The Role of the Scalp Microbiome in the Etiology of Seborrhea, Dandruff, and Hair Loss

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Abstract

This article examines the role of the scalp microbiome in the pathogenesis of dermatological conditions (seborrhea, dandruff, and various forms of alopecia) and assesses the impact of modern hairdressing procedures on the scalp ecosystem. The study aims to identify stable correlations between disruptions to the scalp microbiota and the use of invasive cosmetic procedures, as well as to systematize approaches to their diagnosis in trichological and dermatological practice. To achieve this goal, we utilize theoretical, legal, and natural-scientific analyses of recent publications, as well as methods for systematizing and critically interpreting empirical data presented in clinical and experimental studies. The concluding section substantiates the need to integrate new-generation tests aimed at assessing the state of the microbiome, the barrier function of the epidermis, and the acid-base balance of the scalp into professional hairdressing and trichological diagnostic protocols, as well as the development of personalized programs for restoring the microbiota after chemical procedures. The findings and proposed approaches have practical implications for trichologists, hairdressing technologists working with highly aggressive formulations, and dermatologists dealing with secondary dermatoses induced by cosmetic procedures.

Keywords: scalp microbiome, seborrheic dermatitis, alopecia, hair coloring chemistry, disulfide bonds, hair diagnostics, Malassezia, pH balance, hair reconstruction, scalp dysbiosis.

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1. Introduction

The relevance of the stated topic is driven by the transformation of concepts regarding the scalp as a complex, dynamically organized biological ecosystem, in which the equilibrium of microorganisms (the microbiome) serves as a crucial condition for maintaining the structural integrity and functional activity of hair. Traditional models for explaining seborrhea and alopecia relied for a long time predominantly on hormonal, genetic, and hereditary factors [1, 3]. At the same time, the results of modern studies demonstrate that dysbiosis, defined as a disruption in the qualitative and quantitative composition of the microflora, represents not only a secondary phenomenon but also an independent, significant etiological factor in dermatological pathologies.

Additional complexity is associated with the intensive introduction of aggressive chemical technologies into hairdressing practice, the impact of which on the microbiome and barrier structures of the skin has been studied fragmentarily and has not received systemic conceptualization [2, 4].

The aim of the study is to establish the regularities of the relationship between the structure and functional characteristics of the scalp microbiome, the development of pathological conditions (dandruff, seborrhea, various forms of hair loss), and the influence of chemical agents used in hairdressing practice, with the subsequent development of scientifically grounded and safe service protocols.

To achieve this goal, the following objectives are formulated:

– to conduct an analysis of modern research on the role of bacterial and fungal communities (primarily Malassezia, Cutibacterium, Staphylococcus) in the pathogenesis of dandruff and various variants of alopecia;

– to disclose the molecular and biochemical mechanisms of the effect of oxidative dyes, lightening compositions, and reconstructing compounds on the keratin matrix of the hair, the lipid barrier, and scalp homeostasis;

– to substantiate the necessity of introducing complex instrumental diagnostics of the scalp condition and the application of protective technologies (including plex systems and analogous solutions) to minimize damage to the hair shaft and epidermal barrier, and to preserve the microbiome balance.

The scientific novelty of the research is manifested in an interdisciplinary approach that integrates clinical microbiology, dermatology, applied chemistry of cosmetic products, and elements of legal regulation regarding the turnover of cosmetic products and the provision of personal services. A hypothesis is advanced that the incorrect selection and combination of chemical procedures without a preliminary assessment of the microbiological status of the scalp, pH indicators, and barrier characteristics acts as a catalyst triggering chronic (often subclinical) inflammation, followed by a disruption of the hair growth cycle and the formation of persistent alopecic conditions.

2. Materials and Methods

In the preparation of the article, a complex of complementary methodological approaches was applied, including the comparative method, systematic literature review, and content analysis, which allowed for the juxtaposition of data from clinical, microbiological, and chemical-technological studies within a single analytical field. This combination of methods ensured the possibility not only to record empirical results but also to reconstruct the logical connections between the state of the scalp microbiota, the specific features of the clinical course of dermatological diseases, and the impact of cosmetic product components.

The search strategy for sources focused on maximizing the representativeness and relevance of the empirical base. Information retrieval was carried out in leading international abstract databases, which allowed covering both clinical and experimental studies, as well as interdisciplinary works at the intersection of dermatology, microbiology, and cosmetic chemistry. Search queries were formed using controlled terms and logical operators and included, in particular, the following key phrases: “scalp microbiome”, “seborrheic dermatitis etiology”, “alopecia dysbiosis”, “hair dyeing chemistry”, “hair bond builders”, “Malassezia role”. The inclusion criteria were the availability of the full text of the article and a pronounced emphasis on the relationship between microbiota and skin pathologies or on the chemical composition of cosmetic products and its dermatological significance.

To interpret the obtained data, methods of theoretical modeling of relevant chemical reactions were used, including processes of oxidation, reduction, polycondensation, and the formation of intermolecular bonds in the hair structure, as well as a comparative analysis of the clinical pictures of various scalp dermatoses and forms of alopecia. This approach ensured the comparison of mechanistic models of the impact of specific groups of substances (surfactants, oxidizers, dyes, conditioning agents, “bond-builders”) with phenotypic manifestations of dysbiosis and inflammation described in clinical studies.

3. Results

Analysis of sources [2, 4] confirms that the scalp microbiome functions as a highly organized and dynamic ecosystem. In a physiological state, a delicate balance is maintained between lipophilic yeasts of the genus

Malassezia (predominantly M. restricta and M. globosa), bacteria Cutibacterium acnes, and Staphylococcus epidermidis. Preservation of such homeostasis correlates with the normal course of the anagen phase and a stable skin condition, without signs of inflammation or impaired keratinization.

When the microbial balance shifts (dysbiosis), hypercolonization by Malassezia is registered, followed by the activation of lipase activity. These microorganisms produce lipases that break down sebum triglycerides into free fatty acids, among which oleic acid is given key importance [5]. Metabolites penetrate the epidermal barrier, inducing local inflammation, itching, and abnormal desquamation, clinically manifesting as dandruff. Chronic micro-inflammation of the perifollicular zone is capable of initiating the formation of fibrous changes and leading to telogen effluvium [1]. In androgenetic alopecia, a decrease in microbial diversity and a relative growth of the Propionibacterium population are recorded [3].

In modern trichology, the concept of “microbiome-oriented” scalp care is being developed, which assumes the use of mild surfactants, preparations with prebiotics and postbiotics, as well as the refusal of the systematic use of aggressive antiseptics outside of medical indications [2]. An approach is being formed in which the goal of intervention is recognized not as the total suppression of microflora, but as the restoration of the structural-functional equilibrium of the microbiota and the epidermal barrier, which is of key importance for the prevention of chronic itching, seborrheic dermatitis, and diffuse hair thinning [1, 4].

Correct interpretation of the mechanisms of hair and scalp damage during chemical exposure is impossible without a detailed examination of the dyeing reactions taking place. In the scientific and professional environment, an underestimation of the depth of intervention of permanent dyes into the shaft structure persists [6, 10].

The interaction of the dye with the morphological structures of the hair (cuticle, cortex, medulla) has a staged character. At the first stage, an alkaline agent (ammonia or monoethanolamine) raises the pH of the mixture, which leads to the forced lifting of cuticle scales and the formation of voids for the penetration of active molecules into the cortex. At the second stage, the mixture of dye and oxidizer (hydrogen peroxide) diffuses deep into the shaft. An oxidative process is realized in the cortex: peroxide destroys the natural pigment (melanin), simultaneously initiating the polymerization of small color precursor molecules, which increase in size and become incapable of reverse diffusion, becoming fixed in the hair structure [6].

The concentration of the oxidizer determines the speed and depth of oxidative processes: as the percentage of peroxide increases, the destruction of natural pigment intensifies, and cuticle trauma increases. The differentiation of various dye formulas acquires separate significance:

Ammonia dyes ensure deep penetration and high color fastness; however, they are characterized by high volatility and a pronounced alkaline pH, which creates a risk of scalp irritation and exacerbation of existing dysbiosis.

Acidic dyes do not exert a significant influence on the natural base and act primarily on the surface or in the upper layers of the cuticle. Such compositions are considered relatively safe for the scalp microbiome [10].

Modern dye formulas include innovative additives (bonders/plex systems, proteins, amino acids). These components fulfill the role of buffers and partial structural stabilizers, limiting the scale of destruction of the keratin matrix during dyeing [9]. A trend is forming toward the development of compositions in which an aggressive oxidative block is combined with complexes of protective action, which potentially reduces the risk of cumulative damage and increases the tolerance of sensitive hair and skin.

Lightening (bleaching) is recognized as the most aggressive procedure in terms of impact on the hair, as it is based on the irreversible destruction of melanin—both eumelanin and pheomelanin. Previously used high-alkaline powder compositions often led to deep denaturation of keratin with the formation of the “burnt hair” phenomenon, loss of elasticity, and structural integrity of the shaft. Modern developments are aimed at mitigating the processes occurring while maintaining a sufficient degree of lightening.

Bonders (often based on maleic acid, organic polymers, or their combinations) are introduced into the lightening mixture and participate in the formation of temporary ionic and hydrogen bonds in the keratin matrix. These bonds partially stabilize disulfide bridges and reduce the degree of their rupture during intense oxidative stress [9]. This does not imply the complete prevention of damage, but rather a redistribution of the load on the structural elements of the hair with a decrease in the proportion of irreversible destruction.

Lightening powders possess a high pH level, which causes pronounced swelling of the shaft and an aggressive effect on the cuticle. Cream lighteners and high-lift blondes are considered “milder” systems due to a modernized base and the presence of additional caring components. At the same time, it is necessary to consider that an increase in temperature (natural or artificial) significantly accelerates oxidation reactions, simultaneously increasing the risk of chemical burns to the scalp and exacerbation of existing inflammation.

Upon completion of lightening, the hair represents a highly porous structure with a pronounced alkaline residue. Failure to perform the neutralization and acidic recovery stage (application of shampoos and masks with acidic pH to equalize the acid-base balance) leads to overdrying of the scalp, destabilization of the hydrolipid mantle, and rapid formation of dysbiosis [2]. A correctly constructed post-care protocol is viewed as a mandatory component of safe lightening, not as an optional cosmetic measure.

In this connection, innovative reconstruction methods such as keratin, botox, and treatment are discussed in the professional environment.

Keratin straightening does not classify as a therapeutic procedure. The mechanism is based on the thermal polymerization of aldehydes or glycols with the formation of a dense film on the cuticle surface. Temporary fixation of the shaft shape occurs due to the “sealing” of the cuticle, creating a pronounced visual effect of smoothness and shine, but not ensuring the restoration of disulfide bonds in the cortex [6].

Hair botox represents a deep conditioning procedure. Active components (intra-cylane, amino acids, hyaluronic acid, etc.) fill voids in the cortex, increasing the elasticity and density of the hair. The effect is mainly cosmetic and limited in time, although with a competent selection of the protocol, a reduction in brittleness and mechanical damage to the shaft is possible.

Cold recovery (treatment) combines therapeutic methodologies aimed at replenishing the lipid-protein balance without the use of extreme temperatures. The focus of such therapy includes compositions with ceramides, amino acids, lipid complexes, as well as mild acids that help normalize the pH of the hair surface and scalp.

Regular and correctly selected application of reconstructing procedures contributes to achieving greater hair length by reducing brittleness and eliminating damaged ends. The protective film formed by some compositions reduces the negative impact of external factors, including UV radiation and mechanical friction. However, it is extremely important to prevent hot reconstruction agents from contacting the scalp, as such contact is capable of provoking contact dermatitis and worsening the state of beneficial microflora [7].

Consequently, modern standards form a requirement for multi-stage diagnostics of hair and scalp before conducting aggressive procedures.

At the primary stage, a visual inspection is carried out, including an assessment of hair density and type, the condition of the length, degree of porosity, and the presence and severity of gray hair. Next, trichoscopy (microscope, trichocamera) is applied, allowing for detailing the condition of follicle orifices (presence of sebaceous plugs, hyperkeratosis, signs of inflammation), as well as identifying structural defects of the shaft.

A significant element of the diagnostic algorithm is the elasticity (stretch) test, reflecting the degree of preservation of disulfide bonds in the cortex, and the porosity test, demonstrating how open the cuticle is and how easily the hair loses moisture and pigment. The obtained data set the limits of permissible chemical exposure and allow for predicting the stability of the result.

Upon detection of an open cuticle, signs of pronounced porosity, as well as symptoms of inflammation or irritation of the scalp, the intervention strategy is subject to revision: a refusal of aggressive oxidizers, a shift toward acidic dyes, and preliminary therapy of the scalp with restoration of barrier function and microbial balance are assumed. Diagnosis in this format acts not only as a tool for predicting the result but also as a mechanism for preventing complications, including chemical burns, exacerbation of alopecia, and aggravation of dermatological diseases. A comprehensive approach to diagnostics forms the basis for personalized protocols of coloring, lightening, and reconstruction, reducing the probability of iatrogenic damage and increasing the safety of procedures for hair and scalp.

4. Discussion

This section summarizes and interprets the data obtained. Comparing the results of the literature analysis [1, 5] with the characteristics of the chemical processes described above allows for stating the functional inseparability of the condition of the hair and the scalp microbiome. The indicator of acid-base equilibrium (pH) acquires central importance in this connection. Intact scalp skin is characterized by a weakly acidic environment, forming a natural antibacterial barrier, including against Staphylococcus aureus. The majority of hairdressing manipulations (dyeing, bleaching, perming) proceed under conditions of a pronounced shift to the alkaline side. In the absence of timely restoration of the hydrolipid mantle, a stable substrate is created for the excessive growth of Malassezia and pathogenic bacterial populations.

From the perspective of pathophysiology and microbiological homeostasis, such a pH shift can be viewed as a trigger mechanism for a cascade of disorders: the composition of sebum lipids changes, the integrity of the stratum corneum is violated, and transepidermal moisture loss intensifies, which collectively facilitates the adhesion and invasion of opportunistic and pathogenic microflora [1, 5]. An additional consequence is the modification of the local immune response of the scalp, including an imbalance of pro-inflammatory and anti-inflammatory cytokines, which contributes to the chronicity of inflammation and the formation of clinically significant dermatoses accompanied by structural disorders and hair loss.

Figure 1 schematically presents the pathological cycle that forms when these factors are ignored, consolidating disorders of pH, microbiome, and barrier function of the scalp into a single self-sustaining system.

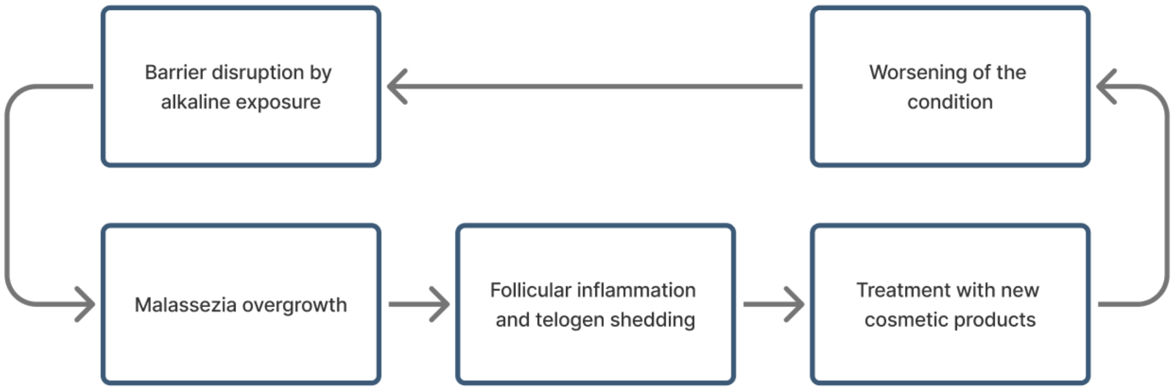

Fig. 1. Cycle "Chemical exposure – Dysbiosis – Hair loss" [1, 5].

Comparison of microbiome characteristics in normal and pathological states, reflected in Table 1, confirms the necessity of environmental control.

Table 1. Comparative characteristics of the scalp microbiome [2, 3].

Skin Condition	Dominant Microflora	Clinical Manifestations
Healthy (Normal)	Balance of *P. acnes* and *S. epidermidis*	Absence of itching, normal growth
Seborrhea / Dandruff	Excess of *Malassezia restricta/globosa*	Scaling, itching, inflammation
Alopecia	Decrease in *P. acnes*, growth of *S. aureus*	Hair thinning, hair loss

The systematization of reconstruction procedures, demonstrated in Table 2, helps specialists choose safe methods.

Table 2. Comparative analysis of reconstruction procedures [2, 3, 7].

Procedure	Main Agent	Goal of Impact	Influence on Hair/Skin Health
Keratin	Hydrolysates + Aldehydes (e.g., formaldehyde)	Straightening, film formation, surface smoothness	Cosmetic. Risk of skin irritation from aldehyde vapors; potential long-term damage if applied improperly.
Botox	Intra-cylane (or similar filling polymers), oils, vitamins	Nutrition, elasticity, structural filling (plumping)	Filling the structure, improving density and shine. Generally safe if technology is followed (no structural modification).
Plex-protection	Maleic acid (or other similar active ingredients like bis-aminopropyl diglycol dimaleate)	Bond protection (disulfide bonds) and reconstruction	Preservation of integrity during harsh chemical treatments (dyeing, lightening). Minimizes damage and breakage.

Based on this, an original algorithm of work is proposed. The author's concept of "Eco-balance of coloring" assumes the implementation of a technological model in which any chemical impact on the hair and scalp is necessarily accompanied by pre- and post-procedural stages aimed at buffering the pH of the skin covering. The application of bonders (plex) is viewed as a mandatory standard of professional practice and cannot be optional in nature [9]. Trichological diagnostics must precede any complex coloring with the aim of excluding procedures on inflamed or clinically unstable skin, which allows for preventing the formation and progression of chronic dermatoses associated with chemical exposures [4, 8].

Within the framework of this concept, "Eco-balance of coloring" functions as an integrative protocol combining dermatological, microbiological, and technological approaches. The systemic inclusion of stages of diagnostics, pH control, use of bonders, and subsequent restoration of the scalp barrier function forms a closed prevention loop: the risk of damage to the keratin hair shaft is minimized, the probability of inducing subclinical inflammation and dysbiotic shifts in the microbiome is reduced, and compliance of procedures with modern requirements of evidence-based trichology and consumer safety is ensured [4, 8]. Such a model can be viewed as a basis for the development of professional standards and regulations for service provision in the hair coloring industry.

5. Conclusion

The conducted study allowed for the realization of the stated aim and the sequential resolution of the set of tasks, which creates a basis for formulating the following generalizing provisions.

Dysbalance of the scalp microbiome, expressed by a persistent predominance of Malassezia and Staphylococcus aureus, should be qualified as a proven etiological factor in the formation of seborrheic dermatitis, as well as a significant cofactor in the progression of various forms of alopecia. These microorganisms, upon disruption of ecosystem equilibrium, initiate and maintain chronic micro-inflammation in the area of hair follicles, which entails structural-functional changes in the hair apparatus and potentially aggravates the course of existing trichological diseases.

Aggressive hairdressing exposures, primarily procedures of ammonia coloring and intensive bleaching, induce a pronounced shift of scalp pH to the alkaline side, leading to the destruction of the acid mantle and loss of barrier properties of the stratum corneum. This condition creates favorable conditions for the formation of dysbiosis and colonization dominance of opportunistic flora. The use of modern acidic dyes, as well as systems for protecting hair disulfide bonds (Plex technologies), statistically significantly decreases the degree of damage to the keratin shaft and reduces the risk of disrupting the integrity of the skin barrier, thereby limiting the likelihood of microbiome-mediated complications.

The integration of instrumental diagnostic methods, such as trichoscopy, phototrichogram, as well as standardized tests for hair porosity and strength, into the daily activity of a hairdresser acts as a necessary condition for the clinical-technological stratification of clients. The application of these methodologies ensures the possibility of scientifically grounded, personalized selection of procedures, allows for the timely detection of early signs of trouble regarding the scalp and hair, and thereby prevents the development of severe trichological complications requiring specialized medical intervention.

The systematization of the obtained data demonstrates the objective necessity of including a microbiome-oriented approach in regulatory and educational regulations of the hairdressing service sphere. The formation of unified interdisciplinary standards of interaction between the trichologist, dermatologist, and hairdresser specialist is capable of ensuring a proper level of risk factor identification, documentation of applied coloring and care protocols, as well as increasing the legal protection of all participants in relations in the sphere of providing cosmetological and hairdressing services, including through the introduction of elements of evidence-based medicine and risk management when choosing coloring and lightening technologies.

The aggregate of research results confirms the advanced hypothesis that the systemic integration of knowledge about the scalp and hair microbiome into protocols of coloristics and accompanying care possesses significant potential for improving the quality of hairdressing services, reducing the frequency of iatrogenic trichological complications, and preserving patient health as a key priority of service and medical practice.

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