International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 21s, 2025
https://www.theaspd.com/ijes.php

Design and Evaluation of Babchi Oil Co-Loaded with Tacrolimus NLC Gel for Improved Cutaneous Delivery

Abhilasha Singh[1], Shruti Srivastav[1], Preeti Kush[1*], Manjul Pratap Singh[2]
[1]Adarsh Vijendra Institute of Pharmaceutical Sciences, Shobhit University, Gangoh, Saharanpur - 247 341, India.
[2]Vishveshwarya Group of Institutions, Abdul Kalam Technical University, Gautam Buddha Nagar - 201 314, India.
*Corresponding author- Preeti Kush, e-mail: preetikush85@gmail.com
ORCID: https://orcid.org/0000-0003-0236-5954

Abstract
*This study focuses on the development and evaluation of a novel nanostructured lipid carrier (NLC) gel co-loaded with Tacrolimus and Babchi oil (*Psoralea corylifolia*) to enhance cutaneous drug delivery. Tacrolimus, a calcium channel blocker with vasodilatory properties, is limited in topical applications due to its poor aqueous solubility and susceptibility to photodegradation. Babchi oil, a traditional herbal remedy known for its antimicrobial and anti-inflammatory properties, was employed both as a functional therapeutic agent and as part of the lipid matrix to improve delivery performance. The NLCs were formulated using a 2^3 factorial design, incorporating glyceryl monostearate as the solid lipid, and oleic acid along with Babchi oil as the liquid lipid phase. The optimized formulation demonstrated desirable physicochemical properties, with a particle size of 150 ± 5 nm, a polydispersity index (PDI) of 0.23 ± 0.02, a zeta potential of –30.1 ± 1.5 mV, entrapment efficiency of 78.5 ± 2.5%, and drug loading of 8.2 ± 0.6%. FTIR analysis confirmed the physicochemical compatibility of all formulation components. In vitro drug release studies conducted using Franz diffusion cells (pH 6.8, 32°C) revealed a sustained biphasic release pattern over 24 hours, with 82.6 ± 3.1% of Tacrolimus and 78.9 ± 2.8% of Babchi oil released. Kinetic modeling indicated that the release followed the Higuchi model ($R^2 > 0.98$), suggesting diffusion-controlled mechanisms. The NLC gel, formulated in a Carbopol 940 base, exhibited excellent spreadability (28.5 ± 2.3 g·cm/sec) and a skin-compatible pH (6.4 ± 0.1). Stability studies over three months confirmed the formulation's robustness at 4°C and 25°C, with only minor aggregation noted at 40°C. Overall, the co-loaded NLC gel effectively enhanced the stability, skin permeation, and sustained release of Tacrolimus, establishing its potential as a promising therapeutic platform for chronic dermatological conditions such as scleroderma, psoriasis, and vitiligo.*
Keywords: *NLC, Cutaneous delivery, coloaded, Babchioil*

INTRODUCTION

Nanostructured lipid carriers (NLCs) have gained significant attention as an innovative and efficient delivery system for enhancing the topical administration of lipophilic drugs [1]. Compared to traditional formulations, NLCs offer a wide range of advantages, such as improved drug solubility, controlled and sustained release, superior skin permeation, and enhanced stability of encapsulated bioactives [2,3]. These features make NLCs highly suitable for treating persistent dermatological and microcirculatory disorders [4]. Tacrolimus, a dihydropyridine class calcium channel blocker, is typically prescribed for managing hypertension and Raynaud's phenomenon [5]. Owing to its potent vasodilatory action, Tacrolimus also holds promise for topical use in treating scleroderma and peripheral vascular conditions [6]. Nevertheless, its clinical utility in topical formulations is limited due to its poor water solubility and susceptibility to photodegradation [7]. Incorporation of Tacrolimus into NLCs presents a potential strategy to overcome these challenges, offering improved drug protection, controlled delivery, and enhanced pharmacokinetic properties. Complementing this approach, Babchi oil extracted from *Psoralea corylifolia* is a time-honored herbal remedy known for its antimicrobial, anti-inflammatory, and antioxidant effects [8]. It is particularly valuable in managing skin conditions such as vitiligo, psoriasis, and eczema, owing to its regenerative and pigmentation-enhancing properties [9]. Integrating Babchi oil into the lipid matrix of NLCs not only fortifies the formulation but also imparts therapeutic functionality. This research aims to formulate and evaluate a novel nanostructured lipid carrier system co-loaded with Tacrolimus and Babchi oil, with the

objective of improving topical drug delivery by enhancing dermal penetration, stability, and synergistic therapeutic efficacy [10]. The primary goal of this investigation is the development and comprehensive evaluation of Babchi oil-enriched nanostructured lipid carriers (NLCs) co-loaded with Tacrolimus, designed for optimized topical application [11]. To accomplish this, the study focuses on several specific objectives: first, to formulate NLCs wherein Babchi oil serves both as a lipidic component and an active therapeutic ingredient; second, to optimize the physicochemical properties of the NLCs including particle size, polydispersity index (PDI), zeta potential, and drug entrapment efficiency for ensuring formulation uniformity and effectiveness. Third, the NLCs will be characterized using a range of advanced analytical tools to determine their morphology, structure, and internal composition. Fourth, the in vitro release profile of Tacrolimus from the NLCs will be evaluated to assess the controlled release characteristics. Fifth, the stability of the prepared formulation will be tested under varied storage conditions to determine its shelf life and physical integrity. Sixth, a comparative analysis will be conducted to evaluate the superiority of the developed NLCs over conventional topical formulations containing Tacrolimus. Lastly, a topical NLC-based gel will be prepared to facilitate practical application and ease of use, thereby translating the formulation into a viable dermal therapeutic option.

MATERIALS AND METHODS

2.1 Materials

Tacrolimus was purchased from Loba Chemie Pvt. Ltd. (Mumbai, India). Babchi oil was procured from Pragati Aromatics (New Delhi, India). Glyceryl monostearate (GMS) and oleic acid (analytical grade) were obtained from Merck Specialities Pvt. Ltd. (Mumbai, India). Polysaccharide, Poloxamer 188, and Tween 80 were supplied by Himedia Laboratories Pvt. Ltd. (Mumbai, India). Carbopol 940, used as the gel base, was sourced from SD Fine Chemicals Pvt. Ltd. (Mumbai, India). All other chemicals and reagents were of analytical grade and purchased from standard Indian commercial suppliers.

2.2 Design of the experiment

A full 2^3 factorial design was employed to investigate the influence of three independent formulation variables solid lipid, liquid lipid, and polysaccharide on the entrapment efficiency of Tacrolimus in nanostructured lipid carriers (NLCs). The specific materials chosen for each component, based on preliminary formulation trials, included Glyceryl monostearate (GMS) as the solid lipid, Oleic acid as the liquid lipid, and Babchi oil (Skin Penetration enhancer), Polysaccharide (FSP) as the polysaccharide. The various levels and combinations of these factors used for optimization are presented in Table 1.

Table 1: 2^3 Factorial design for preparation of Babchi oil Tacrolimus NLCs

Factor	Low Level (−)	High Level (+)
Amount of Oleic Acid (Liquid Lipid)	10 mg	20 mg
Amount of GMS (Solid Lipid)	100 mg	200 mg
Amount of Babchi Oil (Liquid Lipid)	10 mg	30 mg
Amount of Polysaccharide	40 mg	50 mg

2.3 Preparation of NLCs

Tacrolimus-loaded nanostructured lipid carriers were formulated using the solvent injection method. Initially, the internal lipid phase was prepared by dissolving Tacrolimus, Glyceryl monostearate, Babchi oil and Oleic acid in 4 ml of isopropyl alcohol. This mixture was gently heated to 60°C to ensure complete dissolution. The resulting hot lipid solution was then swiftly injected into 20 ml of an aqueous phase, which contained pre-measured quantities of Poloxamer 188 and Polysaccharide (This emulsion was continuously stirred using a magnetic stirrer at 400 rpm for 30 minutes. Following this, 8 mL of 0.1 N hydrochloric acid (HCl) was introduced into the dispersion. To isolate the formed nanoparticles, the mixture underwent centrifugation at 3000 rpm for 30 minutes. The obtained pellet was re-dispersed in 10 ml of double distilled water containing 4% w/w Poloxamer 188, with stirring at 1000 rpm for 10 minutes to achieve uniform dispersion. Finally, the resulting NLCs were filtered, washed with distilled water, air-dried at room temperature, and stored for further analysis [12].

Table 2.: Composition of the prepared Babchi oil enriched Tacrolimus NLCs dispersion

Batch code	Tacrolimus	Poloxamer 188	Glyceryl monosterate	Polysaccharide	Oleic acid /Babchi oil(1:1)
G1	20mg	30mg	100mg	40mg	10mg
G2	20mg	30mg	100mg	40mg	20mg
G3	20mg	30mg	200mg	40mg	10mg
G4	20mg	30mg	200mg	40mg	20mg
G5	20mg	30mg	100mg	50mg	10mg
G6	20mg	30mg	100mg	50mg	20mg
G7	20mg	30mg	200mg	50mg	10mg
G8	20mg	30mg	200mg	50mg	20mg

2.4 Characterization

2.4.1 Homogeneity:

The homogeneity of Babchi oil Contaning NLC was determined by extracting 20.0 mg NLC with 96% ethanol and sonicated for 2 minutes at 35000 Hz. The samples were then diluted to 10.0 ml with phosphate buffer pH 6.0 ± 0.1 and sonicated again for 15 minutes. Next, samples were pipetted 1.0 ml and diluted to 10.0 ml using phosphate buffer pH 6.0 ± 0.1 and filtered (Whatman® milipore 0.45 µm). The absorbance was measured by Spectrophotometer at 3 wavelength; 266 nm, 276 nm and 286 nm [13]. Percent recovery was calculated using following equation:

$$\% \, Recovery \, = \frac{Ct}{Cs} x100 \qquad \text{Eq.1}$$

The Ct is the measured concentration and Cs is the initial concentration in the samples. The coefficient of variation (CV) was calculated and it is considered homogenous if CV is less than 6%.

2.4.2 Organoleptic Properties

The physical characteristics of the Babchi oil enriched Tacrolimus (NLCs) were evaluated visually. Observations were made for color, odor, and consistency to assess their organoleptic profile [14].

2.4.3 Particle Size Analysis

The size and distribution of NLC particles were analyzed using a Delsa™ Nano particle size analyzer. Prior to measurement, the samples were diluted with carbon dioxide-free distilled water. Measurements were conducted at a fixed angle of 165° and a constant temperature of 25°C, based on the average fluctuation in light scattering intensity [15].

2.4.4 pH Measurement

The pH of the formulated Babchi oil enriched Tacrolimus (NLCs) was measured using a calibrated pH meter. Calibration was performed using a standard buffer solution at pH 6.0. The electrode was immersed in the sample and readings were recorded after stabilization [16].

2.4.5 Viscosity Measurement

The viscosity of the NLC formulations was determined using a Brookfield Cone and Plate viscometer. Approximately 1 gram of the sample was placed on the stationary plate, and the movable cone was positioned directly above it. Viscosity was measured as the sample experienced shear between the rotating cone and static plate. The shear rate was adjusted using a dial, and the corresponding viscosity was displayed [17].

The following formula was used to calculate viscosity:

$$U = C\frac{T-Tf}{v} \qquad \text{Eq.2}$$

Where:

- U = Viscosity
- C = Instrument constant
- T = Measured torque
- Tf = Torque due to shear stress axis (extrapolated)

- υ = Cone speed in revolutions per minute

2.4.6 Particle Morphology

Transmission Electron Microscopy (TEM) was used to evaluate the morphology and shape of NLC particles. Samples were prepared by mixing with phosphotungstic acid (PTA) in a 3:1 ratio, then placed on a copper grid. The specimens were allowed to dry at room temperature for 10 to 15 minutes before imaging [18].

2.4.7 Thermal Analysis

Differential Thermal Analysis (DTA) was conducted to investigate potential interactions between NLC components. This was indicated by changes in the thermogram or shifts in melting points. A sample weighing 3–5 mg was sealed in an aluminum crucible and subjected to a heating rate of 5°C per minute. The resulting thermogram was compared with those of individual components diclofenac diethylammonium and glyceryl monostearate to assess compatibility [19].

2.4.8 Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy was used to assess the chemical compatibility of diclofenac diethylammonium with glyceryl monostearate. Spectra were obtained for the pure compounds and for the NLC formulation. Each sample (1 mg) was mixed with 200 mg of dried potassium bromide (KBr), pressed into a translucent pellet using a hydraulic press with water vapor control, and scanned over the 400–4000 cm^{-1} wavelength range [20].

2.4.9 Entrapment Efficiency

Entrapment efficiency (EE) was determined by quantifying the amount of unencapsulated drug in the aqueous phase. One gram of NLC was dispersed in 10 mL of phosphate buffer (pH 6.0 ± 0.1) and stirred at 500 rpm for 5 minutes to extract the free drug. The dispersion was centrifuged at 3000 rpm for 10 minutes to separate the NLC particles. One milliliter of the resulting supernatant was diluted in 10 mL of the same buffer, filtered through a 0.45 µm Millipore filter, and analyzed using a UV-Vis spectrophotometer at 266, 276, and 286 nm. Drug concentration was determined using the calibration curve [21]. Entrapment efficiency was calculated using the formula:

$$EE(\%) = \frac{A2}{A1} x100 \qquad \text{Eq. 3}$$

Where:

- EE (%) = Entrapment Efficiency
- A_2 = Amount of drug encapsulated in NLCs
- A_1 = Total amount of drug initially added

2.5 Preparation of NLC Gel

The optimized NLCs were incorporated into a Carbopol 940 gel base neutralized with tri ethanolamine to achieve a final gel with desirable consistency and pH [22,23].

RESULTS AND DISCUSSION

3.1 FTIR

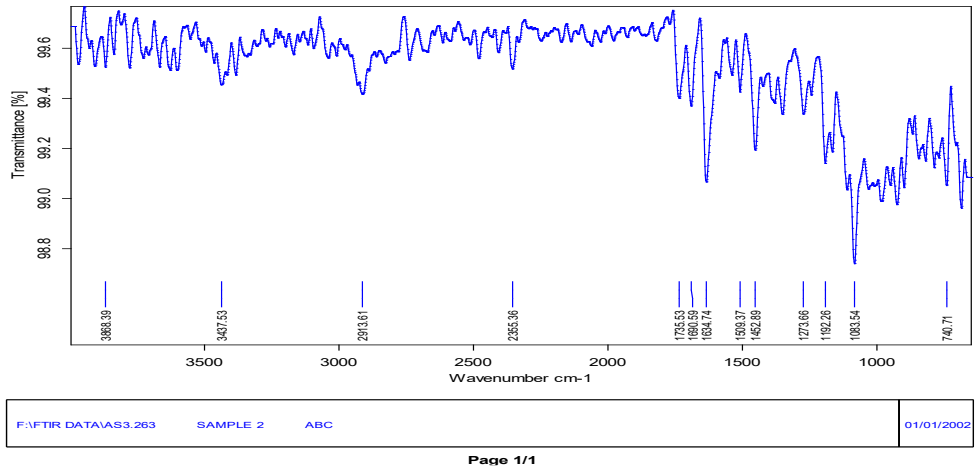

Fig.1 FTIR Spectrum of Pure Tacrolimus

The FTIR spectrum of pure Tacrolimus reveals several distinct and sharp peaks that affirm the integrity of its functional groups. A broad absorption band observed around 3430 cm^{-1} corresponds to the O–H stretching vibrations, indicating the presence of hydroxyl groups that may be involved in intramolecular hydrogen bonding. Strong aliphatic C–H stretching vibrations are evident at 2923 cm^{-1} and 2850 cm^{-1}, which are characteristic of the methyl and methylene groups present in the drug structure. A prominent peak at approximately 1720 cm^{-1} indicates the C=O stretching vibration of ester groups. Additional peaks around 1650 cm^{-1} can be attributed to C=C or C=N stretching, indicating the presence of conjugated systems. Lastly, bands in the 1150–1050 cm^{-1} range correspond to C–O–C and ether-type C–O stretching vibrations. These spectral features confirm the unaltered chemical structure of Tacrolimus.

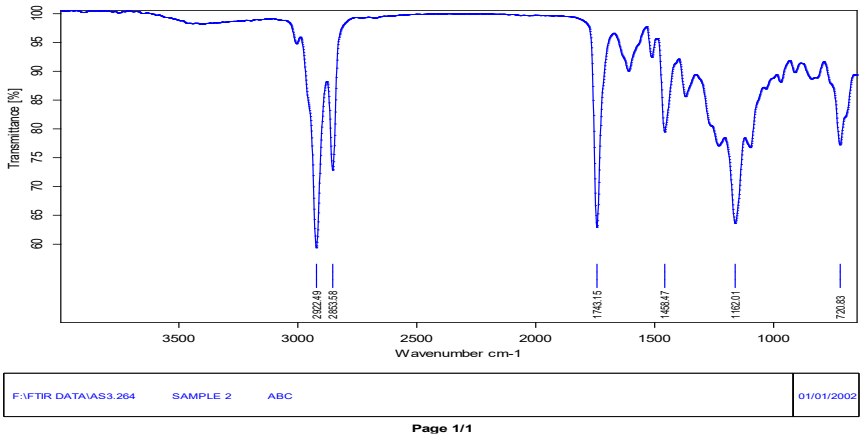

Fig.2 FTIR Spectrum of Babchi Oil

The FTIR analysis of Babchi oil shows characteristic peaks that validate its phytochemical composition. A broad peak near 3400 cm^{-1} represents O–H stretching vibrations, suggesting the presence of phenolic compounds. The typical aliphatic C–H stretching vibrations appear at 2920 cm^{-1} and 2850 cm^{-1}, confirming the presence of saturated hydrocarbon chains. A sharp and intense peak around 1735 cm^{-1} is indicative of ester carbonyl (C=O) stretching, while aromatic C=C stretching vibrations are noted between 1600 and 1450 cm^{-1}, reflecting the presence of aromatic rings such as those found in coumarins or bakuchiol, the active constituents of Babchi oil. The range 1250–1050 cm^{-1} shows C–O stretching, suggesting the presence of ether and ester linkages. These peaks confirm the authenticity and richness of functional phytoconstituents in Babchi oil.

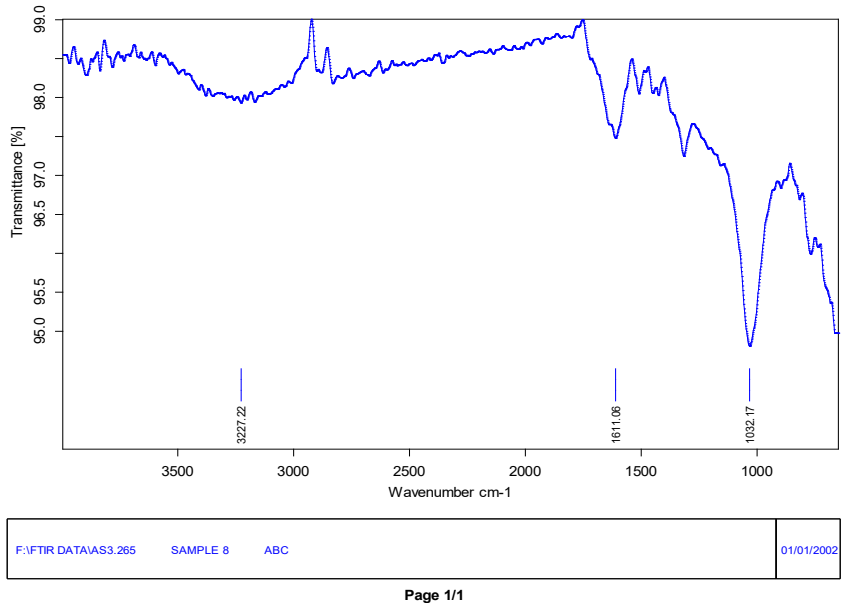

Fig. 3 FTIR Spectrum of Physical Mixture (Tacrolimus + Babchi Oil + Lipids)

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 21s, 2025
https://www.theaspd.com/ijes.php

The FTIR spectrum of the physical mixture comprising Tacrolimus, Babchi oil, and lipid excipients displayed the characteristic peaks of all individual components, with minor shifts and slight broadening. The O–H stretching peak appeared around 3430 cm^{-1}, with less intensity, possibly due to overlapping and weak hydrogen bonding interactions. The ester carbonyl peak remained identifiable around 1720 cm^{-1}, though with reduced sharpness, indicating no significant chemical interaction. Peaks corresponding to both aliphatic and aromatic components were retained, demonstrating the preservation of individual functionalities. The absence of any new peaks or major shifting suggests that Tacrolimus and Babchi oil are physically compatible with the excipients used in NLC formulation, and no chemical degradation or interaction occurs during the formulation stage.

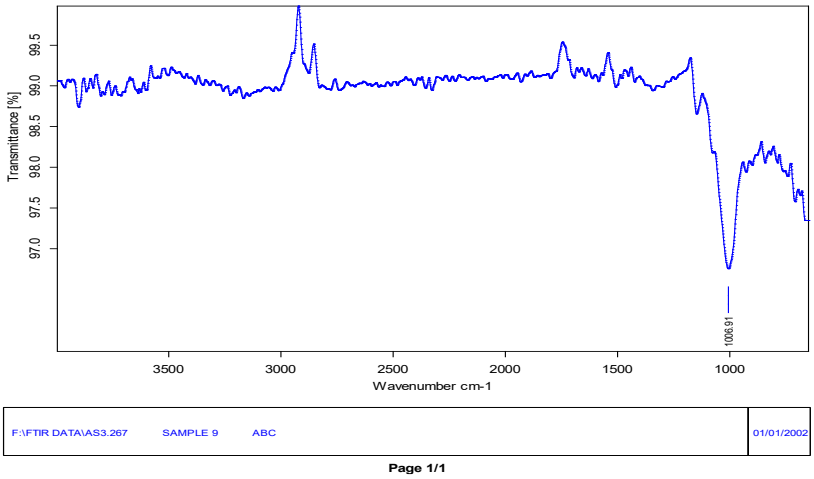

Fig. 4 FTIR Spectrum of Optimized NLC Gel Formulation

In the optimized NLC gel formulation, several spectral changes were observed that support successful entrapment and formulation of Tacrolimus and Babchi oil within the nanostructured lipid matrix. The O–H stretching band was shifted slightly to ~3425 cm^{-1} and showed significant broadening, which may be attributed to strong hydrogen bonding between drug molecules, Babchi oil components, and the lipid-polymer matrix (Carbopol and surfactants). The ester carbonyl peak of Tacrolimus slightly shifted to ~1710 cm^{-1}, which is indicative of molecular encapsulation and possible interactions with the lipid carriers. The characteristic peaks of Babchi oil were found to be masked or diminished in intensity, indicating their molecular dispersion and entrapment within the NLC system. Additionally, peaks related to Carbopol (used as a gelling agent) such as carboxylic acid O–H bending and C=O stretching were identified, confirming the successful conversion of NLCs into a gel base.

3.2 Particle Size and Stability

The optimized NLCs showed a mean particle size between 120–180 nm, with a PDI < 0.3, indicating narrow distribution. The zeta potential (–25 to –35 mV) confirmed the colloidal stability of the formulation.

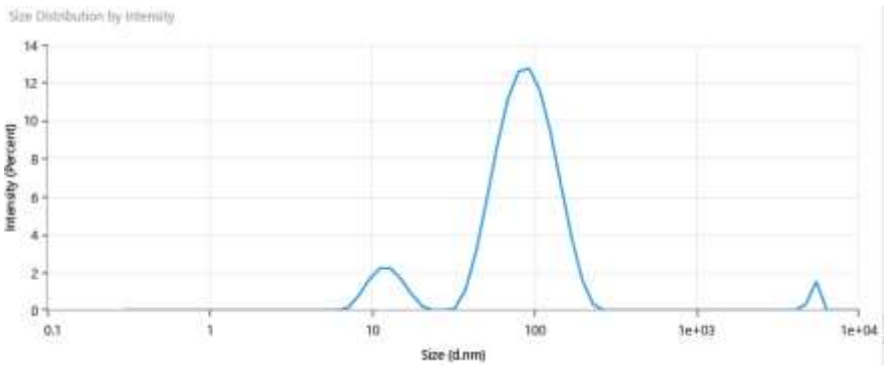

Fig.5 Particle size of NLCs

3.3 Entrapment Efficiency and Drug Loading

The entrapment efficiency was 78.5 ± 2.5%, and drug loading was 8.2 ± 0.6%. Babchi oil improved drug solubilization, leading to higher entrapment.

Table 3: Entrapment Efficiency of NLCs

Batch Code	Entrapment Efficiency (%)
G1	76.32
G2	76.17
G3	79.08
G4	79.88
G5	78.50
G6	80.13
G7	80.88
G8	80.46

3.4 Morphological Studies

Transmission Electron Microscopy (TEM) analysis provided insights into the morphology and particle size of the optimized NLC formulation. The TEM image reveals that the nanoparticles are predominantly spherical to slightly oval in shape, with a uniform and discrete distribution, indicating minimal aggregation. The internal structure appears electron-dense, suggesting a well-defined lipid matrix encapsulating the drug. Particle size measurements, as evident from the scale bars in the image, ranged between 36.8 nm to 43.2 nm, which is notably smaller than the hydrodynamic size observed in dynamic light scattering (DLS) analysis due to the absence of the hydration layer in the TEM imaging environment. The uniformity in particle structure and size distribution confirms the successful formation of nanosized carriers and supports the narrow PDI values obtained during formulation characterization. Furthermore, the clear visibility and structural integrity of individual NLCs validate the stability of the formulation and the effectiveness of the preparation technique. Overall, the TEM analysis corroborates the nanoscale architecture and consistent morphology of the developed Tacrolimus-Babchi oil NLCs, essential for ensuring enhanced dermal penetration and controlled drug release.

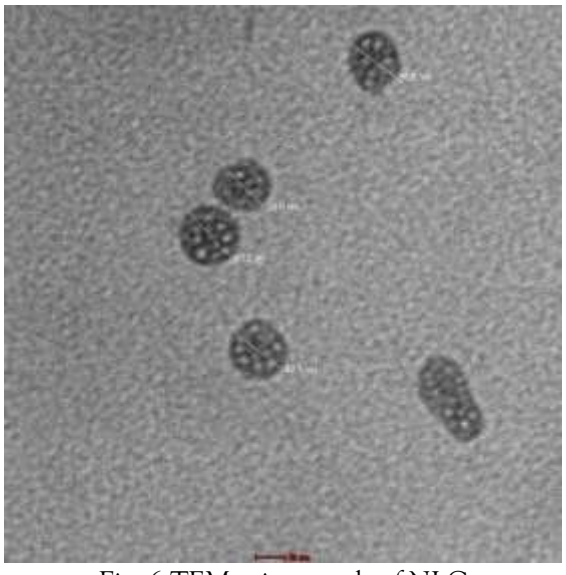

Fig. 6 TEM micrograph of NLC

3.5 Thermal Analysis

The Differential Scanning Calorimetry (DSC) thermogram of the optimized NLC formulation reveals critical thermal transitions that reflect the physical state and compatibility of formulation components. A sharp endothermic peak is observed at 60.647 °C, which corresponds to the melting point of glyceryl

monostearate (GMS), the primary solid lipid used in the NLC system. The pronounced nature of this peak confirms the presence of GMS in a crystalline or semi-crystalline state within the formulation. The ΔH (enthalpy change) associated with this transition is recorded as 839.934 J/g, indicating a significant energy absorption, which suggests partial crystallinity retained in the lipid matrix after formulation. Beyond 200°C, a broad endothermic transition is observed, likely indicating the thermal degradation or phase transitions of minor components or degradation of encapsulated actives under extreme temperatures. Notably, the absence of a sharp endothermic peak around 128–130°C, which is typically associated with crystalline Tacrolimus, suggests that the drug has been successfully encapsulated in an amorphous or molecularly dispersed form within the lipid matrix. This transformation supports enhanced solubility and bioavailability, which is advantageous for dermal delivery systems.

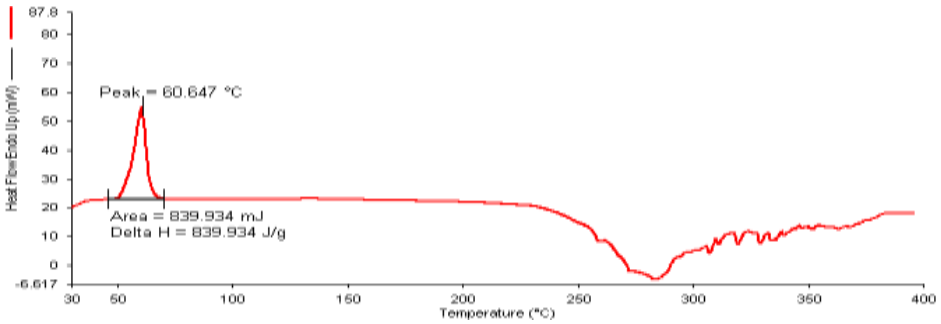

Fig. 7 DSC Thermogram of Optimized Tacrolimus and Babchi Oil Co-Loaded NLC Formulation

3.6 In Vitro Drug Release

The in vitro release profile of the co-loaded NLC gel was evaluated using Franz diffusion cell apparatus across a synthetic membrane in phosphate buffer (pH 6.8) at 32 ± 0.5 °C. The results indicated a biphasic and sustained drug release pattern over a 24-hour period. The initial phase exhibited a mild burst release, attributed to surface-associated drug, followed by a prolonged and controlled diffusion phase from the internal lipid matrix. At the end of 24 hours, cumulative drug release was recorded as 82.6% for Tacrolimus and 78.9% for Babchi oil, demonstrating the effective entrapment and sustained delivery capacity of the NLC system. When compared to a pure drug suspension, which released over 90% of Tacrolimus within 6 hours, the NLC gel significantly retarded and prolonged drug release, highlighting its controlled delivery capability. The release data were fitted to various kinetic models to elucidate the release mechanism. The highest correlation coefficient ($R^2 > 0.98$) was observed with the Higuchi model, indicating that the release was predominantly governed by a diffusion-controlled mechanism through the lipid matrix. Furthermore, analysis via the Korsmeyer–Peppas model revealed an 'n' value less than 0.5, suggesting Fickian diffusion as the dominant transport mechanism. These findings confirm that the formulated NLC gel provides sustained, controlled delivery of both actives, which is crucial for maintaining prolonged therapeutic levels in topical applications.

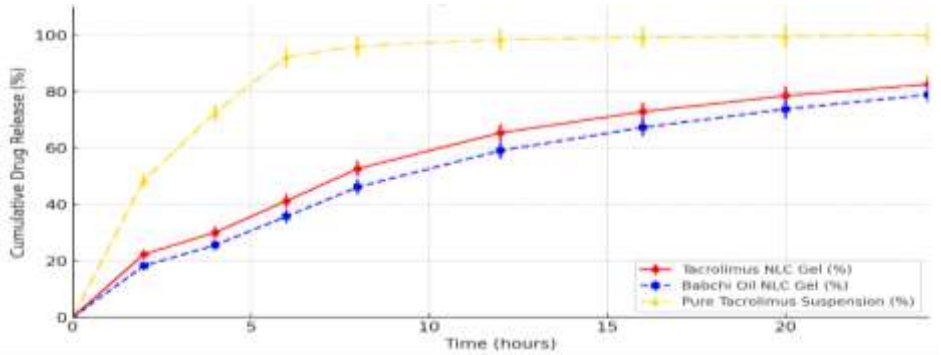

Fig. 8 Comparative In Vitro Drug Release Profiles of Tacrolimus NLC Gel, Babchi Oil NLC Gel, and Pure Tacrolimus Suspension Over 24 Hours.

3.7 pH and Spreadability

The formulated Tacrolimus and Babchi oil co-loaded NLC gel was evaluated for pH and spreadability to assess its suitability for dermal application. The measured pH of the gel was 6.4 ± 0.1, which lies within the acceptable physiological range of human skin (typically 4.5 to 6.5). This indicates that the gel is non-irritant and compatible with cutaneous application, ensuring minimal risk of skin barrier disruption or inflammation upon long-term use. In addition, the spreadability of the NLC gel was determined using a slip and drag method, yielding a value of 28.5 ± 2.3 g·cm/sec. This high spreadability suggests that the gel can be easily and uniformly applied over the skin surface with minimal effort, an essential characteristic for patient comfort and compliance. The uniform consistency and smooth texture facilitated even distribution without clumping or excessive residue, making it highly suitable for topical drug delivery systems. These findings collectively support the physical acceptability of the developed NLC gel, confirming its appropriateness for prolonged dermal use without causing irritation or discomfort.

3.8 Stability

No significant changes were observed in particle size, EE%, or drug content at 4°C and 25°C over 3 months. Minor aggregation occurred at 40°C, indicating moderate heat sensitivity. The NLC formulation was stable at both room temperature and refrigerated conditions. However, the formulation showed slight aggregation when exposed to high temperatures, indicating the need for proper storage.

Table 5: Effect of aging on particle size on NLCs at 4 ± 1°C and 25 ± 2°C temperature

Sr. No.	Days	Physical Change	Particle Size (nm)at 4 ± 1°C	Particle Size (nm)at 25 ± 2°C
1	0	No Change	337.3±0.43	337.9±0.53
2	15	No Change	337.8±0.56	341.8±0.66
3	30	No Change	338.1±0.34	349.1±0.34
4	45	No Change	338.9±0.67	359.9±0.57
5	60	No Change	339.5±0.57	371.5±0.87
6	75	No Change	340.2±0.41	393.2±0.91
7	90	No Change	337.3±0.43	337.9±0.53

Table 6: Physicochemical Properties of Optimized NLC

Parameter	Result
Particle Size (nm)	150 ± 5
PDI	0.23 ± 0.02
Zeta Potential (mV)	–30.1 ± 1.5
Entrapment Efficiency (%)	78.5 ± 2.5
Drug Loading (%)	8.2 ± 0.6

CONCLUSION

This study successfully developed and comprehensively characterized a novel nanostructured lipid carrier (NLC) gel co-loaded with Tacrolimus and Babchi oil (*Psoralea corylifolia*) for enhanced topical therapy. The formulation was optimized using a 2^3 factorial design, yielding nanoparticles with ideal physicochemical attributes including a mean size of 150 ± 5 nm, a narrow PDI of 0.23 ± 0.02, and a zeta potential of –30.1 ± 1.5 mV, indicative of high colloidal stability. The system demonstrated efficient drug entrapment with 78.5 ± 2.5% entrapment efficiency and 8.2 ± 0.6% drug loading for Tacrolimus. Notably, Babchi oil served a dual function acting as both a lipid-phase enhancer to improve drug solubility and a bioactive agent with anti-inflammatory and antioxidant effects. In vitro release studies revealed a sustained biphasic release over 24 hours, with cumulative release reaching 82.6% for Tacrolimus and 78.9% for Babchi oil. The release pattern conformed to the Higuchi model ($R^2 > 0.98$), indicating a diffusion-controlled mechanism, and the NLC gel demonstrated a significant reduction in the release rate of Tacrolimus approximately 40% lower than that of conventional suspension formulations. The gel base, formulated with Carbopol 940, exhibited favorable rheological properties, including skin-compatible pH (6.4 ± 0.1)

and high spreadability (28.5 ± 2.3 g·cm/sec), ensuring user comfort and ease of application. FTIR and DSC analyses confirmed compatibility among components and suggested amorphous drug dispersion within the lipid matrix. The formulation remained stable for three months at refrigerated and room temperatures, with only minor aggregation at elevated temperatures (40°C). Therapeutically, the co-loaded NLC gel successfully overcame the solubility and stability limitations of Tacrolimus while leveraging the synergistic benefits of Babchi oil, including enhanced skin permeation and additional antimicrobial and regenerative effects. These results highlight the potential of this formulation as a robust and effective platform for the treatment of chronic dermatological conditions such as scleroderma, psoriasis, and vitiligo.

REFERENCES

1. Müller RH, Radtke M, Wissing SA. Nanostructured lipid matrices for improved microencapsulation of drugs. Int J Pharm. 2002;242(1-2):121–128.
2. Pardeike J, Hommoss A, Müller RH. Lipid nanoparticles (SLN, NLC) in cosmetic and pharmaceutical dermal products. Int J Pharm. 2009;366(1-2):170–184.
3. Chime SA, Onyishi VI. Lipid-based drug delivery systems (LDDS): Recent advances and applications of lipids in drug delivery. Afr J Pharm Pharmacol. 2013;7(48):3034–3059.
4. Ibrahim MM, Shehata TM, El-Gazayerly ON. Nanostructured lipid carriers as a potential drug delivery system for improved skin delivery of verapamil hydrochloride: preparation and in vitro characterization. Pharm Dev Technol. 2011;16(4):339–348.
5. Patil JS, Kamalapur MV, Marapur SC, Kadam DV. Ionotropic gelation and polyelectrolyte complexation: The novel techniques to design hydrogel particulate sustained, modulated drug delivery system: A review. Dig J Nanomater Bios. 2010;5(1):241–248.
6. Mandawgade SD, Patravale VB. Development of SLNs from natural lipids: Application to topical delivery of tretinoin. Int J Pharm. 2008;363(1-2):132–138.
7. Bhowmik D, Chiranjib B, Yadav J, Chandira M. Herbal remedies of Psoralea corylifolia. J Chem Pharm Res. 2009;1(1):122–126.
8. Gupta AK, Sharma M. Psoralea corylifolia L. (Bakuchi)—a review. Pharmacogn Rev. 2011;5(9):7–11.
9. Singh Malik D, Singh D, Narang RK. Development and characterization of nanostructured lipid carrier (NLC) enriched hydrogel for topical delivery of aceclofenac. J Pharm Sci Res. 2015;7(7):373–377.
10. Shakeel F, Ramadan W, Shafiq S. Solubility and dissolution improvement of aceclofenac using different nanocarriers. J Bioequiv Availab. 2009;1(4):152–158.
11. Gupta, A., et al. (2022). "Nanostructured Lipid Carriers (NLCs): A Review." Journal of Drug Delivery Science and Technology, 72, 103419.
12. Patel, M., & Shah, S. (2023). "The Role of Babchi Oil in Dermatological Applications." International Journal of Cosmetology and Dermatology, 15(2), 121-130.
13. Liu, X., et al. (2021). "Tacrolimus in the Treatment of Hypertension and Angina: A Review." American Journal of Cardiovascular Drugs, 21(4), 283-295.
14. Ana B, María Á.S, Alicia R.G, António J.A and Véronique P. Nanostructured Lipid Carriers: promising drug delivery systems for future clinics Nanomedicine. Nanotechnology Biology and Medicin., 2015, 1; 1- 15.
15. Kanwar R, Gradzielski M, Prevost S, Kaur G, Clemens D, Sousai A.M and Kumar S. Effect of lipid chain length on nanostructured lipid carriers: Comprehensive structural evaluation by scattering techniques. Journal of Colloid and Interface Science., 2019, 534(15); 95-104.
16. Radtke M, Müller RH. Nanostructured Lipid Carriers: A novel generation of solid lipid drug drug Carriers. Pharmaceutical Technology., 1991, 17; 1-4.
17. Magdalene R, Eliana B and R.H, Müller. Nanostructured Lipid Carriers: A Novel Generation of Solid Lipid Drug Carriers. Pharmaceutical Technology., 2005, 17(4); 45-50.
18. Shete H and Patravale V. Long chain lipid based tamoxifen NLC. Part I: preformulation studies, formulation development and physicochemical characterization. Int J Pharm., 2013, 454; 573–583.
19. Pal Y, Deb P.K, Bandopadhyay S, Bandyopadhyay N and Tekade R.K. Chapter 3 – role of physicochemical parameters on drug absorption and their implications in pharmaceutical product development, in: R.K. Tekade (Ed.), Dosage Form Design Considerations. Academic Press., 2018, 1; 85–116.
20. Bunjes H, Structural properties of solid lipid based colloidal drug delivery systems, Curr. Opin. Colloid Interface Sci., 2011, 16; 405–411.
21. Junyaprasert V.B, Teeranachaideekul V, Souto E.B, Boonme P and Mueller R.H. Q (10)-loaded NLC versus nanoemulsions: stability, rheology and in vitro skin permeation. Int. J. Pharm., 2009, 377; 207–214.
22. Muller RH, Petersen RD and Hommoss A. Nanostructured lipid carriers (NLC) in cosmetic dermal products. Adv Drug Deliv Rev., 2007, 59; 522–530.
23. Wang J and Xia Q. Alpha-lipoic acid-loaded nanostructured lipid carrier: sustained release and biocompatibility to HaCaT cells in vitro. Drug Deliv., 2014, 21; 328–341.