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Unlocking the secrets of the hair microbiome: From scalp health to therapeutic advances

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ABSTRACT

The human microbiome, a complex and dynamic community of microorganisms abiding in and on the human body, plays a critical part in maintaining health and impacting complaints. This microbiome includes bacteria, fungi, viruses, and other microbes that are essential for various physiological processes such as digestion, immune function, and pathogen protection. Among the different microbiomes in the body, the hair follicle microbiome is a distinct and vital niche. It influences hair and scalp health, including hair growth, immune responses, and forestallment of pathogenic colonization, and is involved in conditions like dandruff, seborrheic dermatitis, and acne. Recent exploration has begun to uncover the composition and functional places of the hair follicle microbiome, revealing its active participation in maintaining hair and scalp health. This review provides a comprehensive overview of the hair follicle microbiome, discussing its composition, functional roles, and relations with the host, and exploring methods to study these microbial communities. It highlights the remedial potential of targeting the hair follicle microbiome in treating hair and scalp conditions and suggests unborn exploration directions in this field.

Introduction

The human microbiome, a complex and dynamic community of microorganisms abiding in and on the human body, plays a pivotal part in maintaining health and impacting disease. Comprising bacteria, fungi, viruses, and other microbes, these communities are integral to various physiological processes, including digestion, immune function, and protection against pathogens (Ogunrinola et al., 2020). The human microbiome's vast diversity and its symbiotic relationship with the host have been subjects of intense research, revealing their significance in maintaining homeostasis and overall well-being. Among the different microbiomes in the body, similar to those in the gut, skin, mouth, and urogenital tract, each has its unique composition and specific functions (Eloe-Fadrosh and Rasko, 2013). Within this intricate system, the hair follicle microbiome represents a distinct and vital niche. Hair follicles, distributed across the scalp and body, give a unique atmosphere where microbial communities thrive (Lousada et al., 2021a). This niche is characterized by distinct microenvironments due to the presence of sebaceous glands, sweat glands, and hair shafts, all contributing to the specific conditions that support different microbial life (Ito and Amagai, 2023). The hair follicle microbiome influences various aspects of hair and scalp health, including hair growth, vulnerable responses, and the prevention of pathogenic colonization (Fig. 1). It's also intertwined with conditions similar to dandruff, seborrheic dermatitis, and acne, emphasizing its clinical significance (Polak-Witka et al., 2020a).

In recent times, exploration has begun to interpret the composition and functional roles of the hair follicle microbiome. Studies have revealed that this microbiome isn't merely a passive inhabitant but an active participant in maintaining the health of the hair and scalp (Constantinou et al., 2021a). The different microbial populations present within hair follicles can interact with the host in ways that influence original vulnerable responses, modulate sebaceous gland activity, and impact hair follicle dynamics (Andersen et al., 2019). Certain microbial species have been shown to play defensive places by outcompeting pathogenic microbes or by modulating seditious responses. Understanding the factors that impact the diversity and stability of the hair

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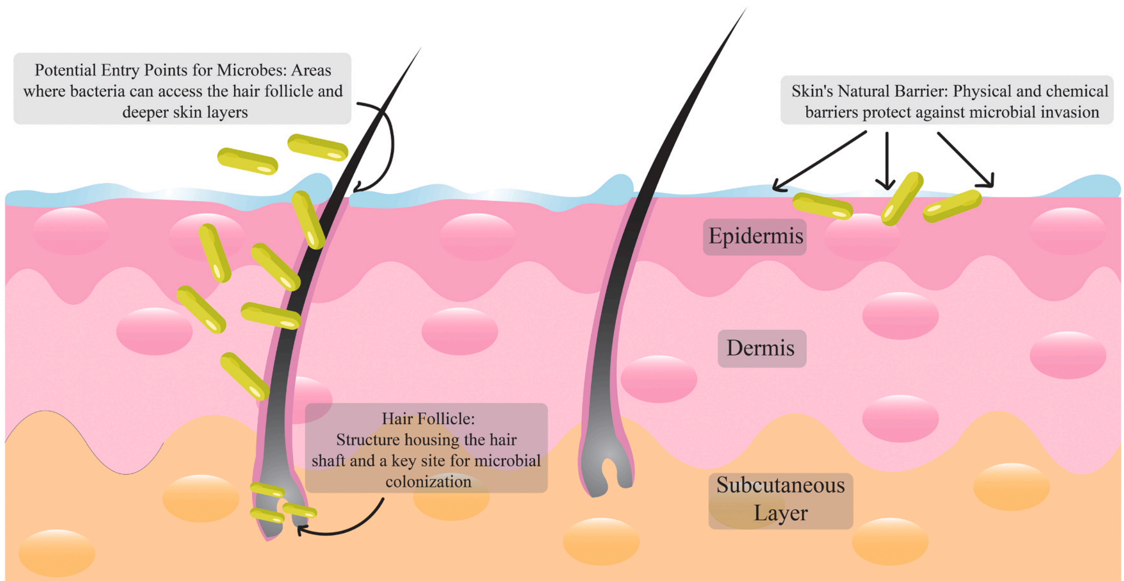

Fig. 1. Schematic representation of microbial colonization in the skin layers. The diagram illustrates the structure of the skin, including the epidermis, dermis, and subcutaneous layer. Hair follicles, which extend from the epidermis into the dermis, serve as key sites for microbial colonization. The bacteria, depicted as green rod-shaped structures, are shown colonizing the surface of the skin, the hair follicle, and the subcutaneous layer. This figure emphasizes the role of hair follicles as a critical environment for microbial growth and interaction with the skin.

follicle microbiome is critical (Kitrinos et al., 2022). Factors such as hormonal fluctuations, environmental exposures, and particular hygiene practices can all influence the composition and health of this microbial community (Watanabe et al., 2019). Advances in microbiome exploration methodologies, including metagenomics and high-outturn sequencing technologies, have handed new perceptivity into the complex relations between hair follicle microbiota and the host (Lin, 2023).

This study aims to provide a comprehensive overview of the hair follicle microbiome, delving into its composition, functional roles, and relations with the host. This study will explore the methods used to study these microbial communities, discuss the factors that impact their diversity and stability, and examine the current understanding of their role in hair and scalp health. This review will also highlight the remedial eventuality of targeting the hair follicle microbiome in treating hair and scalp diseases, as well as the future directions for exploration in this emerging field. Arising exploration suggests that modulating the hair follicle microbiome could offer new strategies for managing hair and scalp conditions. For illustration, probiotics, prebiotics, and other microbiome-modulating treatments may hold promise for restoring balance to disintegrated microbial communities and alleviating associated conditions (Ji et al., 2023).

Through a detailed analysis of current and emerging literatures, this review aims to elucidate the intricate relationship between the hair follicle microbiome and its host. By highlighting the current state of knowledge and relating areas for future disquisition, this study seeks to underscore the importance of the hair follicle microbiome and its implications for dermatology and beyond.

Composition and structure of the hair microbiome

The hair follicle microbiome is a complex and different ecosystem comprising a variety of microorganisms, including bacteria, fungi, viruses, and archaea (Byrd et al., 2018). Bacterial communities within hair follicles are dominated by genera such as *Propionibacterium* (especially Propionibacterium acnes), *Staphylococcus*, and *Corynebacterium* (Schommer and Gallo, 2013). These bacteria play pivotal roles in maintaining follicular health by modulating original vulnerable responses and precluding the colonization of pathogenic microbes. Fungal, particularly species of *Malassezia*, are also abundant (Park et al., 2021a).

Table 1
Overview of microorganisms in the hair follicle microbiome.

Sl no	Microorganism Type	Common Genera/ Species	Role/Significance
1	Bacteria	*Propionibacterium* (e.g., *P. acnes*)	Modulates immune responses, prevents pathogen colonization
		Staphylococcus (e.g., *S. epidermidis*)	Maintains skin barrier, modulates immune function
		Corynebacterium	Part of normal flora, can be opportunistic pathogens
		Cutibacterium (e.g., *C. acnes*)	Involved in lipid metabolism and immune modulation
		Micrococcus	Decomposes sweat, contributes to body odor
2	Fungi	*Malassezia* (e.g., *M. globosa*, *M. restricta*)	Lipophilic yeasts, implicated in dandruff and seborrheic dermatitis
		Candida (e.g., *C. albicans*)	Part of normal flora, can become pathogenic
3	Viruses	Various bacteriophages	Influence bacterial populations, potential roles in skin health
		Human Papillomavirus (HPV)	Can infect skin cells, some types associated with warts
4	Archaea	Methanogens (e.g., *Methanobrevibacter smithii*)	Involved in methane production and skin ecosystem balance
		Halophiles	Survive in salty environments, possible roles in skin health

These lipophilic yeasts are particularly abundant in sebaceous areas and are intertwined in conditions like dandruff and seborrheic dermatitis (Park et al., 2021b). In addition to bacteria and fungi, hair follicles also host viruses and archaea, although their functional roles in this niche are less well understood (Weiland-Bräuer, 2023).

The composition of the hair follicle microbiome exhibits significant spatial variation across different corridors of the scalp and body

Table 2
Functions of the hair microbiome.

Function	Description	Impact on Hair Health	Reference
Protective Roles			
Defense against pathogens	Prevents colonization of harmful microorganisms	Reduces risk of infections and scalp diseases	(Skowron et al., 2021a)
Protection from UV radiation	Microbiota produce compounds that absorb or deflect UV rays	Minimizes UV-induced damage to hair and scalp	(Santos Nogueira and Joekes, 2004)
Production of antimicrobial peptides	Microbiotas secrete substances that inhibit pathogen growth	Enhances scalp immune defense	(Zhang et al., 2021)
Competitive exclusion	Beneficial microbes outcompete harmful ones for resources	Maintains a healthy microbial balance	(Zhou et al., 2024)
Biofilm formation	Microbes form protective layers on hair surface	Shields hair and scalp from external aggressors	(Muhammad et al., 2020)
pH regulation	Microbiota maintain a balanced pH environment	Prevents overgrowth of harmful microorganisms	(Flowers and Grice, 2020b)
Detoxification	Microbes break down harmful substances	Reduces toxin-induced hair damage	(Feng et al., 2022)
Barrier function enhancement	Strengthens the scalp's barrier properties	Protects against environmental pollutants	(Kim et al., 2021)
Interaction with Scalp and Skin Microbiome			
Synergistic interactions	Cooperation with skin microbiome to enhance overall health	Promotes a balanced and healthy scalp environment	(Townsend and Kalan, 2023)
Antagonistic interactions	Inhibition of harmful microbes through microbial competition	Prevents scalp and hair disorders	(Yin et al., 2024a)
Metabolite exchange	Exchange of beneficial metabolites between scalp and hair microbiomes	Supports scalp nutrient supply	(Saxena et al., 2018)
Immune modulation	Modulates local immune responses	Reduces inflammation and allergic reactions	(Jatana et al., 2017)
Communication with host cells	Sends signals to host cells to regulate growth and defense	Promotes hair follicle health	(Wang et al., 2022a)
Influence on sebaceous glands	Affects sebum production and composition	Controls oiliness and maintains scalp moisture balance	(Fan et al., 2018)
Influence on sweat glands	Modulates sweat production	Helps in temperature regulation and scalp hydration	(Wilke et al., 2007)
Effects on Hair Vitality and Development			
Hair follicle health	Supports the structural integrity of hair follicles	Promotes healthy hair growth	(Yu et al., 2006)
Modulation of inflammation	Regulates inflammatory responses	Reduces risk of inflammatory scalp conditions	(Mahe et al., 2021)
Influence on hair growth cycles	Affects anagen (growth) and telogen (rest) phases of hair growth	Enhances hair growth and reduces shedding	(Natarelli et al., 2023a)
Scalp disease prevention	Prevents conditions like dandruff and seborrheic dermatitis	Maintains a healthy scalp	(Dall'Oglio et al., 2022)
Antioxidant production	Microbes produce antioxidants	Reduces oxidative stress on hair and scalp	(Trüeb, 2009)
Vitamin synthesis	Synthesis of vitamins essential for hair growth	Supports overall hair health	(Almohanna et al., 2018)
Amino acid production	Microbes produce amino acids necessary for hair protein synthesis	Strengthens hair structure	(Gupta and Ramnani, 2006)
Lipid metabolism	Microbes help metabolize lipids	Maintains scalp lipid balance	(Chen et al., 2022)
Anti-inflammatory compounds	Production of anti-inflammatory substances	Reduces scalp irritation	(Sakib et al., 2021a)
Immune system training	Trains the immune system to recognize and respond to pathogens	Enhances scalp immune resilience	(Belkaid and Hand, 2014)
Hair shaft protection	Microbial biofilms and compounds protect the hair shaft	Prevents hair damage and breakage	(Lee et al., 2015)
Scalp microenvironment maintenance	Maintains the optimal microenvironment for hair growth	Supports sustained hair growth	(Abreu and Marques, 2021)
Stress response modulation	Helps in managing the scalp's response to stress	Reduces hair loss due to stress	(Pye et al., 2024)
Enhancement of hair strength	Produces compounds that enhance hair tensile strength	Reduces hair breakage and split ends	(Gavazzoni Dias, 2015a)
Improvement of hair elasticity	Microbial activity improves hair elasticity	Provides more resilient hair	(Mysore and Arghya, 2022)
Influence on hair texture	Microbial products can affect hair texture and manageability	Improves hair appearance and feel	(Fernandes et al., 2023a)
Anti-dandruff effects	Inhibits the growth of dandruff-causing microorganisms	Reduces dandruff and associated symptoms	(Fernandes et al., 2023b)
Sebum degradation	Microbes degrade excess sebum	Prevents oily scalp and associated issues	(Suzuki et al., 2021)
Influence on hair pigmentation	Affects melanin production and distribution	Maintains or enhances natural hair color	(Van Neste and Tobin, 2004)

(Table 1). Common genera or species associated with each microbial group are listed along with their primary roles and ecological relevance within the follicular environment. Factors such as sebaceous gland density, hair type, and localized environmental conditions contribute to this spatial diversity. For example, the microbial profile of the scalp differs markedly from that of the face, axillae, or groin, reflecting the unique microenvironments and selective pressures present in each area (Brinkac et al., 2018a).

Functions of the hair microbiome

The human hair microbiome plays a central role in maintaining hair and scalp health through a range of protective and regulatory functions. One of the primary defensive functions of the hair microbiome is its defense against pathogens and harmful environmental factors like UV radiation (Polak-Witka et al., 2020a). Beneficial microorganisms form a protective barrier that prevents colonization by harmful microbes, thereby reducing the risk of infections and scalp disorders. Additionally, the hair microbiome actively interacts with both the scalp and broader skin microbiota, exhibiting synergistic as well as antagonistic relationships (Table 2). This dynamic interplay supports a stable microbial ecosystem—essential for a healthy scalp environment (Flowers and Grice, 2020a). Beyond its defensive role, the hair microbiome influences follicular vitality and development. It regulates inflammation, modulates immune responses, and affects the progression of various hair and scalp conditions, including dandruff and seborrheic dermatitis (Polak-Witka et al., 2020b). A comprehensive understanding of these functions may pave the way for more targeted therapeutic strategies and personalized approaches to hair care.

Mechanistic insights into microbiome–hair follicle interactions

The relationship between the hair follicle microbiome and host physiology is governed by intricate molecular mechanisms. Recent

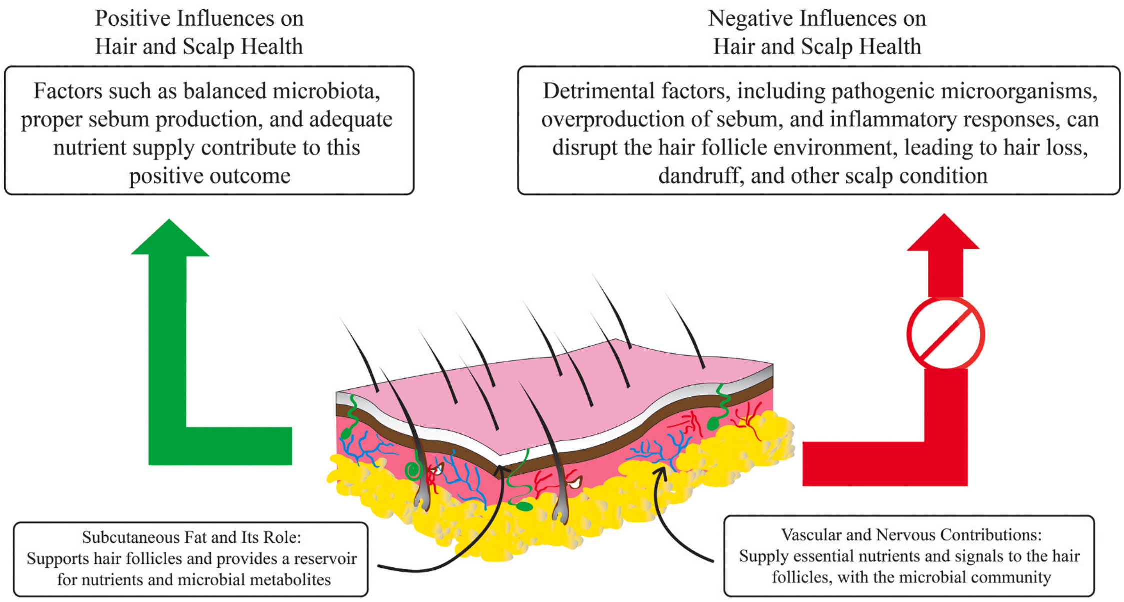

Fig. 2. Factors influencing hair and scalp microbiome composition. The illustration represents the factors that either promote (green arrow) or inhibit (red arrow) the growth of specific microbial communities on the scalp and hair. The green arrow indicates conditions that support a healthy microbiome, such as balanced sebum production and proper hygiene. The red arrow, with a prohibition sign, signifies factors that negatively affect the microbiome, potentially leading to imbalances that contribute to scalp and hair disorders.

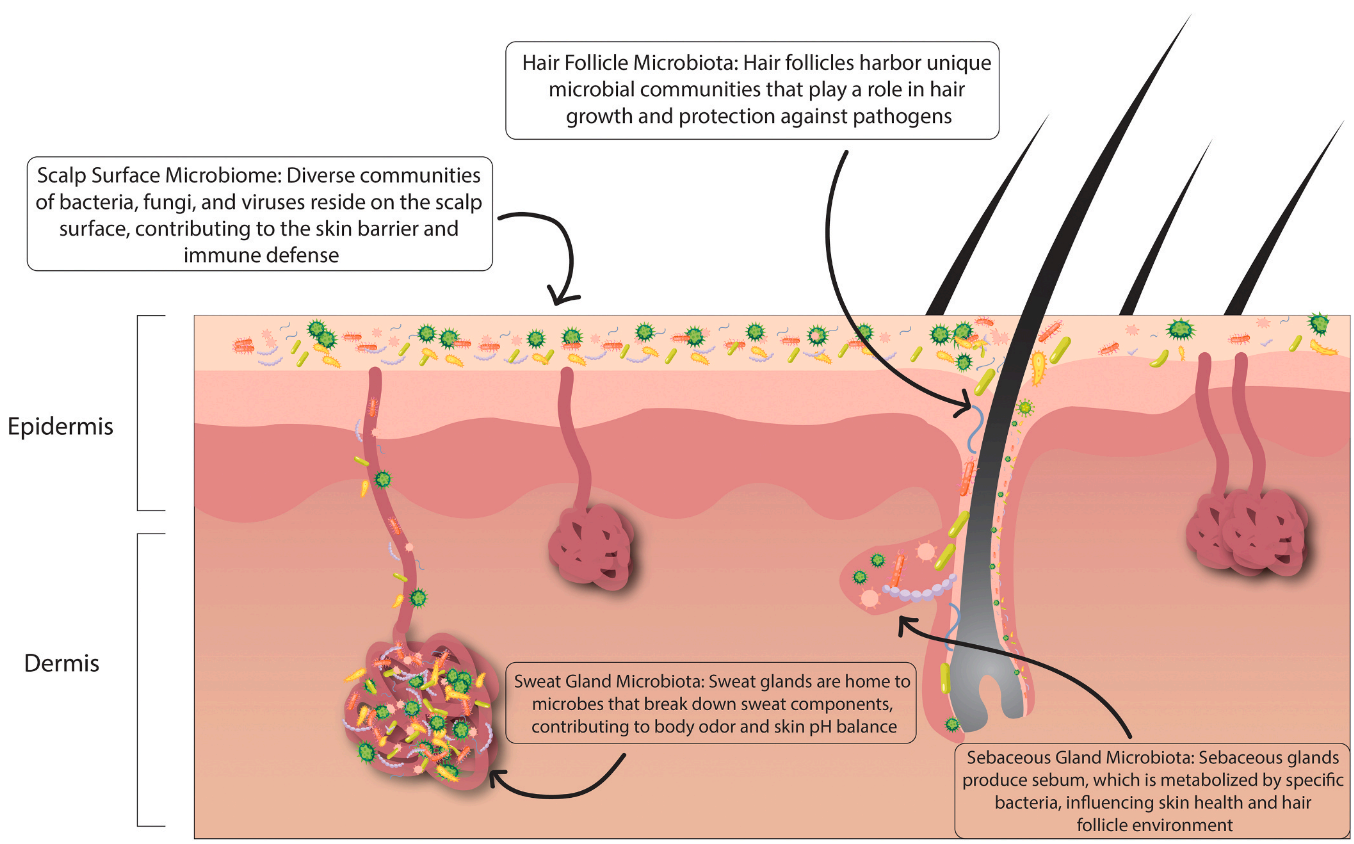

Fig. 3. Illustration of the skin microbiota associated with sweat and sebaceous glands. This figure depicts the distribution and colonization of microbes to the skin's sweat glands and sebaceous glands. The sweat glands, located within the dermis, are inhabited by microbes that metabolize sweat components, contributing to body odor and maintaining skin pH balance. The sebaceous glands, also embedded within the dermis and connected to hair follicles, produce sebum, which is broken down by specific bacteria, influencing both skin health and the microbial environment of the hair follicle. The various microbes are shown in different shapes and colors, representing the diverse bacterial species present in these niches.

Table 3
Impact of microbiome on hair physiology and disorders.

Aspect	Description	Reference
Role in Hair Physiology	Microbial Contributions	
	Scalp pH Regulation: Microbes help maintain an optimal pH, which is crucial for follicle health and microbial balance.	(Townsend et al., 2023a)
	Antimicrobial Peptides: Produced by microbes to combat pathogenic organisms and protect follicles.	(Kenshi and Richard, 2008)
	Sebum Metabolism: Microbial breakdown of sebum prevents accumulation and supports follicle health.	(Swaney and Kalan, 2021)
	Immune Modulation: Microbes influence local immune responses, helping protect hair follicles from infections and inflammation.	(Rahmani et al., 2020)
	Nutrient Synthesis: Certain microbes synthesize vitamins and nutrients, such as biotin and B-vitamins, essential for hair growth.	(Trüeb, 2020)
	Hair Follicle Stimulation: Microbial byproducts can stimulate hair follicle cells, promoting growth and regeneration.	(Wang et al.,)
	Inflammation Control: Microbial communities help modulate inflammatory responses in the scalp, preventing chronic inflammation.	(Bennett et al., 2018)
	Barrier Function: Microbes support the scalp's barrier function, pre (Townsend et al., 2023a)venting pathogen entry and maintaining health.	(Polak-Witka et al., 2020b)
	Hydration Maintenance: Microbial activity contributes to maintaining optimal moisture levels in the scalp.	(Townsend et al., 2023a)
	Detoxification: Microbes assist in breaking down and removing potentially harmful substances from the scalp.	(Hair Detox, 2019)
	Biofilm Formation: Microbial biofilms can protect follicles from environmental damage and pathogens.	(Coenye et al., 2021)
	Oxidative Stress Management: Microbes can mitigate oxidative stress, which impacts follicle health.	(Trüeb et al., 2018a)
	Hair Regeneration: Microbial interactions may support the regeneration of damaged hair follicles.	(Constantinou et al., 2021b)
	Follicle Immunity: Microbial presence influences the immune status of hair follicles, aiding in their resilience.	(Kiselev and Park, 2024)
	Sebum Production Regulation: Microbial activity affects the rate of sebum production, impacting follicle health.	(Zouboulis et al., 2022a)
	Microbial Diversity Impact: High diversity of microbial species supports overall follicle and scalp health.	(Townsend et al., 2023b)
	Nutrient Availability: Microbes can affect the availability and absorption of essential nutrients for hair growth.	(Gilroy and Jones, 2000)
	Hair Follicle Microenvironment: Microbial communities shape the microenvironment of hair follicles, affecting their function.	(Constantinou et al., 2021a)
	Microbial Competition: Competition among microbes can impact follicle health and microbial balance.	(Bauer et al., 2018)
	pH Balance Maintenance: Maintaining the scalp's pH balance through microbial activity helps prevent disease.	(Polak-Witka et al., 2020c)
	Anti-inflammatory Molecules: Microbial production of anti-inflammatory molecules helps keep inflammation in check.	(Tsvetanova, 2024)
	Follicle Protection: Microbes contribute to protecting follicles from damage by environmental factors.	(Samra et al., 2024a)
	Regulation of Local Hormones: Microbes may influence local hormone levels that affect hair growth.	(Grymowicz et al., 2020)
	Hair Follicle Development: Microbes can impact the development and growth phases of hair follicles.	(Hoover et al., 2024)
Hair Disorders	Microbiome Imbalances	
	Androgenetic Alopecia: Microbial dysbiosis may exacerbate follicle miniaturization and inflammation, contributing to hair loss.	(Ho et al., 2019)
	Dandruff: Overgrowth of *Malassezia* species leads to flaky, itchy scalp due to fungal imbalances.	(Rudramurthy et al., 2014)
	Seborrheic Dermatitis: Excessive *Malassezia* can cause scalp redness, scaling, and inflammation.	(Ran et al., 2008)
	Folliculitis: Inflammation and infection of hair follicles due to microbial imbalances, leading to pustules and irritation.	(Winters and Mitchell, 2024)
	Telogen Effluvium: Stress-related hair loss influenced by microbial-induced inflammation and immune responses.	(Gentile, 2022a)
	Alopecia Areata: Autoimmune hair loss condition potentially triggered or exacerbated by microbial changes.	(Novak and Meyer, 2009)
	Psoriasis: Chronic inflammatory condition linked to microbial dysbiosis and scalp inflammation.	(Benhadou et al., 2018)
	Contact Dermatitis: Allergic reactions to hair products can disrupt the microbial balance, leading to dermatitis.	(Yadav et al., 2023)
	Trichotillomania: Psychological condition potentially linked to changes in scalp microbiome affecting hair health.	(Pereyra and Saadabadi, 2024)
	Lichen Planopilaris: Scarring alopecia with possible microbial involvement in follicular inflammation.	(Lepe et al., 2024)
	Hirsutism: Excessive hair growth potentially influenced by hormonal imbalances and microbial interactions.	(Lolou, 2021)
	Periorbital Dermatitis: Inflammation around the eyes possibly related to microbial dysbiosis affecting adjacent areas.	(Feser et al., 2008)
	Pityriasis Versicolor: Fungal infection caused by *Malassezia* affecting the scalp with changes in pigmentation.	(Karray and McKinney, 2024)
	Acne: Inflammation of hair follicles, particularly on the face and back, influenced by *Propionibacterium acnes* imbalance.	(McLaughlin et al., 2019a)
	Microbial Folliculitis: Infection of hair follicles by various microbes causing pustules and inflammation.	(Trüeb et al., 2023)
	Hair Breakage: Weakened hair strands due to imbalances in microbial communities affecting follicle health.	(Townsend et al., 2023c)
	Hair Thinning: Reduced hair density linked to microbial imbalances impacting follicle function.	(Yin et al., 2024a)
	Scalp Eczema: Chronic inflammation of the scalp potentially exacerbated by shifts in microbial populations.	(Trüeb et al., 2018b)
	Scalp Tinea: Fungal infections like ringworm affecting hair follicles, often due to *Trichophyton* species.	(Trüeb and Gavazzoni Dias, 2023)
	Alopecia Totalis: Complete loss of hair on the scalp potentially influenced by microbial dysbiosis.	(Liu and Liu, 2023)
	Pachyonychia Congenita: Genetic disorder affecting hair and nails, potentially impacted by microbial factors.	(Sotiriadis, 2008)
	Scalp Folliculitis Decalvans: Chronic condition with inflammation and microbial dysbiosis leading to hair loss.	(Shah et al., 2024)
	Hidradenitis Suppurativa: Chronic skin condition affecting hair follicles, possibly influenced by microbial imbalances.	(Jiang et al., 2021)
	Erythrasma: Bacterial infection of the scalp caused by *Corynebacterium* species, leading to reddish-brown patches.	(Rajkumar, 2023)
	Acne Keloidalis Nuchae: Scarring alopecia at the nape of the neck possibly related to microbial imbalances.	(Al Aboud and Badri, 2024)
	Scalp Lupus: Autoimmune condition with potential microbial contributions to chronic inflammation and hair loss.	(Colucci and Moretti, 2021)
	Discoid Lupus Erythematosus: Chronic skin condition affecting the scalp, linked to changes in microbial populations.	(McDaniel et al., 2024)
	Sebaceous Cyst: Formation of cysts in sebaceous glands potentially influenced by microbial factors.	(Zouboulis et al., 2022b)
	Frontal Fibrosing Alopecia: Scarring alopecia affecting the hairline, potentially linked to microbial dysbiosis.	(Constantinou et al., 2021b)
	Telogen Effluvium: General hair shedding potentially influenced by microbial-induced inflammation or stress.	(Gentile, 2022b)
	Diffuse Thinning: General thinning of hair due to microbial imbalances affecting follicle health.	(GOKCE et al., 2022)
	Scalp Psoriasis: Chronic autoimmune condition potentially exacerbated by shifts in microbial communities.	(Choi et al., 2022)
	Chronic Folliculitis: Persistent inflammation of hair follicles due to long-term microbial imbalances.	(Lin et al., 2018)
	Lichen Planopilaris: Scarring alopecia where microbial dysbiosis might play a role in inflammation.	(Pinto et al., 2022a)
	Trichorrhexis Nodosa: Hair disorder characterized by hair nodules and breakage potentially linked to microbial factors.	(Martin and Sugathan, 2011)
	Scalp Itchiness: Itchy scalp conditions potentially related to microbial imbalances and inflammatory responses.	(saif et al., 2011)

findings reveal that certain commensal microbes produce bioactive metabolites, such as short-chain fatty acids (SCFAs), which influence keratinocyte proliferation and differentiation (Xiao et al., 2023). These microbial metabolites can activate or suppress pathways like NF-κB, Toll-like receptor signaling, and Wnt/β-catenin, thereby modulating immune responses, inflammation, and hair growth cycles (NF-κB in

Table 4
Overview of diseases associated with human hair follicle microbiome dysbiosis.

Sl no	Disease	Hair Follicle (HF) Microbiome Alteration	Sampling Method	Identification Technique	References
1	Impetigo	Predominantly *Staphylococcus aureus* and *Streptococcus pyogenes* infections	Scalp swabs; Pus samples	Culture; PCR	(Tong et al., 2015)
2	Alopecia areata	Higher Propionibacterium (*P. acnes*); Lower Staphylococcus (*S. epidermidis*); Presence of Alternaria spp.	Scalp swabs;	16S rRNA; Culture	(Lousada et al., 2021b)
3	Pityriasis amiantacea	Overgrowth of *Staphylococcus aureus* and *Malassezia* species	Scalp swabs; Hair samples	16S rRNA; ITS	(Gor et al., 2023)
4	Seborrheic dermatitis	Overgrowth of Malassezia species (*M. globosa* and *M. restricta*)	Scalp swabs	16S rRNA; ITS	(Ran et al., 2008)
5	Dermatophytosis	Infection by dermatophytes like Trichophyton and Microsporum species	Scalp swabs; Hair samples	Culture; PCR	(Begum and Kumar, 2020)
6	Tinea capitis	Increased prevalence of dermatophytes, particularly Trichophyton and Microsporum species	Scalp swabs; Hair samples	Culture; PCR	(Hay, 2017)
7	Acne vulgaris	Elevated levels of P. acnes RT4/RT5; Reduced *P. acnes* RT6; Possible role of *P. granulosum*; Increased Staphylococci and Enterococci	Pore strips; Swabs	Whole Genome Sequencing (WGS); 16S rRNA	(McLaughlin et al., 2019b)
8	Androgenetic alopecia	Increased *P. acnes*; Higher levels of *M. restricta* and *M. globosa*; Hypothesized role of Demodex (unconfirmed)	Follicular biopsy; Plucked hair	16S rRNA; Internal Transcribed Spacer (ITS)	(Sinclair et al., 2015)
9	Dissecting cellulitis of the scalp	Presence of *Staphylococcus aureus* and anaerobic bacteria like Peptostreptococcus	Scalp swabs	16S rRNA; Culture	(Scheinfeld, 2014)
10	Lichen planus	Dysbiosis involving increased Pseudomonas and reduced Lactobacillus species	Scalp swabs; Biopsy	16S rRNA; FISH	(Pinto et al., 2022b)
11	Pseudofolliculitis barbae	Increased *Cutibacterium acnes*; Presence of *Staphylococcus aureus*	Beard area swabs; Hair samples	16S rRNA; Culture	(Durdu and Ilkit, 2013)
12	Central centrifugal cicatricial alopecia	Bacterial infection linked to disease prevalence (Fungal infection not associated)	NA	Survey study	(Gathers and Lim, 2009)
13	Scalp psoriasis	Imbalance in bacterial communities with increased Corynebacterium and Staphylococcus species	Scalp biopsy; Swabs	16S rRNA; Metagenomics	(Chang et al., 2018)
14	Dandruff	Higher *S. epidermidis* and Malassezia levels	Scalp swab	16S rRNA; ITS	(Wang et al., 2022b)
15	Folliculitis decalvans	Increased *S. aureus* and P. acnes (varied across different HFs)	Scalp swabs; Follicular biopsy	16S rRNA; Fluorescence In Situ Hybridization (FISH)	(Lousada et al., 2021c)
16	Psoriasis	Elevated Corynebacterium, Staphylococcus species; Reduced Propionibacterium	Scalp biopsy	16S rRNA; Metagenomics	(Park et al., 2016)
17	Erosive pustular dermatosis	Dysbiosis with increased Enterococcus and Staphylococcus species	Scalp biopsy; Swabs	16S rRNA; WGS	(Michelerio et al., 2021)
18	Folliculitis decalvans-Lichen planopilaris	*S. aureus* infection	Scalp swab	Culture	(Zhang et al., 2022)

biology and targeted,). For instance, *Cutibacterium acnes* and *Malassezia restricta* can either induce or dampen local inflammatory signals depending on their abundance and strain variation (Fischer et al., 2020). Additionally, microbial regulation of sebum production and pH levels directly shapes the follicular environment, creating a feedback loop that further modulates microbial composition and follicular health (Polak-Witka et al., 2020c). Understanding these mechanistic interactions is pivotal for developing precision-targeted therapies and cosmetic formulations that restore and maintain microbial homeostasis.

Microbiome and hair health

The microbiome has a profound impact on hair physiology by altering hair growth, health, and regeneration. Microbial populations residing within the follicles help sustain a healthy scalp environment, which is essential for proper follicular function and hair development (Constantinou et al., 2021a). Beneficial bacteria and fungi in the hair follicles help regulate the pH of the scalp, produce antimicrobial peptides, and modify vulnerable responses, all of which are necessary for follicular health and hair development (Polak-Witka et al., 2020a). Additionally, these microbes participate in the metabolism of sebum and other scalp secretions, affecting follicular health and the hair growth cycle (Fig. 3).

Microbial imbalance, or dysbiosis, can contribute to a wide range of scalp and hair disorders (Yin et al., 2024a). For example, the overpopulation of some microorganisms, like *Malassezia* species, has been related to dandruff and seborrheic dermatitis, both of which beget flakiness and irritation on the scalp (Table 3). Dysbiosis has been implicated in androgenetic alopecia (pattern baldness), where altered microbial compositions and local inflammation may contribute to follicular miniaturization and hair loss (Saxena et al., 2018). Other conditions such as folliculitis and telogen effluvium are similarly influenced by microbial shifts. Understanding these relationships is essential for developing targeted, microbiome-based interventions aimed at restoring balance and promoting hair and scalp health (Barquero-Orias et al., 2021).

Microbial imbalance in hair follicles and its role in hair disease pathogenesis

Dysbiosis, a microbial imbalance within the hair follicle (HF) microbiome, has been increasingly recognized as a critical factor in the pathogenesis of various hair and scalp diseases. The HF microbiome, composed of a complex community of bacteria, fungi, and other microorganisms, plays a pivotal role in maintaining scalp health. When this balance is disrupted, it can lead to or exacerbate conditions such as acne vulgaris, androgenetic alopecia, seborrheic dermatitis, and psoriasis (Polak-Witka et al., 2020a). For instance, an overrepresentation of *Propionibacterium acnes* has been linked to acne vulgaris, while an increase in *Malassezia* species is associated with seborrheic dermatitis and dandruff. Similarly, shifts in the relative abundance of *Staphylococcus aureus* and *Corynebacterium* species have been observed in psoriasis and folliculitis decalvans (McLaughlin et al., 2019a). These microbial alterations can lead to inflammation, immune responses, and structural damage to the hair follicles, thereby contributing to disease progression (Table 4). Understanding the specific microbial shifts and their mechanistic roles in these diseases is essential for developing targeted therapeutic strategies that can restore microbial balance and improve hair and scalp health.

Table 5
Environmental influences on the hair microbiome.

Sl no	Influence Type	Factors	Impact on Microbiome	Reference
1	Environmental Factors	Pollution	Alters microbial diversity and abundance	(hu et al., 2024)
		UV radiation	Can damage microbial DNA, leading to shifts in microbial populations	(Patra et al., 2016)
		Humidity	High humidity promotes growth of specific fungi and bacteria	(Polak-Witka et al., 2020d)
		Temperature	Affects the overall microbial environment and species composition	(Brinkac et al., 2018b)
		Air quality	Exposure to pollutants can lead to microbial imbalances	(Rajput, 2015)
		Exposure to chemicals	Can kill beneficial microbes, reducing diversity	(He et al., 2022)
		Indoor vs. outdoor environments	Indoor environments may have less microbial diversity than outdoor environments	(Amin et al., 2023)
		Water quality	Hard water can affect microbial growth on the scalp	(Srinivasan et al., 2013)
		Seasonal changes	Different seasons can influence microbial diversity and abundance	(Ou et al., 2019)
2	Lifestyle Choices	Diet (high in fats, sugars, probiotics)	Diets high in fats and sugars can promote growth of certain bacteria, while probiotics can enhance beneficial microbes	(De Pessemier et al., 2021)
		Hydration levels	Adequate hydration supports a healthy microbial balance	(Xu et al., 2016)
		Stress levels	Chronic stress can alter immune function and microbial balance	(Faenza and Blalock, 2022)
		Physical activity	Regular exercise can promote a balanced microbiome	(Codella et al., 2018)
		Use of hair care products (shampoos, conditioners)	Can introduce new microbes or kill existing ones, altering the microbiome	(Townsend et al., 2023d)
		Smoking	Tobacco smoke can disrupt microbial communities	(Shapiro et al., 2022)
		Alcohol consumption	Can impact microbial balance and skin barrier function	(Lee and Kim, 2022)
		Exposure to pets	Pets can introduce new microbes to the scalp environment	(Tun et al., 2017)
		Occupation (e.g., working outdoors vs. indoors)	Different work environments expose individuals to different microbial communities	(Meadow et al., 2015)
		Social interactions	Close contact with others can lead to the exchange of microbial communities	(Pierce and Dutton, 2022)
		Travel habits	Exposure to different environments and microbial populations during travel	(Smith et al., 2011)
		Use of antibiotics	Can disrupt microbial balance by killing beneficial microbes	(Patangia et al., 2022)
3	Personal Hygiene	Frequency of hair washing	Regular washing can remove or alter microbial populations	(Punyani et al., 2021b)
		Type of hair washing products (antibacterial, natural)	Antibacterial products can reduce microbial diversity, while natural products may support it	(Yu et al., 2018)
		Grooming habits (combing, brushing)	Physical disruption of microbial communities	(Pan et al., 2019)
		Use of head coverings (hats, scarves)	Can create warm, moist environments conducive to microbial growth	(Sharma and Nonzom, 2021)
		Hair styling techniques (heat, chemicals)	Heat and chemicals can damage microbial communities	(Mixing heat with hair styling,)
		Frequency of haircuts	Regular trimming can affect microbial habitats	(Constantinou et al., 2021c)
		Use of personal items (towels, combs)	Sharing personal items can lead to microbial exchange	(Whitehead et al., 2023)
		Use of protective hair treatments (e.g., leave-in conditioner)	Can alter microbial environments by creating different moisture levels	(Fernandes et al., 2023c)
4	Geography and Climate	Climate zone	Different climates promote different microbial communities	(Osborne et al., 2020)
		Urban vs. rural environments	Urban areas may have different microbial exposure compared to rural areas	(Skowron et al., 2021b)
		Altitude	High altitudes can have unique microbial exposures	(Zeng et al., 2017)
		Proximity to water bodies	Microbial communities can be influenced by nearby water sources	(Wang et al., 2023)
		Air quality	Higher pollution levels can disrupt microbial communities	(Gupta et al., 2022)
		Vegetation and flora	Local plant life can influence the types of airborne microbes	(Li et al., 2021)
		Industrial vs. natural surroundings	Industrial areas may have different microbial exposures compared to natural surroundings	(Maukonen and Saarela, 2009)
		Climate change and environmental shifts	Long-term environmental changes can alter the microbiome	(Cavicchioli et al., 2019)
5	Genetic Factors	Genetic predisposition	Genetic factors can influence susceptibility to certain microbial colonization	(Sánchez-Pellicer et al., 2022)
		Family history of skin conditions	May affect microbial diversity due to inherited traits	(Polak-Witka et al., 2020e)
6	Health Conditions	Hormonal fluctuations	Hormonal changes can impact microbial composition and skin conditions	(Constantinou et al., 2021d)
		Chronic illnesses (e.g., diabetes)	Can alter microbial balance due to changes in skin environment or immune function	(Yang et al., 2024)
		Dermatological conditions (e.g., psoriasis)	Specific conditions can influence the abundance and types of microbe's present	(Polak-Witka et al., 2020f)
7	Social Factors	Cultural practices	Different cultural practices may impact personal hygiene and hair care routines	(Bowen and O'Brien-Richardson, 2017)
		Socioeconomic status	Can influence access to personal care products and treatments	(McMaughan et al., 2020)
		Public health policies	Policies affecting air quality, water quality, and access to health care can impact microbial health	(Rosenthal et al., 2020)

Influences on the hair microbiome

The composition of the hair microbiome is profoundly influenced by a variety of environmental factors, lifestyle choices, and personal hygiene practices. Environmental factors such as pollution, humidity, and exposure to ultraviolet (UV) radiation can significantly alter the microbial communities residing in hair follicles (Burns et al., 2019). Lifestyle choices, including diet, stress levels, and the use of hair care products, also play crucial roles in shaping the microbiome (Knaggs and Lephart, 2023). For instance, diets high in fats and sugars can promote the growth of certain bacteria, while the use of shampoos and conditioners can impact the diversity and abundance of microbial populations (Adu et al., 2020). Personal hygiene practices, such as the frequency of hair washing and grooming habits, further modulate the hair follicle

Table 6
Therapeutic approaches for modulating the hair microbiome.

Sl. No.	Therapeutic Approach	Impact on Hair Microbiome	Effects on Hair Health	Reference
1.	Antibiotics	Microbial Disruption: Can alter microbial balance, reducing beneficial microbes.	Potential Negative Effects: Increased risk of fungal infections, exacerbation of dandruff, and inflammation.	(Krüger et al., 2019)
2.	Probiotics	Restoration of Balance: Introduces beneficial bacteria to support a healthy microbiome.	Improved Scalp Health: May reduce dandruff, folliculitis, and improve hair growth.	(Yin et al., 2024b)
3.	Synthetic Odorants	Targeted Microbial Interaction: Designed to modify microbial activity.	Potential Benefits: May reduce pathogenic load and support beneficial microbes.	(Jing et al., 2024)
4.	Topical Antifungals	Fungal Reduction: Targets and reduces fungal populations on the scalp.	Reduction in Fungal Disorders: Decreases dandruff and seborrheic dermatitis.	(Okokon et al., 2015)
5.	Anti-inflammatory Agents	Inflammation Control: Reduces inflammation in the scalp.	Improved Scalp Condition: Can alleviate irritation and support healthier hair growth.	(Sakib et al., 2021b)
6.	Sebum Regulators	Sebum Production Modulation: Adjusts sebum levels on the scalp.	Reduced Oily Scalp: Helps prevent acne and folliculitis.	(Dapkevicius et al., 2023)
7.	Moisturizers	Hydration Maintenance: Provides moisture to the scalp.	Enhanced Scalp Health: Reduces dryness and flakiness, supporting hair health.	(Nobile et al., 2024)
8.	Scalp Exfoliants	Dead Skin Removal: Helps remove dead skin cells and debris.	Clearer Follicles: Improves follicle health and reduces buildup.	(Enechukwu and Ogunbiyi, 2022)
9.	Hair Growth Stimulators	Follicle Activation: Stimulates hair follicles for increased growth.	Promoted Hair Growth: Enhances hair density and reduces thinning.	(Natarelli et al., 2023b)
10.	Laser Therapy	Cellular Stimulation: Uses light to stimulate hair follicles.	Improved Hair Regrowth: Can reverse hair loss and improve thickness.	(Pillai and Mysore, 2021)
11.	Essential Oils	Microbial Modulation: Natural oils with antimicrobial properties.	Enhanced Scalp Health: May reduce dandruff and improve hair quality.	(Junior and Bastos, 2024)
12.	Vitamin Supplements	Nutrient Support: Provides essential vitamins for hair health.	Improved Hair Growth: Supports overall follicle health and strength.	(Finner, 2013)
13.	Anti-androgens	Hormone Regulation: Reduces androgens that contribute to hair loss.	Reduced Hair Loss: Particularly useful for androgenetic alopecia.	(Seyed Jafari et al., 2024)
14.	Hair Masks	Nutrient Infusion: Deep conditioning treatments.	Improved Moisture and Strength: Enhances hair softness and resilience.	(Prashar, n.d)
15.	Scalp Massage	Blood Circulation: Enhances blood flow to hair follicles.	Stimulated Hair Growth: Can improve follicle health and hair density.	(Natarelli et al., 2023c)
16.	Phytochemical/ Chemical Peels	Exfoliation: Removes dead skin cells and improves scalp health.	Clearer Follicles: Helps in the treatment of dandruff and folliculitis.	(Paul et al., 2024; Samargandy and Raggio, 2024)
17.	Retinoids	Cell Turnover: Promotes cell renewal on the scalp.	Improved Follicle Health: Can help in treating scalp conditions and promoting hair growth.	(Sadgrove and Simmonds, 2021)
18.	Zinc-Based Treatments	Microbial Control: Zinc has antimicrobial properties.	Reduced Scalp Inflammation: Can alleviate dandruff and seborrheic dermatitis.	(Ranganathan and Mukhopadhyay, 2010)
19.	Hormonal Treatments	Hormone Balance: Adjusts hormonal levels affecting hair growth.	Improved Hair Health: Can help manage conditions like androgenetic alopecia.	(Vinay et al., 2018)
20.	Peptide Therapy	Cellular Repair: Uses peptides to repair and stimulate hair follicles.	Enhanced Hair Growth: Supports follicle regeneration and hair thickness.	(Hwang et al., 2022)
21.	Biotin	Nutrient Support: Provides biotin essential for hair growth.	Strengthened Hair: Can improve hair health and reduce brittleness.	(Patel et al., 2017)
22.	Omega−3 Fatty Acids	Anti-inflammatory: Reduces inflammation and supports scalp health.	Improved Hair Quality: Supports overall hair health and reduces dryness.	(Huhmann and Mueller, 2019)
23.	Green Tea Extract	Antioxidant Properties: Reduces oxidative stress on the scalp.	Enhanced Hair Health: May reduce hair loss and support growth.	(Choi et al., 2024)
24.	Amino Acids	Protein Support: Provides essential amino acids for hair strength.	Stronger Hair: Enhances hair resilience and reduces breakage.	(Liu et al., 2023)
25.	Copper Peptides	Cell Regeneration: Stimulates collagen production and follicle health.	Improved Hair Growth: Supports hair thickness and reduces hair loss.	(Pickart and Margolina, 2018)
26.	Caffeine	Follicle Stimulation: Promotes hair follicle activity.	Reduced Hair Loss: Can enhance hair growth and reduce shedding.	(Chen et al., 2024)
27.	Saw Palmetto	DHT Inhibition: Blocks dihydrotestosterone (DHT), a hormone linked to hair loss.	Reduced Hair Loss: Particularly effective for androgenetic alopecia.	(Evron et al., 2020)
28.	Ginseng	Stimulation of Follicles: Enhances blood flow and follicle health.	Promoted Hair Growth: Can support thicker and healthier hair.	(Truong and Jeong, 2021a)
29.	Coconut Oil	Moisturizing: Provides deep conditioning and hydration.	Improved Hair Health: Reduces dryness and adds shine.	(Gavazzoni Dias, 2015b)
30.	Aloe vera	Soothing Properties: Reduces inflammation and hydrates the scalp.	Enhanced Scalp Condition: Can help alleviate itching and dryness.	(Saleem et al., 2022)
31.	Tea Tree Oil	Antimicrobial Properties: Fights against harmful microorganisms.	Clearer Scalp: Reduces dandruff and prevents fungal infections.	(Carson et al., 2006)
32.	Hyaluronic Acid	Hydration: Provides deep hydration and maintains moisture.	Improved Scalp Health: Supports moisture retention and reduces dryness.	(Juncan et al., 2021)
33.	Niacinamide	Anti-inflammatory: Reduces inflammation and improves skin barrier.	Enhanced Hair Health: Can reduce scalp irritation and support growth.	(Gehring, 2004)
34.	Spironolactone	Hormonal Regulation: Blocks androgen receptors to reduce hair loss.	Improved Hair Growth: Useful for managing androgenetic alopecia.	(Nestor et al., 2021)
35.	Minoxidil	Follicle Stimulation: Promotes hair growth by increasing blood flow.	Effective Hair Growth: Widely used for treating hair loss and thinning.	(Suchonwanit et al., 2019)
36.	Ketoconazole	Antifungal Treatment: Targets fungal populations on the scalp.	Reduced Dandruff: Helps manage seborrheic dermatitis and dandruff.	(Gary, 2013)

(continued on next page)

Table 6 (*continued*)

Sl. No.	Therapeutic Approach	Impact on Hair Microbiome	Effects on Hair Health	Reference
37.	Silicon-Based Products	Strengthening: Adds strength and elasticity to hair strands.	Reduced Breakage: Supports overall hair health and reduces damage.	(de Araújo et al., 2016)
38.	Charcoal Treatments	Detoxification: Absorbs impurities and toxins from the scalp.	Clearer Follicles: Helps in removing buildup and improving scalp health.	(Activated Charcoal For Hair, 2021)
39.	Sulfur-Based Products	Antimicrobial Properties: Reduces microbial load on the scalp.	Improved Scalp Health: Can alleviate dandruff and seborrheic dermatitis.	(Turner et al., 2012)
40.	Calcium Supplements	Nutrient Support: Provides essential calcium for hair growth.	Strengthened Hair: Supports overall hair health and strength.	(I. of M. US C. to R.D.R.I. for V.D. and Calcium, 2011)
41.	Magnesium Supplements	Nutrient Support: Provides magnesium for improved scalp health.	Enhanced Hair Quality: Can support hair growth and reduce thinning.	(Jaripur et al., 2022)
42.	Vitamin D Supplements	Bone and Hair Health: Supports scalp health and hair follicle function.	Improved Hair Growth: Can reduce hair loss associated with vitamin D deficiency.	(Rehman et al., 2019)
43.	Ginger Extract	Circulation Enhancement: Stimulates blood flow to the scalp.	Promoted Hair Growth: May support follicle health and reduce hair loss.	(Truong and Jeong, 2021b)
44.	Pomegranate Extract	Antioxidant Properties: Reduces oxidative stress on hair follicles.	Enhanced Hair Health: Can support overall hair growth and strength.	(Hoang et al., 2021)
45.	Fermented Products	Probiotic Benefits: Introduces beneficial microorganisms to the scalp.	Improved Microbial Balance: Supports a healthier scalp environment.	(Yin et al., 2024a)

environment, influencing the balance of microbial species (Punyani et al., 2021a).

Geography and climate are additional critical determinants of the hair microbiome. Individuals living in different geographical regions exhibit distinct microbial profiles due to variations in environmental conditions such as temperature, humidity, and air quality (Table 5). The factors impacting the hair microbiome are comprehensively listed in this enlarged table, which illustrates the intricate interactions between environmental, lifestyle, genetic, health-related, and social factors. Comprehending these variables facilitates the identification of plausible domains for intervention and the upkeep of a robust hair microbiome (Fig. 2). People residing in tropical climates, characterized by high humidity and temperatures, tend to have higher levels of *Malassezia* species, which thrive in warm, moist environments (Chen et al., 2023). Conversely, individuals in arid or temperate climates may have different microbial compositions, reflecting the lower humidity and cooler temperatures. These geographic and climatic variations underscore the adaptability and responsiveness of the hair microbiome to external environmental pressures (Chen et al., 2023).

Therapeutic potential

Modulating the hair microbiome presents a promising frontier in the management of scalp and hair disorders. While antibiotics remain a standard treatment for bacterial infections, can significantly disrupt the scalp's microbial balance. Although effective in targeting pathogens, antibiotics often reduce beneficial microbial populations, which may lead to unintended consequences such as fungal overgrowth, increased inflammation, and worsened scalp conditions like dandruff or folliculitis (Langdon et al., 2016). These disruptions can contribute to conditions like dandruff, folliculitis, and indeed complicate hair diseases by disturbing the scalp's natural microbiological balance.

In contrast, probiotics and synthetic odorants represent innovative approaches to modulating the hair microbiome appreciatively (Regina et al., 2024). Probiotics are live beneficial microorganisms that have demonstrated potential in rebalancing microbial communities, inhibiting harmful species, and enhancing scalp health (Table 6). This extensive table provides a thorough overview of diverse therapeutic approaches aimed at modulating the hair microbiome. Each approach offers unique mechanisms for influencing scalp health and hair growth, highlighting the potential for targeted treatments to address various hair-related issues. By introducing specific strains of probiotics, it's possible to enhance the abundance of salutary microbes, inhibit pathogenic organisms, and support overall scalp health (Kechagia et al., 2013). Synthetic odorants, on the other hand, are designed to interact with microbial communities in a controlled manner, potentially altering microbial activity and promoting a healthier scalp terrain. Harnessing these strategies could lead to more personalized and effective interventions for maintaining hair health and treating microbiome-related disorders (Edelkamp et al., 2023).

Impact of hair treatments and cosmetic practices on the hair follicle microbiome

Cosmetic and medical interventions such as hair coloring, bleaching, straightening, and transplantation can profoundly impact the scalp microbiome. Chemical treatments often involve harsh agents like ammonia, hydrogen peroxide, and formaldehyde, which may disrupt the balance of commensal microbes and compromise the scalp's barrier integrity (Zhang et al., 2024). For instance, oxidative stress caused by bleaching agents can reduce the abundance of protective species like *Staphylococcus epidermidis* while promoting opportunistic pathogens, increasing the risk of scalp irritation and infections (Severn and Horswill, 2023). Hair transplantation procedures, though sterile, temporarily alter the follicular microenvironment at both donor and recipient sites, potentially influencing microbial repopulation and post-surgical outcomes (Zito and Raggio, 2025). Moreover, the repeated use of styling tools, heat, and hair products can alter sebum secretion, follicular pH, and moisture levels—factors critical for maintaining microbial homeostasis (Variation of Skin Surface,). Therefore, incorporating microbiome-friendly practices and post-treatment care may help preserve a healthy scalp ecosystem and enhance treatment outcomes.

Regulatory considerations and clinical translation

As microbiome-based interventions gain popularity in both clinical dermatology and cosmetic science, regulatory considerations have become increasingly important. In the United States, live biotherapeutic products (LBPs), including microbiome-targeted treatments, fall under the regulatory jurisdiction of the FDA and must meet rigorous safety and efficacy standards (Cordaillat-Simmons et al., 2020). In contrast, in Europe, such products may be classified either as cosmetics or therapeutic agents depending on their intended use and claims (Overview of Cosmetic Regulatory Frameworks around the World,). Furthermore, the use of probiotics and postbiotics in scalp and hair care requires clear labeling and scientific validation to avoid misleading claims (Yin et al., 2024b). Consistent microbiome characterization protocols, standardized product testing, and human clinical trials are essential to ensure the

Table 7
Emerging technologies and future directions in hair microbiome research.

Sl No.	Technology/Research Area	Description	Impact/Importance	Referenece
1.	Metagenomics	Advanced technique for comprehensive analysis of microbial communities	Identifies novel microorganisms and their roles in hair health	(Nam et al., 2023b)
2.	Longitudinal Studies	Research tracking changes in the hair microbiome over time	Understands dynamic changes and long-term impacts	(Saxena et al., 2021)
3.	Standardized Methods	Development of consistent sampling and analysis techniques	Ensures consistency and comparability across studies	(Lee et al., 2006)
4.	Environmental and Lifestyle Factors	Study of how external factors and personal habits affect the hair microbiome	Provides a holistic understanding of influences on hair health	(Ahn and Hayes, 2021)
5.	Personalized Hair Care	Tailoring hair care products and treatments based on individual microbiome profiles	Promises more effective and customized solutions for hair health	(Litman, 2019)
6.	Next-Generation Sequencing (NGS)	High-throughput sequencing technologies that provide detailed microbial profiles	Offers deeper insights into microbial diversity and function	(Cao et al., 2017)
7.	Proteomics	Study of the protein content of the hair microbiome	Identifies functional proteins and their roles in hair health	(Adav et al., 2018)
8.	Metabolomics	Analysis of metabolic profiles to understand microbial metabolism in the hair ecosystem	Reveals metabolic interactions and their impact on hair health	(Pinto et al., 2020)
9.	CRISPR-Cas Technology	Gene-editing tool used to manipulate microbial genomes	Enables functional studies of specific microorganisms	(Wei and Li, 2023)
10.	Microbiome-Based Diagnostics	Development of diagnostic tools that analyze microbiome profiles for health assessments	Provides insights for early detection and personalized treatment	(Kashyap et al., 2017)
11.	In-Situ Hybridization	Technique for detecting specific microbial RNA/DNA in hair samples	Allows visualization of microbial distribution and activity	(Rolph et al., 2024)
12.	Machine Learning and AI	Application of artificial intelligence to analyze complex microbiome data	Enhances data interpretation and predictive modeling	(Stafford et al., 2022)
13.	Functional Genomics	Study of gene functions and interactions within the microbiome	Identifies key genetic factors influencing hair health	(Cuevas-Diaz Duran et al., 2024)
14.	Humanized Mouse Models	Use of genetically engineered mice with human-like microbiomes for research	Provides insights into human microbiome interactions and effects	(Chen and Roop, 2008)
15.	Biomarker Discovery	Identification of microbial or host biomarkers associated with hair health conditions	Facilitates development of targeted treatments and diagnostics	(Hajjo et al., 2022)
16.	High-Resolution Imaging	Advanced imaging techniques to visualize microbial communities in hair samples	Offers detailed spatial information on microbiome distribution	(Noecker et al., 2017)
17.	Environmental Exposure Studies	Research on how pollutants and other environmental factors impact the hair microbiome	Understands external influences on microbiome health	(Samra et al., 2024b)
18.	Scalp Microbiome Manipulation	Techniques to modify or restore a healthy scalp microbiome through interventions or products	Aims to improve scalp health and treat disorders	(Hu et al., 2024)

safety, reproducibility, and translational success of these emerging therapies. As the field advances, a harmonized global regulatory framework will be critical to support innovation while safeguarding public health.

Emerging technologies and future directions

Advancements in technology have significantly enhanced our understanding of the human hair microbiome. One similar advancement is metagenomics, an important approach that allows for the comprehensive analysis of microbial communities without the need for culturing. Metagenomics provides detailed perceptivity into the diversity and function of the hair microbiome, enabling the identification of new microorganisms and their roles in hair health (Nam et al., 2023a). This technique has unveiled complex microbial relations and metabolic pathways that were preliminarily unknown, paving the way for further targeted and effective hair care results (Table 7). The table highlights key advancements and future research directions in hair microbiome studies. It includes technologies like metagenomics and Next-Generation Sequencing (NGS) for detailed microbial analysis, proteomics and metabolomics for studying proteins and metabolic activities, and CRISPR-Cas for gene editing. Future research focuses on longitudinal studies to track microbiome changes, personalized hair care based on microbiome profiles, and environmental exposure studies to understand external impacts. Techniques such as high-resolution imaging and machine learning are advancing data analysis and visualization, while biomarker discovery and scalp microbiome manipulation aim to improve diagnostics and treatments.

Conclusion

The hair follicle microbiome is a complex and different ecosystem that plays a pivotal role in maintaining hair and scalp health. The microbial populations within hair follicles interact with the host in ways that influence immune responses, sebum products, and hair follicle dynamics. Environmental factors, life choices, and particular hygiene practices significantly impact the composition and health of the hair follicle microbiome. Understanding these factors and their influence on the microbiome is essential for developing targeted treatments and personalized hair care results. Emerging research suggests that modulating the hair follicle microbiome could offer new strategies for managing hair and scalp conditions. Probiotics, prebiotics, and other microbiome-modulating treatments may hold promise for restoring balance to disintegrated microbial communities and easing associated conditions. Continued exploration will deepen the understanding of microbial functions and therapeutic mechanisms, ultimately paving the way for microbiome-informed solutions in both dermatological treatment and cosmetic innovation.

Author contribution statement

Jibon Kumar Paul (JKP) and Mahir Azmal (MA) have conceptualized, data curation, formal analysis draft manuscript writing, editing the manuscript and contributed equally to the manuscript. Omar Faruk Talukder (OFT), ANM Shah Newaz Been Haque (ANMSNH), and Meghla Meem (MM) have investigated the data, resource collection, citation, formal analysis, draft writing and contributed equally to the manuscript.

Ajit Ghosh (AG) conceived the idea, project administration, supervision, and reviewed the manuscript. All the authors read the final version of the manuscript.

Methodological Note

This review follows a narrative structure and does not include meta-analyses or systematic synthesis. Literature was selected based on scientific relevance and credibility, aiming to provide a comprehensive thematic overview rather than statistical aggregation.

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CRediT authorship contribution statement

Haque ANM Shah Newaz Been: Writing – original draft, Methodology, Data curation. **Meem Meghla:** Writing – original draft, Methodology, Data curation. **Ghosh Ajit:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Azmal Mahir:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Talukder Omar Faruk:** Writing – original draft, Methodology, Formal analysis, Data curation. **Paul Jibon Kumar:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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