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Original Article

Development and Evaluation of A Multifunctional Antiaging and Skin-Brightening Cosmeceutical Hydrogel Containing Niacinamide, Sodium Ascorbyl Phosphate, Hyaluronic Acid, and Herbal Bioactive Extracts

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ABSTRACT

Background: Skin aging and hyperpigmentation are primarily driven by oxidative stress, collagen degradation, ultraviolet exposure, and environmental factors, necessitating multifunctional cosmeceutical formulations with synergistic mechanisms of action. **Objectives:** To develop and optimize a Carbopol® 940-based multifunctional cosmeceutical hydrogel containing niacinamide, Sodium Ascorbyl Phosphate (SAP), hyaluronic acid,*Aloe vera*, and*Camellia sinensis* extracts for antiaging and skin-brightening applications. **Materials and Methods:** Three hydrogel Formulations (F1-F3) with varying Carbopol® 940 concentrations (0.75-1.25% wt/wt) were prepared using controlled hydration and neutralization techniques. Formulations were evaluated for physicochemical characteristics, pH, viscosity (Brookfield DV-II+, spindle 64, 10 r.p.m.), spreadability, rheological behavior,*in vitro* antioxidant activity (DPPH assay), accelerated stability (40°C/75% RH for 90 days), and primary skin irritation ($n = 6$ healthy volunteers). Statistical analysis was performed using one-way ANOVA followed by Tukey's *post hoc* test ($p < 0.05$). **Results:** The optimized formulation (F2, 1.0% Carbopol®) exhibited pH 5.9 ±0.1, viscosity 4,850 ± 120 cP, and spreadability 6.8 ± 0.2 g cm/s, indicating optimal topical rheology. F2 demonstrated significant antioxidant activity (78.4 ± 1.6% DPPH inhibition), comparable to ascorbic acid, 94.2 ± 0.8% and significantly higher than placebo gel (8.3 ± 1.2%) ($p < 0.001$). Accelerated stability studies showed no significant changes in pH, viscosity, or spreadability over 90 days ($p > 0.05$). The Primary Irritation Index was 0.00, confirming dermatologic safety. **Conclusion:** The optimized multifunctional hydrogel (F2) demonstrated excellent stability, safety, antioxidant activity, and optimal rheological performance. The synergistic combination of niacinamide, SAP, hyaluronic acid, and herbal antioxidants provides a promising cosmeceutical platform for antiaging and skin-brightening applications pending clinical validation.

Keywords: Cosmeceutical, Hydrogel, Antiaging, Skin Brightening, Niacinamide, Sodium Ascorbyl Phosphate, Hyaluronic Acid, Antioxidant, Topical Delivery, Stability Study.

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INTRODUCTION

Skin aging is a multifactorial biological process influenced by intrinsic aging, ultraviolet radiation, environmental pollution, and oxidative stress, collectively termed the skin aging exposome (Krutmann *et al*., 2017; Vierkötter and Krutmann, 2021). These factors accelerate collagen degradation, elastin fragmentation, and dysregulated melanogenesis, leading to wrinkles, loss of elasticity, dullness, and hyperpigmentation (Fisher *et al*., 2002). Modern cosmeceutical science emphasizes multifunctional formulations capable of targeting multiple biological pathways simultaneously while maintaining cosmetic elegance and dermatologic safety (Draelos, 2021).

Niacinamide (Vitamin B3) is a well-established cosmeceutical active known for its ability to inhibit melanosome transfer, enhance epidermal barrier function, stimulate ceramide synthesis, and reduce transepidermal water loss (Gehring, 2004; Hakozaki *et al*., 2002). Clinical investigations have demonstrated its efficacy in improving fine lines, wrinkles, and uneven skin tone associated with photoaging (Bissett *et al*., 2005).

Sodium Ascorbyl Phosphate (SAP), a stable vitamin C derivative, offers superior formulation stability compared to l-ascorbic acid while retaining antioxidant, collagen-stimulating, and tyrosinase-modulating properties (Farris, 2005; Pullar *et al*.,

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2017). SAP protects against reactive oxygen species-mediated damage and supports dermal matrix repair (Kameyama *et al.*, 1996).

Hyaluronic acid, a naturally occurring glycosaminoglycan, possesses exceptional water-binding capacity and plays a critical role in maintaining dermal hydration and elasticity (Fallacara *et al.*, 2018). Topical application improves skin smoothness, reduces wrinkle depth, and enhances viscoelastic properties of the skin (Bukhari *et al.*, 2018).

Additionally,*Aloe vera* polysaccharides and*Camellia sinensis* polyphenols provide complementary anti-inflammatory and antioxidant effects by modulating NF-κB signaling pathways and neutralizing free radicals associated with photoaging (Katiyar and Elmets, 2001; Kim *et al.*, 2022). Hydrogel-based delivery systems, particularly Carbopol®-based matrices, offer advantages including high water content, nongreasy texture, enhanced spreadability, and improved patient compliance (Peppas *et al.*, 2000; Teleanu *et al.*, 2022).

Therefore, the present study aimed to develop, optimize, and evaluate a multifunctional Carbopol®-based cosmeceutical hydrogel incorporating synergistic antiaging and skin-brightening bioactives for potential dermatologic and commercial application.

MATERIALS AND METHODS

Materials

Niacinamide (Lonza, Switzerland), sodium ascorbyl phosphate (DSM, Switzerland), Carbopol® 940 (Lubrizol, United States), hyaluronic acid (Bloomage Biotech, China),*Aloe vera* extract (Aloe Corp., United States),*Camellia sinensis* extract (Naturex, France), glycerin (Merck, Germany), triethanolamine (Sigma-Aldrich, United States), methyl paraben and propyl paraben (BASF, Germany). Purified water (Milli-Q® Integral System, Merck Millipore, United States) was used throughout the study. All ingredients were cosmetic/pharmaceutical grade.

Formulation Composition

Three Formulations (F1-F3) were developed with varying concentrations of Carbopol® 940 to optimize rheological properties (Table 1). Active ingredients were maintained at constant concentrations based on literature-reported efficacious ranges.

Method of Preparation

Carbopol® 940 was slowly dispersed in 70% of total purified water under mechanical stirring at 500 r.p.m. for 30 min using a mechanical stirrer (Remi RQT-124A, India). The dispersion was allowed to hydrate completely for 24 hr at 25 ± 2°C to form a smooth polymer matrix.

In a separate vessel, niacinamide, 4.0% wt/wt, sodium ascorbyl phosphate (2.0% wt/wt), and glycerin, 3.0% wt/wt were dissolved in a portion of remaining purified water with gentle heating (40°C) as required. Hyaluronic acid, 0.5% wt/wt was prehydrated separately in cold water for 2 hr to prevent lump formation upon incorporation.

After complete polymer hydration, the aqueous active phase was added slowly with continuous stirring at 500 r.p.m. Prehydrated hyaluronic acid was incorporated, followed by*Aloe vera* extract (5.0% wt/wt),*Camellia sinensis* extract (2.0% wt/wt), and preservatives (methyl paraben 0.18% wt/wt, propyl paraben 0.02% wt/wt) under continuous stirring at 600 r.p.m.

Triethanolamine was added dropwise with constant stirring to adjust pH to 5.5-6.0, simultaneously neutralizing Carbopol® and inducing gel formation. Final homogenization was performed at 800 r.p.m. for 15 min. The volume was adjusted to 100% with purified water, and the gel was stored in airtight containers for evaluation.

The active ingredients were maintained constant across all formulations: Niacinamide, 4.0% wt/wt, Sodium ascorbyl phosphate (2.0% wt/wt), hyaluronic acid, 0.5% wt/wt, *Aloe vera* extract (5.0% wt/wt), and *Camellia sinensis* extract (2.0% wt/wt).

Physical Appearance and Homogeneity

Formulations were visually examined against white and black backgrounds for color, clarity, consistency, and presence of particulate matter or air bubbles.

pH determination

The pH of a 1% wt/wt aqueous solution of each hydrogel was measured in triplicate using a digital pH meters (Eutech Instruments, Singapore) calibrated with standard buffer solutions (pH 4.0, 7.0) at 25 ± 1°C.

Viscosity Measurement

Viscosity was determined using a Brookfield Viscometer (DV-II+ Pro, Brookfield Engineering Laboratories, United States) with spindle no. 64 at 10 r.p.m. and 25 ± 1°C. Readings were recorded after 2 min of spindle rotation to ensure equilibrium. Measurements were performed in triplicate.

Spreadability Test

Spreadability was evaluated using the parallel plate method (Garg, Aggarwal, Garg, and Singla, 2002). Approximately 0.5 g of gel was placed within a 1 cm diameter circle on a glass plate. A second glass plate was placed on top, and a 20 g weight was allowed to rest on the upper plate for 5 min to expel air and provide uniform film formation. Spreadability was calculated using the formula:

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

where:

- S = spreadability (g cm/s).

- M = Weight tied to upper plate (20 g).
- L = Length of glass slide (cm).
- T = Time taken for complete separation of slides (seconds).

Measurements were performed in triplicate.

In vitro Antioxidant Activity (DPPH Radical Scavenging Assay)

The antioxidant activity was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging method adapted from Brand-Williams, Cuvelier, and Berset (1995). Briefly, 1 g of hydrogel was dissolved in 10 mL of methanol and centrifuged at 3,000 r.p.m. for 10 min using a laboratory centrifuge (Eppendorf 5,804, Germany). From the supernatant, 1 mL was mixed with 3 mL of 0.1 mm methanolic DPPH solution. The mixture was vortexed and incubated in the dark for 30 min at room temperature. Absorbance was measured at 517 nm using a UV-visible spectrophotometer (Shimadzu UV-1800, Japan). Methanol served as blank, while a control was prepared using methanol instead of sample. Ascorbic acid, 0.1 mg mL^{-1} was used as positive control, and placebo gel (without actives) served as negative control.

Percentage inhibition was calculated as:

$$\% \text{ Inhibition} = [(A_0 - A_1)/A_0] \times 100$$

Where:

- A_0 = Absorbance of control
- A_1 = Absorbance of sample

All measurements were performed in triplicate.

Stability Studies

Accelerated stability studies were conducted according to ICH guidelines for cosmetic formulations (ICH harmonised tripartite guideline, 2003). Formulations were stored in laminated aluminum tubes at:

- 25°C ±2°C/60% RH ±5% RH (long-term conditions).
- 40°C ±2°C/75% RH ±5% RH (accelerated conditions).

Samples were evaluated at 0, 30, 60, and 90 days for physical appearance, pH, viscosity, spreadability, and phase separation.

Primary Skin Irritation Study

The study protocol was approved by an Independent Ethics Committee (IEC/SW/2025/01) and conducted in accordance with the Declaration of Helsinki principles. Six healthy human volunteers (age 25-40 years, 3 male, 3 female) with no history of dermatologic conditions provided written informed consent before participation.

A 24-hr occlusive patch test was performed (Draize *et al.*, 1944). Approximately 0.5 g of optimized formulation (F2) was applied to the volar forearm (3-cm^2 area) and covered with hypoallergenic adhesive tape. The site was examined for erythema, edema, and irritation at 1, 24, and 48 hr after patch removal. Scoring was performed using a standard 5-point scale (0 = no reaction, 4 = severe erythema with edema). Primary Irritation Index (PII) was calculated as mean score across volunteers.

Statistical Analysis

All data were expressed as Mean ± Standard Deviation (SD) of three replicate measurements (n = 3). Statistical analysis was performed using one-way Analysis of Variance (ANOVA) followed by Tukey's *post hoc* test (GraphPad Prism 9.0, United States). A p-value <0.05 was considered statistically significant.

Table 1: Formulation Composition (% wt/wt).

Ingredient	F1	F2	F3	Function
Carbopol® 940	0.75	1.00	1.25	gelling agent
Niacinamide	4.0	4.0	4.0	antiaging, brightening
Sodium ascorbyl phosphate	2.0	2.0	2.0	antioxidant
Hyaluronic acid	0.5	0.5	0.5	hydrating agent
Aloe vera extract	5.0	5.0	5.0	soothing, moisturizing
Camellia sinensis extract	2.0	2.0	2.0	antioxidant
Glycerin	3.0	3.0	3.0	humectant
Methyl paraben	0.18	0.18	0.18	preservative
Propyl paraben	0.02	0.02	0.02	preservative
Triethanolamine	q.s.	q.s.	q.s.	pH neutralizer
Purified water	to 100	to 100	to 100	vehicle

RESULTS AND DISCUSSION

Physicochemical Characterization

All Formulations (F1-F3) appeared as transparent, homogeneous hydrogels with smooth, glossy texture and no visible particulate matter or phase separation (Table 2).

The pH of all formulations ranged from 5.7 to 6.1, which falls within the acceptable range for topical applications (4.5–6.5) and is compatible with normal skin physiology, minimizing irritation risk (Lambers *et al.*, 2006). The slight increase in pH with increasing Carbopol® concentration correlates with higher polymer content requiring additional neutralization.

Viscosity increased proportionally with Carbopol® concentration ($p < 0.001$ between all formulations). F1 exhibited lower viscosity (3,200 cP), resulting in poor retention and tendency to run off during application on vertical surfaces. F3 demonstrated excessive viscosity (7,100 cP), causing difficulty in extrusion from the tube and uneven spreading, potentially compromising patient compliance (Clochard *et al.*, 2020). F2 provided optimal rheological balance (4,850 cP) for topical delivery-sufficient for skin retention while maintaining ease of application.

Spreadability values inversely correlated with viscosity. F1 showed highest spreadability (7.5 g cm/s) but compromised retention, while F3 exhibited poor spreadability (5.2 g cm/s) requiring excessive shear for application. F2 demonstrated optimal spreadability (6.8 g cm/s), enabling uniform coverage with minimal application force (Tamburic and Craig, 1995).

Rheological Behavior

All formulations exhibited pseudoplastic (shear-thinning) flow behavior, characterized by decreasing viscosity with increasing shear rate (Figure 1). This property is highly desirable for topical hydrogels, as formulations become less viscous during application (rubbing), facilitating spreading, and rapidly recover viscosity once shear is removed, ensuring adequate skin retention and sustained active delivery (Lee *et al.*, 2009).

In vitro Antioxidant Activity

The DPPH radical scavenging assay revealed significant antioxidant activity for F2 formulation (Table 3):

F2 demonstrated 78.4% DPPH scavenging, significantly higher than placebo gel ($p < 0.001$) and comparable to previously reported SAP-based antioxidant hydrogels (75–82%) (Figure 2) (Yuli *et al.*, 2023). This activity is attributed to the synergistic

Table 2: Physicochemical properties of formulations (Mean ± SD, *n* = 3).

Parameter	F1 (0.75% Carbopol®)	F2 (1.0% Carbopol®)	F3 (1.25% Carbopol®)
pH	5.7 ± 0.2	5.9 ± 0.1	6.1 ± 0.2
Viscosity (cP) at 10 r.p.m.	3,200 ± 110	4,850 ± 120	7,100 ± 150
Spreadability (g cm/s)	7.5 ± 0.3	6.8 ± 0.2	5.2 ± 0.2

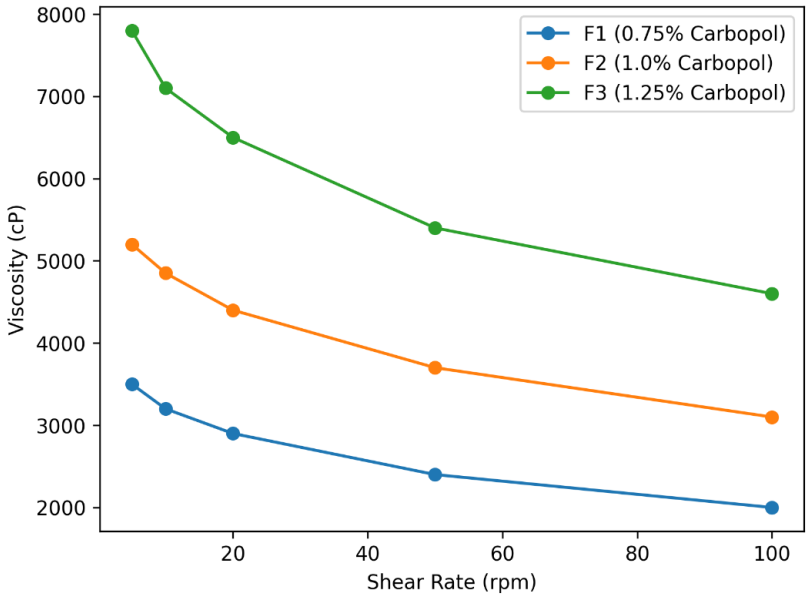

Figure 1: Rheological profile (viscosity vs. shear rate) of F1, F2, and F3 hydrogels demonstrating pseudoplastic (shear-thinning) flow behavior suitable for topical application. Data points represent Mean ± SD (*n* = 3). F1 (0.75% Carbopol®) shows lowest viscosity, F3 (1.25% Carbopol®) shows highest viscosity, and F2 (1.0% Carbopol®) demonstrates optimal rheological profile for topical application.

antioxidant action of sodium ascorbyl phosphate and*Camellia sinensis* polyphenols, which effectively neutralize reactive oxygen species responsible for photoaging and oxidative skin damage (Spiclin *et al.*, 2003; Zhang and Duan, 2018). The preservation of antioxidant activity confirms that manufacturing processes did not degrade these sensitive bioactives.

Mechanistic Interpretation of Antiaging and Brightening Activity

The optimized F2 formulation targets multiple aging pathways through complementary mechanisms:

- **Niacinamide, 4.0% wt/wt:** inhibits melanosome transfer from melanocytes to keratinocytes by regulating the Rho kinase signaling pathway, reducing visible hyperpigmentation independent of melanin synthesis inhibition (Gehring, 2004; Greatens *et al.*, 2005). Concurrently, it enhances epidermal barrier function by stimulating keratinocyte differentiation and increasing ceramide, free fatty acid, and cholesterol synthesis, reducing transepidermal water loss and improving skin texture (Bissett *et al.*, 2005).
- **Sodium ascorbyl phosphate (2.0% wt/wt):** provides dual functionality: as a potent antioxidant, it scavenges superoxide anion and hydroxyl radicals, protecting against UV-induced oxidative damage (Pullar *et al.*, 2017); as a collagen synthesis modulator, it serves as a cofactor for prolyl hydroxylase and lysyl hydroxylase, enzymes critical for collagen stabilization and cross-linking (Farris, 2005). Additionally, SAP inhibits tyrosinase through copper chelation at the enzyme's active site, reducing melanin synthesis (Kameyama *et al.*, 1996).
- **Hyaluronic acid, 0.5% wt/wt:** provides exceptional moisture retention, improving stratum corneum hydration and reducing wrinkle depth through dermal volume enhancement (Fallacara *et al.*, 2018). Its low-molecular-weight forms a viscoelastic film on the skin surface, providing immediate smoothing effects, while lower molecular weight fractions penetrate the epidermis to stimulate endogenous hyaluronic acid synthesis via CD44 receptor activation (Bukhari *et al.*, 2018).
- **Herbal bioactives:** *Aloe vera* polysaccharides and*Camellia sinensis* polyphenols (epigallocatechin gallate)-provide complementary anti-inflammatory effects through NF-κB pathway inhibition and antioxidant protection through direct radical scavenging and metal chelation (Katiyar and Elmets, 2001; Kim *et al.*, 2022).
- The Carbopol® 940 hydrogel matrix (1.0% wt/wt) enables sustained topical delivery through mucoadhesive properties, improving bioavailability of active ingredients while providing a nonocclusive, breathable film with superior sensory properties (Peppas *et al.*, 2000; Peppas *et al.*, 2021).

Stability Studies

Accelerated stability studies at 40°C/75% RH for 3 months revealed no significant changes in physicochemical parameters for F2 formulation ($p > 0.05$, ANOVA) (Figure 3 and Table 4).

Table 3: **DPPH radical scavenging activity (Mean ± SD, *n* = 3).**

Sample	% inhibition
F2 hydrogel	78.4 ± 1.6
Ascorbic acid (positive control)	94.2 ± 0.8
Placebo gel (negative control)	8.3 ± 1.2

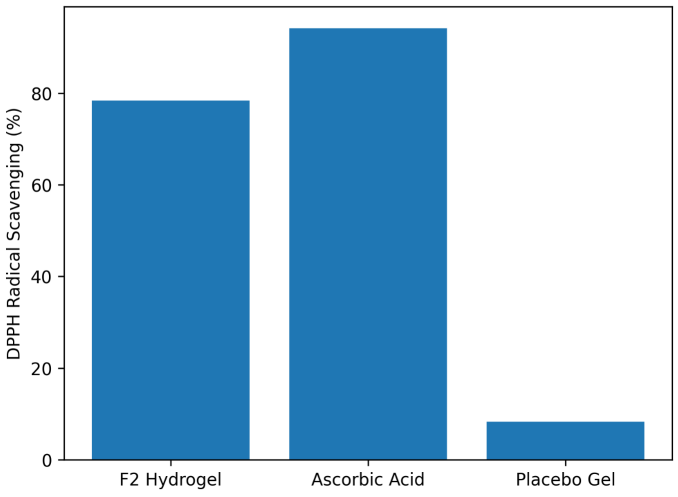

Figure 2: Comparative DPPH radical scavenging activity of F2 hydrogel, ascorbic acid (positive control), and placebo gel (negative control). Bars represent Mean ± SD ($n = 3$). $^{***}p < 0.001$ vs. placebo gel.

Table 4: **Stability profile of F2 formulation under accelerated conditions (40°C/75% RH).**

Parameter	Initial	30 days	60 days	90 days	*p*-value
pH	5.9 ± 0.1	5.9 ± 0.1	5.8 ± 0.1	5.8 ± 0.1	0.342
Viscosity (cP)	4,850 ± 120	4,820 ± 130	4,790 ± 140	4,760 ± 150	0.178
Spreadability (g cm/s)	6.8 ± 0.2	6.8 ± 0.2	6.7 ± 0.2	6.7 ± 0.2	0.451

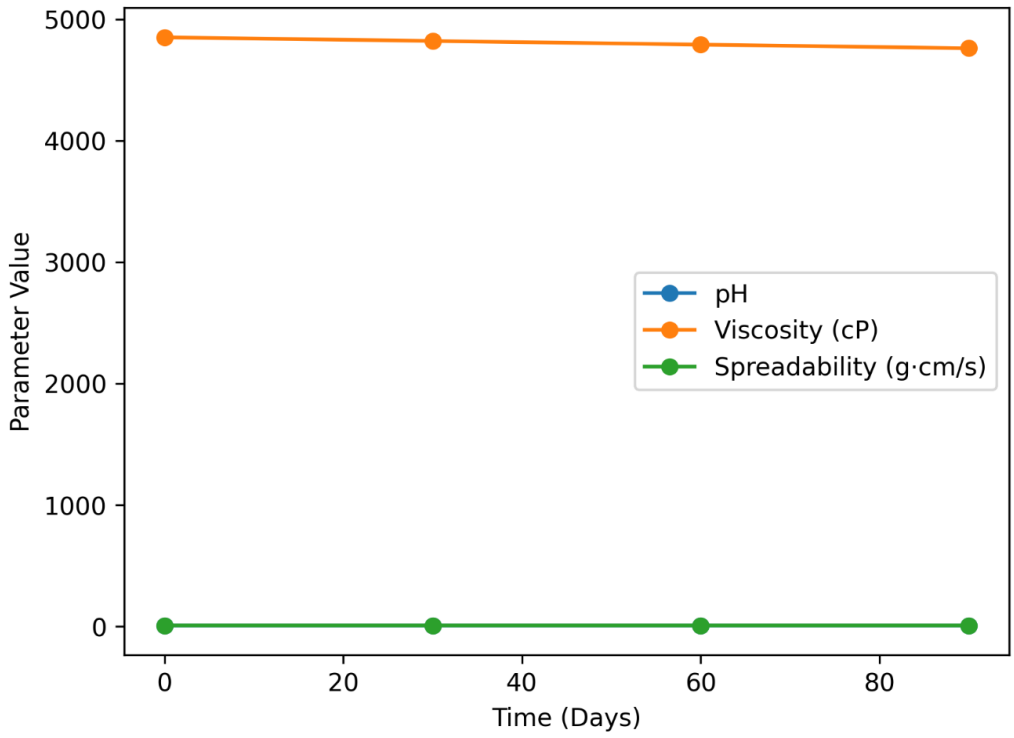

Figure 3: Stability trend analysis of optimized F2 hydrogel under accelerated conditions (40°C/75% RH) over 90 days showing minimal variation in pH, viscosity, and spreadability ($p > 0.05$). Data points represent Mean ± SD ($n = 3$). All parameters remained within acceptable ranges throughout the study period, confirming formulation robustness.

No phase separation, discoloration, odor development, or syneresis was observed throughout the study period. The robust stability profile confirms adequate preservative efficacy and formulation compatibility, meeting ICH requirements for cosmetic product stability (ICH harmonised tripartite guideline, 2003).

Primary Skin Irritation

Patch testing on six healthy volunteers revealed no signs of erythema, edema, itching, or burning sensation at 1, 24, or 48 hr post-application. The PII was calculated as 0.00, confirming that F2 is nonirritant and safe for topical cosmetic application (Draize, Woodard, and Calvery, 1944). This favorable safety profile is attributed to the skin-compatible pH, absence of known irritants, and the soothing properties of*Aloe vera* extract (West and Zhu, 2003).

LIMITATIONS AND FUTURE PERSPECTIVES

The study is limited by the absence of long-term clinical efficacy data and instrumental skin analysis. While the*in vitro* antioxidant activity, stability profile, and safety data are promising, quantitative clinical validation is essential for substantiating antiaging and skin-brightening claims under regulatory frameworks (European Commission, 2009).

Future investigations should include:

1. **Randomized, double-blind, placebo-controlled clinical trials** evaluating wrinkle depth reduction (via profilometry), melanin index reduction (via mexameter), and skin elasticity improvement (via cutometer) over 8–12 weeks in human volunteers.
2. **Comparative efficacy studies** against marketed benchmark products to establish competitive positioning.
3. **Confocal microscopyandhistological analysis** to confirm dermal structural improvements.
4. **Consumer perception and acceptability studies** to optimize sensory attributes for potential commercial application.

CONCLUSION

These studies would enable full regulatory compliance for antiaging and skin-brightening claims under cosmetics regulations (FDA, EU Cosmetics Regulation, CDSCO) and support potential intellectual property protection for the synergistic composition (Food and Drug Administration, 2020).

A multifunctional antiaging and skin-brightening cosmeceutical hydrogel was successfully developed and optimized using Carbopol® 940 as the gelling matrix. The F2 formulation (1.0% Carbopol®) exhibited ideal pH (5.9), viscosity (4,850

cP), and spreadability (6.8 g cm/s), along with significant antioxidant activity (78.4% DPPH scavenging). The formulation demonstrated excellent accelerated stability over 90 days with no significant physicochemical degradation ($p > 0.05$) and a nonirritant dermatologic safety profile (PII = 0.00).

The synergistic combination of niacinamide, 4.0% wt/wt, sodium ascorbyl phosphate (2.0% wt/wt), hyaluronic acid, 0.5% wt/wt,*Aloe vera* (5.0% wt/wt), and*Camellia sinensis* (2.0% wt/wt) provides a scientifically robust platform targeting multiple pathways of skin aging and hyperpigmentation. The Carbopol® hydrogel matrix ensures optimal rheology for topical delivery and sustained active release.

The formulation demonstrates strong potential for clinical translation, commercialization, and intellectual property development following further clinical validation.

ABBREVIATIONS

Niacinamide: Nicotinamide (Vitamin B3); **SAP:** Sodium Ascorbyl Phosphate; **HA:** Hyaluronic Acid; **ROS:** Reactive Oxygen Species; **NF-κB:** Nuclear Factor Kappa-B; **DPPH:** 2,2-Diphenyl-1-picrylhydrazyl; **TEWL:** Transepidermal Water Loss; **PII:** Primary Irritation Index; **IEC:** Independent Ethics Committee; **ICH:** International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use; **RH:** Relative Humidity; **r.p.m.:** Revolutions Per Minute; **UV:** Ultraviolet; **cP:** Centipoise; **SD:** Standard Deviation; **ANOVA:** Analysis of Variance; **q.s.:** Quantity Sufficient; **wt/wt:** Weight by Weight.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

Sachinkumar Jadhao conceptualized, designed, and supervised the research. Saylee Jadhao contributed to formulation development and product positioning.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Approved by Independent Ethics Committee (IEC/SW/2025/01). Written informed consent obtained from all volunteers.

SUMMARY

- Synergistic hydrogel combining niacinamide, 4.0%, sodium ascorbyl phosphate (2.0%), and hyaluronic acid, 0.5% for dual antiaging and skin-brightening effects.
- Optimized Carbopol® 940 concentration (1.0% wt/wt) providing ideal rheology (4,850 cP) and spreadability (6.8 g cm/s).
- Significant antioxidant activity (78.4% DPPH scavenging) due to Sodium Ascorbyl Phosphate (SAP) and green tea polyphenol synergy.
- Excellent accelerated stability (40°C/75% RH, 3 months) with no significant physicochemical degradation ($p > 0.05$).
- Nonirritant dermatologic profile confirmed (Primary Irritation Index =0.00).

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