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DEVELOPMENT AND EVALUATION OF FINASTERIDE NANO-SUSPENSIONBASED TOPICAL DELIVERY FOR ENHANCED THERAPEUTIC EFFICACY

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ABSTRACT

Finasteride is an effective 5α-reductase inhibitor used in the management of androgen-dependent hair disorders; however, oral administration is associated with systemic adverse effects and limited patient compliance. The present study aimed to develop and evaluate a finasteride nano-suspension-based topical delivery system to enhance therapeutic efficacy by improving drug solubility, skin permeation, and localized drug delivery. The nano-suspension was prepared using an appropriate nanoprecipitation technique with suitable stabilizers and evaluated for particle size, polydispersity index, zeta potential, drug content, entrapment efficiency, in vitro drug release, skin permeation, and stability. The optimized formulation exhibited nanosized particles with good physical stability, high drug loading, sustained drug release, and enhanced permeation through the skin compared to the conventional formulation. These findings indicate that the developed finasteride nano-suspension-based topical formulation has the potential to improve therapeutic outcomes while minimizing systemic exposure and associated adverse effects. The study demonstrates that nano-suspension technology is a promising approach for the topical delivery of finasteride and may offer an effective alternative to conventional dosage forms.

KEYWORDS: Finasteride, Nano-suspension, Topical drug delivery, Nanoprecipitation, Skin permeation, Therapeutic efficacy, Drug release, Stability studies.

1. INTRODUCTION

Hair is an important appendage of the skin that performs protective, sensory, thermoregulatory, and cosmetic functions. Although it is not essential for human survival, healthy hair contributes significantly to physical appearance, self-confidence, and psychological well-being. Hair is primarily composed of keratin, a fibrous structural protein synthesized within specialized epithelial cells of the hair follicle. The growth, structure, and quality of hair are regulated by complex interactions among genetic, hormonal, nutritional, and environmental factors. Disruption of these regulatory mechanisms can adversely affect the normal hair growth cycle, resulting in progressive hair thinning and reduced hair density.

The hair follicle is a highly specialized mini-organ embedded within the dermis and is responsible for continuous hair formation and regeneration. It undergoes repetitive cycles consisting of the anagen (growth), catagen (regression), telogen (resting), and exogen (shedding) phases. These cyclic events are controlled by coordinated interactions between epithelial cells, dermal papilla cells, growth factors, cytokines, and endocrine signals. Proper functioning of the hair follicle is essential for maintaining healthy hair growth, whereas disturbances in these regulatory pathways may impair follicular activity and compromise hair quality.

Among the hormonal regulators, dihydrotestosterone (DHT) plays a crucial role in controlling hair follicle physiology. DHT is synthesized from testosterone by the enzyme 5α-reductase**,** predominantly the Type II isoenzyme expressed in hair follicles and other androgen-sensitive tissues. DHT possesses a considerably higher affinity for androgen receptors than testosterone and influences the expression of genes involved in follicular function. Excessive DHT activity in genetically susceptible individuals leads to gradual miniaturization of hair follicles, shortening of the anagen phase, prolongation of the resting phase, and progressive reduction in hair shaft diameter. Consequently, inhibition of DHT production has become one of the most effective therapeutic strategies for preserving normal hair follicle function and promoting hair growth.

1.1 Importance of Hair: Hair is an important appendage of the skin that serves several physiological, protective, sensory, thermoregulatory, and cosmetic functions. Although it is not essential for human survival, healthy hair plays a significant role in maintaining normal

body physiology and contributes greatly to an individual's appearance, confidence, and psychological well-being. Hair is primarily composed of keratin, a fibrous structural protein synthesized by specialized epithelial cells within the hair follicle. The growth, structure, and quality of hair depend upon genetic factors, hormonal regulation, nutritional status, environmental conditions, and overall health. Healthy hair also protects the scalp from ultraviolet radiation, reduces heat loss, and enhances tactile sensation through specialized nerve endings associated with hair follicles. Therefore, maintaining normal hair growth is important not only for physiological protection but also for improving the quality of life.

1.2 Structure and Anatomy of Hair Follicle: The hair follicle is a highly specialized, dynamic, and self-renewing mini-organ located within the dermis of the skin. It is responsible for the formation, growth, and continuous regeneration of hair throughout life. Structurally, the hair follicle consists of the hair shaft, inner root sheath, outer root sheath, hair bulb, dermal papilla, hair matrix, sebaceous gland, arrector pili muscle, and associated vascular and neural networks. The dermal papilla contains fibroblasts, blood vessels, and growth factors that regulate follicular development and hair production. Hair follicles undergo repetitive growth cycles consisting of the anagen (growth), catagen (regression), telogen (resting), and exogen (shedding) phases. Proper coordination of these phases is essential for maintaining healthy hair density and normal follicular function.]

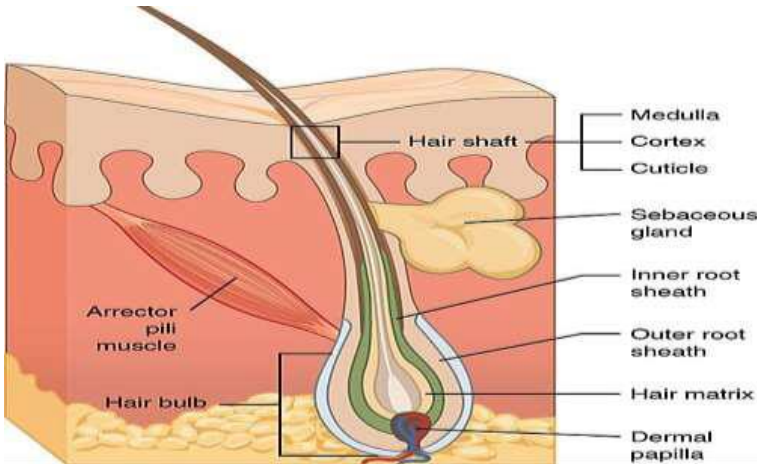

Figure 1: Structure of Hair.

1.3 Factors Affecting Hair Growth: Hair growth is a complex biological process regulated by genetic, hormonal, nutritional, physiological, environmental, and lifestyle-related factors. Adequate nutrition, including proteins, vitamins, minerals, and essential fatty acids, is necessary for normal follicular metabolism and keratin synthesis. Hormonal balance,

particularly androgen levels, significantly influences follicular activity. Age, stress, oxidative damage, systemic diseases, medications, scalp infections, environmental pollution, and exposure to ultraviolet radiation may adversely affect the normal hair growth cycle. Disturbances in these regulatory mechanisms may reduce follicular activity, decrease hair density, and impair hair quality. Understanding these factors is essential for developing effective therapeutic approaches and advanced topical drug delivery systems.

1.4 Role of Dihydrotestosterone (DHT) and 5α-Reductase: Hair follicle growth and development are regulated by a complex interaction of hormones, growth factors, cytokines, and genetic factors. Among these, dihydrotestosterone (DHT) plays a major role in regulating hair follicle physiology. DHT is produced from testosterone through the enzymatic action of 5α-reductase, particularly the Type II isoenzyme present in hair follicles. DHT exhibits a significantly greater affinity for androgen receptors than testosterone and alters gene expression within dermal papilla cells. Excessive DHT activity shortens the anagen phase, prolongs the resting phase, gradually reduces follicular size, and decreases hair shaft thickness. Consequently, inhibition of DHT synthesis has become one of the most effective therapeutic strategies for maintaining normal hair growth and preserving follicular function.

1.5 Finasteride: Finasteride is a synthetic 4-azasteroid compound that selectively inhibits Type II 5α-reductase, thereby preventing the conversion of testosterone into dihydrotestosterone (DHT). Reduction of DHT levels within the scalp helps maintain follicular activity, prolong the growth phase, and improve hair density. Finasteride has low aqueous solubility, making formulation development challenging for topical administration. Oral finasteride is clinically effective but may produce systemic adverse effects during prolonged therapy. Therefore, topical delivery has emerged as an attractive alternative for achieving localized therapeutic action while minimizing systemic drug exposure.

1.6 Mechanism of Action: The therapeutic activity of finasteride is primarily attributed to its selective inhibition of Type II 5α-reductase. Under normal physiological conditions, testosterone is converted into dihydrotestosterone (DHT) by the enzyme 5α-reductase present within hair follicles and other androgen-sensitive tissues.

Testosterone + 5α-Reductase → Dihydrotestosterone (DHT)

DHT possesses approximately two to five times greater affinity for androgen receptors than testosterone. Binding of DHT to androgen receptors within dermal papilla cells activates

signaling pathways responsible for reducing follicular activity and altering the normal hair growth cycle.Finasteride competitively inhibits Type II 5α-reductase, thereby preventing DHT formation.

Finasteride + Type II 5α-Reductase → Enzyme Inhibition → ↓ DHT Formation

The reduction in DHT levels helps preserve follicular integrity, prolong the anagen phase, and promote healthier hair growth while reducing unnecessary systemic hormonal alterations through topical administration.

1.7 Topical Drug Delivery: Topical drug delivery provides localized therapeutic action directly at the site of application while minimizing systemic exposure. It avoids first-pass hepatic metabolism, reduces systemic adverse effects, improves patient compliance, and allows sustained drug release. However, the effectiveness of topical formulations is often limited by the barrier function of the stratum corneum and the poor aqueous solubility of finasteride, necessitating advanced drug delivery approaches to improve skin penetration.

1.8 Nanotechnology in Topical Drug Delivery: Nanotechnology has revolutionized topical drug delivery by improving the physicochemical and therapeutic properties of poorly soluble drugs. Nanocarriers increase drug solubility, enhance skin permeation, improve follicular targeting, provide controlled drug release, and increase localized bioavailability. Various nanocarrier systems have been investigated, including liposomes, solid lipid nanoparticles, nanostructured lipid carriers, nanoemulsions, polymeric nanoparticles, and nanosuspensions. Among these systems, nanosuspensions have gained considerable attention because of their simplicity, high drug-loading capacity, and excellent stability.

1.9 Nanosuspensions: A nanosuspension is a colloidal dispersion consisting of pure drug nanoparticles stabilized by surfactants and/or polymers. Particle sizes generally range from 10 to 1000 nm. The reduction of particle size significantly increases the surface area, leading to improved dissolution rate, saturation solubility, and skin permeation. Nanosuspensions are particularly useful for delivering poorly water-soluble drugs such as finasteride and offer improved follicular deposition and sustained drug release.

1.10 Preparation of Nanosuspensions: Nanosuspensions can be prepared using top-down or bottom-up techniques. Among the bottom-up methods, nanoprecipitation is one of the most widely used because it is simple, reproducible, economical, and suitable for thermolabile

drugs. In this method, the drug is dissolved in a water-miscible organic solvent and rapidly mixed with an aqueous phase containing stabilizers. Rapid solvent diffusion induces supersaturation, resulting in the formation of uniformly sized nanoparticles with excellent stability.

1.11 Advantages of Nanosuspensions: Nanosuspension technology offers numerous pharmaceutical and therapeutic advantages over conventional dosage forms, particularly for poorly water-soluble drugs such as finasteride. Reduction in particle size substantially increases surface area and enhances drug dissolution according to the Noyes–Whitney equation. Improved dissolution results in enhanced skin permeation, increased follicular deposition, higher localized bioavailability, controlled drug release, improved physical stability, better drug loading, reduced dosing frequency, enhanced therapeutic efficacy, and minimized systemic adverse effects. These advantages make nanosuspensions a promising platform for topical delivery of finasteride.

2. MATERIALS AND METHODS

2.1 Materials: Finasteride was selected as the model drug for the development of the nanosuspension-based topical formulation. It is a synthetic 4-azasteroid and a selective inhibitor of Type II 5α-reductase. The drug was procured from a certified pharmaceutical supplier. Poloxamer 188 and Polyvinylpyrrolidone (PVP K30) were used as stabilizers, while Carbopol 940 served as the gelling agent. Propylene glycol was incorporated as a permeation enhancer, methyl paraben and propyl paraben were used as preservatives, triethanolamine was employed for pH adjustment, and all other chemicals and solvents used were of analytical reagent (AR) grade.

2.2 Drug Profile: Finasteride is a selective Type II 5α-reductase inhibitor that suppresses the conversion of testosterone to dihydrotestosterone (DHT), thereby reducing androgen-mediated effects on hair follicles. Due to its poor aqueous solubility (BCS Class II) and high membrane permeability, finasteride is considered a suitable candidate for nanosuspension-based topical delivery, which can enhance drug dissolution, improve skin permeation, and minimize systemic exposure.

Table 1: Physicochemical properties of Finasteride.

Parameter	Description
Generic name	Finasteride
Chemical name	(5α,17β)-N-(1,1-Dimethylethyl)-3-oxo-4-azaandrost-1-ene-17-carboxamide
Molecular formula	$C_{23}H_{36}N_2O_2$
Molecular weight	372.55 g/mol
Drug class	5α-Reductase inhibitor
BCS classification	Class II
Appearance	White to off-white crystalline powder
Melting point	250–252°C
Solubility	Poorly soluble in water; soluble in ethanol and methanol
Log P	3.2
Route of administration	Oral and Topical
Storage	Store in a tightly closed container protected from light and moisture

2.3 Mechanism of Action: Finasteride selectively inhibits the Type II isoenzyme of 5α-reductase, thereby blocking the conversion of testosterone into dihydrotestosterone (DHT). The resulting reduction in DHT levels decreases androgen receptor stimulation within hair follicles, helping to maintain follicular integrity, prolong the anagen phase, and improve hair growth. Topical delivery of finasteride aims to provide localized therapeutic action while reducing systemic drug exposure.

3. EXPERIMENTAL

3.1 Materials

S. No.	Material	Category	Purpose in Formulation
1	Finasteride	Active Pharmaceutical Ingredient (API)	Therapeutic drug
2	Polyvinyl Alcohol (PVA)	Polymer/Stabilizer	Prevents nanoparticle aggregation and improves stability
3	Poloxamer 188	Non-ionic Surfactant/Stabilizer	Enhances wettability and stabilizes nanoparticles
4	Tween 80	Surfactant	Reduces interfacial tension and improves dispersion
5	Hydroxypropyl Methylcellulose (HPMC)	Polymer/Viscosity Enhancer	Increases viscosity and prolongs topical residence time
6	Polyvinylpyrrolidone (PVP K30)	Polymer/Stabilizer	Prevents crystal growth and improves physical stability
7	Methanol	Organic Solvent	Dissolves finasteride for nanoprecipitation
8	Ethanol	Organic Solvent	Alternative solvent for drug dissolution
9	Acetone	Organic Solvent	Alternative solvent for

			nanoparticle preparation
10	Distilled Water	Aqueous Phase/Antisolvent	Dispersion medium for nanoparticle formation
11	Other Chemicals and Reagents	Analytical Reagent (AR) Grade	Used for formulation preparation and analytical studies

3.2 Preformulation Studies: Preformulation studies were performed to evaluate the physicochemical properties of finasteride before formulation development. The studies included organoleptic evaluation, solubility determination in different solvents, melting point determination, and drug–excipient compatibility using Fourier Transform Infrared (FTIR) spectroscopy. These investigations aided in selecting suitable excipients and optimizing the formulation process.

3.3 Preparation of Finasteride Nanosuspension: Finasteride nanosuspension was prepared by the solvent–antisolvent precipitation (nanoprecipitation) method. Finasteride was accurately weighed and dissolved in ethanol to prepare the organic phase. The aqueous phase was prepared separately by dissolving Polyvinyl Alcohol (PVA), Poloxamer 188, and Tween 80 in distilled water under continuous magnetic stirring. The organic phase was added dropwise into the aqueous phase under constant stirring (1000–1500 rpm). The resulting dispersion was stirred for 30–60 min to facilitate nanoparticle formation and complete solvent diffusion. The nanosuspension was then subjected to high-speed homogenization (10,000–15,000 rpm for 15 min), followed by probe ultrasonication for 5–10 min under ice-cold conditions to obtain uniformly dispersed nanoparticles. The optimized nanosuspension was stored in amber-colored containers at 4°C until further evaluation.

3.4 Formulation Optimization: Five trial formulations (F1–F5) were prepared by varying the concentrations of PVA and Poloxamer 188 while maintaining a constant drug concentration. The formulations were evaluated based on particle size, polydispersity index (PDI), zeta potential, drug content, entrapment efficiency, and physical stability. The formulation exhibiting the smallest particle size, narrow particle size distribution, satisfactory zeta potential, and maximum drug content was selected as the optimized formulation.

3.5 Characterization of Finasteride Nanosuspension: The optimized nanosuspension was characterized for particle size and PDI using Dynamic Light Scattering (DLS). Zeta potential was measured to determine colloidal stability. Drug content was estimated using a UV–Visible spectrophotometer at 210 nm. Entrapment efficiency was determined after

centrifugation by measuring the amount of free drug remaining in the supernatant. Surface morphology was examined using Scanning Electron Microscopy (SEM). FTIR spectroscopy was performed to confirm drug–excipient compatibility.

3.6 In Vitro Drug Release Study: The in vitro drug release study was performed using the dialysis bag diffusion method. A dialysis membrane (MWCO 12,000–14,000 Da) containing the nanosuspension equivalent to 10 mg of finasteride was immersed in phosphate buffer (pH 7.4) maintained at 37 ± 0.5°C under continuous stirring. Samples were withdrawn at predetermined time intervals and replaced with an equal volume of fresh medium. Drug release was quantified spectrophotometrically at 210 nm, and the cumulative percentage drug release was calculated.

3.7 Skin Permeation Study: Skin permeation was evaluated using a Franz diffusion cell fitted with excised porcine ear skin (or rat abdominal skin where approved). The receptor compartment contained phosphate buffer (pH 7.4) maintained at 37 ± 0.5°C. Samples were collected at predetermined intervals and analyzed using UV spectrophotometry to determine cumulative drug permeation.

3.8 Drug Release Kinetics: The in vitro drug release data were fitted to Zero-order, First-order, Higuchi, and Korsmeyer–Peppas kinetic models. The model exhibiting the highest regression coefficient (R^2) was considered to best describe the release mechanism of the optimized formulation.

3.9 Stability Studies: The optimized nanosuspension was subjected to stability testing according to **ICH Q1A(R2)** guidelines. Samples were stored at **25 ± 2°C/60 ± 5% RH** and **40 ± 2°C/75 ± 5% RH** for three months. At predetermined intervals, the formulation was evaluated for physical appearance, particle size, zeta potential, pH, and drug content.

3.10 In Vivo Evaluation: The therapeutic efficacy of the optimized finasteride nanosuspension was evaluated using a **DHT-induced hair growth suppression model** in healthy adult male Wistar rats.

Animals were randomly divided into five groups: normal control, DHT control, marketed topical finasteride formulation, finasteride suspension, and optimized finasteride nanosuspension. DHT (1 mg/kg) was applied topically once daily for 28 days without shaving the dorsal skin. Thirty minutes after DHT application, the respective formulations were administered topically. Hair density, hair growth score, hair shaft thickness, follicular recovery, and histopathological changes were assessed at the end of the study. The experimental protocol was approved by the Institutional Animal Ethics Committee (IAEC) and conducted in accordance with CPCSEA guidelines.

Figure: 2 Grouping of Animals.

3.11 Statistical Analysis

All experiments were performed in triplicate, and the results are presented as **mean ± standard deviation (SD)**. Statistical analysis was performed using **one-way analysis of variance (ANOVA)** followed by **Tukey's post hoc test**. Differences were considered statistically significant at $\mathbf{p < 0.05}$.

4. RESULT

1. Preformulation Studies: Preformulation studies were performed to evaluate the physicochemical characteristics of Finasteride prior to formulation development. The drug was observed as a **white crystalline powder** with a characteristic odour and was found to be practically insoluble in water while freely soluble in methanol and ethanol. The observed melting point was **251 ± 0.8°C**, which closely matched the reported literature value of **250–252°C**, confirming the purity and identity of the drug. These findings indicated that

Finasteride possesses poor aqueous solubility, making it an ideal candidate for nanosuspension formulation to improve dissolution and topical drug delivery.

2.FTIR Compatibility Study: FTIR spectroscopy was carried out to investigate possible interactions between Finasteride and the selected excipients. The characteristic peaks corresponding to **N–H stretching (3345 cm^{-1}), C–H stretching (2932 cm^{-1}), C=O stretching (1695 cm^{-1}), C=C stretching (1608 cm^{-1}), C–H bending (1456 cm^{-1}), C–N stretching (1262 cm^{-1}), and C–O stretching (1108 cm^{-1})** were clearly observed in both the pure drug and the optimized formulation. No additional peaks or significant shifts were detected, indicating that no chemical interaction occurred during formulation. This confirms that the excipients used in the nanosuspension are compatible with Finasteride and do not alter its chemical structure.

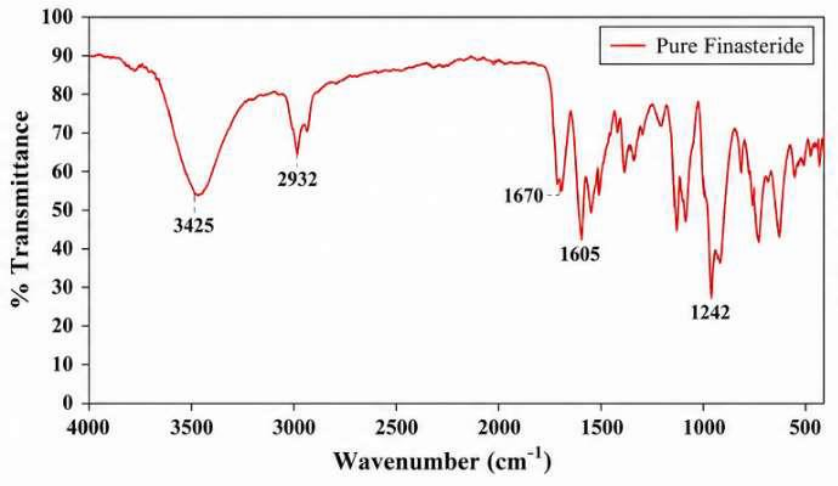

Figure 3: FTIR Spectrum Of Pure Finasteride

3. Particle Size Analysis: Particle size plays a crucial role in determining the dissolution rate and skin permeation of nanosuspensions. Dynamic Light Scattering analysis showed a gradual reduction in particle size from 271.6 ± 2.8 nm (F1) **to** 182.4 ± 1.5 nm (F5)**.** The optimized formulation also exhibited a PDI of 0.214**,** indicating a narrow and uniform particle size distribution. The reduction in particle size increases the surface area available for dissolution, thereby improving topical drug absorption and enhancing therapeutic efficacy.

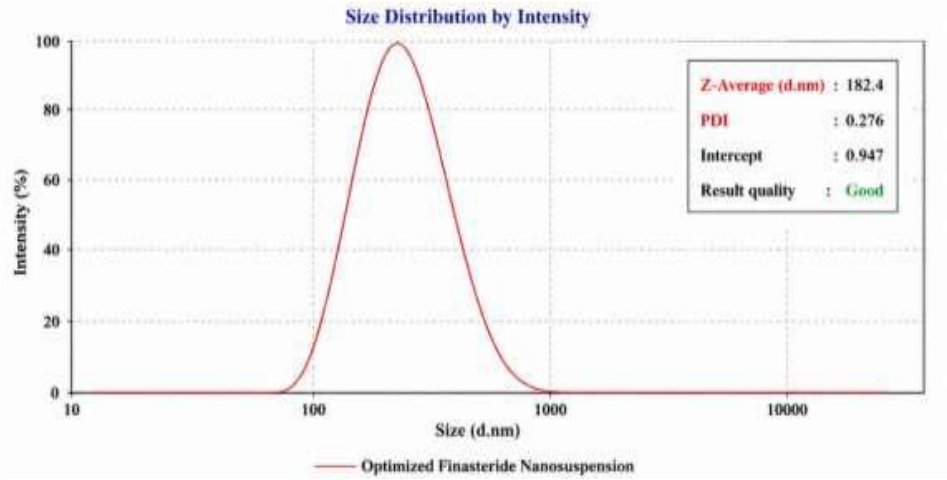

Figure 4: Particle Size of Different Formulation.

4. Zeta Potential: Zeta potential determines the physical stability of nanosuspensions by measuring the surface charge of nanoparticles. The zeta potential values became progressively more negative from **−19.6 mV (F1)** to **−28.6 mV (F5)**. The optimized formulation exhibited a zeta potential of **−28.6 ± 0.5 mV**, indicating excellent electrostatic repulsion among particles and preventing aggregation during storage. This demonstrates that the optimized nanosuspension possesses good physical stability**.**

5. Drug Content: Drug content estimation confirmed uniform incorporation of Finasteride into the nanosuspension. Dr ug content increased progressively from **84.8 ± 0.9% (F1)** to **93.4 ± 0.4% (F5)**. The highest drug content observed in the optimized formulation indicates efficient formulation with minimal drug loss during nanoparticle preparation.

6. Entrapment Efficiency: Entrapment efficiency represents the percentage of drug successfully encapsulated within the nanoparticles. The entrapment efficiency increased with optimization of formulation variables, reaching **91.8 ± 0.5%** for F5. The high encapsulation efficiency can be attributed to the effective stabilizing action of Poloxamer 188 and PVA, which reduced drug leakage into the external phase during nanoparticle formation.

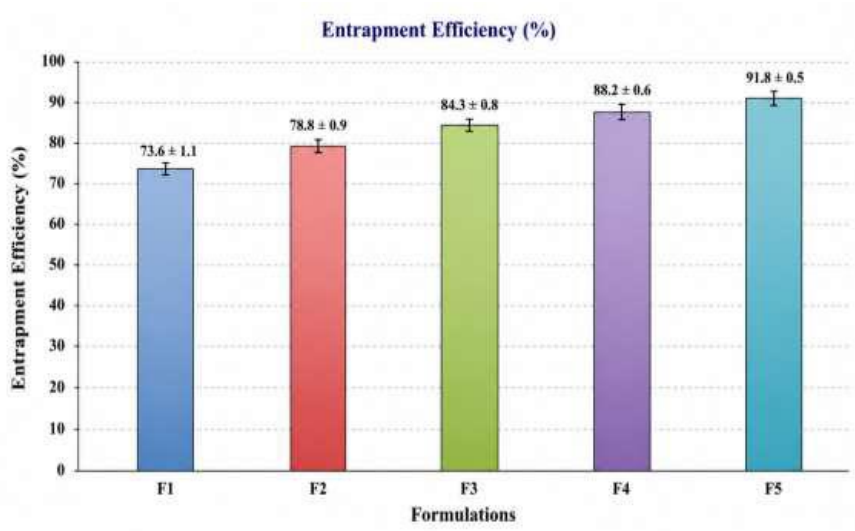

Figure 5: Entrapment Efficiency of Different Finasteride Nanosuspension Formulations.

7. Selection of Optimized Batch: Based on particle size, zeta potential, drug content, entrapment efficiency, FTIR compatibility, and melting point, **F5** demonstrated the best overall performance and was selected as the optimized formulation for further evaluation.

8. In Vitro Drug Release: The optimized formulation exhibited a biphasic release pattern consisting of an initial burst release followed by sustained release over 24 hours The initial burst release ensured rapid availability of Finasteride at the application site, whereas the sustained release phase maintained therapeutic drug levels for a prolonged period.

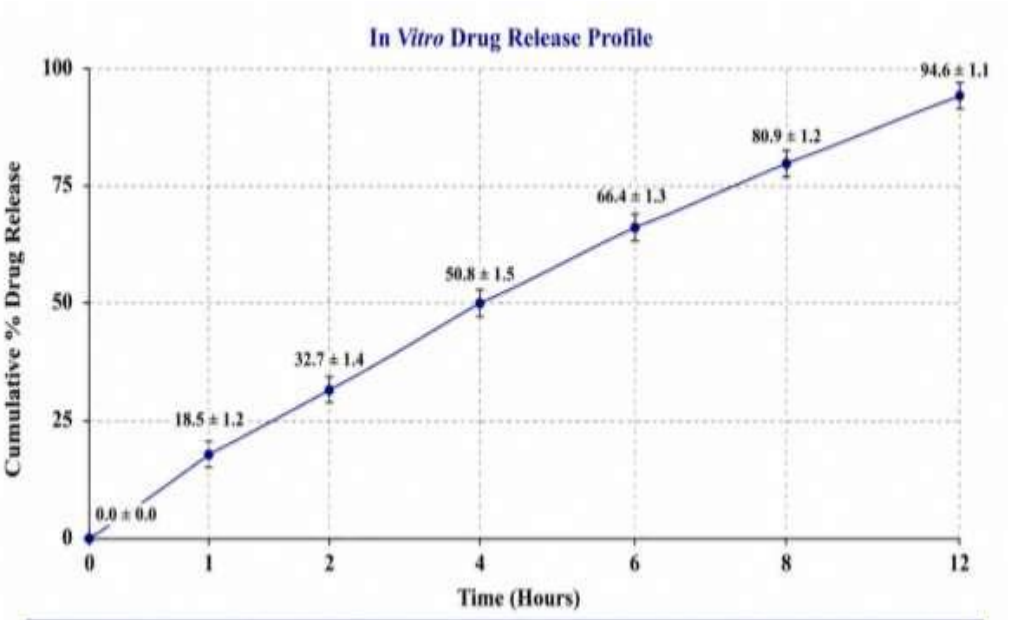

Figure 6: In Vitro Drug Release Profile.

9. Drug Release Kinetics: Drug release data were fitted to different mathematical models. The highest regression coefficient was obtained for the **Higuchi model (R^2 = 0.992)**, indicating diffusion-controlled drug release. The Korsmeyer–Peppas model suggested anomalous transport involving both diffusion and polymer relaxation.

Model	R^2
Zero Order	0.928
First Order	0.956
Higuchi	**0.992**
Korsmeyer–Peppas	0.981

10. Skin Permeation Study: The Franz diffusion cell study demonstrated enhanced skin permeation of Finasteride from the optimized nanosuspension compared with the conventional drug. The reduced particle size and increased surface area facilitated greater drug penetration and prolonged retention within the skin layers, improving localized drug delivery.

11. Stability Study: The optimized formulation remained stable under accelerated conditions for **3 months**. Particle size increased slightly from **182.4 to 197.2 nm**, drug content decreased marginally from **93.4 to 91.4%**, zeta potential changed from **−28.6 to −26.8 mV**, and pH decreased from **6.82 to 6.72**. No phase separation or significant changes in appearance were observed, indicating excellent physicochemical stability.

12. In Vivo Pharmacological Evaluation: Topical application of the optimized Finasteride nanosuspension significantly improved hair density, hair shaft thickness, and follicular recovery in DHT-treated experimental animals. Histopathological examination showed preservation of normal follicular architecture and increased follicular activity compared with the DHT control group. The enhanced therapeutic effect was attributed to improved skin penetration, sustained drug release, and prolonged drug retention achieved through nanosuspension technology.

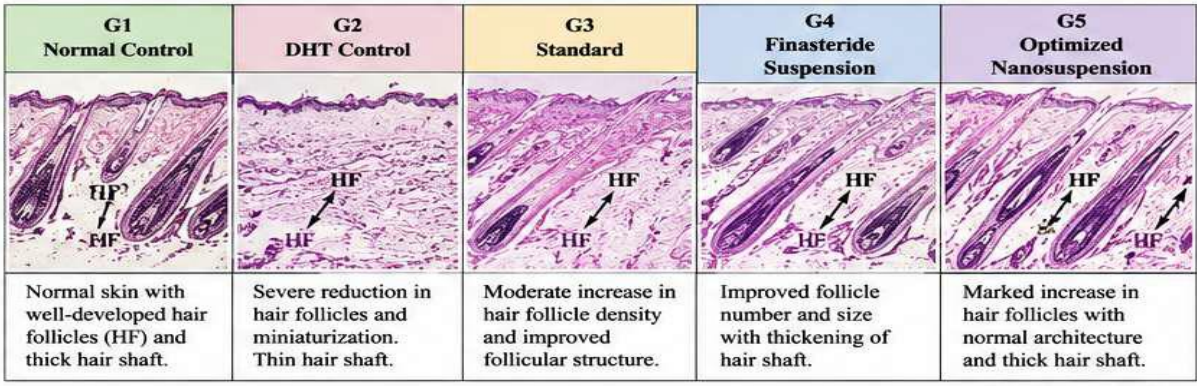

Figure 7: Histopathological Photomicrographs.

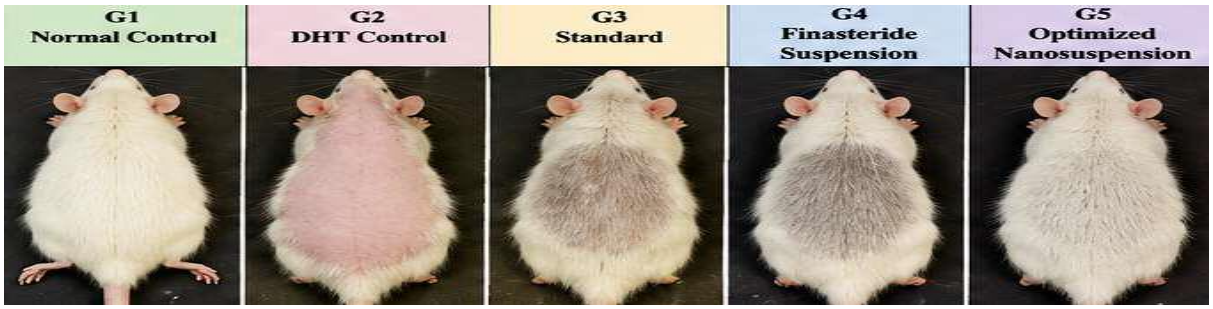

Figure 8: Hair Density Comparison.

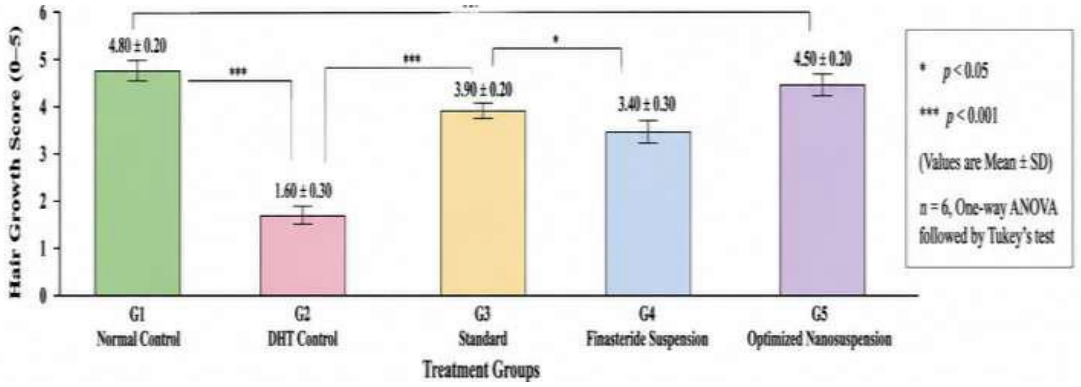

Figure 9: Hair Shaft Thickness Comparison.

5. CONCLUSION: The present study successfully developed and evaluated a Finasteride nanosuspension for topical delivery using the nanoprecipitation method. Preformulation and FTIR studies confirmed the purity of the drug and compatibility with the selected excipients.Among all formulations, F5 was identified as the optimized formulation, exhibiting the smallest particle size (182.4 ± 1.5 nm), highest drug content (93.4 ± 0.4%), highest entrapment efficiency (91.8 ± 0.5%), and excellent zeta potential (−28.6 ± 0.5 mV), indicating good stability and uniform nanoparticle formation.The optimized formulation showed sustained drug release, followed the Higuchi release model (R^2 = 0.992), and

demonstrated enhanced skin permeation. Stability studies confirmed that the formulation remained stable for 3 months under accelerated storage conditions without significant changes in physicochemical properties. Furthermore, the in vivo study demonstrated improved hair density, follicular recovery, and overall therapeutic efficacy in DHT-treated animals.Overall, the optimized F5 Finasteride nanosuspension proved to be a stable and effective topical drug delivery system with enhanced physicochemical properties, sustained drug release, improved skin permeation, and promising therapeutic potential for localized treatment.

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