



Bioactive phytoconstituents for hair growth: Signalling pathways and emerging delivery system

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Abstract

Alopecia, commonly known as hair loss, is a multifactorial dermatological condition that affects both men and women globally. It poses aesthetic, psychological, and emotional challenges. Current treatments such as minoxidil and finasteride offer efficacy but are often associated with undesirable side effects. Consequently, the search for alternative therapies has led to increased interest in plant-derived bioactive compounds. This review provides a comprehensive overview of herbal and phytochemical agents that promote hair growth, their mechanisms of action, and their potential integration into clinical practice. Eighteen medicinal plants traditionally used for hair restoration are discussed, with emphasis on their pharmacological mechanisms, key phytoconstituents, and experimental or clinical evidence. The review also explores future trends, including the role of nanotechnology, stem cell therapy, and gene modulation in alopecia management.

Keywords: Alopecia, herbal medicine, hair loss, phytochemicals, hair growth, natural therapy

Introduction

Hair plays a vital role in human identity and self-esteem. Alopecia, or hair loss, is a condition with both aesthetic and medical implications. It may arise from genetic, autoimmune, hormonal, nutritional, or environmental causes. Conventional therapies include topical and systemic agents such as minoxidil and finasteride, which promote hair regrowth by targeting androgen and vascular pathways. However, long-term use of these drugs is often limited due to adverse effects including hormonal imbalance, skin irritation, and cardiovascular complications. The growing interest in alternative and complementary medicine has drawn attention to herbal therapies with proven pharmacological benefits.

Pathophysiology and Types of Alopecia

Alopecia can be broadly classified into non-scarring and scarring types. The non-scarring types include androgenetic alopecia (AGA), alopecia areata (AA), and telogen effluvium, whereas scarring alopecia involves irreversible destruction of follicles. The pathogenesis involves genetic predisposition, autoimmune dysfunction, hormonal imbalance, nutritional deficiencies, and psychological stress. The key molecular target is dihydrotestosterone (DHT), which miniaturises hair follicles in androgenetic alopecia. Herbal compounds with 5 α -reductase inhibitory, anti-inflammatory, antioxidant, and proliferative actions are therefore potential therapeutic agents.

1. Alopecia Areata
2. Alopecia Totalis
3. Alopecia Universalis
4. Androgenic Alopecia

Current Therapeutic Approaches

Minoxidil and finasteride are the only FDA-approved drugs for alopecia. Minoxidil enhances blood circulation and prolongs the anagen phase, while finasteride inhibits 5 α -reductase, reducing DHT levels. Despite their efficacy, both drugs can cause side effects such as scalp dryness,

hypotension, sexual dysfunction, and hormonal imbalance. Hence, herbal alternatives with comparable efficacy and fewer adverse reactions are being explored.

Herbal Medicines for Alopecia

Numerous plants have shown promising results in promoting hair growth through multiple mechanisms such as DHT inhibition, improvement in follicular vascularisation, and activation of growth factors. The following eighteen medicinal plants have demonstrated hair growth-promoting potential through *in vitro*, *in vivo*, or clinical studies:

- Eclipta alba (Bhringraj)
- Phyllanthus emblica (Amla)
- Azadirachta indica (Neem)
- Trigonella foenum-graecum (Fenugreek)
- Hibiscus rosa-sinensis (Hibiscus)
- Aloe barbadensis (Aloe vera)
- Sesamum indicum (Black sesame)
- Glycyrrhiza glabra (Licorice)
- Rosmarinus officinalis (Rosemary)
- Allium cepa (Onion)
- Phyllanthus niruri (Keezhanelli)
- Acacia concinna (Shikakai)
- Lawsonia inermis (Henna)
- Panax ginseng (Ginseng)
- Zingiber officinale (Ginger)
- Murraya koenigii (Curry leaves)
- Mentha piperita (Peppermint)
- Serenoa repens (Saw Palmetto)

Herbal approaches in the management of alopecia: a comprehensive review

Herbal sources used for alopecia

The following table summarizes major medicinal plants with reported activity against alopecia. Each herb is described with its botanical source, family, major phytoconstituents, primary actions, and marketed brand names.

Table 1

Source	Common Name	Family	Phytoconstituents	Primary Actions	Brand Name
Bhringraj	Eclipta alba	Asteraceae	Wedelolactone, Ecliptine, Flavonoids	Promotes anagen phase, enhances follicular blood flow	Indulekha Bringha Oil, Biotique Bio Bhringraj Oil
Amla	Phyllanthus emblica	Phyllanthaceae	Ascorbic acid, Gallic acid, Ellagic acid	Antioxidant, DHT blocker, strengthens roots	Dabur Amla Hair Oil, Patanjali Amla Hair Oil
Neem	Azadirachta indica	Meliaceae	Azadirachtin, Nimbin, Quercetin	Antifungal, antibacterial, reduces scalp inflammation	Himalaya Anti-Dandruff Cream, Patanjali Kesh Kanti Neem Shampoo
Fenugreek	Trigonella foenum-graecum	Fabaceae	Diosgenin, Saponins, Flavonoids	Stimulates follicles, reduces hair fall	Mamaearth Onion & Fenugreek Hair Oil
Hibiscus	Hibiscus rosa-sinensis	Malvaceae	Flavonoids, Saponins, Amino acids	Promotes follicular proliferation, antioxidant	Khadi Hibiscus Shampoo, Indulekha Hibiscus Hair Oil
Aloe vera	Aloe barbadensis	Asphodelaceae	Aloin, Vitamins A, C, E, Polysaccharides	Soothes scalp, enhances hydration	WOW Aloe Vera Hair Gel, Mamaearth Aloe Hair Oil
Licorice	Glycyrrhiza glabra	Fabaceae	Glycyrrhizin, Liquiritin	Inhibits 5 α -reductase, promotes papilla growth	SoulTree Licorice Hair Repair Shampoo
Rosemary	Rosmarinus officinalis	Lamiaceae	Rosmarinic acid, Carnosic acid, Cineole	Improves circulation, anti-DHT	Weleda Rosemary Hair Tonic, Briogeo Scalp Revival Oil
Onion	Allium cepa	Amaryllidaceae	Sulfur compounds, Quercetin	Stimulates follicular regeneration, improves keratin	Mamaearth Onion Hair Oil, WOW Red Onion Oil
Peppermint	Mentha piperita	Lamiaceae	Menthol, Menthone	Enhances IGF-1, stimulates growth	Organix Mantra Peppermint Oil, Infinix Peppermint Oil
Saw Palmetto	Serenoa repens	Arecaceae	β -sitosterol, Fatty acids, Flavonoids	Blocks DHT, supports hair density	Botanical Green Care Saw Palmetto Shampoo

Mechanisms of Action and Phytochemical Pathways

Herbal agents influence multiple signaling pathways involved in hair follicle regulation. These include the Wnt/ β -catenin, IGF-1, VEGF, and TGF- β pathways. Key phytochemicals such as wedelolactone, rosmarinic acid, ginsenosides, and glycyrrhizin exhibit 5 α -reductase inhibition, enhanced dermal papilla proliferation, and prolonged anagen phase activity. Herbal extracts like Eclipta alba and Rosmarinus officinalis have shown comparable effects to minoxidil in preclinical models.

Future Perspectives

Alopecia, characterized by partial or complete hair loss, remains a major dermatological and psychosocial concern due to its profound impact on an individual's emotional well-being and self-esteem. The therapeutic landscape for alopecia is rapidly evolving, driven by innovations in molecular biology, regenerative medicine, nanotechnology, and phytopharmacology.

Among emerging research directions, phytochemical-based therapy has gained considerable attention. Phytochemicals—naturally occurring bioactive compounds derived from plants—exhibit significant potential in modulating the hair growth cycle. These compounds act by stimulating dermal papilla cells, extending the anagen (growth) phase, reducing follicular inflammation, and inhibiting enzymes such as 5 α -reductase, which contribute to follicular miniaturization. Notable phytochemicals including rosmarinic acid, cubebin, jatanamsic acid, and various flavonoids have demonstrated promising outcomes in preclinical investigations.

A major advancement in regenerative medicine involves stem cell therapy, particularly the use of dermal papilla and follicular stem cells to regenerate hair follicles. This approach aims to restore natural hair growth and provide a long-term therapeutic solution, moving beyond the temporary results offered by conventional treatments. Likewise, gene therapy represents an emerging frontier, offering potential for the targeted treatment of androgenetic

alopecia and alopecia areata through the silencing or modification of disease-associated genes.

Low-Level Laser Therapy (LLLT) is another FDA-approved, non-invasive modality showing substantial promise. It utilizes red or near-infrared light to activate follicular cells, enhance ATP synthesis, and stimulate hair regrowth. Its favorable safety profile and efficacy have made it a preferred adjunct therapy in recent years. Concurrently, extensive research is focused on elucidating molecular signaling pathways that govern follicular regeneration. The modulation of these pathways could pave the way for novel gene-level interventions against hereditary and acquired forms of alopecia.

The application of nanotechnology in drug delivery is also revolutionizing alopecia management. Nanoformulations such as liposomes, solid lipid nanoparticles, and nanoemulsions improve the transdermal penetration and bioavailability of both synthetic and herbal agents, thereby enhancing therapeutic efficacy while minimizing adverse effects.

Platelet-Rich Plasma (PRP) therapy, another minimally invasive and autologous approach, has exhibited encouraging clinical outcomes. PRP stimulates dormant hair follicles, promotes angiogenesis, and increases hair density and thickness, particularly in androgenetic alopecia and alopecia areata.

In parallel, herbal medicine continues to be a growing area of exploration. Medicinal plants such as Eclipta alba, Aloe vera, Panax ginseng, and Withania somnifera have shown significant hair growth-promoting effects in experimental models. With increasing scientific validation, standardization, and clinical trials, these botanicals may soon be integrated into evidence-based therapeutic regimens.

Furthermore, the incorporation of Artificial Intelligence (AI) and digital diagnostic technologies is transforming the management of alopecia. AI-driven systems facilitate early detection, monitor disease progression, and enable personalized treatment planning based on individual genetic, hormonal, and lifestyle parameters.

In conclusion, the future of alopecia therapy is moving toward a multidisciplinary, personalized, and integrative paradigm. The convergence of modern biomedical innovations—such as stem cell research, gene editing, nanomedicine, and AI—with the traditional wisdom of herbal therapeutics promises the development of more effective, targeted, and sustainable treatments. Continued scientific exploration and rigorous clinical validation will be essential to overcoming the current therapeutic limitations and enhancing the overall quality of life of individuals affected by alopecia.

Conclusion

The reviewed evidence suggests that herbal therapies offer safe and effective alternatives to synthetic drugs in the management of alopecia. Phytochemicals such as flavonoids, alkaloids, lignans, and saponins act through multi-target pathways to restore hair growth. Further clinical validation and standardisation of herbal formulations are essential to establish their therapeutic potential and integration into mainstream dermatological practice.

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