In-vitro release of the optimized formulation was investigated using a Franz diffusion cell. A pre-soaked dialysis membrane was positioned between the donor and receptor compartments. The receptor compartment contained phosphate buffer pH 7.4 or an appropriate ethanol-buffer medium and was maintained at $37 \pm 0.5^\circ\text{C}$ with continuous stirring.

The formulation was placed in the donor compartment. Samples were withdrawn at predetermined intervals and replaced with an equivalent volume of fresh receptor medium. The withdrawn samples were analyzed spectrophotometrically using appropriate calibration curves.

Stability Study

The optimized formulation was subjected to stability testing under room-temperature, long-term and accelerated storage conditions.

The storage conditions were:

- $25 \pm 2^\circ\text{C}/60 \pm 5\% \text{ RH}$
- $30 \pm 2^\circ\text{C}/75 \pm 5\% \text{ RH}$
- $40 \pm 2^\circ\text{C}/75 \pm 5\% \text{ RH}$

Samples were evaluated initially and after 1, 2 and 3 months for physical appearance, pH, SPF and drug content (Shahare et al., 2025)..

RESULTS AND DISCUSSION

Drug–Excipient Compatibility

The physical compatibility study demonstrated that the selected UV filters and formulation components could be combined without observable incompatibility during the preliminary compatibility period. The samples did not exhibit visible discoloration, phase separation, liquefaction, aggregation or caking. Zinc oxide remained uniformly dispersed.

FTIR spectra further supported compatibility of the formulation components. Uvinul T150 and Uvasorb HEB showed characteristic absorption bands corresponding to O–H/N–H stretching, aliphatic C–H stretching, carbonyl stretching, aromatic C=C/C=N stretching and C–O/C–N vibrations. In the physical mixture and optimized formulation, characteristic bands were retained without disappearance of major peaks or formation of new characteristic bands. These observations suggest the absence of significant chemical interaction between the UV filters and selected excipients.

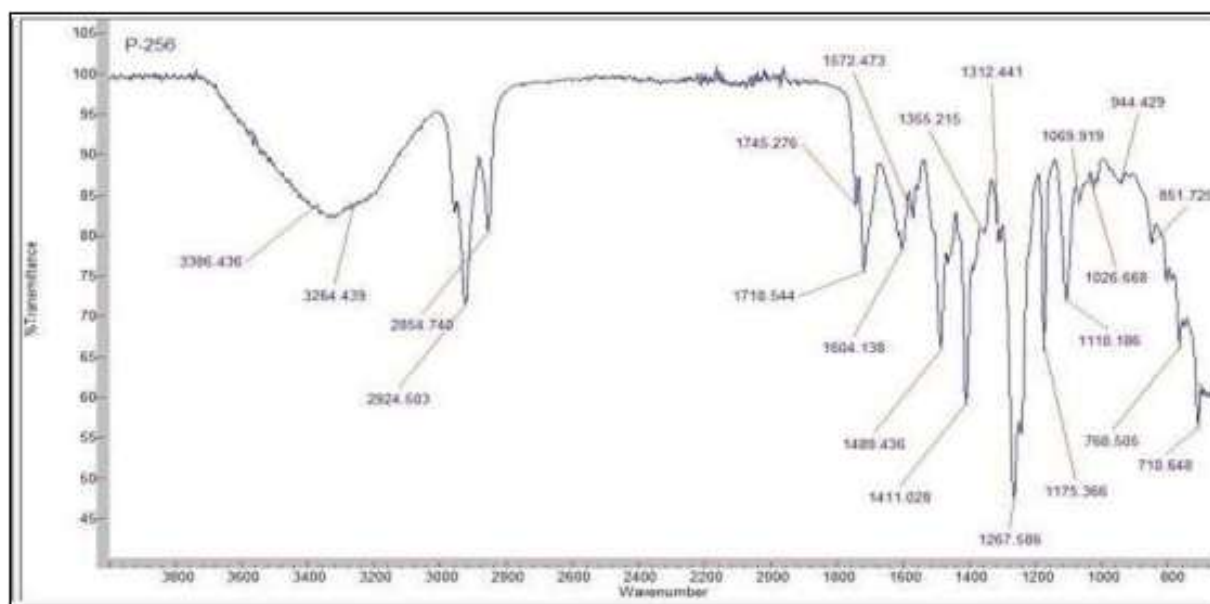


Figure 1. FTIR of SLN based Sunscreen Hydrogel

DSC Analysis

Uvinul T150 exhibited a defined endothermic melting transition in the approximately 120–130°C region, whereas Uvasorb HEB showed a broad endothermic transition around 140–150°C.

The physical mixture exhibited a broad endothermic event around 105°C and a thermal transition with an onset of 128.50°C and maximum temperature of 129.95°C. The characteristic thermal transitions of the active substances and glyceryl monostearate were retained without appearance of new peaks.

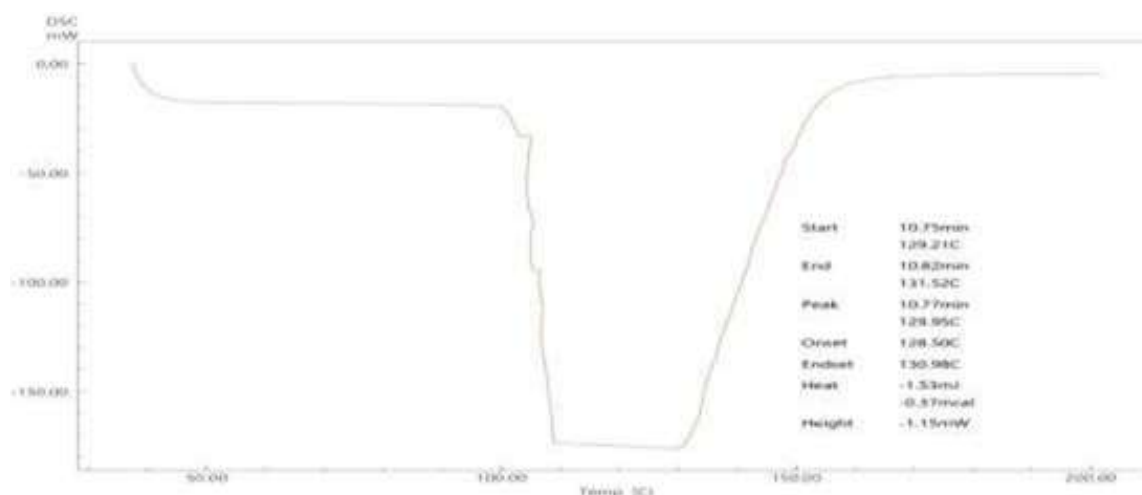


Figure 2. DSC of UV Filters and Excipients

The broadening and reduction in intensity of some peaks may be attributed to dilution and homogeneous distribution of components within the formulation matrix. Overall, the thermal findings support compatibility of the selected formulation components.

QbD Optimization and Factorial Design

Eight experimental batches were prepared according to the 2^3 factorial design. The observed responses are summarized in Table 1.

Table 1. Factorial Design and Observed Responses of SLN-Based Sunscreen Hydrogel

Formulation	GMS (% w/w)	Cetiol CC (% w/w)	Lecithin (% w/w)	Particle size (nm)	Viscosity (cP)	EE Uvinul T150 (%)	EE Uvasorb HEB (%)
F1	2	3	0.9	145.2	2450	91.4	93.2
F2	3	3	0.5	210.5	3100	94.8	96.1
F3	3	2	0.9	162.8	3350	93.1	94.7
F4	2	3	0.5	188.4	2200	89.5	91.3
F5	2	2	0.9	132.1	2300	88.2	90.4
F6	3	3	0.9	174.6	3400	96.2	97.8
F7	2	2	0.5	165.3	2150	86.1	88.5
F8	3	2	0.5	198.7	2950	92.3	93.9

The particle size of the formulations varied between 132.1 and 210.5 nm. The viscosity ranged from 2150 to 3400 cP. Entrapment efficiency of Uvinul T150 varied from 86.1 to 96.2%, whereas Uvasorb HEB showed entrapment efficiency between 88.5 and 97.8%.

The formulation containing 3% GMS, 3% Cetiol CC and 0.9% lecithin (F6) showed the highest viscosity and the highest entrapment efficiencies among the tested formulations while maintaining a nanoscale particle size. The Design-Expert optimization procedure generated multiple possible solutions, from which the formulation with desirability closest to unity was selected. The optimized composition corresponded to 3% w/w GMS, 3% w/w Cetiol CC and 0.9% w/w lecithin.

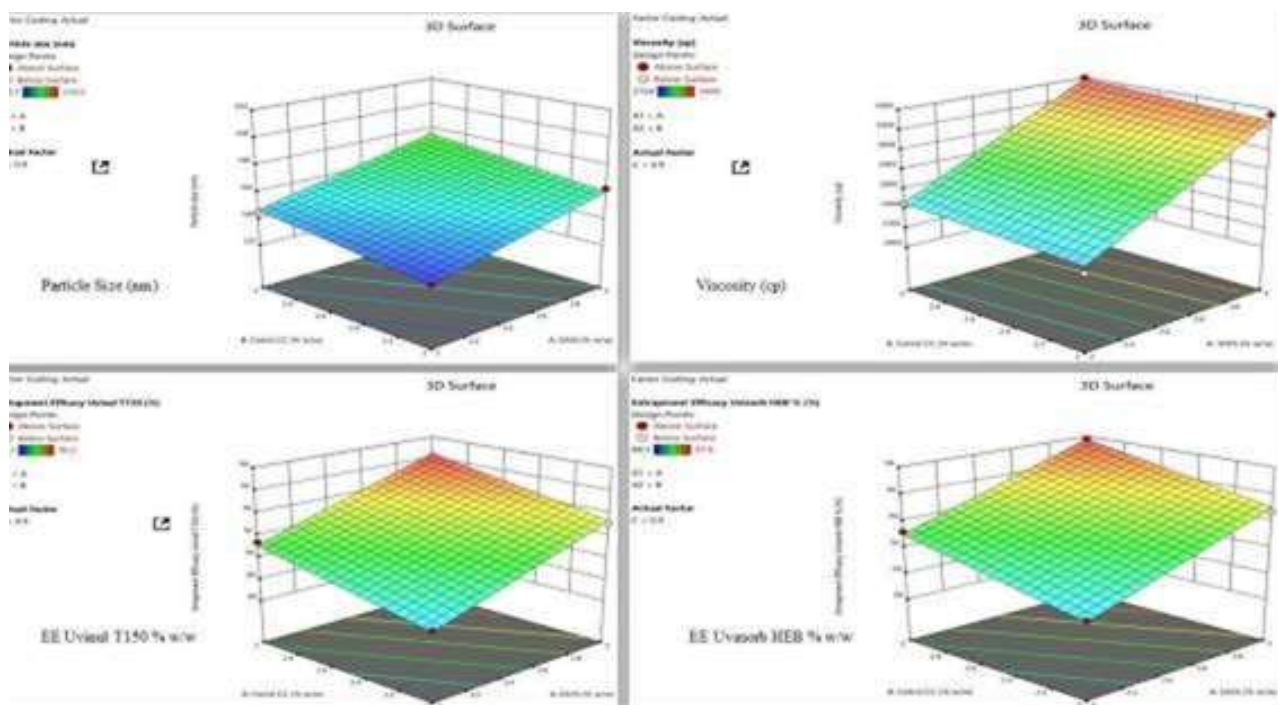


Figure 3. Three-dimensional response surface plots showing the effects of formulation variables on particle size, viscosity and entrapment efficiencies

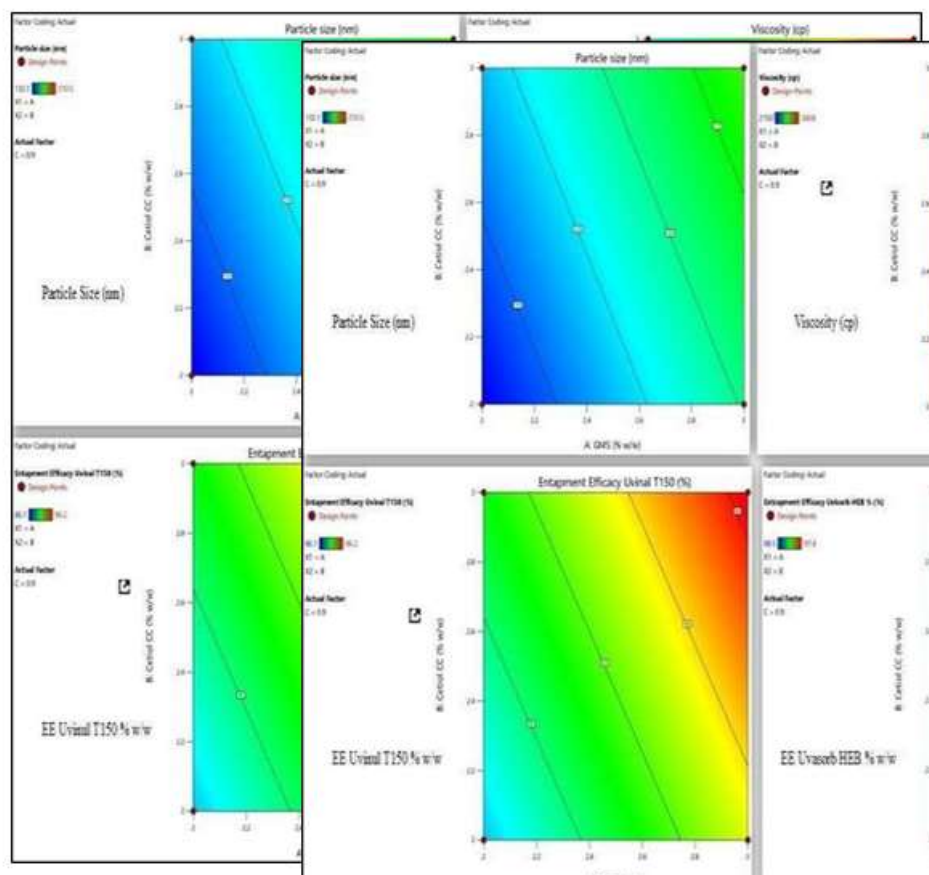


Figure 4. Two-dimensional contour plots representing the design space for the selected responses.

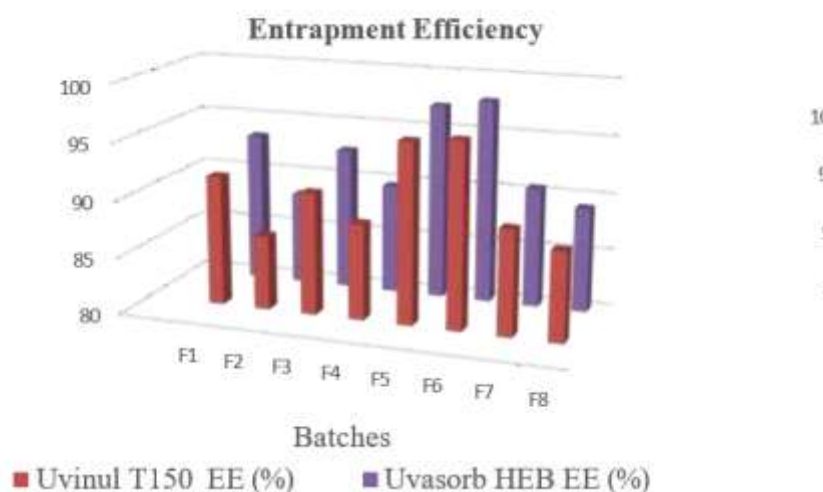


Figure 5. Evaluation of SLN-Based Sunscreen Hydrogel Formulations: Entrapment Efficiency

Physical Appearance

All formulations were visually smooth and homogeneous without obvious phase separation. Progressive improvement in the physical characteristics was observed among the formulations, with F6 exhibiting a smooth, homogeneous and non-gritty appearance. The desirable physical characteristics of F6 are particularly relevant for topical sunscreen application because uniformity of the formulation facilitates consistent distribution of UV filters over the skin surface.

Particle Size, PDI and Zeta Potential of Optimized F6

The optimized F6 formulation exhibited a particle size of **174.6 nm**, indicating successful formation of nanosized lipid particles. The PDI was **0.225**, suggesting a relatively narrow particle-size distribution. The zeta potential was **-27.9 mV**. The negative surface charge may contribute to electrostatic repulsion between particles and therefore support dispersion stability.

The nanoscale size of the SLNs provides a high interfacial surface area and is advantageous for topical distribution of incorporated UV filters.

pH

The pH values of F1–F8 ranged from **5.4 to 6.1**, indicating that the formulations were within a range suitable for topical application. The optimized F6 formulation exhibited a pH of **5.9**. The slightly acidic pH is close to the physiological acidic environment of the skin and may therefore be advantageous for topical compatibility.

Viscosity

The viscosity of the formulations ranged from **2150 to 3400 cP**. The highest viscosity was observed with F6, which exhibited a viscosity of **3400 cP**. The increase in viscosity indicates development of a stronger hydrogel network. The viscosity of F6 was sufficient to provide structural integrity while retaining spreadability, making the formulation suitable for topical application.

Spreadability

The optimized F6 formulation exhibited a spreadability of:

462.96 ± 17.14 g·cm/sec

Despite its relatively high viscosity of 3400 cP, F6 showed satisfactory spreading characteristics. Good spreadability is important for sunscreen formulations because uniform spreading contributes to formation of a continuous film over the skin and may improve the consistency of UV protection.

Drug Content

The optimized F6 formulation exhibited high drug-content uniformity.

Table 2. Drug Content of Optimized F6

UV filter	Drug content (%)
Uvinul T150	97.7 ± 0.2
Uvasorb HEB	97.9 ± 0.2

The high drug-content values indicate efficient incorporation of both UV filters into the SLN-hydrogel system and suggest minimal loss during formulation processing.

Sun Protection Factor

The UV-visible absorbance values obtained for F6 between 290 and 320 nm were used for SPF calculation.

Table 3. SPF Calculation of Optimized F6

Wavelength (nm)	EE × I	Absorbance	EE × I × Abs
290	0.0150	1.25	0.01875
295	0.0817	1.32	0.10784
300	0.2874	1.40	0.40236
305	0.3278	1.48	0.48514

310	0.1864	1.55	0.28992
315	0.0839	1.50	0.12585
320	0.0180	1.42	0.02556
Total			1.4554

Using the correction factor of 10, the calculated SPF was **14.55**. After application of the dilution factor specified in the original study, the reported practical SPF was **36.37**.

The high SPF value may be attributed to the combined UV-filter system consisting of Uvinul T150, Uvasorb HEB and zinc oxide. The nanosized lipid carrier may further support uniform distribution of the UV filters, while zinc oxide contributes UV scattering and absorption. The SLN-based film-forming system may additionally improve coverage of the skin surface.

In-vitro Drug Release

The optimized F6 formulation demonstrated a controlled and sustained release pattern over the 10-h study period. Approximately **20% release occurred within the first hour**, followed by gradual release to approximately **85% at 8 h** and approximately **90% at 10 h**.

The release profile suggests an initial release of relatively accessible UV-filter molecules followed by slower diffusion from the lipid matrix and hydrogel network. The solid lipid matrix can act as a diffusion barrier, while the hydrogel creates an extended diffusional pathway.

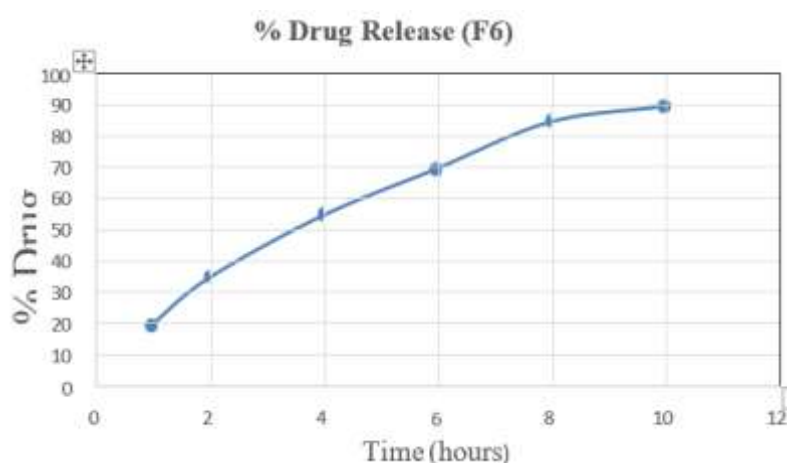


Figure 6. In-vitro release profile of Uvinul T150/Uvasorb HEB from optimized F6 SLN-based sunscreen hydrogel over 10h

Stability Study

The optimized F6 formulation was evaluated under room-temperature, long-term and accelerated storage conditions for three months.

Table 4. Stability Evaluation of Optimized F6

Storage condition	Parameter	Initial	1 month	2 months	3 months
25 ± 2°C/60 ± 5% RH	Physical appearance	Smooth, homogeneous, non-gritty	No change	No change	No change
	pH	5.90	5.89	5.88	5.87
30 ± 2°C/75 ±	Physical	Smooth, homogeneous,	No	No change	No change

5% RH	appearance	non-gritty	change		
	pH	5.90	5.88	5.86	5.84
40 ± 2°C/75 ± 5% RH	Physical appearance	Smooth, homogeneous, non-gritty	No change	Slight change in consistency	No significant change
	pH	5.90	5.84	5.79	5.74

F6 maintained a smooth, homogeneous and non-gritty appearance throughout the three-month study. A slight decline in pH was observed under all storage conditions, with a comparatively greater change under accelerated conditions. The pH nevertheless remained within a range suitable for topical application. The limited change in physical appearance and pH indicates satisfactory short-term physicochemical stability of the optimized SLN hydrogel.

The developed SLN-based sunscreen hydrogel demonstrated desirable physicochemical characteristics, including suitable pH, viscosity, spreadability and stability. The nanosized carrier system provides a distinct formulation approach compared with conventional sunscreen vehicles.

The improved retention and sustained-release characteristics may be associated with the lipid matrix and hydrogel network. However, direct superiority over marketed products should be interpreted cautiously because the present comparative assessment was based primarily on formulation characteristics rather than a controlled head-to-head clinical efficacy study.

REGULATORY CONSIDERATIONS

The developed SLN based sunscreen hydrogel was evaluated for various physicochemical parameters such as particle size, PDI, zeta potential, pH, viscosity, spreadability, drug content, entrapment efficiency, in vitro release and stability studies using proper excipients and UV filters. The optimized formulation exhibited good stability, uniformity, and photoprotective activity, as well as satisfactory quality attributes, which suggests the optimized formulation would be suitable for topical application as a sunscreen and further development to a pharmaceutical product. The prepared sunscreen hydrogel with SLNs should be within the limits of the UV filters and excipients as per CDSCO and BIS regulations, along with the assessment on the product quality, safety, stability, skin compatibility, and efficacy to protect skin from UV rays. In the case of SLNs, additional attention must be paid to the nanosafety issues, size distribution of particles, physical stability, and drug release pattern.

CONCLUSION

A broad-spectrum sunscreen hydrogel incorporating Uvinul T150, Uvasorb HEB and zinc oxide-loaded solid lipid nanoparticles was successfully developed using a Quality by Design approach. The 2³ factorial design enabled systematic investigation of GMS, Cetiol CC and lecithin concentrations and facilitated selection of the optimized F6 formulation.

F6 exhibited a particle size of 174.6 nm, PDI of 0.225, zeta potential of -27.9 mV, viscosity of 3400 cP, pH 5.9 and satisfactory spreadability. The formulation showed high entrapment efficiencies and drug contents for both organic UV filters. The reported SPF of 36.37 demonstrated substantial UVB photoprotective potential. In-vitro release showed a controlled release pattern extending to 10 h, while the three-month stability study demonstrated satisfactory physical stability with only minor changes in pH.

The combination of SLN technology and hydrogel delivery provided a promising platform for improving topical distribution, residence and sustained delivery of UV filters. Nevertheless, further studies involving photostability testing, skin permeation/retention, irritation and sensitization assessment, long-term stability, in-vivo photoprotection and clinical evaluation are necessary before translation toward commercial application.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest associated with this manuscript. The authors have no financial, professional or personal relationships that could have influenced the reported work.

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