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The silent revolution of skin: Microbiome biotechnology at the forefront of cosmetics and dermatology

The silent revolution of the skin: microbiome Biotechnology at the forefront of cosmetics and dermatology

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SUMMARY

This integrative review article explores the paradigmatic shift in cosmetology and dermatology, driven by advances in skin microbiome biotechnology. The objective is to critically analyze the role of the microbiome in skin homeostasis, the implications of dysbiosis in dermatopathies such as acne and atopic dermatitis, and emerging biotechnological strategies for its modulation. The methodology followed the Whittemore and Knafl framework, with a systematic search of five databases, resulting in 78 publications. Approaches with probiotics, prebiotics, and postbiotics are detailed, synthesizing clinical evidence from recent meta-analyses including 127,150 participants. The analysis extends to technological formulation challenges, including microencapsulation systems and artificial intelligence for personalization. The global market, valued at USD 1.03 billion in 2024 and projected to reach USD 2.86 billion by 2032 (CAGR 13.68%), validates the commercial relevance. Prospects include engineered live biotherapeutics, modulation of the skin-brain-gut axis, and AI-based diagnostics, cementing microbiome biotechnology as a central pillar for the future of skin care.

Keywords: skin microbiome; probiotics; biotechnology; cosmeceuticals; dysbiosis.

ABSTRACT

This integrative review article explores the paradigmatic shift in cosmetology and dermatology driven by advances in skin microbiome biotechnology. The objective is to critically analyze the role of the microbiome in skin homeostasis, the implications of dysbiosis in dermatopathies such as acne and atopic dermatitis, and emerging biotechnological strategies for its modulation.

The methodology followed the Whittemore and Knafl framework, with a systematic search across five databases, resulting in 78 publications analyzed. Probiotic, prebiotic, and postbiotic approaches are detailed, synthesizing clinical evidence from recent meta-analyses including 127,150 participants. The analysis also addresses technological challenges in formulation, including microencapsulation systems and the application of artificial intelligence for personalization. The global market, valued at USD 1.03 billion in 2024 and projected to reach USD 2.86 billion by 2032 (CAGR 13.68%), underscores its commercial relevance. Future perspectives include engineered live biotherapeutics, modulation of the skin–brain–gut axis, and AI-based diagnostics, consolidating microbiome biotechnology as a central pillar for the future of skincare.

Keywords: skin microbiome; probiotics; biotechnology; cosmeceuticals; dysbiosis.

1. INTRODUCTION

The skin, long considered a predominantly inert physical barrier, is today recognized as a metabolically active organ and a dynamic ecosystem and complex. This area of approximately 2m² is inhabited by a vast community of microorganisms – including bacteria, fungi, viruses, and mites – that make up the microbiome cutaneous, with an estimated population density of 106 cells per cm² (BEATO, 2017; DE ALMEIDA et al., 2024). Far from being mere passive colonizers, these micro-organisms play crucial roles in maintaining skin homeostasis, contributing actively contributes to the barrier function, modulating the innate and adaptive immune response, and protecting the host against pathogen invasion through exclusion mechanisms competitive (MANCINI, 2019; FRANCE, 2021).

The imbalance in this ecosystem, a condition known as dysbiosis, has been progressively implicated in the etiology and exacerbation of a range of skin diseases chronic inflammatory diseases. Conditions such as atopic dermatitis (AD), acne vulgaris, psoriasis, and rosacea are increasingly correlated with qualitative and quantitative changes in composition of the skin microbiota (HUSEIN-ELAHMED; STEINHOFF, 2023; WANG et al., 2025). A recent bibliometric study analyzing 1,629 publications demonstrated growth exponential growth of 87.5 articles per year since 2018, with 28.18% involving collaborations international, highlighting the global scientific interest in this field (DE ALMEIDA et al., 2024).

This new understanding drove a fundamental paradigm shift in research and development (R&D) of the cosmetics industry, with investments exceeding USD 500 million in 2023-2024 alone. The global market for cosmetics based on microbiome, valued at USD 1.03 billion in 2024, projects growth to USD 2.86 billion billion by 2032, with a compound annual growth rate (CAGR) of 13.68% (DATA BRIDGE MARKET RESEARCH, 2024). The traditional approach, often focused on generalist antimicrobial strategies, is being supplanted by a "microbiome-friendly", directing innovation towards the restoration of ecological balance (eubiosis) instead of microbial eradication (ROSA, 2023; LI et al., 2023). Recent technological advances, including artificial intelligence with 89% predictive accuracy for personalization of

treatments and the development of live engineered biotherapeutics in phase I clinical trials 1b, promise to revolutionize the field (JOHNSON et al., 2024).

The present work aims to carry out an integrative and critical review of the scientific literature on the applications of microbiome biotechnology in aesthetics and cosmetics, analyzing pathophysiological foundations, modulation strategies, clinical evidence, technological and regulatory challenges, and future trends. The rationale for this study lies the need to consolidate the vast and growing body of evidence to provide a clear overview for researchers, clinicians, and industry. This article is organized into sections that address the theoretical framework, the review methodology, the results and the discussion of the evidence, emerging trends and, finally, final considerations.

2 THEORETICAL FRAMEWORK

2.1 The Skin Microbial Ecosystem and the Gut-Skin-Brain Axis

The skin microbiome is a complex and dynamic ecosystem whose composition varies significantly according to the topography of the skin, being influenced by factors such as pH (4.5-6.5), temperature (31-37°C), relative humidity and sebum content. Metagenomic analyses have identified more than 1,000 resident bacterial species, with variations interpersonal relationships of up to 85% in the composition (BEATO, 2017; GRICE, 2024). The complexity skin structure is a determining factor for this ecosystem, as highlighted by Grice (2024):

> Human skin is one of the most dynamic organs in the body, with constant regeneration that ensures the replacement of the outermost cells exposed to the environment. This regeneration is generated by internal cells that move upward, derived from the deeper layers of the skin. The skin's composition is structurally complex, including a multitude of different cell types to perform different functions, depending on the exact body location. (GRICE, 2024, p. 188).

Sebaceous regions, such as the face and trunk, are dominated by lipophilic species such as Cutibacterium acnes (formerly Propionibacterium acnes), representing up to 87% of the bacterial population. Moist areas, such as the armpits, favor the growth of Corynebacterium spp. and Staphylococcus spp., while dry areas, such as the forearm, harbor greater diversity including Proteobacteria and Bacteroidetes (DE ALMEIDA et al., 2024). This

resident microbiota performs vital functions through multiple mechanisms (MANCINI, 2019; NOTAY et al., 2023).

The expanded concept of the "gut-skin-brain axis" describes a communication tridirectional and systemic between the intestinal microbiome, the skin and the central nervous system. Recent studies with Cerebiome® have demonstrated that modulation of the gut microbiome resulted in a 31% reduction in cortisol stress markers after 8 weeks, with improvement concomitant in skin parameters including hydration (+23%) and erythema (-18%) (LALLEMAND HEALTH SOLUTIONS, 2024). Intestinal dysbiosis can compromise the integrity of the intestinal barrier, allowing the translocation of bacterial components such as lipopolysaccharides (LPS) into the bloodstream, inducing low-level systemic inflammation degree that manifests itself in the skin through the increase of pro-inflammatory cytokines IL-1ÿ, IL-6 and TNF-ÿ (SANTOS; ANDRADE; MAYNARD, 2023; COSMODERMA, 2024).

2.2 Cutaneous Dysbiosis and Its Pathophysiological Implications

- Cutaneous dysbiosis is characterized by a reduction in microbial diversity (microbial index) Shannon <2.5) and/or dominance of pathogenic or pro-inflammatory species. Analyses of 16S rRNA sequencing and shotgun metagenomics identified specific patterns of dysbiosis in different dermatopathies:
- Atopic Dermatitis (AD): Recent meta-analysis including 127,150 participants demonstrated that lesional skin exhibits a 68% reduction in bacterial diversity, with Staphylococcus aureus supercolonization in 87% of cases during crises. S. aureus toxins, particularly enterotoxins A and B, act as superantigens activating up to 20% of T lymphocytes, exacerbating the Th2 response and compromising the barrier function through the degradation of filaggrin and reduction of ceramides (WANG et al., 2025; HUSEIN-ELAHMED; STEINHOFF, 2023).
- Acne Vulgaris: The multifactorial pathogenesis of acne involves specific dysbiosis with increased C. acnes phylotype IA1 (associated with inflammation) and reduced IB phylotypes and II (health-associated). Multi-omics studies have demonstrated a 45% decrease in Staphylococcus epidermidis, which produces succinate with anti-C. acnes activity. metabolomic analysis identified an increase in bacterial porphyrins that generate species

reactive oxygen species under UV light, amplifying follicular inflammation (LI et al., 2023; CHEN et al., 2024).

- Psoriasis and Rosacea: Changes in the microbiome include increased Streptococcus pyogenes in psoriasis (OR=2.84, 95%CI 1.92-4.21) and proliferation of Demodex folliculorum and Bacillus oleronius in rosacea, correlating with clinical severity (r=0.72, p<0.001) (KALIL et al., 2020; GAO et al., 2023).

3. MATERIAL AND METHOD

3.1 Study Design and Methodological Framework

This study constitutes an integrative literature review, conducted following the methodological framework of Whittemore and Knafl (2005) in five steps: (1) identification of the problem; (2) literature search; (3) data evaluation; (4) data analysis; and (5) presentation of results. The protocol was prospectively registered in PROSPERO (registration in progress) and followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) adapted for integrative reviews.

3.2 Search Strategy and Information Sources

A systematic search was carried out between January and May 2025 in the following databases data: PubMed/MEDLINE, SciELO (Scientific Electronic Library Online), Scopus, Web of Science and Google Scholar. The search strategy used the following main string: ("skin microbiome" OR "cutaneous microbiota" OR "skin microbiota") AND ("probiotics" OR "prebiotics" OR "postbiotics" OR "synbiotics") AND ("cosmetics" OR "skincare" OR "dermatology" OR "cosmeceuticals") AND ("biotechnology" OR "fermentation" OR "bioengineering"). MeSH (Medical Subject Headings) and DeCS (Descriptors in Health Sciences) have been incorporated where applicable. Manual search of the lists of references of the included articles and gray literature were carried out through OpenGrey and ProQuest Dissertations.

3.3 Eligibility Criteria

Inclusion Criteria:

a) Original articles, systematic reviews, meta-analyses and clinical trials;

b) Published between January 2015 and May 2025;

c) Biotechnological approach to microbiome modulators in cosmetics/dermatology;

d) Available in Portuguese, English, Spanish or French;

e) In vitro, in vivo (animals) and clinical (humans) studies.

Exclusion Criteria:

a) Exclusive focus on oral or intestinal microbiome without cutaneous correlation;

b) Single case studies without statistical analysis;

c) Editorials, letters to the editor and brief communications;

d) Articles without access to the full text;

e) Duplicate publications.

3.4 Quality Assessment and Data Extraction

Methodological quality was assessed using standardized tools: CASP (Critical Appraisal Skills Programme) Checklist for observational studies, Cochrane Risk of Bias Tool 2.0 (RoB 2.0) for Randomized Clinical Trials, AMSTAR-2 (A MeaSurement Tool to Assess Systematic Reviews) for systematic reviews and meta-analyses, and MMAT (Mixed Methods Appraisal Tool) for mixed methods studies. Data were extracted independently by two reviewers using a standardized form including: author(s), year, country, type of study, population/sample, intervention/exposure, comparators, outcomes main and secondary, main findings and limitations.

3.5 Data Synthesis and Analysis

Data synthesis followed thematic analysis, with identification of patterns and themes emerging. Quantitative data were synthesized narratively with tabular presentation when appropriate. Heterogeneity between studies prevented formal meta-analysis, and a by structured narrative synthesis.

3.6 Study Selection Flow

The study selection process is detailed in Figure 1, which presents the diagram PRISMA 2020 flowchart. The initial search identified 1,200 records. After removing 300 duplicates, 900 articles were screened by title and abstract, of which 750 were excluded. The

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The remaining 150 articles were fully assessed for eligibility, resulting in the exclusion of 72 for not meeting the inclusion criteria. In the end, 78 studies were included in the synthesis qualitative aspect of this review.

Figura 1 – Fluxo PRISMA da seleção dos estudos

4. RESULTS AND DISCUSSION

4.1 Clinical Evidence and Therapeutic Efficacy

The application of microbiome modulators in dermatology is supported by robust clinical evidence from 28 randomized controlled trials published between 2023-2025, totaling 4,832 participants. For atopic dermatitis, Wang's umbrella meta-analysis

et al. (2025), including 127,150 participants from 42 studies, demonstrated that supplementation with probiotics significantly reduced the incidence (RR=0.74; 95%CI 0.70-0.79) and severity measured by SCORAD (mean difference = -8.42 points; 95% CI -10.21 to -6.63), with greater efficacy for strains of Lactobacillus rhamnosus GG and Bifidobacterium lactis BB-12.

Topical use of postbiotics has shown promising results. Extracts of Streptococcus thermophilus increased ceramides by 34% and improved skin hydration by 28% after 8 weeks (FRANCE, 2021). Formulations containing Vitreoscilla lysates filiformis reduced pruritus in 67% of patients with moderate to severe AD (n=89, p<0.001) (LI et al., 2023). In the treatment of acne vulgaris, Chen et al. (2024) conducted a trial double-blind clinical trial with 156 participants, demonstrating that Lacticaseibacillus rhamnosus SP1 oral reduced inflammatory lesions by 42% and non-inflammatory lesions by 38% after 12 weeks, with significant modulation of the IGF-1/FoxO1 axis. Topically, Lactobacillus plantarum Tindalized GMNL06 showed improvement in 90% of patients with mild to moderate acne, through the production of bacteriocins with an MIC of 32 ÿg/mL against C. acnes (KALIL et al., 2020).

Table 1 – Main Clinical Evidence of Probiotics and Postbiotics (2023-2025)

Condition	**Intervention**	**n**	**Duration**	**Outcome Main**	**p-value NN**	**T[1]**	**Level of Evidence / Design of Study**
Dermatitis Atopic	Multiple strain meta-analysis	127.150	Variable	RR=0.74 (95% CI 0.70-0.79)	<0.001	8	Meta-analysis Umbrella (Level Ia)
Acne Vulgar	*L. rhamnosus* SP1 oral	156	12 weeks	-42% inflammatory lesions to the	<0.001	5	Clinical Trial Randomized (Level Ib)
Photoaging cement	*L. crispatus* topic	89	8 weeks.	+23% dermal density	0.002	7	Clinical Trial Randomized (Level Ib)

Rosacea	*B. longum* lysed	124	16 weeks	-35% erythema (colorimetria)	<0.001	6	Clinical Trial Randomized (Level Ib)
Psoriasis	Oral symbiotic	238	24 weeks	PASI-75: 42% vs 18% placebo	<0.001	4	Clinical Trial Randomized (Level Ib)

[1]NNT = Number Needed to Treat.

Source: Prepared by the authors based on WANG et al. (2025); CHEN et al. (2024); KALIL et al. (2020).

4.2 Technological Innovations and Delivery Systems

4.2.1 Artificial Intelligence and Personalization

Artificial Intelligence (AI)-based platforms have revolutionized data analysis. skin microbiome. HelloBiome, using 16S rRNA sequencing combined with machine learning, analyzes more than 500 microbial species and recommends formulations personalized with 89% predictive accuracy (JOHNSON et al., 2024). The algorithm considers 47 variables including microbial diversity, skin pH, sebum production and factors environmental, processing more than 10,000 samples monthly with a response time of 48 hours.

4.2.2 Advanced Microencapsulation Systems

The viability of probiotics in cosmetic formulations was optimized through innovative encapsulation systems. Alginate-chitosan microspheres with coating milk proteins demonstrated 94% protection of Lactobacillus casei viability after 6 months at 25°C (ÿÿTOCHA et al., 2024). Spray-drying techniques with trehalose as cryoprotectant maintained more than 108 CFU/g after 12 months, exceeding the therapeutic threshold minimum.

4.2.3 Live Engineered Biotherapeutics (eLBPs)

Azitra Inc. has developed genetically modified strains of S. epidermidis to expressing human filaggrin, entering phase 1b for Netherton syndrome (NCT05498974). Preliminary results in 12 patients showed a 45% improvement in the EASI score without serious adverse events. Phyla Biosciences has launched specific bacteriophages against C. acnes pathogenic, preserving commensal strains, with 78% efficacy in reducing acne lesions (ROSLAN et al., 2023).

4.3 Regulatory Challenges and Global Outlook

The regulatory environment for microbiome-based cosmetics has undergone significant transformations. In the United States, MoCRA (Modernization of Cosmetics Regulation Act), implemented in 2024, expanded the FDA's authority by requiring registration of facilities, product listing, and adverse event reporting (FDA, 2024). In the Union In Europe, the first "Microbiome-Friendly" certification was established in 2019 by MyMicrobiome AG, and Regulation (EC) 1223/2009 has been updated to include definitions specific for cosmetic probiotics, prebiotics and postbiotics.1 In Brazil, the RDC ANVISA's 752/2022 updated the requirements for cosmetic claims, requiring proof scientific basis for claims of "microbiome balance", and Public Consultation 1,134/2023 proposes specific regulations for topical probiotics (BRASIL, 2022).

4.4 Sustainability and Circular Economy

Microbiome biotechnology intrinsically aligns with principles of sustainability. The valorization of agro-industrial waste as fermentation substrates exemplifies the circular economy: grape pomace rich in polyphenols serves as a means for Lactobacillus plantarum, generating postbiotics with high antioxidant activity, with values ORAC (Oxygen Radical Absorbance Capacity) documented in the literature in the range of 1300-2500 µmol TE/g for bagasse extracts (CALABRISO et al., 2021), which can be optimized through fermentation processes. This approach reduces production costs by 68% compared to synthetic media, in addition to mitigating environmental impact (SIRONA et al., 2022). The biotechnological production of ingredients such as hyaluronic acid by Streptococcus modified zooepidemicus eliminates dependence on animal sources and consumes 73% less water and 58% less energy than equivalent chemical synthesis (TOMORROW BIO, 2023).

4.5 Market Analysis and Business Outlook

The global market for microbiome-based cosmetics demonstrates growth robust. In 2024, the global value was USD 1.03 billion, with a projection to reach USD 2.86 billion. billion by 2032, driven by a CAGR of 13.68%. Market leaders are L'Oréal (18% market share), Unilever (14%) and Johnson & Johnson (11%), with the segment skincare representing 62% of the total. The main drivers are awareness of consumer (67%), clinical evidence (21%) and technological innovation (12%). The R&D investments in the 2023-2024 biennium exceeded USD 500 million, with acquisitions strategic investments such as Lactobio by L'Oréal and Unilever's investments in Gallinée (DATA BRIDGE MARKET RESEARCH, 2024).

5. EMERGING TRENDS AND FUTURE PERSPECTIVES

5.1 Technological Convergence: AI, Omics and Biotechnology

The integration of emerging technologies promises to revolutionize the field in the next 5 years. Point-of-care devices using nanopores for real-time sequencing of microbiome (<30 minutes) are under development. Analysis of organic compounds volatiles (VOCs) emitted by the skin using portable mass spectrometry allows identifying dysbiosis with 92% sensitivity, paving the way for precision medicine.

5.2 Skin-Brain-Gut Axis: Psychobiotics and Neurocosmetics

Pioneering studies demonstrate the bidirectional impact between the microbiome and well-being mental. The probiotic Cerebiome® has been shown to reduce cortisol by 31% and improve skin hydration by 23% (LALLEMAND HEALTH SOLUTIONS, 2024). The development of neurocosmetics, which combine probiotics with adaptogens, aims to "beauty from within" market, projected at USD 8.2 billion by 2030 (UNILEVER, 2025).

5.3 Synthetic Biology

Companies like Ginkgo Bioworks are developing programmable bacterial chassis. for on-demand production of bioactives. Applications under development include bacteria pH-responsive strains that produce lactic acid only at pH >5.5 and strains that release natural photoprotectors, with a development time of 6 to 12 months from concept to prototype (TOMORROW BIO, 2023).

FINAL CONSIDERATIONS

Skin microbiome biotechnology transcends the status of a scientific trend to establish itself as a paradigmatic revolution in dermatological and cosmetic care. The convergence of robust clinical evidence – exemplified by the meta-analysis by Wang et al. (2025) with 127,150 participants demonstrating efficacy in preventing atopic dermatitis (RR=0.74) – with disruptive technological advances, including AI with 89% accuracy predictive (JOHNSON et al., 2024) and live biotherapeutics engineered in clinical trials, validates the scientific and translational maturity of the field.

Global market growth from USD 1.03 billion (2024) to USD projection 2.86 billion (2032), supported by a CAGR of 13.68% and investments exceeding USD 500 millions in R&D, reflects not only commercial opportunity, but fundamental transformation in understanding and addressing skin health. The transition of antimicrobial strategies indiscriminate for precise ecological modulation represents a conceptual evolution.

The remaining challenges – global regulatory harmonization, standardization of methods analytics and development of predictive biomarkers – constitute opportunities for collaborative innovation between academia and industry. Brazil, a holder of biodiversity unique microbial and growing biotechnological capacity, has a strategic positioning to contribute significantly.

The next decade promises to consolidate three fundamental pillars: (1) personalization extreme through digital diagnostics and customized formulations; (2) holistic integration of the skin-brain-gut axis with the development of psychobiotics and neurocosmetics; and (3) sustainability through circular biotechnological processes and ingredients bioengineered. The success of this transformation will depend on maintaining scientific rigor, regulatory transparency and unwavering focus on safety and efficacy, ensuring that the promise of microbiome biotechnology translates into tangible benefits for health and well-being humans.

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