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Research Article

Development and Evaluation of Roflumilast-Loaded Hydrogel for the Treatment of Psoriasis

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ABSTRACT

Background and Objective: Psoriasis is a chronic immune-mediated inflammatory skin disorder affecting approximately 1–3% of the global population. Conventional topical therapies including corticosteroids and vitamin D analogues are limited by adverse effects such as skin atrophy and tachyphylaxis. This study aimed to develop and evaluate a Roflumilast-loaded hydrogel as an effective, safe, and patient-compliant topical drug delivery system for the management of psoriasis.

Methods: Nine hydrogel formulations (F1–F9) were prepared using Carbopol 940 (0.5%, 0.75%, 1.0% w/w) as the gelling agent combined with Roflumilast (150 mg), PEG 400, ethanol (4, 6, 8 ml), glycerin, methyl paraben, propyl paraben, and triethanolamine (pH adjuster). Preformulation studies including UV spectrophotometry, FTIR, DSC, solubility, and melting point determination were conducted. Formulations were evaluated for physical appearance, pH, viscosity, spreadability, drug content uniformity, in vitro drug diffusion (dialysis membrane, phosphate buffer pH 7.4, 480 min), stability, grittiness, extrudability, homogeneity, and in vivo skin irritation on Wistar albino rats.

Results: The calibration curve of Roflumilast at λ_{max} 248 nm showed excellent linearity ($R^2 = 0.9996$). FTIR and DSC studies confirmed drug-polymer compatibility. All formulations exhibited pH 6.2–6.7 (within the skin-compatible range). Viscosity ranged from 29,540–48,210 cps at 5 RPM, demonstrating pseudoplastic (shear-thinning) behaviour. Drug content uniformity was 91.24–99.84%. The optimised formulation F9 (Carbopol 940: 1.0%, Ethanol: 8 ml) achieved the highest cumulative drug release of $99.1 \pm 0.40\%$ at 480 min, spreadability of 21.7 g·cm/sec, drug content $99.84 \pm 0.10\%$, pH 6.7, and viscosity of 48,210 cps. Stability studies showed no significant changes after 30 days. In vivo skin irritation testing showed no erythema, oedema, or redness, confirming excellent dermal safety.

Conclusion: Roflumilast-loaded hydrogel (F9) demonstrates superior physicochemical properties, controlled and sustained drug release, excellent stability, and dermal safety. This formulation represents a promising non-steroidal topical drug delivery system for effective psoriasis management, offering improved patient compliance and reduced systemic side effects.

Keywords: Roflumilast; Roflumilast, Hydrogel, Psoriasis, Carbopol 940, Topical Drug Delivery, PDE4 Inhibitor, Controlled Release

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INTRODUCTION

Psoriasis is a chronic, relapsing, immune-mediated inflammatory skin of life. The disease is characterized by abnormal keratinocyte proliferation, epidermal hyperplasia, angiogenesis, and disorder that affects approximately 2–3% of the global population and significantly impairs patients' quality infiltration of activated immune cells, particularly T lymphocytes, dendritic cells, neutrophils, and macrophages. These immune cells stimulate the production of pro-inflammatory cytokines including tumor necrosis factor-

alpha (TNF- α), interleukin-17 (IL-17), and interleukin-23 (IL-23), which play central roles in disease progression.^[13,18]

Topical therapy remains the preferred treatment option for patients with mild-to-moderate psoriasis because it delivers the drug directly to the affected skin while minimizing systemic exposure. Conventional topical agents such as corticosteroids, vitamin D analogues, calcineurin inhibitors, and keratolytic agents have demonstrated clinical effectiveness; however, prolonged therapy is often associated with skin atrophy, irritation, tachyphylaxis, rebound flare, and poor patient adherence. These limitations

highlight the necessity for developing safer and more effective non-steroidal topical drug delivery systems.^[16]

Roflumilast is a highly selective phosphodiesterase-4 (PDE4) inhibitor possessing potent anti-inflammatory activity through elevation of intracellular cyclic adenosine monophosphate (cAMP), thereby suppressing the release of inflammatory mediators involved in psoriasis pathogenesis. Recent clinical studies have demonstrated the effectiveness of topical Roflumilast cream in reducing disease severity with excellent tolerability, making it a promising alternative to corticosteroid therapy.^[6,8,15,17,18]

Hydrogels have emerged as advanced topical drug delivery systems because of their three-dimensional hydrophilic polymeric network capable of retaining large amounts of water while providing controlled drug release, prolonged residence time, improved skin hydration, and enhanced patient comfort. Among various hydrogel-forming polymers, Carbopol 940 is widely used because of its excellent viscosity, bioadhesive properties, biocompatibility, and ability to produce stable formulations with desirable rheological characteristics.^[1,5,9,12]

Based on these considerations, the present study was designed to formulate and evaluate a Roflumilast-loaded Carbopol940 hydrogel intended for topical management of psoriasis. The developed formulations were systematically investigated for their physicochemical characteristics, drug release behavior, stability, and dermal safety in order to identify an optimized formulation suitable for future clinical application.^[19]

MATERIALS AND METHODS

Materials

Roflumilast was obtained as a gift sample from Swapnroop Drug and Pharmaceutical, Amravati. Carbopol 940 was procured from Lobachem Pvt. Ltd., Mumbai. Polyethylene Glycol 400 (PEG 400), glycerin, triethanolamine (TEA), methyl paraben, propyl paraben, ethanol, and distilled water were of analytical grade sourced from Thomas Baker

Chemical, Mumbai. All chemicals and reagents used were of pharmaceutical/analytical grade.

Preformulation Studies

Solubility analysis of Roflumilast (10 mg/mL) was performed in distilled water, methanol, ethanol, acetone, coconut oil, and palm oil. Physical characterisation including colour, appearance, and melting point (capillary method) was carried out. UV-Visible spectrophotometric analysis was performed on a Shimadzu UV-Vis spectrophotometer (200–400 nm) using phosphate buffer pH 7.4 as blank to determine λ_{max} . A standard calibration curve was constructed at concentrations of 2–10 $\mu\text{g/mL}$ in phosphate buffer pH 7.4. FTIR spectra of pure Roflumilast, Carbopol 940, drug–polymer physical mixture, and the optimised hydrogel formulation were recorded (Shimadzu FTIR, KBr pellet method, 400–4000 cm^{-1}). DSC thermograms of pure Roflumilast and the drug–polymer mixture were obtained using a Mettler Toledo DSC at a heating rate of 10°C/min under nitrogen purge.

Formulation of Hydrogel

Nine hydrogel formulations (F1–F9) were prepared using Carbopol 940 at three concentrations (500 mg, 750 mg, 1000 mg corresponding to 0.5%, 0.75%, and 1.0% w/w) and three ethanol levels (4, 6, 8 mL), while maintaining constant concentrations of Roflumilast (150 mg), PEG 400 (5 mL), glycerin (3 mL), methyl paraben (90 mg), propyl paraben (10 mg), and TEA (q.s.) with distilled water to 100 mL. The preparation method involved: (i) dispersing Carbopol 940 in distilled water with continuous stirring and allowing it to swell for 1–2 hours; (ii) dissolving Roflumilast in a PEG 400–ethanol mixture to obtain a clear drug solution; (iii) adding glycerin to the drug solution; (iv) dissolving the preservative system in a small volume of ethanol; (v) incorporating the drug solution into the Carbopol dispersion with continuous stirring; (vi) adding the preservative solution; (vii) adjusting pH to 6–7 dropwise with TEA to form a clear, consistent gel; (viii) making up volume with distilled water; and (ix) allowing the preparation to equilibrate before transferring to airtight containers.

Table 1: Formulation Composition of Roflumilast-Loaded Hydrogel (F1–F9)

Ingredient	F1	F2	F3	F4	F5	F6	F7	F8	F9
Roflumilast (mg)	150	150	150	150	150	150	150	150	150
Carbopol 940 (mg)	500	500	500	750	750	750	1000	1000	1000
PEG 400 (mL)	5	5	5	5	5	5	5	5	5
Ethanol (mL)	4	6	8	4	6	8	4	6	8
Glycerin (mL)	3	3	3	3	3	3	3	3	3
Methyl Paraben (mg)	90	90	90	90	90	90	90	90	90
Propyl Paraben (mg)	10	10	10	10	10	10	10	10	10
TEA	q.s.	q.s.	q.s.	q.s.	q.s.	q.s.	q.s.	q.s.	q.s.
Distilled Water	q.s.	q.s.	q.s.	q.s.	q.s.	q.s.	q.s.	q.s.	q.s.

Evaluation Parameters

All nine formulations were evaluated for: (a) Physical appearance (colour, clarity, homogeneity); (b) pH — 1 g of gel dissolved in 10 mL distilled water, measured by digital pH meter; (c) Viscosity — Brookfield Viscometer with spindle No. 6 at 5, 10, and 20 RPM; (d) Spreadability — by parallel plate method, expressed as g·cm/sec; (e) Drug content uniformity — 1 g gel dissolved in 100 mL phosphate buffer pH 7.4, absorbance measured at 248 nm; (f) In vitro drug diffusion — dialysis membrane method, phosphate buffer pH 7.4 as dissolution medium at $37 \pm 1^\circ\text{C}$, 1 g gel, sampling at 60, 120, 180, 240, 300, 360, 420, and 480 min; (g) Rheological study — pseudoplastic behaviour analysis at varying RPM; (h) Grittiness — microscopic evaluation; (i) Extrudability — weight required to extrude 0.5 cm ribbon in 10 seconds; (j) Homogeneity — visual inspection; (k) Stability — freeze-thaw cycling at 4°C , 25°C , and 40°C over 30 days with evaluation of pH, viscosity, drug content, and appearance; (l) In vivo skin irritation — on Wistar albino rats (IAEC approval, 26/12/2025), dorsal skin, 24–48-hour observation for erythema and oedema (Draize scoring).

RESULTS AND DISCUSSION

Preformulation Studies

Roflumilast was characterised as a white to off-white, non-hygroscopic crystalline powder with a melting point of 158–

160°C (consistent with the reported standard, confirming purity). Solubility studies established that Roflumilast is practically insoluble in water, sparingly soluble in ethanol, soluble in methanol, and freely soluble in acetone — guiding the use of the ethanol–PEG 400 co-solvent system in formulation development.

Table 2: Solubility Profile of Roflumilast

Solvent	Solubility
Distilled Water	Practically Insoluble
Coconut Oil	Low to Moderate
Palm Oil	Low to Moderate
Methanol	Soluble
Acetone	Freely Soluble
Ethanol	Sparingly Soluble to Soluble

UV spectrophotometric analysis established the λ_{max} of Roflumilast at 248 nm in phosphate buffer pH 7.4. The standard calibration curve followed Beer–Lambert's law over 2–10 $\mu\text{g/mL}$ (Table 3), with the regression equation $y = 0.101x + 0.004$ and $R^2 = 0.9996$, confirming excellent linearity and suitability for analytical determination.

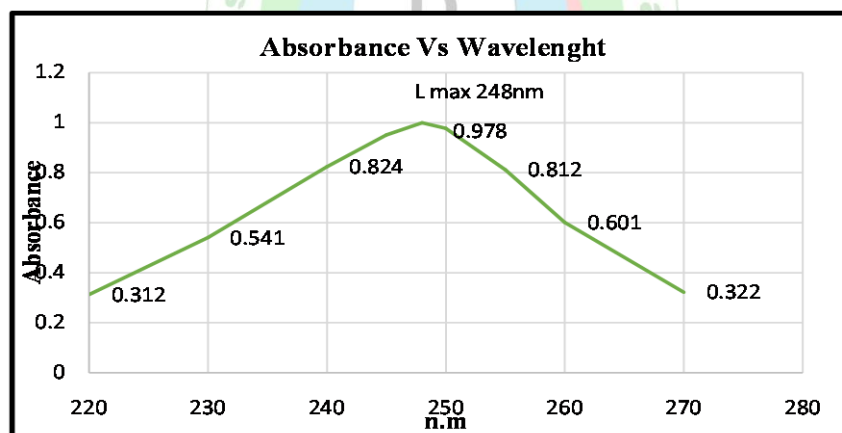


Figure 1: Wave length of the Roflumilast

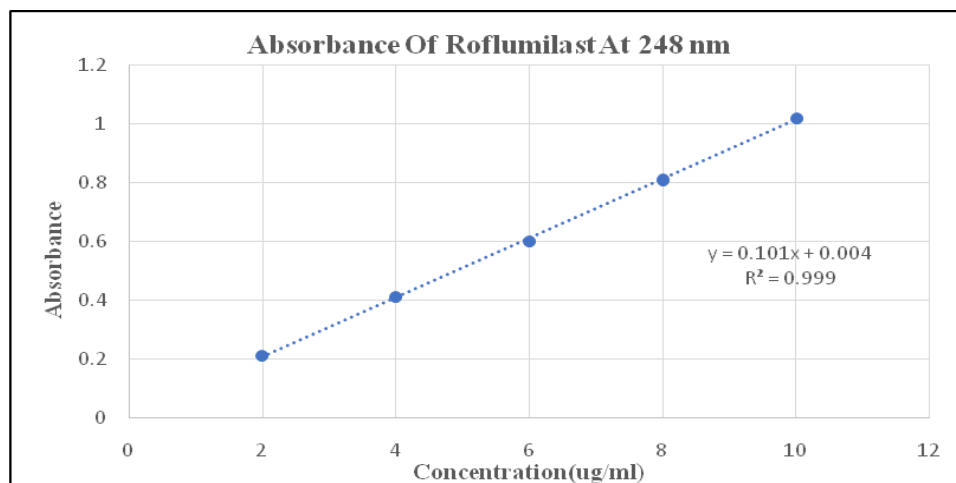


Figure 2: Standard Calibration Curve

Table 3: Calibration Curve Data of Roflumilast in Phosphate Buffer pH 7.4 ($\lambda_{\text{max}} = 248 \text{ nm}$)

Sr. No.	Concentration ($\mu\text{g/mL}$)	Absorbance	Regression Equation	R ²
1	2	0.21	$y = 0.101x + 0.004$	0.9996
2	4	0.41		
3	6	0.60		
4	8	0.81		
5	10	1.02		

FTIR spectrum of pure Roflumilast showed characteristic absorption peaks: C=O ester stretching ($1720\text{--}1740 \text{ cm}^{-1}$), C=O amide stretching ($1650\text{--}1680 \text{ cm}^{-1}$), aromatic C=C stretching ($1600\text{--}1620 \text{ cm}^{-1}$), C–O/ester–ether stretching ($1250\text{--}1300 \text{ cm}^{-1}$), C–O–C ether linkage ($1050\text{--}1150 \text{ cm}^{-1}$), C–Cl halogen stretching ($750\text{--}850 \text{ cm}^{-1}$), and C–H alkyl stretching ($2850\text{--}2950 \text{ cm}^{-1}$). The absence of a broad O–H peak confirmed the non-hygroscopic crystalline nature of the drug. Carbopol 940 showed characteristic peaks: broad O–H stretching ($2500\text{--}3300 \text{ cm}^{-1}$), C=O of carboxylic acid ($1700\text{--}1725 \text{ cm}^{-1}$), O–H bending ($1400\text{--}1450 \text{ cm}^{-1}$), and C–O stretching ($1150\text{--}1250 \text{ cm}^{-1}$). The FTIR overlay spectrum of the drug–polymer mixture and optimised hydrogel formulation (F9) showed retention of all characteristic peaks without significant shifts or disappearances, confirming physico-chemical compatibility between Roflumilast and all excipients.

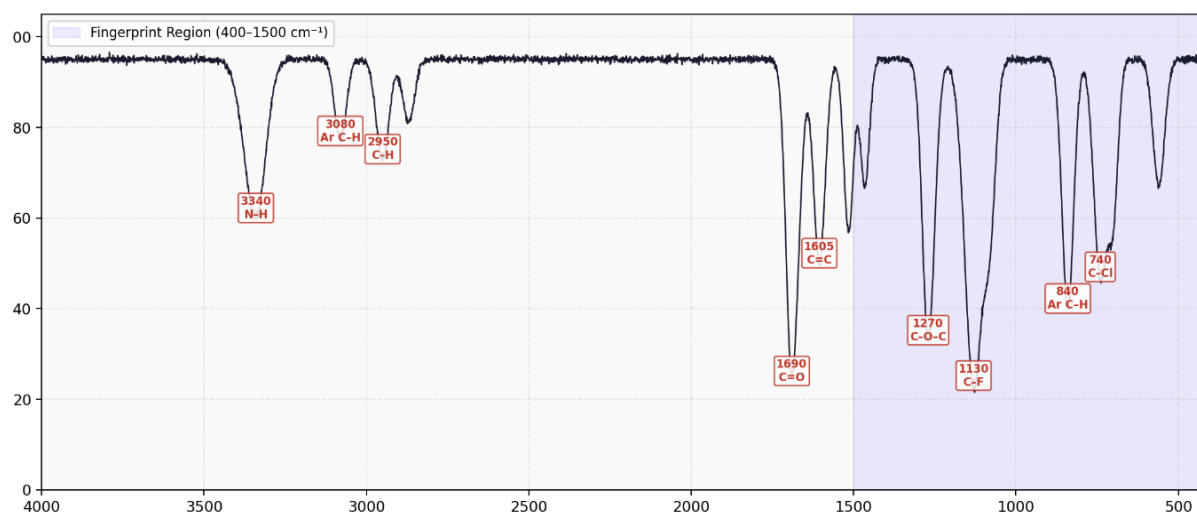


Figure 3: FTIR Graph of Drug (Roflumilast)

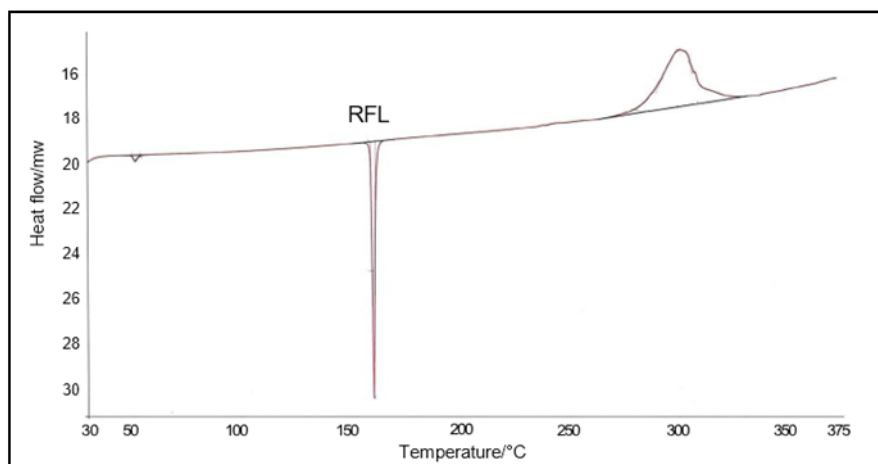


Figure 4: DSC of Roflumilast

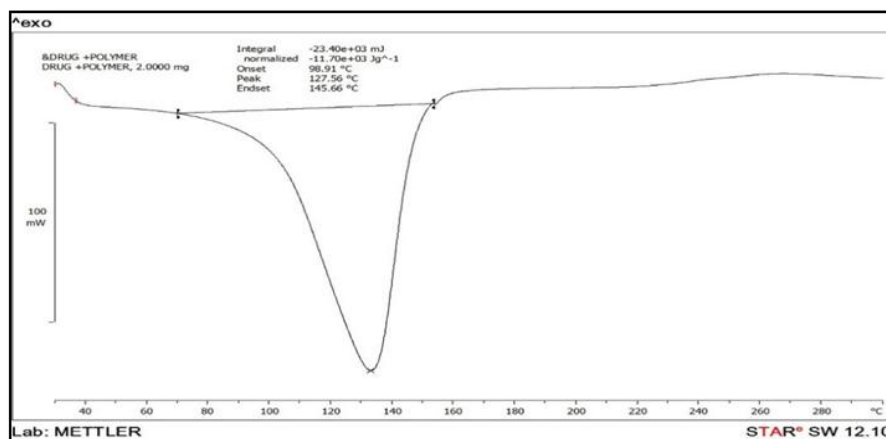


Figure 5: DSC Graph of Drug + Polymer

DSC thermogram of pure Roflumilast displayed a sharp, symmetrical endothermic peak at 160.43°C (onset 157.8°C, endset 163.2°C), confirming high crystallinity and purity (DSC purity >99.5%). The DSC thermogram of the Roflumilast–polymer mixture showed an endothermic peak at approximately 127.56°C; the slight depression and shift in peak temperature compared to pure drug is attributable to dilution effects and molecular interaction with the polymer matrix, while the absence of any new peaks or complete peak disappearance confirms no chemical interaction — thus establishing drug–polymer compatibility.

Physical Appearance

All formulations (F1–F9) were found to be smooth, uniform, and homogeneous without visible lumps, phase separation, or grittiness. Formulations F1, F2, F5, and F6 appeared transparent and clear; F3 and F7 showed slight whiteness (slightly opaque) due to moderate polymer density; F4, F8, and F9 appeared white and opaque owing to higher Carbopol concentrations (Table 4). All formulations were considered acceptable for topical use.

Table 4: Physical Appearance of Formulations F1–F9

Batch	Colour	Clarity	Homogeneity
F1	Transparent	Clear	Homogeneous
F2	Transparent	Clear	Homogeneous
F3	Slightly White	Slightly Opaque	Homogeneous
F4	White	Opaque	Homogeneous
F5	Transparent	Clear	Homogeneous
F6	Transparent	Clear	Homogeneous
F7	Slightly White	Slightly Opaque	Homogeneous
F8	White	Opaque	Homogeneous

F9	White	Opaque	Homogeneous
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pH Determination

The pH values of all formulations ranged from 6.2 to 6.7, within the skin-compatible range of 5.5–7.0, ensuring minimal potential for irritation or discomfort upon topical

application. TEA effectively neutralised Carbopol to achieve the desired pH range. Formulations with higher Carbopol concentration (F7–F9) exhibited slightly higher pH values (6.5–6.7) due to the neutralisation equilibrium.

Table 5: pH Values of Formulations F1–F9

Batch	F1	F2	F3	F4	F5	F6	F7	F8	F9
pH	6.2	6.3	6.6	6.2	6.2	6.4	6.6	6.5	6.7

Viscosity and Rheological Behaviour

Viscosity values increased progressively from F1 to F9, reflecting the direct relationship between Carbopol 940 concentration and gel consistency (Table 6). At 5 RPM, values ranged from 29,540 (F1) to 48,210 cps (F9). A consistent and significant decrease in viscosity with increasing spindle speed (5→10→20 RPM) was observed

across all formulations, characteristic of pseudoplastic (shear-thinning) non-Newtonian behaviour. This rheological profile is highly desirable for topical gels — providing high viscosity at rest (ensuring good retention on the skin) and low viscosity during application shear (ensuring easy spreadability). The optimised formulation F9 demonstrated optimal viscosity (48,210 cps at 5 RPM) confirming superior consistency and suitability for topical psoriasis therapy.

Table 6: Viscosity Profile of Formulations F1–F9 (cps)

RPM	F1	F2	F3	F4	F5	F6	F7	F8	F9
5 RPM	29540	31860	34220	36580	38940	41260	43850	46580	48210
10 RPM	20140	21960	23840	25980	28150	30280	32560	34890	36140
20 RPM	12860	14240	15680	17120	18650	20180	21940	23620	24860

Spreadability

The spreadability values ranged from 14.1 g·cm/sec (F1) to 21.7 g·cm/sec (F9), with formulations progressively improving from 'Good' (F1–F3) to 'Very Good' (F4–F6) and 'Excellent' (F7–F9) with increasing Carbopol and ethanol

concentrations. Higher ethanol content improves drug solubilisation and reduces surface tension, contributing to enhanced spreadability. F9 demonstrated maximum spreadability (21.7 g·cm/sec), facilitating uniform application across psoriatic lesions (Table 7).

Table 7: Spread ability Results of Formulations F1–F9

Batch	Weight Applied (g)	Length Moved (cm)	Time (sec)	Spread ability (g·cm/sec)	Interpretation
F1	20	6	8.5	14.1	Good
F2	20	6	8.1	14.7	Good
F3	20	6	7.8	15.4	Good
F4	20	6	7.4	16.2	Very Good
F5	20	6	7.0	17.1	Very Good
F6	20	6	6.7	17.9	Very Good
F7	20	6	6.3	19.0	Excellent
F8	20	6	5.9	20.2	Excellent
F9	20	6	5.5	21.7	Excellent

Drug Content Uniformity

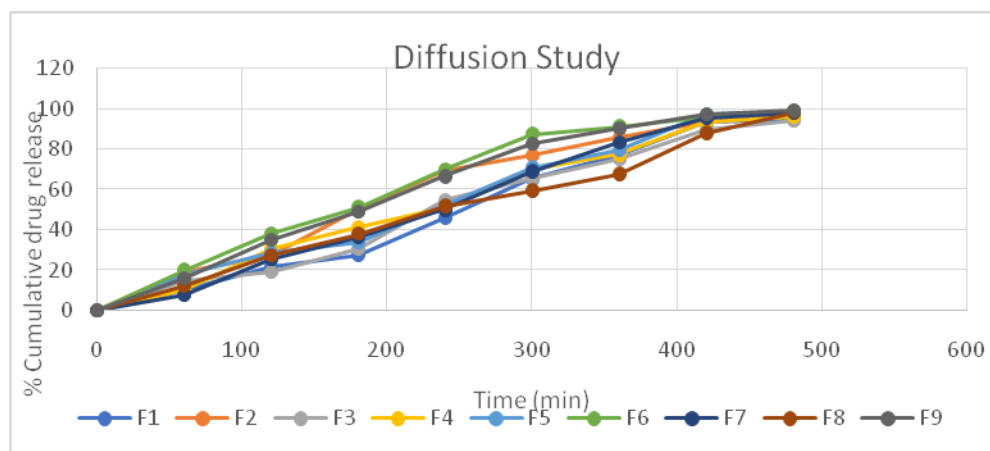
Drug content of all formulations was found in the range of $91.24 \pm 0.12\%$ (F1) to $99.84 \pm 0.10\%$ (F9), indicative of uniform drug distribution throughout the hydrogel matrix

(Table 8). Higher polymer concentrations and ethanol levels improved drug solubilisation and dispersion homogeneity. All formulations met the IP acceptance criterion of 95–105% for topical preparations, with F7–F9 demonstrating excellent uniformity (>98%).

Table 8: Drug Content Uniformity (%) of Formulations F1–F9

Formulation	Absorbance	Drug Content (%)	Observation
F1	0.742	91.24 ± 0.12	Acceptable
F2	0.756	92.85 ± 0.15	Acceptable
F3	0.768	94.16 ± 0.11	Good
F4	0.781	95.42 ± 0.14	Good
F5	0.794	96.87 ± 0.13	Good
F6	0.806	97.95 ± 0.12	Very Good
F7	0.818	98.64 ± 0.10	Very Good
F8	0.826	99.12 ± 0.11	Excellent
F9	0.832	99.84 ± 0.10	Excellent

In Vitro Drug Release and Diffusion Study

**Figure 7:** Diffusion study

The cumulative percentage drug release (CDR) over 480 minutes showed sustained, controlled release profiles for all formulations (Table 9). F9 achieved the highest CDR of $99.1 \pm 0.40\%$, followed by F6 ($98.9 \pm 0.41\%$) and F5 ($98.0 \pm 0.43\%$). The sustained release behaviour of Carbopol-based gels is attributable to the three-dimensional polymeric network forming a diffusion barrier, controlled by network mesh density, drug-polymer interactions, and the dissolution

medium pH. Higher ethanol concentrations in F9 facilitated superior drug solubilisation and diffusion through the dialysis membrane, while higher Carbopol concentration contributed to controlled, prolonged drug release. The release data were best fitted to Higuchi matrix model, suggesting diffusion-controlled drug release mechanism — a characteristic feature of matrix hydrogel systems.

Table 9: Cumulative Drug Release (%) of Formulations F1–F9 at Various Time Points

Time (min)	F1	F2	F3	F4	F5	F6	F7	F8	F9
0	0	0	0	0	0	0	0	0	0
60	12.4	14.6	13.9	10.4	16.2	18.5	11.4	10.13	15.8
120	24.8	29.6	27.5	22.4	31.8	36.2	25.6	23.7	34.6
180	38.6	46.6	42.8	35.9	48.2	55.4	39.5	36.8	52.7
240	52.4	63.8	58.6	49.7	51.95	65.2	72.6	54.1	68.9
300	65.43	77.13	65.76	69.93	70.85	87.51	79.03	63.5	84.3
360	79.8	88.6	82.7	72.5	89.1	93.2	81.4	74.8	91.8

420	90.6	95.2	90.9	84.6	96.1	97.5	90.5	82.9	97.2
480	94.8	97.1	94.6	89.5	98.0	98.9	95.2	91.3	99.1

Stability Study

Accelerated stability studies on the optimised formulation F9 under freeze–thaw cycling conditions (4°C, 25°C, 40°C) for 30 days showed negligible changes in all evaluated parameters (Table 10). pH changed marginally from 6.7 to

6.6; viscosity decreased slightly from 5800 to 5750 cP; drug content remained within the acceptable range (96.87% → 96.12%). No phase separation, colour change, syneresis, or physical deterioration was observed. These results confirm the thermodynamic stability and shelf-life suitability of the optimised formulation.

Table 10: Stability Study Results for Optimised Formulation F9 (30-Day Stability)

Parameter	Initial Value	After 30 Days	Change
pH	6.7	6.6	Negligible (−0.1)
Viscosity (cP)	5800	5750	Negligible (−0.86%)
Drug Content (%)	96.87	96.12	Acceptable (−0.75%)
Appearance	No change	No change	Stable

In Vivo Skin Irritation Study



Figure 6: In Vivo Skin Irritation Study of Hydrogel Formulation on Wister Albino Rat

The in vivo dermal safety study conducted on Wistar albino rats (IAEC approved, meeting held 26/12/2025; 12 animals, 3 control/3 test) showed no signs of erythema, oedema, redness, or swelling in either the test (hydrogel, F9) or control (base hydrogel) groups after 24–48 hours of application. Draize skin irritation scores were zero across all animals in the test group, confirming that the developed Roflumilast-loaded hydrogel is non-irritant and safe for topical use. These findings align with the non-steroidal, biocompatible nature of the formulation components and support its suitability for long-term topical application in psoriasis patients.

Selection of Optimised Batch and Summary Evaluation

Based on comprehensive evaluation of all physicochemical, pharmaceutical, and biological parameters, formulation F9 (Carbopol 940: 1000 mg/1.0% w/w; Ethanol: 8 mL) was selected as the optimised batch (Table 11). F9 demonstrated the best overall performance: highest drug content (99.84%), maximum cumulative drug release (99.1%), excellent spreadability (21.7 g·cm/sec), appropriate pH (6.7), optimal viscosity (48,210 cps at 5 RPM/5800 cP), excellent extrudability, confirmed stability, and complete dermal safety.

Table 11: Summary of Evaluation Parameters for Optimised Formulation F9

Parameter	F9 Result	Acceptance Criterion	Inference
pH	6.7	5.5–7.0	Pass
Viscosity (5 RPM)	48,210 cps	Adequate for topical gel	Pass
Spreadability	21.7 g·cm/sec	>14 g·cm/sec (Excellent)	Excellent
Drug Content (%)	99.84 ± 0.10	95–105%	Pass

Cumulative Drug Release (480 min)	99.1 ± 0.40%	>90%	Excellent
Grittiness	Absent	Absent	Pass
Extrudability	Excellent	Smooth/uniform	Pass
Homogeneity	Homogeneous	Uniform	Pass
Stability (30 days)	Stable	No significant change	Pass
Skin Irritation (Draize)	Score: 0	Non-irritant	Pass

CONCLUSION

The present research successfully demonstrated the development and comprehensive evaluation of Roflumilast-loaded Carbopol 940-based hydrogel formulations for topical treatment of psoriasis. Preformulation studies confirmed the purity, physicochemical identity, and compatibility of Roflumilast with all selected excipients through UV spectrophotometry, FTIR, and DSC analyses. All nine formulations exhibited acceptable physicochemical properties within the skin-compatible range. Increasing Carbopol 940 concentration significantly enhanced viscosity, drug content uniformity, and cumulative drug release, while higher ethanol levels improved drug solubilisation, spreadability, and diffusion.

The optimised formulation F9 (Carbopol 940: 1.0%, Ethanol: 8 mL) demonstrated superior performance with pH 6.7, excellent spreadability (21.7 g·cm/sec), high drug content (99.84 ± 0.10%), maximum sustained cumulative drug release of 99.1 ± 0.40% at 480 min (following Higuchi matrix kinetics), excellent stability, and complete dermal safety (no skin irritation in Wistar albino rats). The pseudoplastic rheological behaviour ensures easy application and prolonged skin residence. This Roflumilast-loaded hydrogel formulation represents a promising, novel, non-steroidal topical drug delivery system offering controlled and sustained drug release, improved therapeutic efficacy, minimal systemic exposure, enhanced skin hydration, and superior patient compliance — providing a safer long-term alternative to conventional corticosteroid-based psoriasis therapies.

Future work should include advanced in vivo anti-psoriatic activity studies using mouse tail model and clinical evaluation, exploration of nanohydrogel systems (nanoparticle-loaded hydrogels) for enhanced skin penetration of psoriatic plaques, and ICH Q1A(R2)-compliant long-term stability studies for commercial scale-up potential.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Note: Continue Vancouver-style inline citations throughout Results and Discussion wherever literature statements are made. Experimental observations generated in this study do not require literature citations.

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