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Piper nigrum (Black Pepper) Leaf: A Comprehensive Review of Its Phytochemistry, Pharmacological Activities, and Cosmeceutical Potential

Neha Patil[1], Pratiksha Meshram[2]*, Sonali Shambarkar[3], Ruchira Gajbhiye[4] ,Manoj Girase[5]
Research Scholar, Department of Cosmetics Technology [1]
Department of Cosmetic Technology,
R. C. Patel Institute of Pharmaceutical Education and Research, Shirpur, India[2*345]
*Corresponding author Email: meshrampratiksha1998@gmail.com [Ms. Pratiksha Meshram]

Abstract: *Piper nigrum (black pepper) is widely recognized for the medicinal and commercial importance of its fruits; however, its leaves remain comparatively underexplored despite possessing a rich phytochemical composition and significant therapeutic potential. The leaves contain various bioactive constituents, including flavonoids, terpenoids, alkaloids, and essential oils, which exhibit antioxidant, anti-inflammatory, antimicrobial, and wound-healing activities, highlighting their relevance in cosmeceutical applications. A comprehensive review of peer-reviewed literature was conducted to evaluate the ethnobotanical significance, phytochemical profile, pharmacological activities, and formulation approaches of P. nigrum leaves, particularly for scalp and hair-care applications. Key constituents such as β-caryophyllene and α-bisabolol demonstrated CB2 receptor agonistic activity and enzyme inhibitory effects, suggesting potential neurocosmetic benefits in managing stress-related scalp disorders and reducing hair fall. In addition, advanced delivery systems including liposomes and nanoemulsions were reported to enhance the stability, penetration, and bioavailability of volatile phytoconstituents, thereby improving the efficacy of topical formulations. Overall, P. nigrum leaves represent a sustainable and multifunctional botanical ingredient with considerable promise for the development of next-generation cosmeceuticals, supporting emerging trends in neurocosmetics and holistic scalp care with substantial therapeutic and commercial potential..*

Keywords: Antioxidant activity, Advanced delivery systems, Hair fall prevention, *Piper nigrum*, Scalp inflammation

I. INTRODUCTION

The demand for plant-based cosmeceuticals has grown rapidly due to consumer preference for natural, safe, and multifunctional ingredients [1]. Among such botanicals, *Piper nigrum* L. (black pepper) has long been recognized in traditional systems of medicine for its therapeutic value. While the fruits of *P. nigrum* are widely studied, its leaves remain comparatively underexplored despite being rich in bioactive constituents [1,2].

Recent investigations show that black pepper leaves contain diverse phytochemicals, including flavonoids, terpenoids, and essential oil components such as α-bisabolol and β-caryophyllene, which exhibit notable antimicrobial, antioxidant, and anti-inflammatory activities [3]. Advances in green extraction techniques have further enabled efficient recovery of these compounds from what is often considered agricultural waste, highlighting the leaves as a cost-effective and sustainable resource [4].

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Given their promising biological properties, *P. nigrum* leaves offer significant potential for modern cosmeceutical applications, particularly in skin and hair care [5]. This review summarizes the phytochemical profile, pharmacological properties, cosmeceutical relevance, safety considerations, and future research opportunities associated with black pepper leaf.

Piper nigrum L. (black pepper), a perennial climber of the family *Piperaceae,* is widely cultivated in tropical regions, with India recognized as its center of origin. The plant bears heart-shaped leaves and spike-like inflorescences, producing peppercorns that are commercially important [6]. It thrives in warm, humid climates and well-drained soils, commonly cultivated in mixed cropping systems across South and Southeast Asia [7].

Although the fruits of *P. nigrum* are extensively used in food and traditional medicine, the leaves have received comparatively less attention despite their ethnomedicinal relevance. In Ayurveda, Unani, and local folk practices, black pepper leaves have been applied as poultices or decoctions for managing muscle pain, inflammation, respiratory discomfort, and skin infections. Their reported antimicrobial and anti-inflammatory properties align with their traditional topical applications [8,9].

Despite this long-standing therapeutic use, scientific exploration of *P. nigrum* leaves remains limited, warranting detailed investigation into their phytochemistry and potential cosmeceutical applications.

Fig.1. *Piper nigrum* L. (black pepper)

Materials and methods

A. Materials

The materials used for this review included peer-reviewed scientific publications, ethnobotanical records, phytochemical databases, and authenticated reference books related to medicinal plants and cosmeceuticals. Digital sources such as PubMed, Scopus, ScienceDirect, Web of Science, and Google Scholar provided primary research articles and analytical data on *Piper nigrum* leaves. Additional information was gathered from reports on extraction methods, analytical techniques, and cosmetic formulation standards. All selected materials were evaluated for relevance, scientific credibility, and focus on the phytochemistry, biological activities, and potential cosmeceutical applications of *Piper nigrum* leaf extracts.

B. Methods

This review was conducted using a structured literature search approach to compile and evaluate current scientific evidence on the phytochemical composition, pharmacological activities, and cosmeceutical potential of Piper nigrum leaves. Research articles, reviews, books, and reports published in reputable databases such as PubMed, Scopus, Google Scholar, ScienceDirect, and Web of Science were screened. Keywords including Piper nigrum, black pepper leaf, phytochemistry, antioxidant activity, antimicrobial activity, cosmeceutical applications, and hair or skin benefits were used. Studies focusing specifically on leaf extracts, essential oils, biological activities, formulation strategies, and

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safety assessments were prioritized. Relevant data were extracted, compared, and synthesized to present an updated and comprehensive understanding of the therapeutic and cosmetic significance of Piper nigrum leaves.

C. Phytochemistry of Black Pepper Leaf

1. Alkaloids

Alkaloid scuring piperine and its analog piperamides are also present in black pepper leaves, but in negligible amounts compared to those in the fruits. Piperine strengthens scalp microcirculation, ensuring that hair follicles receive the nutrients necessary for hair growth [10]. It is also a bioavailability enhancer, allowing for deeper penetration and effect. The possible 5α-reductase inhibitory activity of piperine could be helpful in treating androgenetic alopecia [11,12].

2. Flavonoids

Flavonoids, such as quercetin, kaempferol, and rutin, have been identified in *P. nigrum* leaves and exert powerful antioxidant effects by inactivating free radicals that may destroy hair follicle cells [13]. Flavonoids also exhibit anti-inflammatory activity on the scalp, which has been shown to aid in reducing dandruff and folliculitis, two major causes of hair loss [14].

3. Phenolic Compounds

Phenolic acids, such as gallic, ferulic, and caffeic acid, function as effective free radical scavenging agents and are equally efficient in preventing oxidative threats to scalp tissues [15]. Ferulic acid improves photoprotection and stabilizes other antioxidants, thus being useful in scalp serum applications against photodamage and premature graying of hair [16].

4. Tannins

Most astringent or antimicrobial tannins regulate excessive sebum production on the scalp and strengthen the hair fibers. The presence of such ingredients in hair care formulations not only reduces the microbial load but also alleviates irritation, promoting scalp cleanliness, which is essential for hair- fall prevention [17].

5. Terpenoids and Essential Oils

Volatile components such as caryophyllene, limonene, and linalool are responsible for the anti-inflammatory, antimicrobial, and analgesic activities of black pepper leaf oil. Overall, these terpenoids also induce circulation and promote follicular activity, which adds to new hair growth and strengthens the root, making the product more pleasant to use owing to fragrance choice and enhanced user experience in hair care products [17].

6. Steroids and Saponins

Phytosterols, such as β-sitosterol and stigmasterol, have shown potential 5α-reductase inhibitory action, resulting in an estimated reduction in dihydrotestosterone (DHT), a major cause of hair loss in androgenetic alopecia [18]. Although present in smaller quantities, saponins are natural surfactants that help cleanse and emulsify herbal shampoos and scalp serums.

7. Glycosides

The glycosides present in *P. nigrum* leaves act as antioxidant precursors and are enzymatically hydrolyzed to provide bioactive aglycones that promote scalp health and decrease inflammation. Such abilities to increase the solubility of lipophilic active ingredients may be attractive for improving overall formulation stability and delivery [19].

Table I : Phytochemical Classes of *Piper nigrum* and Their Cosmeceutical Relevance

Phytochemical Class	Representative Compounds	Reported Biological Activity	Cosmeceutical Relevance	Reference
Alkaloids	Piperine, Piperlongumine, Pellitorine	Anti-inflammatory, antimicrobial, hair growth	Enhances bioavailability; scalp and skin care	[20.21]
Flavonoids	Quercetin, Kaempferol, Rutin, Catechin	Antioxidant, anti-aging, UV protection	Prevents oxidative damage, maintains collagen	[22.23]

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Terpenoids	Caryophyllene, Limonene, Sabinene	Anti-inflammatory, antimicrobial, follicle stimulation	Hair growth promotion, skin soothing	[24,25]
Phenolics	Gallic acid, Ellagic acid	Antioxidant, astringent	Anti-aging, skin tightening	[26,27]
Tannins	Condensed tannins	Antioxidant, antimicrobial	Skin barrier protection	[28]
Glycosides & Saponins	Various glycosides, saponins	Antioxidant, antimicrobial	Barrier support, formulation stability	[29,30]

D. Pharmacological and Biological Activities

The leaves of black pepper (*Piper nigrum*) are gaining respect for their various pharmacological and biological activities owing to their phytochemical constitution. Leaves are rich in bioactive compounds, including volatile oils, sesquiterpenes, flavonoids, alkaloids, terpenoids, and phenolic acids, which exhibit antimicrobial, antioxidant, anti-inflammatory, and cytotoxic properties [31]. These compounds distinguish the leaf extract from the more pungent fruit extract, making the leaf extract more suitable for cosmeceutical and dermatological applications. The entire array of therapeutic potential of black pepper leaf extract provides a scientific rationale for its use in formulations for hair fall prevention and scalp health, especially when if delivered through advanced nanotechnology-based systems.

1. Anti-inflammatory Activity

Scalp inflammation, especially inflammation affecting hair follicles, is prime culprit in hair fall conditions such as androgenetic alopecia, alopecia areata, and telogen effluvium. When inflammation occurs in the scalp, hair follicles are stressed, causing them to shrink, age, and become susceptible to attacks from the immune system [31]. Anti-inflammatory ingredients in hair care products subdue this inflammatory reaction by inhibiting harmful signals such as IL-6, IL-8, and TNF-α, as well as modifying NF-κB and COX-2 pathways that induce inflammation [32]. The leaves of *Piper nigrum* (black pepper) contain potent natural compounds, including β-caryophyllene, α-cubebene, and α-bisabolol, which soothe the scalp. For example, β-caryophyllene selectively interacts with anti-inflammatory CB2 receptors to all ease inflammation [33]. α Cubebene downregulates IL-6 and IL-8, while α-bisabolol calms inflammation stemming from nerve irritation [33]. Together, they protect hair follicles and encourage healthy hair growth, making *Piper nigrum* leaf extract an excellent candidate for formulating liposomal hair serum designed to prevent hair fall and promote scalp health [34].

2. Antioxidant Activity

Oxidative stress is leading causes of hair aging and certain hair loss disorders, such as androgenetic alopecia and telogen effluvium. It occurs because of the accumulation of reactive oxygen species (ROS), especially superoxide radicals and hydrogen peroxides, resulting from environmental exposure (UV radiation, pollution), as well as inflammation and metabolic disturbances. ROS damage most follicle components, particularly dermal papilla cells, which are mainly involved in the control of growth and movement from one hair cycle phase to another. These strategies involve the application of antioxidant-rich hair care formulations Bioactive components, such as flavonoids (quercetin), phenolic acids, and essential oils (eugenol and limonene), exhibit potent antioxidant efficacy. These substances neutralize reactive oxygen species (ROS) and inhibit lipid peroxidation, thereby maintaining cell membrane integrity. They also enhance microcirculation on the scalp, nutrient delivery to hair follicles, and extend the anagen (growth) phase, increasing the resilience and density of the follicle [35]. Advanced formulations enriched with antioxidant extracts from the leaves of *Piper nigrum* are protective to scalp tissues and reduce cell degeneration induced by follicular senescence. Their antioxidant efficacy is usually determined using standardized assays such as DPPH (radical- scavenging capacity), ABTS (hydrophilic/lipophilic antioxidant potential), and FRAP (electron-donating ability) [36]. Collectively, these mechanisms establish antioxidant activity as the basis for developing effective and scientifically credible cosmeceutical interventions.

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3. Antimicrobial Activity

The presence of bioactive compounds, such as eugenol, β-caryophyllene, and α-humulene, in *Piper nigrum* (black pepper) leaf extract may be responsible for its antimicrobial action [37,38]. These compounds disrupt the microbial cell membrane, causing leakage of cellular contents and interruption of essential enzyme functions [39]. Ethanolic and essential oil extracts of the leaves have been shown to have broad-spectrum activity against gram-positive bacteria, such as *Staphylococcus aureus* and *Bacillus subtilis*; gram-negative strains, such as *Escherichia coli* and *Pseudomonas aeruginosa* and fungi, such as *Candida albicans* and *Aspergillus niger* [40,41,42]. This antimicrobial action is directly related to hair care, where these pathogens play a significant role in inducing scalp infections, dandruff, and hair loss due to inflammation. By attenuating microbial colonization and attendant inflammatory activities, black pepper leaf extract provides a conducive environment for scalp affliction, thereby preventing an injurious effect on the follicles and supporting antioxidative mechanisms in cosmeceutical formulations [43]. Its incorporation into targeted delivery systems further enhances bioavailability and targeted actions. Thus, black pepper leaf extract is an attractive natural option for synthetic antimicrobials for the treatment of the scalp.

E. Other Activities of Black Pepper Leaf Extract

1. Insecticidal Activity

The essential oil of *Piper nigrum* leaves exhibits significant insecticidal and repellent activity due to its high content of terpenoids such as sabinene, limonene, and β-caryophyllene. These compounds interfere with insect neurosensory pathways, leading to paralysis and mortality. Such activity has been demonstrated against several vectors, including *Aedes* and *Culex* species [44,45]. In the context of hair and scalp care, these properties are particularly relevant for managing lice infestations. Unlike conventional pediculicides, which may cause irritation or resistance with prolonged use, black pepper leaf oil offers a natural alternative capable of reducing scalp discomfort and maintaining hygiene when incorporated into topical formulations like serums or oils [46].

2. Wound-Healing Activity

Black pepper leaf extract supports tissue repair through multiple mechanisms. Its polyphenols and terpenes enhance fibroblast proliferation, stimulate collagen deposition, and promote faster epithelialization. These activities are further strengthened by the extract's antioxidant capacity, which reduces oxidative stress commonly associated with impaired wound healing. In scalp-care applications, these mechanisms are valuable for soothing irritated or damaged areas caused by scratching, dandruff, or parasitic infestations. By promoting regeneration of the scalp surface and supporting follicular resilience, the extract contributes to overall hair health and recovery [47].

3. Skin Penetration Enhancement

The essential oil is rich in monoterpenes and sesquiterpenes known for their ability to transiently modify the lipid arrangement of the stratum corneum. This disruption enhances the permeability of the skin barrier, allowing deeper delivery of co-administered actives [48]. When used in hair-care formulations, black pepper leaf oil can facilitate the penetration of ingredients such as caffeine, biotin, and minoxidil, improving their bioavailability at the follicular level. This natural penetration-enhancing effect supports the development of more efficient and synergistic formulations for hair strengthening and growth promotion [49].

4. Neurocosmetic (Aromatherapeutic) Effect

Volatile constituents of the leaf oil, including linalool and eugenol, contribute to its neurocosmetic benefits. Upon inhalation or topical application, these molecules interact with olfactory receptors and influence the limbic system, contributing to reduced stress and improved emotional well-being. As chronic stress is a key factor in hair disorders such as telogen effluvium, the aromatherapeutic actions of black pepper leaf oil offer an added advantage in cosmetic formulations. Products incorporating this oil may therefore provide dual benefits supporting psychological relaxation while promoting scalp and hair health aligning with modern neurocosmetic trends [50].

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F. Mechanisms of Action

1. Interaction with Microbial Cell Membranes

Phytochemicals in *Piper nigrum* leaves particularly terpenoids and phenolics disrupt microbial cell membranes by integrating into the lipid bilayer and increasing permeability. This leads to leakage of intracellular contents and cell lysis. Extracts have shown inhibitory activity against common pathogens such as *Staphylococcus aureus*, *E. coli*, and *Klebsiella* spp., indicating their potential for managing scalp and skin infections [51].

2. Free Radical Scavenging

The leaf extract exhibits strong antioxidant activity due to its rich phenolic and flavonoid content. These compounds neutralize reactive oxygen species and reduce oxidative stress, which helps protect hair follicles and skin cells from damage. In vitro assays confirm significant radical-scavenging capacity, supporting the use of *P. nigrum* leaf-derived antioxidants in cosmeceutical formulations targeting scalp health, skin protection, and anti-aging [52,53].

3. Enzyme Inhibition

Bioactive constituents such as β-sitosterol, stigmasterol, and caryophyllene derivatives demonstrate inhibitory effects on key enzymes linked to hair and skin conditions. Notably, inhibition of 5α-reductase may help reduce dihydrotestosterone (DHT)-mediated hair loss, while phenolics show activity against tyrosinase and elastase, enzymes involved in hyperpigmentation and skin aging. These mechanisms highlight the multifunctional potential of *P. nigrum* leaves in hair growth and anti-aging applications [54,55].

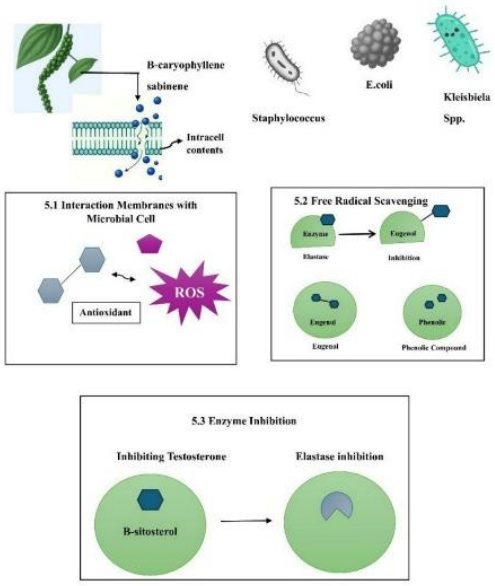

Fig.2. Mechanism of action

II. RESULTS AND DISCUSSION

A. Formulation and Application Potential

The leaves of *'Piper nigrum'* are extremely useful in several industries owing to their antioxidant, antimicrobial, and anti-inflammatory properties. The bioactive profiles of these plants are characterized by high levels of polyphenols and essential oils, supporting their application in pharmaceuticals, cosmetics, functional foods, and nutraceuticals. However, factors such as volatility and poor solubility of some constituents (e.g., eugenol and limonene) have led to the application of advanced delivery systems to improve their stability and efficacy.

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B. Applications Across Cosmeceutical

This is valued in the cosmetics industry for hair and scalp care purposes. The extract contains valuable essential oils and polyphenolic compounds, which help improve the microcirculation of the scalp with bioactives, such as eugenol and caryophyllene, to support the delivery of nutrients to hair follicles and promote the growth of healthier hair. It has very strong antimicrobial properties, which affect scalp-associated microorganisms, especially the *Malassezia* species associated with dandruff and seborrheic dermatitis; [56, 57]. therefore, it is suitable for therapeutic shampoos and for targeted scalp treatments. The antioxidant constituents present in these products protect scalp cells against oxidative damage caused by reactive oxygen species (ROS), thus delaying cellular aging and preserving the integrity of the hair cycle [58]. In addition, the warm and spicy aroma of the extract provides a sensory experience that can further enhance emotional well-being, as noted in the emerging neurocosmetic principles. These benefits render *Piper nigrum* leaf extract a highly valued active ingredient in leave-on formulations, such as serums, emulsions, and gels, designed to treat hair loss, scalp irritation, and premature skin aging.

C. Nanoformulations and Advanced Delivery Systems

Nanoformulation has become an innovative tool for application in cosmetic science, with special reference to the stabilization and enhancement of the efficacy of essential oil components, such as eugenol and limonene, which suffer from high volatility, poor stability, and extremely low water solubility (WS). These characteristics make liposomes, which comprise phospholipid bilayers, excellent carriers for black pepper leaf extracts in serum formulations because they can engulf both hydrophilic and lipophilic molecules. Furthermore, having a structure similar to that of cell membranes, effective dermal penetration with controlled release becomes possible, which can improve bioavailability. In contrast, nanoemulsions are fine oil-in-water dispersions that can be used to stabilize volatile oils and contribute to the sensory attributes of topical products, such as texture and skin feel while improving shelf-life [59]. For example, of scalp applications, SLN constitutes a protective system that confines sensitive compounds, such as eugenol, against deterioration and promotes the delivery of antioxidants and their sustained release at the site of action [60]. All the aforementioned novel delivery systems address potential formulation problems and improve efficacy in cosmeceutical applications.

D. Future Prospects

Although *Piper nigrum* leaves are rich in bioactive compounds, they remain underutilized compared to the fruits. Future work should focus on clinical studies validating the safety and efficacy of leaf extracts for skin and hair applications. Standardizing key phytochemicals and comparing their performance with established actives will help determine their therapeutic value. Improved delivery systems such as liposomes or nanoemulsions may enhance stability and bioavailability. Utilizing leaf biomass as a sustainable raw material also offers eco-friendly and cost-effective opportunities. Overall, advancing research and formulation strategies could establish *P. nigrum* leaves as a validated multifunctional cosmeceutical ingredient.

Discussion

This review underscores the broader significance of *Piper nigrum* leaves as a functional botanical resource within cosmeceutical science, particularly in the context of sustainable ingredient development. The collective observations suggest that leaf-derived phytochemicals may offer synergistic benefits relevant to scalp homeostasis and hair care, addressing oxidative stress, microbial imbalance, and inflammatory responses that are commonly associated with scalp disorders and hair deterioration. These attributes position *P. nigrum* leaves as a viable alternative to synthetic actives currently used in topical formulations.

From a formulation perspective, the enhanced performance associated with advanced delivery systems highlights the importance of delivery optimization in translating phytochemical potential into practical efficacy. Improved stability and targeted action suggest that formulation strategy may be as critical as ingredient selection in achieving consistent cosmetic outcomes. Additionally, the favorable dermal compatibility reported across studies supports the practical applicability of *P. nigrum* leaf–based formulations in routine cosmetic use.

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Nevertheless, the transition from experimental evidence to commercial application requires further refinement. Greater emphasis on standardization, clinical relevance, and scalable formulation approaches will be essential to ensure reproducibility, regulatory acceptance, and industrial feasibility. Addressing these challenges will ultimately determine the successful integration of *P. nigrum* leaf extracts into next-generation hair and scalp care products.

IV. CONCLUSION

Piper nigrum leaves represent a valuable yet underexplored source of bioactive phytochemicals with significant antioxidant, anti-inflammatory, antimicrobial, and wound-healing activities relevant to scalp and hair health. Key constituents such as flavonoids, terpenoids, and essential oils support hair-fall prevention, scalp protection, and neurocosmetic benefits. The use of advanced delivery systems enhances the stability and bioavailability of these actives, improving their cosmeceutical performance. Overall, *P. nigrum* leaf emerges as a sustainable and multifunctional ingredient for next-generation hair and scalp care formulations.

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