

# Enhancing the Bioavailability of Herbal Compounds in Hair Care Formulations Through Nano systems: A Review

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## Abstract:

Lipophilic herbal compounds, widely valued for their antioxidant, anti-inflammatory, and restorative properties, play a crucial role in hair care formulations. However, their poor aqueous solubility, limited scalp penetration, and instability often restrict their therapeutic potential. Nanosystems such as nanoemulsions, liposomes, solid lipid nanoparticles, and nanostructured lipid carriers have emerged as promising strategies to overcome these challenges. These nanocarriers enhance the solubility, protect bioactives from degradation, improve scalp delivery, and sustain the release of lipophilic herbal compounds, ultimately boosting their bioavailability and efficacy. This review explores the types of nanosystem applied in herbal hair care, their mechanisms of action, recent advancements, safety concerns, and future opportunities. The integration of nanotechnology into herbal hair formulations offers a transformative approach to developing highly effective, natural-based hair care products.

## Introduction

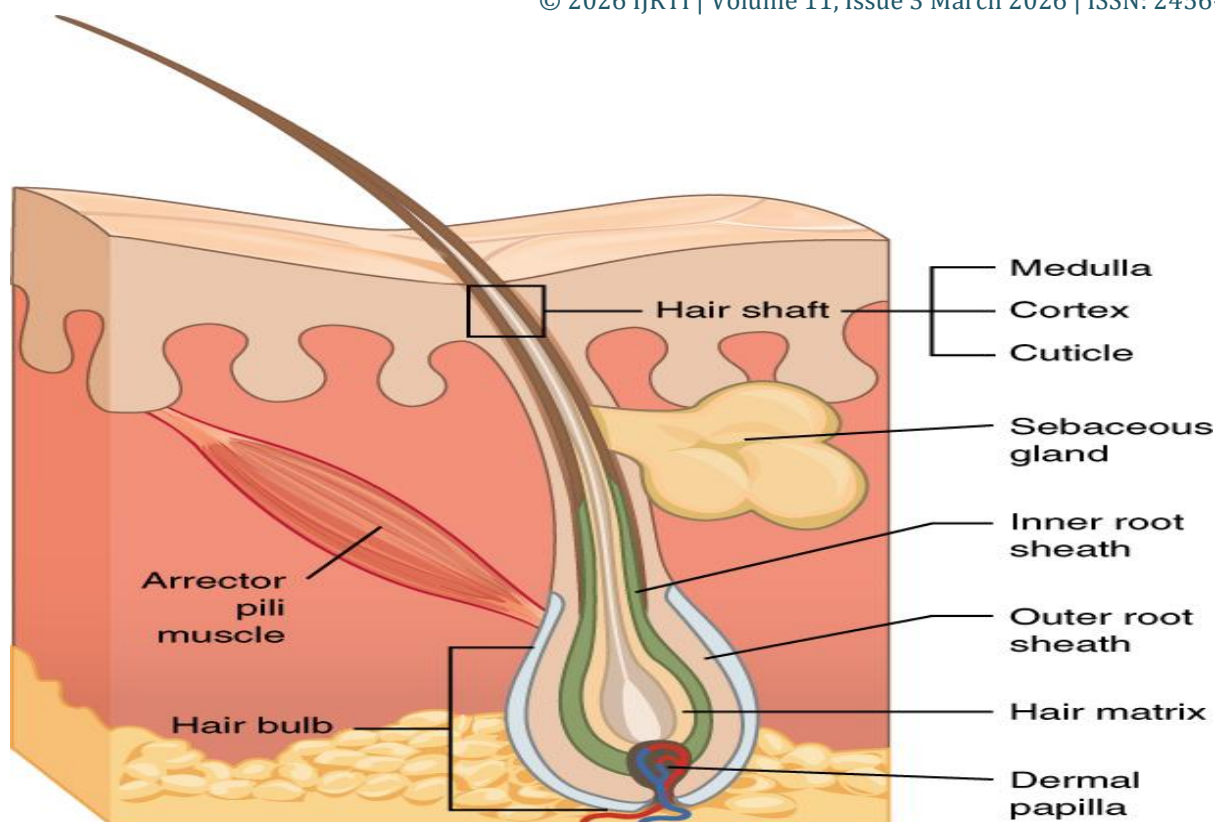
The growing consumer demand for natural and sustainable hair care solutions has fuel ed significant interest in herbal-based formulations. Herbal compounds, such as essential oils, plant-derived extracts, and fatty acids, offer a range of therapeutic benefits, including hair growth stimulation, scalp nourishment, and protection against oxidative stress. However, the successful incorporation of herbal actives into conventional hair care products presents several challenges. While lipophilic herbal compounds generally demonstrate good permeability through the lipid-rich layers of the scalp, they often suffer from poor aqueous solubility, instability, and difficulties in achieving controlled release. On the other hand, hydrophilic herbal compounds face significant barriers to permeation, limiting their therapeutic efficacy at the target site, such as the hair follicles.[1]

Nanotechnology presents an innovative approach to overcome these formulation challenges. By employing nanocarriers such as nanoemulsions, liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs), researchers have been able to enhance the solubility, stability, protection from degradation, and controlled delivery of both lipophilic and hydrophilic herbal actives. These nanosystems not only improve the physical and chemical stability of herbal compounds but also optimize their bioavailability, ensuring better therapeutic outcomes in hair care applications.[2]

This review explores the potential of nanosystems in enhancing the bioavailability and efficacy of herbal compounds in hair care formulations. It will discuss the nature of herbal actives, barriers to effective delivery, the types of nanosystems available, recent advances in herbal nanomedicine for hair treatment, and the challenges and future perspectives for clinical translation into effective, next-generation hair care products.

## HAIR MORPHOLOGY

Human hair plays a crucial role in our daily lives. Ectoderm-derived germinative cells undergo keratinization to produce hair, an epidermal derivative . Hair has many functions, including regulating body temperature, reducing friction between hair shafts, shielding the body from sunlight, and defending against environmental influences . One of the chemical constituents of the fibrous alpha-keratin proteins that comprise hair is carbon.[4]



**Fig no:1 HAIR MORPHOLOGY**

**Table No:1(Components of Hair)[4]**

<b>Component</b>	<b>Location / Composition</b>	<b>Key Features</b>	<b>Function / Importance</b>
<b>Medulla</b>	Innermost central core of the hair shaft	Thin cylindrical layer, high lipids, low cysteine (>30%)	Provides structural support (may be absent in fine hair)
<b>Cortex</b>	Middle layer (~75% of hair shaft), between cuticle & medulla	Spindle-shaped cells (50–60 μm × 3 μm), keratin filaments aligned with hair shaft, rich in sulphur proteins & disulfide bonds	Determines hair <b>texture, elasticity, shape, and colour</b>
<b>Cuticle – A Layer</b>	Outermost protective layer (Inner sublayer of cuticle)	Composed of cross-linked cysteine, highly resistant	Provides <b>mechanical and physical strength</b>
<b>Cuticle – B Layer (Exocuticle)</b>	Middle sublayer of cuticle	Physically rigid, high cysteine content	Adds <b>durability</b>
<b>Cuticle – C Layer (Epicuticle)</b>	Outermost hydrophobic lipid layer	Contains 8-methyleicosonic acid, ~3% cysteine	<b>Water repellent</b> , gives <b>shine</b> ; expansion when wet makes hair prone to breakage

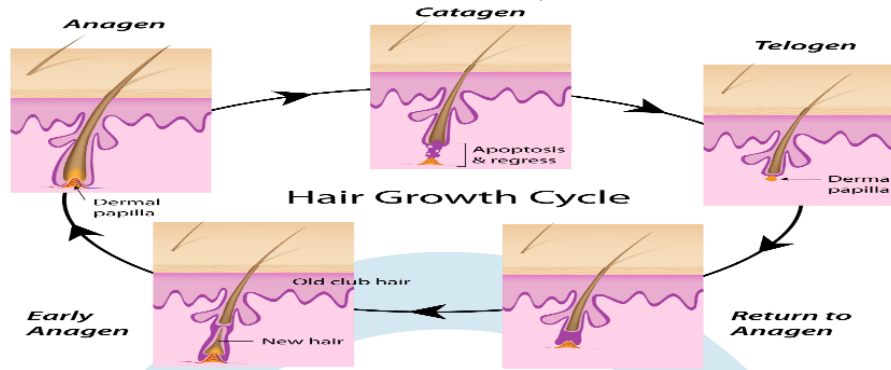


Fig no:02 HAIR GROWTH CYCLE

**Hair Cycle**

Phase / Process	Key Features	What Happens in the Follicle
<b>Hair Formation</b>	<b>Keratinocytes form the visible hair shaft</b>	<b>Stem cells divide → keratinocytes migrate upward → flatten → die → form keratinized hair</b>
<b>Anagen (Growth Phase)</b>	<b>Active fibre production; lasts years</b>	<b>Follicle has onion-like shape; rapid cell division; new hair shaft emerges (pro-anagen → met-anagen)</b>
<b>Catagen (Transition Phase)</b>	<b>Regression phase lasting weeks</b>	<b>Apoptosis reduces follicle size to 1/6th; club hair forms; triggered by stress, deficiency, thyroid imbalance</b>
<b>Telogen (Resting Phase)</b>	<b>No hair growth; 10–15% of scalp hairs</b>	<b>Follicle is inactive; duration varies (weeks for eyelashes, up to a year for scalp hair)</b>
<b>Exogen (Shedding Phase)</b>	<b>Old hairs are shed naturally</b>	<b>Club hairs fall out during brushing, washing, or friction</b>

Table No :02 HAIR GROWTH CYLCE[5]

**Reasons for Hair Loss and Their Mechanisms**

Reason for Hair Loss	Underlying Mechanism	Examples / Notes	Ref.
<b>Genetic &amp; Hormonal Factors</b>	Increased DHT production and receptor sensitivity → follicular miniaturization; shortened anagen phase	Androgenic alopecia; familial predisposition	
<b>Autoimmune Causes</b>	Breakdown of follicular immune privilege; T-cell-mediated attack on hair bulb	Alopecia areata, alopecia totalis, alopecia universalis	
<b>Hair Cycle Dysregulation</b>	Premature transition to telogen or accelerated catagen; altered Wnt/ $\beta$ -catenin, FGF, SHH, and TGF- $\beta$ signaling	Telogen effluvium; impaired anagen initiation	
<b>Nutritional Deficiencies</b>	Reduced keratin synthesis; weakened follicle structure; impaired microcirculation	Deficiency of iron, zinc, protein, vitamins A/B/C/D/E	

<b>Stress &amp; Psychological Factors</b>	Elevated cortisol disrupts follicular cycling; increased telogen shedding	Emotional stress, illness, postpartum changes	
<b>Drug- &amp; Treatment-Induced Hair Loss</b>	Cytotoxic or metabolic damage to matrix keratinocytes; interrupted anagen	Chemotherapy (anagen effluvium), anticoagulants, retinoids, antidepressants, OCPs	
<b>Mechanical &amp; Physical Trauma</b>	Direct follicle damage from tension, friction, or thermal/chemical exposure	Traction alopecia, trichotillomania, heat/chemical damage	
<b>Endocrine &amp; Systemic Disorders</b>	Metabolic imbalance affecting follicle growth and cycling	Thyroid disorders, PCOS, anemia, lupus	
<b>Infections &amp; Scalp Disorders</b>	Inflammation or fungal invasion damages follicles	Tinea capitis, seborrheic dermatitis, folliculitis	
<b>Environmental &amp; Oxidative Stress</b>	Excess ROS leads to follicular DNA damage, apoptosis, and premature catagen	UV radiation, pollution, harsh chemicals	
<b>Aging</b>	Reduced follicular stem cell activity, slower cycling, and thinning	Natural age-related hair thinning	

### Factors Affecting Hair Modulation

Different variables that affect hair physiology include prostaglandin synthase (PGDS), B-catenin, sonic hedgehog (SHH), hepatocyte growth factor, fibroblast growth factor 7, vascular endothelial growth factor, lymphatic enhancement factor, protein kinase, and the Wnt pathway. These elements play a significant role in hair cycle physiology. It was found that overexpression of prostaglandin synthase (PGDS) causes premature catagen. The premature phase prevents hair development [11]. It was discovered that genome studies did not provide genetic evidence for PGDS, but WNT04 expression may have a role (Wnt route). Leiros et al. discovered that androgen action inhibits canonical Wnt/ $\beta$ -Catenin activity, leading to shrinkage of hair follicles. Hair follicle development is governed by gene expression, proteins, and other factors. Hair follicle formation requires the presence of B-catenin. This factor is involved in Wnt signaling. Sonic hedgehog (SHH) aids in the completion of the telogen phase, allowing follicles to enter the anagen phase. The hepatocyte's growth factor encourages follicles to enter the anagen phase. Fibroblast growth factor 7 promotes the entry of hair follicles into the anagen phase and increases hair follicle number. Vascular endothelial growth factor promotes the growth of dermal papilla cells and blood circulation. The lymphatic enhancement factor contributes to the Wnt signaling system, which regulates hair growth. The melanin receptor, which is responsible for changes in hair color hormone, stimulates alpha melanocytes to bind to the MCR and activate adenylate cyclase, which raises cAMP. [12][4][13]

ROS play a role in hair follicle (HF) development by promoting HF cell proliferation. However, excessive ROS levels, especially during the catagen (regression) phase, can trigger hair follicle degeneration by causing oxidative stress, DNA damage, and activating proteins like Trx1 and Foxp1. Although cells have DNA repair mechanisms, when damage exceeds repair capacity, it can lead to aging, apoptosis, or even malignancies. [14]

A key player in DNA repair is PARP1, an enzyme that maintains genomic stability through several repair pathways (BER, HR, and NHEJ). Yet, overactivation of PARP1 during DNA repair can paradoxically lead to cell death by triggering AIF-mediated apoptosis. This apoptosis is crucial for driving the hair cycle transition from anagen (growth) to catagen. Recent studies suggest that drugs like cyclosporine A can delay this transition by suppressing PARP1 and AIF activity, highlighting their potential as targets for promoting hair growth. [15]

Macrophages, the immune cells responsible for clearing apoptotic cells, also play an important role in the hair cycle. Through a process called efferocytosis, macrophages help maintain tissue homeostasis and promote regeneration by shifting from a pro-inflammatory (M1) to an anti-inflammatory (M2) phenotype. M2 macrophages stimulate hair follicle regeneration by releasing growth factors like VEGF, EGF, and FGF. Their polarization during the hair cycle, especially from anagen to catagen, appears to be critical for hair renewal, though more research is needed to fully understand these mechanisms.[16]

Sr. No	Factors	Effects	Stimulation/Inhibition for Growth.
1	Insulin-like Growth Factor (IGF)	Stimulates cellular proliferation and inhibits DHT.	Stimulation
2	Vascular endothelial growth factor (VEGF)	Supply the nutrients and increased the blood circulation on the scalp, resulting in stimulation of hair growth.	Stimulation
3	Fibroblast growth factor-2 (FGF-2)	Stimulation to the hair follicle development.	Stimulation
4	Fibroblast growth factor-5 (FGF-5)	Inhibition of hair growth in the anagen phase.	Inhibition
5	Epidermal growth factor (EGF)	Proliferation and formation of hair follicles.	Stimulation
6	Wingless-related integration site (WNT)	Stimulates, the growth, and development of hair follicles.	Stimulation
8	Prostaglandin (PGD)	Hair growth inhibition.	Inhibition
9	Transforming growth factor beta (TGF- $\beta$ )	Reduce the duration of a cycle.	Inhibition

### Corneum Stratum Barriers

These obstacles need to be removed in order to achieve efficient chemical delivery via the skin to prevent and treat hair diseases and disorders as well as to prevent them from occurring in the first place. Because the skin functions as a barrier, in vivo research show less promise than in vitro studies, which demonstrate good results from a number of herbal extracts and their isolated portions. Phytoconstituents can have a preference for either fat or water. Lipids are arranged in two layers to form the skin. The pharmacokinetics, efficacy, and bioavailability of highly hydrophilic compounds can all be significantly lowered by the stratum corneum. Because large molecules have difficulty passing through membranes, they are also ineffective. Herbal medications cannot enter the body because of the stratum corneum. The outermost layer of the epidermis, known as the stratum corneum, is primarily composed of lipids and proteins. The protein structure of the corneocytes is composed of bundles of keratin filaments. These corneocytes lack both organelles and nuclei. Several proteins make up their hard outer shell. A corneocyte is surrounded by an external lipid matrix. The extracellular lipid matrix is cross-linked like a cornfield and contains two layers of cholesterol, ceramides, and free fatty acids. How much lipid is present in the cell determines how permeable the cell membrane is. Lipophilic medications cannot enter the enhanced lipid structure, whereas hydrophilic drugs can remain there. Extracellular lipids generate a bilayer lamellar phase. Effective lateral packing is crucial for maintaining healthy skin. The packing density of orthorhombic structures is great. Hexagonal packing is less dense. The concentration of lipids, specifically ceramides, determines the lamellar structure.[17][19][4]

## CHALLENGES FOR HERBAL FORMULATIONS

Numerous phytochemicals/ secondary metabolites are produced by plants, including terpenes (like carotenoids), phenolic compounds (like phenolic acids, flavonoids, stilbenes, and tannins), and compounds that contain sulphur and nitrogen (like alkaloids). Plant-derived chemicals have been attributed a variety of biological effects, such as antibacterial, anti-inflammatory, anticancer, anti-atherosclerotic, and antioxidant[19]. The latter are used extensively in the food, pharmaceutical, and cosmetic sectors as natural flavourings, colorants, antioxidants, antimicrobials, and nutraceuticals. They can be isolated molecules, extracts, or essential oils[17]. There are significant challenges, nonetheless, when it comes to their direct integration into different products. The bulk of the plant bioactive components, in particular, are prone to deterioration. A number of variables can affect their stability, including light, temperature, oxygen, pH, and the presence of metal ions during production, storage, or gastrointestinal digestion. Additionally, hydrophobic substances are neither soluble or absorbed due to their limited water solubility. These substances' restricted permeability and diffusion across intestinal epithelial cells also affects their bioavailability, or the quantity of an eaten bioactive chemical that is absorbed in the stomach following digestion. Additionally, the high volatility of essential oils restricts their use.[22]

### **Solubility:**

Their poor solubility in water or oil is one of the main obstacles preventing the direct integration of plant bioactive components into meals, drinks, cosmetics, and pharmaceutical goods. While chemicals with poor oil solubility are difficult to include into oil-based goods, compounds with poor water solubility (such as carotenoids) are easily incorporated into aqueous-based products.[17]

### **Lack of Targeted Delivery**

-Specifically targeting the hair follicles, the crucial location for treating hair development, hair loss, and scalp issues, is one of the main drawbacks of traditional herbal hair care solutions. Most traditional formulations (such as oils, creams, and lotions) rely on passive diffusion and general topical application, resulting in non-specific distribution of active ingredients across the scalp area.

-When herbal compounds are administered topically, they frequently remain on the stratum corneum (the outermost skin layer) or are absorbed into the scalp's upper layers without sinking deep enough to reach the hair follicle bulge region, which contains hair stem cells and dermal papillae. A considerable amount of the actives may also be removed, degraded, or metabolized before reaching the target location.

-Large molecules and substances with poor diffusion coefficients have a difficult time reaching the follicular unit.

-Conventional formulations enable no control over spatial distribution, so even if some herbal actives reach the follicular region, their concentration may be insufficient or unevenly distributed to achieve a therapeutic effect because there is non uniform distribution.[24]

### **Inconsistent absorption and efficacy in herbal hair products.**

One of the major disadvantages of using traditional herbal formulations for hair care is the lack of consistency in how active compounds are absorbed and how efficiently they perform. This discrepancy is caused by the complex nature of herbal extracts as well as the variety in formulation procedures, which all contribute to uncertain therapeutic outcomes. Many herbal ingredients do not penetrate the scalp or hair follicles consistently due to variances in molecular weight, solubility, and lipophilicity. Some chemicals absorb well, while others remain on the surface or decay quickly, resulting in partial or insignificant effects.

Example:A product containing both hydrophilic polyphenols and lipophilic terpenoids may have unequal penetration, with one kind of molecule reaching the follicle and the other remaining inactive[23]

## Poor permeation of hydrophilic herbal actives

One of the primary obstacles in developing successful herbal hair care products is the restricted permeability of hydrophilic (water-soluble) herbal chemicals through the scalp and into the deeper epidermal and follicular layers. The stratum corneum, the scalp's outermost layer, serves as a significant barrier to penetration and is mostly composed of lipid-rich components. This makes it especially resistant to the infiltration of hydrophilic molecules, which do not easily diffuse through lipid membranes[23]

### Why Hydrophilic Compounds Struggle to Permeate.

The stratum corneum is lipophilic, which promotes fat-soluble compounds. Hydrophilic substances prefer to stay on the epidermis' surface or in the aqueous layers, rather than entering into the hair follicle or dermis, where they are needed. Without the support of permeability enhancers or delivery methods, these compounds frequently exhibit low bioavailability and poor therapeutic results. ex: **Apigenin** which is found in chamomile and basil, has been demonstrated to stimulate hair growth through vasodilation and better circulation. However, its water-soluble nature restricts passive skin permeability, lowering its efficacy.[23]

### Issues for lipophilic herbal compounds

Most of herbal products like shampoo and conditioners are water based ,as lipophilic are difficult to dissolve in aqueous phase leads to phase separation, instability, inconsistency in distribution of active ingredients, to resolve this issue sometimes solubilizer like alcohols and emulsifier are used. This can sometimes cause irritation to scalp which effects the overall performance of products. Many lipophilic herbal extracts, particularly oils and fatty acids, are prone to **oxidation** when exposed to air and light. This can lead to a loss of efficacy and the development of unpleasant odours. Antioxidants need to be carefully incorporated to mitigate this.[ 32]

### Nanotechnology for Herbal products

Herbal treatments have been utilized for centuries all throughout the world. Herbal medications used in India are known as "Ayurveda." Indian medicine relies on herbal or herbo-mineral preparations. Ayurveda uses seven medicinal metals: gold, silver, copper, iron, lead, tin, and zinc. Metals undergo numerous steps before becoming therapeutically effective. Herbal medications are popular in the pharmaceutical sector due to their proven effectiveness and lack of negative effects. Herbal medicinal compounds are challenging to deliver as medications due to their limited solubility, poor permeability, instability, and low bioavailability. Encapsulating or attaching nanoparticles can overcome these limitations. Nanotechnology is the 21st century's most sophisticated scientific technology.[28] .Nanotechnology utilizes nanoparticles with high surface area and small size, allowing them to approach specific targets. Combining nanotechnology and herbal science can improve the effectiveness of herbal medications. The creation of a unique drug delivery method for herbal remedies comprises nano-dose, which improves bio solubility and bioavailability, protects against toxicity, and allows for prolonged delivery. These innovative medication delivery methods have site-specific activity and a predefined rate. Nanocarriers are made of harmless components, such as biodegradable polymers, lipids, and polysaccharides. In new drug technology, the medicine is incorporated into nanocarriers to manage its distribution. Nanocarriers have a larger surface area, improve solubility and bioavailability, and allow for precise medication targeting compared to microcarriers. As a result of specificity, the amount of medicine required to incorporate into nanocarriers is substantially lower than when encapsulated. This is particularly handy when employing pricey phyto molecules . Optimal utilization of phyto molecules enhances the product's cost-effectiveness.[22]

### Need of Nano formulation for Herbal drugs.

- Nanoparticles allow herbal medications to target specific organs, improving effectiveness and safety while reducing dosage.
- Improved herbal medicine solubility and targeted action for greater efficacy.
- Their distinctive size and great loading capacity enable them to deliver high concentrations of medicines to disease locations.

- Smaller medication particles increase their surface area, leading to faster delivery and breakdown in the bloodstream.
- Small size and inadequate lymphatic drainage, such as in tumors, can lead to greater permeation.
- Lower incidence of adverse effects.[33]

## **Nano formulation for herbal products**

### **1. Liposome**

Liposomes are spherical vesicular structures made up of single or multiple phospholipid and cholesterol bilayers organized around an aqueous core. Liposomal vesicles are classed as uni lamellar or multilamellar based on the number of bilayers. Uni lamellar vesicles can be small, large, or huge, with diameters ranging from 25 nm to  $\mu\text{m}$ . [29]

### **2. Niosome nano delivery system**

Niosomes are developed by self-assembly of non-ionic surfactants in aqueous solution that form closed bilayer structures; they are considered analogous to liposomes in structure. The structure consists of an aqueous interior core containing non-ionic surfactants, which formed the bilayer niosome vesicles. Compared with traditional liposomes, niosome offer more benefits in terms of low production cost, ease of production, higher stability, and storage. Because of the development of niosomes using non-ionic surfactant, this nanocarrier is non-irritant, biodegradable, biocompatible, and non-immunogenic. In addition, non-ionic surfactants have multiple functions in the cosmeceuticals field, such as emulsifiers, solubilizers, permeability enhancers, and wetting agents [29]

### **Micellar nanoparticle delivery method.**

Micellar nanoparticle technology is a popular and effective nanotechnology-based cosmeceutical that is used by a variety of brands for cleansing products. This nanocarrier provides a robust and adaptable delivery mechanism for forming smaller nanoparticles of active substances ( $<100\text{ nm}$ ), which is beneficial in cosmetic development. Oil-in-water (O/W) and water-in-oil (W/O) nanoemulsions are a viable approach for producing micellar nanoparticles and enriching cosmetic compositions. This nanosystem creates surfactant aggregates that are integrated with the active components (mostly hydrophobic), also known as micelles/micellar nanoparticles, via an aqueous solution (usually water). In the cosmetics sector, O/W nanoemulsion is commonly employed because the main role of this nanosystem is to contain lipophilic or hydrophobic elements. [28]

### **Ethosome**

Ethosomes, a modified variant of liposomes, are lipid vesicles consisting of phospholipids, ethanol, and water. They have an aqueous core with an ethanolic drug solution and an exterior layer with a lipid bilayer. They are effective transdermal transporters. The effect of ethanol on phospholipid bilayers contributes to the formation of vesicles with pliable structures, allowing molecules (drugs, medicines, or active substances) to penetrate deeper layers of the skin. Because of their instability and low permeability, liposome-based drug delivery has yielded limited results in transdermal formulations. To address concerns about liposome stability, a novel vesicular carrier, niosomes, was developed. Liposomes and niosomes were not effective in improving skin permeability. Ethanolic vesicles have been developed to improve medication penetration over the skin. Ethosomes range in size from nanometers to microns. They have a higher transdermal flux and skin permeability. [26]

**Phytosomes**, also known as herbosomes, are composed of polar botanical derivatives and water-soluble compounds found in plants. They provide benefits such as improved absorption of lipid-insoluble polar phytoconstituents, leading to improved efficacy, stability, and reduced adverse effects.[31]

### Transferosomes

Transferosomes are phospholipid sac-like vesicles utilized for transdermal drug delivery. It overcomes the stratum corneum's obstacles to penetration. Due of its hardness, it can easily pass through the skin's intracellular pores. Transferosome administration of colchicine leads to extended, migratory, and targeted distribution without the gastrointestinal side effects associated with oral treatment. Transferosomes move hydrophobic and hydrophilic globules of varying sizes across the subcaste.[17]

### Solid Lipid Nanoparticle

Extracellular lipids generate a bilayer lamellar phase. Effective lateral packing is crucial for maintaining healthy skin. The packing density of orthorhombic structures is great. Hexagonal packing is less dense. The concentration of lipids, specifically ceramides, determines the lamellar structure. This concentration justifies SC's barrier quality. Solid lipid nanoparticles (SLNs) have been developed as carriers for active cosmetic components, medicinal medicines, and herbal constituents. Because of their particle nature, they have been demonstrated to behave as active sunscreen carriers. SLNs are lipid-based colloidal carriers that range in size from 50 to 1000 nm. They are dispersed in water or an aqueous surfactant solution. SLN possess unique qualities such as tiny size, vast surface area, high drug loading, and phase interaction at the interface. There are four types of SLNs: traditional SLN, polymer-lipid hybrid nanoparticles (PLN), nanostructured lipid carriers (NLC), and lipid-drug conjugate .SLNs are considered as one of the most appropriate carriers for the delivery of lipophilic ingredients (such as quercetin) as they ensure high drug encapsulation and controlled release properties.

In the next generation of lipid nanoparticles, NLCs are modified SLNs that improve stability and loading capacity. **Nanostructured lipid carriers (NLCs)** are a newer type of lipid nanoparticle that aims to address the shortcomings of the original generation, known as SLNs. NLCs have emerged as a promising carrier system for the delivery of pharmaceuticals via oral, injectable, ocular, lung, skin, and transdermal routes. NLCs are composed of both solid and liquid lipids, resulting in a less organized lipid core.[4]

### Polymeric Nanoparticles

Polymeric nanoparticles are tiny particles (10–1000 nm) made from natural or synthetic biodegradable polymers that encapsulate herbal actives. They help in controlled delivery, protect sensitive herbal compounds, and improve penetration into the hair and scalp. The herbal extract is encapsulated or entrapped inside the polymer matrix. Once applied (shampoo, serum, mask), the nanoparticles gradually release the active ingredient onto the scalp and hair. The polymer degrades slowly into harmless byproducts (like lactic acid, glycolic acid, or natural gums).[38]

### Dendrimers

Dendrimers are highly branched, nanosized macromolecules with a distinct architecture that includes a central core, many inner layers, and numerous surface functional groups. Their unusual structure enables them to encapsulate both hydrophilic and lipophilic herbal actives, resulting in excellent drug loading capacity and regulated release. Polyamidoamine (PAMAM) dendrimers, for example, have been investigated for transporting antioxidants and anti-inflammatory herbal components to the scalp and hair follicles, hence improving therapeutic efficacy.[39]

### Micelles

Micelles are self-assembled nanostructures generated by amphiphilic molecules in aquatic conditions, with a hydrophobic core and a hydrophilic shell. They are especially effective at solubilizing herbal components that are poorly water soluble, increasing their stability, bioavailability, and penetration into the scalp. Polymeric micelles have been employed to deliver lipophilic herbal actives including curcumin and eugenol, resulting in sustained release and less scalp discomfort.[41]

**Table . Advantages of Nanocarrier Systems in Herbal Hair Care**

This table summarizes the key advantages offered by nanocarrier systems in herbal hair care formulations. Nanocarriers improve the solubility, stability, and permeation of herbal actives, facilitating better delivery to the scalp and hair follicles. They enable controlled and sustained release of bioactives, reducing the need for frequent application and enhancing therapeutic efficacy. Additionally, nanocarriers help reduce skin irritation and improve the overall safety profile of herbal products. Their versatility allows incorporation into various hair care formulations, making them highly suitable for both cosmetic and therapeutic applications.

<b>Advantage</b>	<b>Explanation</b>
<b>Enhanced solubility &amp; stability</b>	Improves the solubility of poorly water-soluble herbal actives and protects them from degradation (light, heat, oxygen).
<b>Improved permeation &amp; penetration</b>	Enhances scalp absorption and delivery of actives into hair follicles, especially useful for hydrophilic or large-molecule compounds.
<b>Controlled &amp; sustained release</b>	Provides prolonged therapeutic effect, reduces frequency of application, and improves user compliance.
<b>Targeted follicular delivery</b>	Directs actives to hair follicles, maximizing local action and minimizing systemic side effects.
<b>Reduced irritation &amp; improved safety</b>	Encapsulation lowers skin exposure to potentially irritating herbal compounds, reducing the risk of sensitization or allergic reactions.
<b>Versatility in formulations</b>	Nanocarriers can be incorporated into shampoos, conditioners, serums, oils, and other hair care products, increasing their commercial and therapeutic appeal.

**Safety and Toxicity Considerations of Nanotechnology-Based Herbal Hair Products:**

<b>Aspect</b>	<b>Description / Concern</b>	<b>Example</b>
<b>Skin penetration</b>	Nanocarriers may cross the scalp barrier and reach deeper tissues or systemic circulation.	Lipid nanoparticles, nanoemulsions.
<b>Skin irritation / allergy</b>	Metallic or synthetic nanoparticles can cause irritation, allergic reactions, or sensitization.	Silver nanoparticles, zinc oxide nanoparticles.
<b>Oxidative stress</b>	Some nanomaterials may generate reactive oxygen species (ROS), leading to cell damage or inflammation.	Metallic nanoparticles, poorly stabilized nanocarriers.
<b>Long-term accumulation</b>	Non-biodegradable nanoparticles may build up in tissues due to unclear clearance pathways.	Carbon-based nanocarriers, synthetic dendrimers.
<b>Herbal-nano interactions</b>	Combined effects of herbal actives and nanocarrier materials may change biological activity or toxicity.	Phytochemicals in liposomes or polymeric carriers.
<b>Testing limitations</b>	Conventional safety tests may not fully capture nanoparticle behavior or risks.	Need for advanced in vitro / in vivo testing models.
<b>Regulatory oversight</b>	FDA, EU, and other agencies require detailed safety and toxicology assessments for nanomaterials in cosmetics.	Physicochemical profiling, skin absorption studies.

<b>Safety strategies</b>	Use of biocompatible, biodegradable materials; optimized particle size; eco-friendly manufacturing methods.	Lipid-based carriers, natural polymer nanoparticles.
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## Herbal Agents for Hair Growth

**1. Ashwagandha (*Withania somnifera*)** – An adaptogenic root used in Ayurveda. It lowers cortisol and boosts DHEA, supporting the hair growth cycle. In vitro, it has antioxidant and anti-inflammatory effects on hair follicles. A recent human trial found that a topical ashwagandha root extract serum significantly *increased hair density and thickness and reduced hair shedding* versus placebo over 75 days. An animal study (rats) showed that a 30-day topical formulation containing ashwagandha fruit extract accelerated onset of hair growth by a day compared to control. [49]

**Traditional use:** strengthening hair, reducing hair fall.

**Application:** usually as an oil or serum to the scalp.

**Side effects:** generally mild; high-dose oral use can cause gastrointestinal upset or hypertension (due to glycyrrhizin), but topical use is well tolerated with rare irritation.

**2. Amla (Indian gooseberry, *Phyllanthus emblica*)** – A fruit rich in vitamin C and flavonoids. It has potent antioxidant and anti-inflammatory activity that protects hair follicles from oxidative stress. In Ayurveda and Unani medicine amla is used for hair tonic and graying. Amla extract (e.g. syrup) has shown promise in small trials in female androgenic alopecia, though data are limited. [47]

**Application:** oils or masks containing amla pulp or extract.

**Side effects:** safe topically; excess ingestion can cause acidity or kidney stones (high oxalate content).

**3. Bhringraj (*Eclipta prostrata*, a.k.a. false daisy)** – A staple hair-oil herb in Ayurveda. Its extracts promote the hair follicle anagen (growth) phase: in mice, oral or topical bhringraj increased FGF-7 expression and decreased FGF-5 in dermal papilla, driving follicle growth. (In one rodent study, 14 days of bhringraj induced anagen characteristics and activated mTOR signaling in follicles.) [51]

**Traditional use:** hair regrowth and darkening; often applied as oil.

**Application:** Bhringraj oil massage (alone or in formulation) to scalp.

**Side effects:** very rare; high oral doses may affect thyroid function, but topical use is regarded as safe.

3. **Hibiscus (*Hibiscus rosa-sinensis*)** – An Ayurvedic hair remedy. A petroleum-ether extract of hibiscus leaves (1% in oil) significantly increased hair length and follicle anagen ratio in shaved rats versus control. (Flowers had similar but lesser effect.) The mechanism is not fully known but may involve enhancing local nutrition to follicles. **Traditional use:** hair and scalp conditioning (often as a paste or oil infusion). **Application:** oils infused with hibiscus flowers/leaves or extracts painted on scalp.

**Side effects:** usually safe; may cause contact irritation in sensitive individuals. [51]

## Western and General Herbal Remedies

4. **Rosemary (*Rosmarinus officinalis*)** – An evergreen herb. Its oil contains caffeic/rosmarinic acids and terpenes that are antioxidant, anti-inflammatory, and improve microcirculation. A landmark RCT found that daily 3.7 mg/mL rosemary oil lotion (applied topically) increased hair count in men with AGA **as effectively as 2% minoxidil** (6 months), with less scalp itching. In mice and in vitro, rosemary extract strongly inhibited 5 $\alpha$ -reductase and blocked DHT binding (e.g. 94.6% 5 $\alpha$ -reductase inhibition at 500 mg/mL, comparable to finasteride). [46][52]

**Traditional use:** hair-growth tonic dating back to ancient Greece.

**Application:** 1–3% essential oil in carrier oil or extracts in shampoos/lotions.

**Side effects:** generally safe; high concentrations can irritate skin. Use is contraindicated in epilepsy (strong scent) and pregnancy (avoid concentrated oils).

5. **Peppermint (*Mentha piperita*)** – An essential oil herb. Its menthol content induces scalp vasodilation and a cooling sensation. In a mouse model (daily 3% solution), topical peppermint oil produced **92% hair regrowth** at 4 weeks (vs. 55% for 3% minoxidil). It increased anagen follicle number, alkaline phosphatase (a vascular marker), and IGF-1 expression, suggesting a vasodilatory/promotility effect[56].

**Traditional use:** invigorating scalp circulation in aromatherapy.

**Application:** diluted (e.g. 0.5–3%) in carrier oil, massage into scalp.

**Side effects:** a tingling cooling sensation; can cause mild irritation or allergic contact dermatitis if not properly diluted. Avoid eyes and broken skin.

6. **Tea Tree (*Melaleuca alternifolia*)** – A disinfectant essential oil. It's rich in terpinen-4-ol and other terpenes. While pure tea tree hasn't been trialed alone for hair regrowth, a small RCT of a *compound topical* (5% minoxidil + 5% tea tree + 0.5% diclofenac) showed faster and greater hair count increases in men with AGA than minoxidil alone [14]. Tea tree's role is likely as an antifungal/antimicrobial and anti-inflammatory adjunct, improving scalp health.

**Traditional use:** antiseptic for scalp (dandruff, etc.).

**Application:** diluted in carrier oil or shampoo (commonly 5–10%).

**Side effects:** can irritate or sensitize some scalps; always dilute.

7. **Lavender (*Lavandula spp.*)** – A flowering herb. In a mouse RCT, topical lavender oil (3–5%) produced about **90–95% hair regrowth** at 4 weeks (vs. 99.8% for 3% minoxidil). Lavender's constituents (linalool, linalyl acetate, etc.) are antimicrobial and soothe inflammation, which may indirectly support follicle growth.

**Traditional use:** calming aromatherapy, sometimes in hair cleansers.

**Application:** diluted 1–5% in carrier oils or shampoo.

**Side effects:** generally very well tolerated, though it can rarely cause contact dermatitis.

8. **Green Tea (*Camellia sinensis*)** – Contains EGCG and other catechins. EGCG stimulates dermal papilla cell proliferation and inhibits apoptosis, and selectively blocks 5 $\alpha$ -reductase. Thus green tea promotes anagen phase and lowers DHT. Small human trials (topical green tea extract) reported improved hair density/thickness in pattern hair loss. **Traditional use:** beverage; in Japan/China used for scalp cooling and health. **Application:** topical extracts or brewed rinse (standardized EGCG formulations). **Side effects:** minimal (caffeine sensitivity unlikely topically).

9. **Pumpkin Seed Oil (*Cucurbita pepo*)** – Rich in phytosterols (e.g.  $\beta$ -sitosterol) and fatty acids.  $\beta$ -sitosterol inhibits 5 $\alpha$ -reductase, reducing DHT. In a 3-month RCT in women with female-pattern alopecia, 1 mL topical pumpkin seed oil daily significantly improved hair-shaft calibre (measured by decreased diversity of shaft diameters). An animal study showed that 10% topical pumpkin seed oil countered testosterone-induced hair loss almost as well as 2% minoxidil.

**Traditional use:** nutritional tonic; seed oil used for hair on Baltic folk lore.

**Application:** oil rubbed into scalp (alone or as component of lotions).

**Side effects:** mild scalp greasiness; high-quality oil usually safe and non-irritating.

10. **Licorice (*Glycyrrhiza glabra*)** – The root contains glycyrrhizic and glycyrrhetic acids. 18 $\beta$ -Glycyrrhetic acid strongly stimulated human dermal papilla and outer root sheath cell proliferation in culture and inhibited 5 $\alpha$ -reductase (IC<sub>50</sub>  $\approx$  137  $\mu$ M). It also suppressed TGF- $\beta$ 1 (a signal that drives follicles into catagen). In short, licorice may prolong anagen and counteract DHT.

**Traditional use:** Ayurveda and TCM as an anti-inflammatory sweetener.

**Application:** extracts in shampoos or oils.

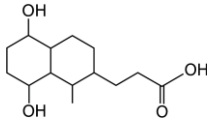
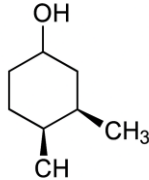
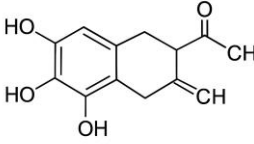
**Side effects:** safe topically, but concentrated oral liquorice can cause oedema, hypertension (due to cortisol-mimetic effects); not a concern for scalp use.

11. **Onion (*Allium cepa*)** – A garden vegetable long used in folk medicine for alopecia areata. Onion juice is rich in sulfur amino acids and antioxidants (quercetin, flavonoids). A small RCT in alopecia areata (45 patients) found that applying raw onion juice to the scalp twice daily for 8 weeks led to *complete regrowth in 87%* of patients, vs. only 13% with water. The proposed mechanism is that sulfur nourishes keratin, and the mild contact dermatitis from onion phenolics may invoke antigenic competition to counter autoimmunity.

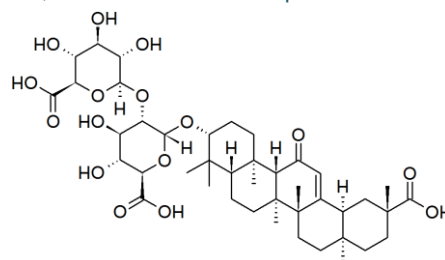
**Traditional use:** hair rinse to stop hair loss.

**Application:** apply fresh onion juice directly (often mixed with a carrier or in shampoo).

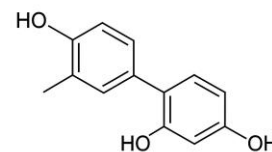
**Side effects:** strong odour and scalp burning; can irritate eyes or damaged skin.

Herb	Mechanism(s)	Traditional Uses	Structure
<b>Rosemary (<i>R. officinalis</i>)</b>	↑Scalp vasodilation/ $\beta$ -adrenergic activity, antioxidant/anti-inflammatory, 5 $\alpha$ -reductase inhibitor	Hair tonic (Greece, Ayurveda)	 <p>Carnosic acid</p>
<b>Peppermint (<i>M. piperita</i>)</b>	Menthol-induced vasodilation and increased IGF-1/ALP in follicles	Scalp stimulant (traditional aromatherapy)	 <p>Menthol</p>
<b>Tea Tree (<i>M. alternifolia</i>)</b>	Antimicrobial/anti-inflammatory (improves scalp environment).	Antifungal for scalp (Australia)	
<b>Green Tea (<i>C. sinensis</i>)</b>	EGCG stimulates dermal papilla proliferation, inhibits apoptosis, and blocks 5 $\alpha$ -reductase	Antioxidant, used as rinse (Japan/China)	 <p>EGCG</p>
<b>Pumpkin Seed Oil (<i>C. pepo</i>)</b>	Phytosterols ( $\beta$ -sitosterol) inhibit 5 $\alpha$ -reductase; anti-inflammatory ( $\downarrow$ IL-6)	Nourishing oil (folk remedy)	

**Licorice** (*G. glabra*) (G. 18β-Glycyrrhetic acid → ↑DP/ORS cell proliferation, inhibits 5α-reductase, ↓TGF-β1 (prolongs anagen) Soothing, hormone modulator (Ayurveda)

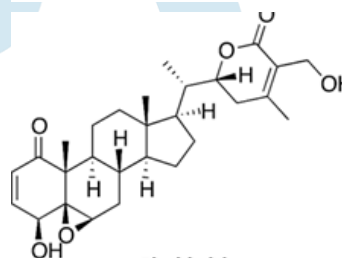


**Onion Juice** (*Allium cepa*) Sulfur-rich, antioxidant; induces mild irritant (contact dermatitis) that may trigger hair regrowth (antigenic competition) Hair tonic (folk remedy worldwide)



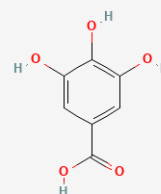
QUERCETIN

**Ashwagandha** (*W. somnifera*) Adaptogen: ↓cortisol, ↑DHEA; antioxidant/anti-inflammatory (withanolides) Rejuvenative tonic (Ayurveda)

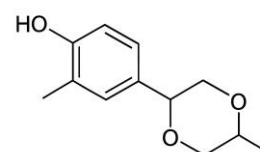


Glychirizin

**Amla** (*P. emblica*) (P. Powerful antioxidant and anti-inflammatory, protecting follicles from damage Hair darkening, strengthening agent (Ayurveda)

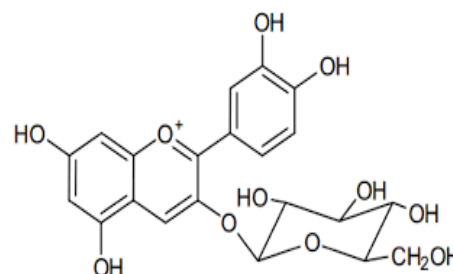


**Bhringraj** (*E. prostrata*) (E. Induces anagen via ↑FGF-7 and ↓FGF-5 in dermal papilla Hair revival oil (Ayurveda)



WEDELOLCTONE

**Hibiscus** (*H. rosa-sinensis*) (H. Unclear – likely provides flavonoids/carotenoids that nourish follicles. Hair conditioning and shine (folk)



## Case studies

### Rosemary (*R. officinalis*)

Begum et al. (2023) investigated the potential of a 1% herbal hair lotion, which contains a methanolic extract of *Rosmarinus officinalis*, for promoting hair growth in C57BL/6 male mice. The subjects were categorized into three groups (n=6): a control group receiving water, a test group receiving the 1% rosemary lotion, and a standard group receiving 2% minoxidil. The formulations were applied topically twice a day for a duration of 30 days on the shaved dorsal skin. The parameters evaluated included the initiation and completion of hair growth, hair length and weight, total protein content, histological alterations, and skin irritation. The group treated with rosemary exhibited a quicker initiation of hair growth (3 days) and completion (15 days) in comparison to the minoxidil group (16 days) and the control group (27 days). By the end of the fourth week, the hair length in the test group reached  $76.3 \pm 0.35$  mm, while the minoxidil group measured 45.9 mm and the control group 44.3 mm, alongside a greater hair weight of  $57 \text{ mg/cm}^2$  and elevated blood protein levels of 4.0 g/dL. Histological examination demonstrated a faster onset of anagen phase and a greater density of follicle formation ( $16 \pm 1.0$ ) in mice treated with rosemary, showing no indications of irritation or edema. The research concluded that the rosemary-infused lotion markedly improved hair regrowth and follicular activity, probably owing to its flavonoid, phenolic, and terpenoid components that possess antioxidant and antiandrogenic characteristics, suggesting its potential as a safe and effective natural substitute for minoxidil.

### Peppermint (*Mentha piperita*)

Suryani et al. (2025) explored the hair growth properties of nanoliposomes containing peppermint essential oil (NANO-SERF-OPs) using male Sprague Dawley rats. The nanoliposomes were created through the thin-layer hydration technique utilizing Phospholipon® 80H\* and Phytosolve®, resulting in spherical vesicles with a particle size of  $96.7 \pm 1.9 \text{ nm}^{**}$ , a polydispersity index (PDI) of  $0.4 \pm 0.02$ , and a zeta potential of  $-12.6 \pm 0.5 \text{ mV}^{**}$ . The formulated nanoliposome gel demonstrated appropriate pH (5.78), viscosity (3,904 cP), and spreadability, indicating its stability and suitability for topical application. The rats were divided into five groups: control, gel base, commercial tonic, peppermint oil gel, and nanoliposome gel. The formulations were administered twice a day for 30 days on a shaved dorsal skin area measuring  $3 \times 3$  cm. Ethical approval was secured (Ref. No. 159/KEP-PKU/X/2023). No signs of erythema or edema were detected (PII = 0), confirming the safety of the treatment for the dermal layer.

### Hibiscus (*H. rosa-sinensis*)

The hair growth potential of hibiscus leaf ethanol extract was evaluated in rabbits divided into five groups: a positive control, a negative control, and formulations containing 10% (FI), 15% (FII), and 20% (FIII) extract. Hair length was the key parameter. The negative control showed the smallest growth (2.44 mm, 4.23 mm, and 5.54 mm on days 8, 15, and 21), whereas the 20% formulation (FIII) produced the greatest hair length (6.01 mm, 8.70 mm, and 12.43 mm on the same days).<sup>4</sup>

One-Way ANOVA Repeated Measures showed significant differences across the three weeks, and pairwise comparisons confirmed that each weekly measurement varied significantly. All hibiscus extract creams (10%, 15%, and 20%) promoted hair growth comparable to the positive control (minoxidil) and exceeded the effects of the negative control, with the 20% formulation demonstrating the strongest activity.

Phytochemical screening revealed flavonoids, phenols, and saponins, with flavonoids likely contributing to the hair growth effect by strengthening capillaries, improving microcirculation, and enhancing nutrient supply to hair follicles.

## Conclusion

Nanotechnology offers a robust strategy to overcome the intrinsic limitations of herbal actives in hair care—namely poor solubility, instability, inadequate follicular penetration, and inconsistent bioavailability. Advanced nanosystems such as nanoemulsions, liposomes, SLNs, NLCs, polymeric

nanoparticles, and ethosomes markedly enhance the physicochemical stability, scalp permeation, and targeted follicular delivery of both lipophilic and hydrophilic phytoconstituents. Evidence from experimental models demonstrates that nano-enabled herbal formulations significantly improve anagen induction, follicular density, and overall hair regeneration compared to conventional preparations.

Despite these promising outcomes, challenges persist regarding long-term safety, nanoparticle–skin interactions, and regulatory standardization. Nevertheless, the cumulative data indicate that nanoscale delivery systems represent a scientifically validated and highly effective platform for maximizing the therapeutic potential of herbal compounds in next-generation hair care formulations.

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