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Review

The Skin Microbiome Revolution: The Science and Challenges of Prebiotics, Probiotics, and Postbiotics in Skincare

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Abstract

The skin microbiome comprises a diverse community of bacteria, fungi, and archaea, all of which play a foundational role in maintaining skin health, immune tolerance, and barrier integrity. Recent advances in cosmetic science focus on the skin microbiome through the incorporation of prebiotics, probiotics and postbiotics in topical skincare formulations. This review critically examines the scientific understanding of the skin microbiome, explores the mechanisms and extractions of key "biotics" ingredients, and evaluates the clinical and regulatory landscape surrounding their use in the cosmetic industry. Despite promising scientific data and early clinical findings, there are notable challenges, including limited robust in vivo evidence, regulatory ambiguity, difficulties in formulation, and inconsistent definition and marketing claims. Regulatory harmonisation and the development of standardised testing protocols are necessary to fill the gap in today's research and to maximise the benefits of "biotics" in the cosmetic industry.

Keywords: skin microbiome; gut–skin axis; skin disorders; prebiotics; probiotics; postbiotics; formulation stability; cosmetic regulations

1. Introduction

1.1. The Skin Microbiome and Cutaneous Homeostasis

The skin functions as a complex and dynamic barrier composed of physical, chemical, and immunological components that protect the host from external environmental challenges. From birth, the skin is rapidly colonised by a diverse and heterogeneous community of microorganisms, including bacteria, archaea, and fungi [1]. Early-life microbial exposure plays a critical role in immune system development, particularly in the establishment of immune tolerance [2].

As the host matures, commensal skin microorganisms actively shape cutaneous immunity by regulating cytokine production and inducing the synthesis of antimicrobial peptides (AMPs) [3]. These processes strengthen the skin's innate defence mechanisms and limit colonisation by opportunistic pathogens [4]. In parallel, the gut microbiota is established during the postnatal period and develops into a highly diverse ecosystem that contributes to systemic immune regulation and metabolic homeostasis throughout life [4].

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Disruption of the skin microbiome, commonly referred to as dysbiosis (Figure 1), is increasingly recognised as a key contributor to a range of immune-mediated dermatological conditions, including acne, alopecia areata, eczema, psoriasis, rosacea, and vitiligo [5–10]. Under homeostatic conditions, resident microbial communities promote immune tolerance, support wound healing, and protect against pathogenic colonisation [11]. The loss of this balance can shift immune responses towards chronic inflammation and barrier dysfunction [12].

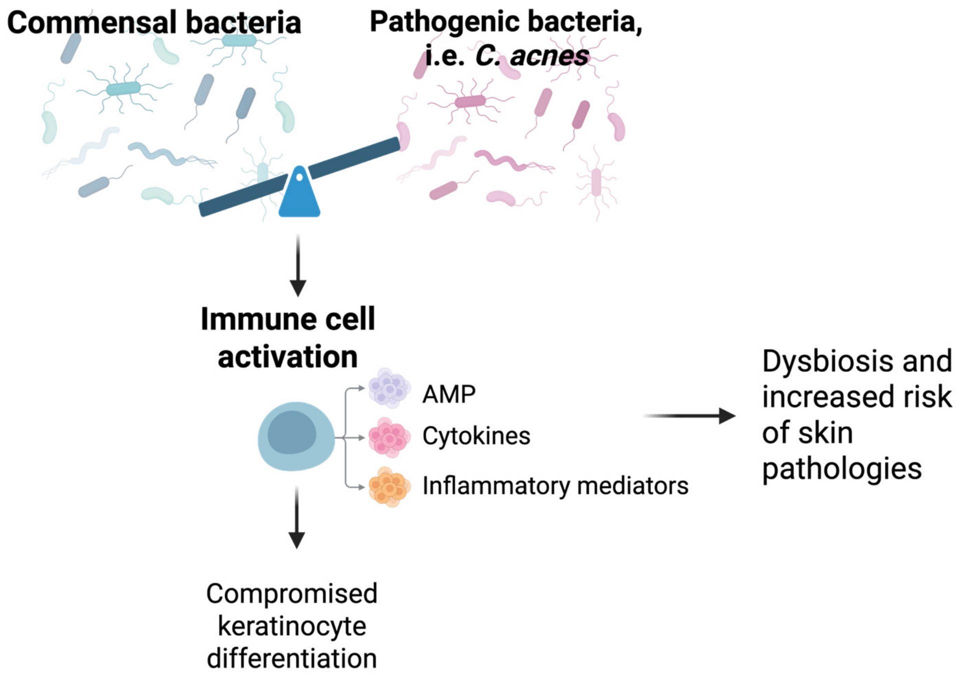

Figure 1. Microbiome imbalance and immune modulation. Schematic illustration of microbial dysbiosis, showing a shift from a balanced microbial community to a pathogenic-dominated state. This imbalance influences host immune cells, leading to altered cytokine and mediator release that contributes to downstream inflammatory responses and disease progression. Created in BioRender. Borrello, M. (2026) https://BioRender.com/m92pkau.

For example, in acne, inflammatory responses and impaired keratinocyte differentiation are exacerbated by overproliferating strains of *Cutibacterium acnes* (*C. acnes*) [13]. Similarly, the skin dominance of *Staphylococcus aureus* (*S. aureus*) reduces microbial diversity, particularly through the suppression of commensal species such as *Staphylococcus epidermidis* (*S. epidermidis*), which normally provide a beneficial effect to the skin through the production of AMPs. This imbalance compromises epidermal barrier integrity and skews immune responses, contributing to the development and persistence of inflammatory skin conditions [7]. Psoriasis is a condition characterised by scaly plaques on the skin due to impaired barrier formation [14]. It is associated with reduced microbial diversity and an increased abundance of *Streptococcus* spp., which in turn activate antigen-presenting cells and promote Th17 cell differentiation. This results in the elevated production of the human cathelicidin interleukin (IL)-17 and IL-22 peptides, driving keratinocyte hyperproliferation, sustained inflammation, and the disruption of epidermal architecture [15–17]. Therefore, maintaining a healthy skin biome is essential for the maintenance of dermal health and prevents the manifestation of skin disorders.

1.2. The Gut–Skin Axis in Health and Disease

Beyond local effects at epithelial surfaces, the microbiota mediates bidirectional communication between the gut and the skin through the gut–skin axis (GSA). This interaction

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is driven not only by microbial composition but also by microbiota-derived metabolites and micronutrients that act as systemic signalling mediators [18].

Gut microorganisms metabolise indigestible complex polysaccharides into essential nutrients, including vitamin K and water-soluble B vitamins, which support a range of physiological processes, particularly tissue repair and wound healing [19]. For example, vitamin K is well documented as having a critical role in wound healing [20], particularly in the coagulation cascade, tissue renewal, and protection against oxidative injury [21]. Vitamin K activates specific proteins such as Matrix Gla Protein (MGP), Protein S, Growth Arrest-Specific Protein 6 (Gas6), and Protein C [22]; these proteins mediate endothelial integrity, promoting tissue renewal, modulating antioxidant enzyme expression levels, and reducing reactive oxygen species (ROS) for anti-inflammatory properties. This is prevalent in lipid-rich environments such as cell membranes [22]. In addition, the gut microbiota breaks down resistant starches and dietary fibres, producing short-chain fatty acids (SCFAs) which function as bioactive signalling molecules influencing immune regulation, epithelial barrier function, and inflammatory pathways within the GSA [23].

Vitamin D receptor (VDR) signalling represents a key regulatory mechanism within this axis [24]. Expressed in both the gut and the skin, VDR activation regulates antimicrobial peptide production and supports microbial homeostasis and host defence against pathogenic organisms [24]. Vitamin D also modulates regulatory T-cell activity, which is essential for maintaining immune tolerance and limiting excessive inflammation [25]. Importantly, dermal injury can initiate complex skin–gut crosstalk, resulting in significant alterations in the intestinal microbiome and the disruption of systemic immune balance [4].

Dysregulation of the gut–skin axis arises from a combination of host-related and environmental factors, including genetic background, immune status, diet (particularly high-sugar, low-fibre diets), exposure to xenobiotics such as antibiotics and pharmaceuticals, and hygiene practices [26–28]. These influences are associated with a reduced microbial metabolic capacity and the promotion of systemic inflammation, which can affect distant organs including the skin, ultimately disrupting cutaneous homeostasis and increasing susceptibility to inflammatory skin disorders [29].

The inclusion of the gut–skin axis is relevant because systemic immune regulation and metabolite signalling influence cutaneous homeostasis and may modulate responsiveness to topical biotic interventions.

2. The History and Evolution of Biotics

The concept of biotics has evolved over more than a century, reflecting advances in the understanding of host–microbe interactions and their implications for human health [30]. Early research focused primarily on the role of live microorganisms in promoting host wellbeing, giving rise to the concept of *probiotics*. As scientific knowledge expanded, attention shifted towards non-digestible substrates that selectively support beneficial microbial populations (*prebiotics*) and, more recently, towards non-viable microbial components and metabolites capable of exerting biological effects (*postbiotics*) [31,32]. Collectively, these approaches represent distinct yet complementary strategies for modulating microbial ecosystems in both the gut and the skin.

Interest in the incorporation of biotics into cosmetic formulations has re-emerged in recent years, driven by growing evidence linking the skin and gut microbiomes to immune modulation, skin barrier integrity, and overall cutaneous homeostasis [33]. Advances in microbiome research have underscored the importance of host–microbe interactions beyond the gastrointestinal tract, prompting renewed focus on biotic-based strategies to support skin health [34].

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Probiotic research can be traced back to the early 1900s and is commonly attributed to Elie Metchnikoff at the Pasteur Institute in Paris [35]. Metchnikoff proposed that replacing harmful gut microorganisms with beneficial bacteria found in fermented milk could improve health and longevity. This hypothesis was further supported by the identification of Lactobacillus bulgaricus, which was suggested to counteract detrimental gastrointestinal processes associated with disease and ageing [35]. The earliest formal definition of probiotics was published in 2002 by the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO), defining probiotics as "live microorganisms which, when administered in adequate amounts, confer a health benefit on the host." This definition was reviewed in 2014 by the International Scientific Association for Probiotics and Prebiotics (ISAPP), which concluded that it remained scientifically valid and appropriate for describing probiotics [36].

The concept of prebiotics originated in 1921, when Rettger and Cheplin observed that carbohydrate consumption could induce shifts in microbial community composition. Building on these early findings, Gibson and Roberfroid formally defined prebiotics in 1995 as "non-digestible food ingredients that beneficially affect the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria in the colon" [31]. Early research focused on demonstrating that dietary fibres, such as inulin and fructo-oligosaccharides (FOS), selectively promoted the growth of beneficial gut-associated microorganisms, particularly *Bifidobacterium* and *Lactobacillus* species [31]. As the understanding of host–microbe interactions broadened, the definition was updated in 2017 to "non-digestible substrates that are selectively utilised by host microorganisms, conferring a health benefit" [31], reflecting the recognition that prebiotic effects may extend beyond the colon to other microbial ecosystems, including the skin.

Postbiotics have gained increasing attention due to their demonstrated physiological benefits and the advantage of not requiring microbial viability [37]. Derived from inactivated microbial cells and/or their structural components, postbiotics offer improved stability and safety compared with live microorganisms [37]. The ISAPP emphasised that the defining feature of postbiotics is the presence of a demonstrated health benefit rather than microbial origin, and highlighted their potential applications beyond the gut, including the skin and other epithelial surfaces [38]. Earlier definitions of postbiotics often focused narrowly on microbial metabolites or non-viable microorganisms and frequently restricted their origin to probiotics, limiting conceptual clarity and innovation [39]. Many lacked clear criteria for demonstrating health benefits or failed to distinguish postbiotics from substances produced in situ following administration [39]. To address these limitations, ISAPP redefined postbiotics as "preparations of inanimate microorganisms and/or their components that confer a health benefit" [39]. Despite this progress, a skin-specific definition of postbiotics has yet to be formally established.

3. Prebiotics: Modulation of the Skin Microbiome Through Selective Nutrient Supply

3.1. Biological Rationale and Mechanism of Action

Prebiotics have traditionally been associated with nutricosmetic and gut health applications [31], but increasing evidence supports their relevance in topical cosmetic formulations, particularly for maintaining skin microbiome balance [31]. Unlike probiotics, prebiotics are non-living compounds that function as selective substrates for host microorganisms [31]. Within the skin microbiome, prebiotics provide nutrients that preferentially support the growth of commensal bacteria (Figure 2), while indirectly suppressing pathogenic species [40]. This selectivity is largely dictated by their chemical structure, as prebiotics are commonly non-digestible carbohydrates derived from plant- or sugar-based sources [41,42]. Commensal Gram-positive (G^+) bacteria such as *S. epidermidis* and *C. acnes* possess enzymatic machinery capable of metabolising these substrates [43]. Their metabolism leads to the production of SCFAs, which lower the skin's surface pH [41]. This acidification creates an environment that is unfavourable to pathogenic bacteria, thereby limiting their growth and supporting microbiome homeostasis [44].

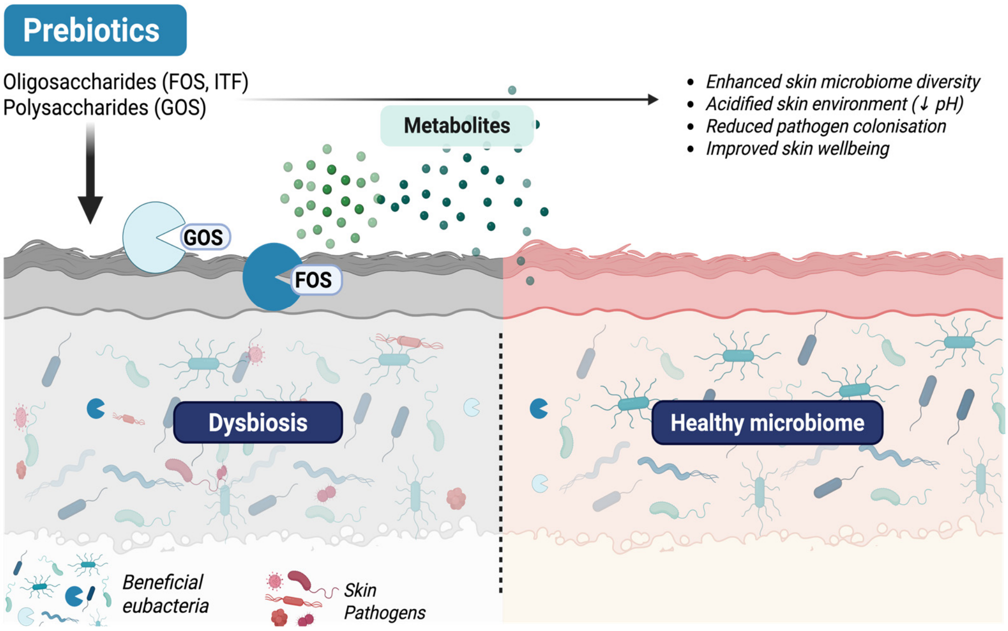

Figure 2. Topical prebiotics as cosmetic ingredients to modulate the skin microbiome. Schematic illustration of prebiotics incorporated into cosmetic formulations (e.g., galacto-oligosaccharides, GOS, and fructo-oligosaccharides, FOS) and applied to the skin. These substrates selectively support beneficial skin microbiota, promote the production of microbial metabolites, suppress pathogenic species, and contribute to the maintenance or restoration of a healthy skin microbiome. Created in BioRender. Borrello, M. (2026) https://BioRender.com/x2qjkxq.

3.2. Classification, Sources, and Production of Cosmetic Prebiotics

Prebiotics used in cosmetic science are predominantly carbohydrate-based and can be broadly classified into oligosaccharides and polysaccharides, each differing in molecular complexity, origin, and functional performance [42]. *Oligosaccharides* are short-chain carbohydrates widely utilised in both nutricosmetic and cosmetic applications [42]. A major subgroup includes *fructans* [31], such as inulin and fructo-oligosaccharides (FOS), which are naturally derived from plant sources including chicory root and Jerusalem artichoke [44,45]. The glycosidic linkages within fructans are resistant to human enzymatic digestion but are selectively metabolised by commensal skin bacteria [44]. This selective metabolism promotes beneficial bacterial growth and generates acidic metabolites that suppress pathogenic species [44].

Another important class of oligosaccharides are *galactans* [31], particularly galacto-oligosaccharides (GOS) [44]. While GOS occur naturally in dairy products, cosmetic-grade GOS are typically produced via the enzymatic conversion of milk-derived sugars, offering improvements in consistency and controlled scalability [46,47]. Although a growing number of novel oligosaccharides are emerging within cosmetic research, many remain insufficiently validated for widespread use [31]. Polysaccharides, despite their larger molecular size, can also exhibit prebiotic activity when appropriately processed. Colloidal oat is one of the most well-established examples, containing β-glucans and oligosaccharide fractions that selectively promote *S. epidermidis* growth while enhancing lactic acid production [43]. Lactic acid plays a crucial role in maintaining the acidic pH of the skin [43], thereby supporting microbiome balance [44]. More recently, blackcurrant-derived polysaccharides have demonstrated potential prebiotic effects by supporting commensal bacteria and inhibiting pathogenic species [48].

3.3. Formulation Considerations and Cosmetic Application of Prebiotics

Although prebiotic carbohydrates occur naturally, their direct application in raw form is impractical due to the presence of unwanted co-extracted components [48], limited natural availability, molecular complexity, and inconsistent performance [46,47]. Consequently, cosmetic prebiotics undergo controlled extraction and refinement to ensure safety, efficacy, and reproducibility.

Oligosaccharides such as FOS are commonly produced via hot water extraction of inulin, followed by inulinase-mediated hydrolysis to reduce chain length and improve microbial accessibility [44]. Alternatively, enzymatic synthesis from sucrose enables efficient industrial-scale production [44]. For polysaccharides, enzyme-assisted extraction (EAE) using pectinases and glycosidases produces smaller, more bioavailable oligosaccharide fractions that may enhance interaction with skin microbiota [48]. Enzymatically treated blackcurrant extracts, for example, exhibit increased prebiotic potential compared to unprocessed material due to the breakdown of rigid plant cell walls [48].

Prebiotics are particularly attractive for cosmetic formulation because they are chemically stable, non-reactive, and non-viable, making them compatible with a wide range of active ingredients and preservative systems [49]. Studies evaluating prebiotic diffusion in hydrogels and oil-in-water (O/W) emulsions have demonstrated excellent topical stability, with efficient delivery to the skin surface and minimal penetration into deeper skin layers [47]. This diffusion profile is attributed to the high molecular weight and hydrophilic nature of GOS, which limits transepidermal penetration while promoting localisation within the stratum corneum. Such surface-restricted diffusion is advantageous for cosmetic applications, as prebiotics are intended to selectively support the skin microbiome rather than penetrate viable epidermal layers [47]. Although prebiotics do not require viability preservation, formulators must still consider vehicle selection, skin contact time, and delivery efficiency [47]. Advanced strategies such as nanotechnology may further enhance performance by achieving targeted delivery and prebiotic interaction with the skin microbiome [40].

4. Probiotics: Competitive Exclusion and Skin Barrier Support

4.1. Mechanisms of Microbial Competition and Immune Modulation

Probiotics used in cosmetic products most commonly belong to the genera *Lactobacillus* and *Bifidobacterium* [50–52]. These microorganisms may be incorporated as live bacteria, although they are more frequently included as ferments or lysates due to formulation challenges (Figure 3) [53]. Probiotics contribute to skin health primarily through the competitive exclusion of pathogenic microorganisms and the modulation of inflammatory pathways (Figure 3) [54].

Skin disorders such as acne, atopic dermatitis, and psoriasis are associated with microbial imbalance or the overgrowth of pathogenic species including *C. acnes*, *S. aureus*, and *Streptococcus* spp., as presented in Figure 1 [24]. When applied topically, probiotics compete with harmful bacteria for adhesion sites and nutrients, thereby limiting pathogen colonisation [55,56]. Additionally, probiotics release bacteriocins and antimicrobial peptides, which support skin barrier recovery and immune regulation [50,57].

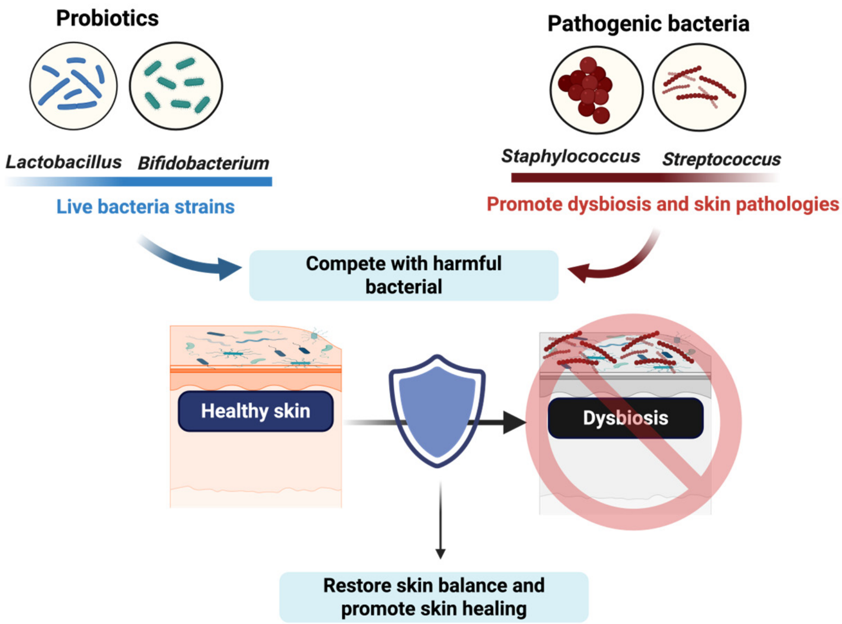

Figure 3. Topical probiotics in cosmetic formulations for skin microbiome modulation. Schematic representation of live beneficial microorganisms (e.g., *Lactobacillus* and *Bifidobacterium* species), as well as probiotic-derived ferments and lysates, incorporated into cosmetic products and applied to the skin. These ingredients compete with pathogenic bacteria, help limit dysbiosis, and support skin barrier integrity, contributing to the maintenance of healthy skin and the promotion of skin recovery. Created in BioRender. Borrello, M. (2026) https://BioRender.com/6b5r6tv.

Although numerous patents and experimental studies exist, the precise molecular mechanisms underlying probiotic–host interactions remain an active area of research, as seen in filed patents (EP3362038A1 [58] and WO2020056359 [59]).

Most of the research conducted so far has been applied to the context of the gut; however, studies that are more specific to the skin can benefit the industry moving forward. Furthermore, probiotic activity is highly strain-specific, hence more robust research is required to clarify these effects to substantiate the benefits of probiotics in cosmetic applications.

4.2. Stability Challenges and Delivery Strategies in Cosmetic Formulation

The incorporation of live probiotic bacteria into cosmetic formulations presents significant challenges related to viability, moisture sensitivity, and preservative compatibility. As a result, formulation strategies are essential to maintain stability and efficacy throughout product shelf-life [60]. Common preservation techniques include freeze-drying (lyophilisation), microencapsulation [53], and oil-based delivery systems [61].

Freeze-drying involves freezing bacterial cells followed by sublimation under reduced pressure, producing a dry and stable material [62]. However, freeze-drying alone does not fully protect probiotics from moisture- or preservative-induced degradation. To enhance protection, microencapsulation is frequently employed. This technique encloses probiotic cells within a polymeric shell, allowing controlled release and shielding bacteria from formulation stressors [63].

Alginate is a commonly used encapsulation material due to its biocompatibility and ability to preserve bacterial viability [64]. Alginate casings have been shown to improve the loading capacity and survival of cells [65]. Studies have been conducted in the context of the gut; however, this concept can be reapplied to the context of topical cosmetics, as the pH of the gut is much lower than that of the skin [65], which gives an alginate matrix a greater advantage to protect the viable probiotics under less acidic conditions. Despite the proven efficacy of alginate matrices, formulation challenges can still exist if the formulation contains chelating agents. Chelating agents can disrupt the gel network [66]; thus, if an alginate network is used as an encapsulation material, a balance of ingredients in the formulation is needed. In addition to polysaccharide-based matrices such as alginate, other encapsulation approaches, such as lipid-based vesicles [67,68] and chitosan-coated particles [69,70], have been explored in oral and pharmaceutical probiotic delivery systems. Despite promising encapsulation strategies, conclusive evidence demonstrating their ability to maintain viable probiotic counts within topical cosmetic matrices remains scarce, given that most investigations have focused on postbiotic preparations [67–69] rather than live bacterial systems or focused mainly on the gastrointestinal tract [70]. Further investigation is necessary to determine their stability during cosmetic storage and usage conditions, especially in the presence of conventional preservative systems.

Oil-based delivery systems provide an alternative approach by maintaining low water activity and preventing premature bacterial activation. A 2021 study evaluated the stability of a commercial-freeze dried probiotic blend comprising *Lactobacillus rhamnosus* (LRC-14) and *Lactobacillus reuteri* (LGR-1) when suspended in various anhydrous lipid carriers, including petroleum jelly, mineral oil, coconut oil, and olive oil. The powdered probiotic served as a control [71]. Viability was assessed over a six-month period using colony-forming unit (CFU) enumeration and the results showed that petroleum jelly and mineral oil retained significantly higher proportions of viable bacteria compared with the powdered control for up to five months. This suggests that low water activity, hydrophobic systems may reduce premature metabolic activation and degradation [71]. However, this study focused on vaginal applications, and there was an absence of conventional cosmetic ingredients such as emulsifiers and preservatives. While these findings provide a proof of concept for anhydrous lipid systems as potential carriers for viable probiotics, further investigation is required to determine stability within topical cosmetic formulations.

Hybrid strategies combining freeze-drying with encapsulation or oil-based systems represent promising avenues for optimising probiotic stability and efficacy in cosmetic formulations [72].

5. Postbiotics: Bioactive Metabolites for Barrier Repair and Immune Balance

5.1. Nature and Functional Diversity of Postbiotics and Molecular Mechanisms Underpinning Skin Barrier Repair and Anti-Inflammatory Effects

Postbiotics comprise non-viable microbial cells, cell fragments, or bioactive metabolites derived from probiotic microorganisms [73]. Common postbiotics used in cosmetic formulations include fermentation filtrates (e.g., *Galactomyces*, *Saccharomyces*, *Bifida*), bacterial lysates, exopolysaccharides (EPS), organic acids, peptides, and short-chain fatty acids (Table 1). Their non-living nature offers significant advantages in terms of stability, safety, and regulatory compliance, making postbiotics particularly attractive for cosmetic applications.

Postbiotics contribute to skin homeostasis by strengthening the epidermal barrier, regulating inflammation, and supporting microbiome balance (Figures 4 and 5) [83].

Studies demonstrate that postbiotics enhance barrier integrity by upregulating tight junction proteins such as occludin, claudin-1, and zonula occludens-1 through the activation of the Phosphatidylinositol 3-kinase/Protein Kinase B (PI3K/Akt) signalling pathway, leading to reduced transepidermal water loss (TEWL) and improved elasticity [83]. The literature has acknowledged the strong association of the PI3K/Akt pathway with epidermal tissue formation via keratinocyte proliferation and differentiation; the pathway involves the phosphorylation of the HspB1 (Hsp27) protein, facilitating the synthesis of filaggrin from profilaggrin, a crucial protein for stratum corneum formation [84]. In atopic dermatitis, where claudin-1 expression is compromised, postbiotic treatment has been shown to restore tight junction integrity and reduce inflammation [85,86]. Extracts derived from *Aquaphilus dolomiae* (*A. dolomiae*), a bacterium endemic to the Avène thermal springs [87], have demonstrated barrier repair, antimicrobial activity, and enhanced epidermal regeneration in clinical studies involving over 1300 participants [82]. In 2020, a study investigating the repairing properties of *A. dolomite* extract was conducted in vitro and ex vivo on injured human skin models [88]. From this, the extract increased the re-epithelialisation of the ex vivo injured human skin model, whereby the thickness of the newly formed epidermis was measured using an Axiophot II microscope at 10x magnification and Improvision Openlab 5.0.2 software. In vitro results from this study showed significant proliferation of normal human dermal fibroblasts [88].

Table 1. Types of postbiotics and their functions. Cosmetic formulations can contain a range of non-living products derived from microorganisms, several of which have been shown to have beneficial effects on the skin.

Postbiotic Type	Example	Main Benefit
Lysates	*Lactobacillus* lysate	Barrier repair, soothing [74]
Ferments	*Galactomyces* ferment filtrate, *Saccharomyces* ferment	Enhanced elasticity, hydration [75,76]
Metabolites	SCFAs, peptides	Anti-inflammatory [77,78]
Cell wall fragments	Peptidoglycan fractions	Immunomodulation [79,80]
EPS	Bacterial polysaccharides	Moisturising [81]
Paraprobiotics	Heat-killed *Lactobacillus*	Microbiome-friendly, calming [81]
Organic acids	Lactic acid	Exfoliation, pH balance [82]
Bacterial extracts	*Bifida* extract	Soothing [83]

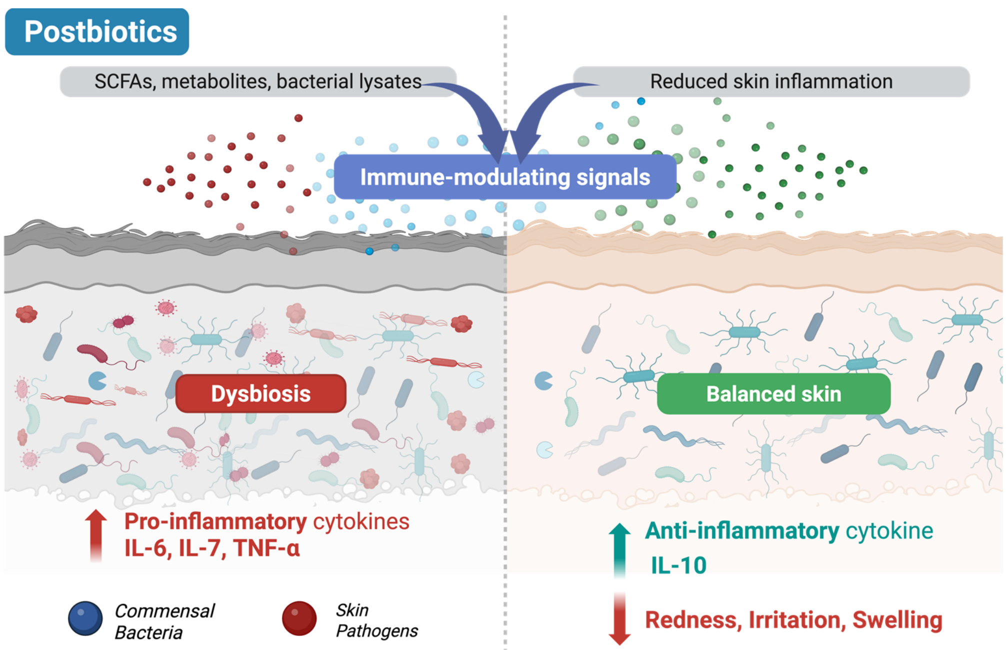

Figure 4. Postbiotics in cosmetic formulations for modulation of skin inflammation and microbiome balance. Schematic representation of postbiotics, including short-chain fatty acids (SCFAs), microbial metabolites, and bacterial lysates, incorporated into topical cosmetic products. These bioactive components deliver immune-modulating signals that help counteract dysbiosis, reduce pro-inflammatory cytokine expression, promote anti-inflammatory responses, and contribute to a more balanced, resilient skin state with reduced visible signs of irritation. Created in BioRender. Borrello, M. (2026) https://BioRender.com/qrqkxwe.

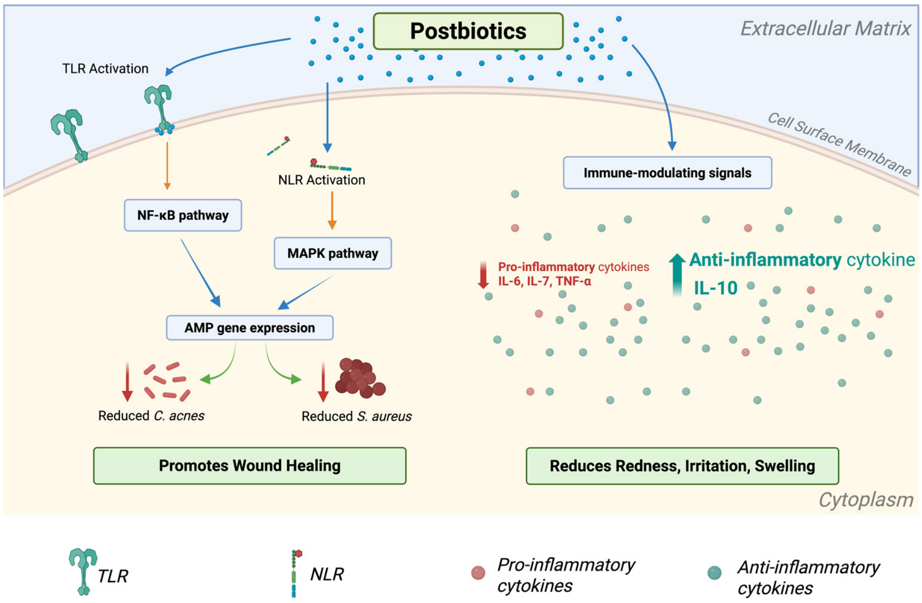

Figure 5. Postbiotics mechanism of action. Postbiotics modulate skin immune responses by activating TLR and NLR signalling pathways, leading to NF-κB and MAPK activation and increased antimicrobial peptide (AMP) expression. This results in reduced C. acnes and S. aureus colonisation and promotes wound healing. Postbiotics also suppress pro-inflammatory cytokines (IL-6, IL-7, TNF-α) while enhancing anti-inflammatory IL-10, thereby reducing skin inflammation, redness, and irritation. Created in BioRender Borrello, M. (2026) https://BioRender.com/to7ve58.

Additionally, postbiotics stimulate the production of antimicrobial peptides such as β-defensin-2, RNASE7, and cathelicidin LL-37, all of which provide rapid broad-spectrum defence [89]. Pattern Recognition Receptors (PRRs) such as toll-like receptors (TLRs) and NOD-like receptors (NLRs), found on the surface of postbiotic and intracellular membranes respectively, detect postbiotic content and are activated (Figure 5). The activation of these receptors triggers the nuclear factor-kappa B (NF- κB) and mitogen-activated protein kinase (MAPK) signalling pathways [75]. These pathways ultimately lead to the expression of gene coding to produce AMPs [90]. These mechanisms enhance resistance to *C. acnes* and *S. aureus* while supporting wound healing.

Postbiotics further modulate immune responses by downregulating pro-inflammatory cytokines (IL-6, IL-17, TNF-α) and upregulating anti-inflammatory IL-10, thereby reducing redness (erythema), irritation, and swelling (oedema), while maintaining immune balance [91–93] (Figure 4).

5.2. Production, Inactivation, and Formulation of Postbiotics

Postbiotic production involves controlled microbial fermentation, followed by downstream processing to isolate bioactive components. Selected microbial strains are cultured in bioreactors under tightly regulated conditions, with scale-up achieved using anaerobic stirred-tank reactors to optimise biomass yield [94].

Downstream processing typically includes centrifugation and filtration to separate biomass from cell-free supernatants, or cell lysis using physical, chemical, or enzymatic methods to release intracellular and cell wall-derived compounds [94]. Target metabolites are extracted using organic solvents such as ethanol or ethyl acetate, followed by homogenisation and standardisation to ensure reproducibility and regulatory compliance [95]. For cosmetic application, postbiotics may undergo thermal or non-thermal inactivation, with heating at 80–121 °C for 10–30 min effectively eliminating microbial viability while preserving bioactivity [96].

Prior to and following inactivation, the quantification of postbiotics is performed to allow characterisation and confirm non-viability and reproducibility. Flow cytometry is often employed for quantifying inanimate cell count and distinguishing live, damaged, and dead cells, commonly measured as Total Fluorescent Units (TFUs) [97]. They are commonly incorporated into gels, creams, films, and ointments, demonstrating enhanced barrier repair and wound healing in vivo [98,99]. This is important for staying within the definitions of the term "postbiotic" according to the ISAPP.

To protect sensitive metabolites from degradation caused by oxidation, pH fluctuations, or light exposure, encapsulation systems such as liposomes or nano-vesicles are increasingly employed [99]. Liposomal gel formulations, which consist of liposomes and a gel matrix, have demonstrated controlled release and improved in vitro antimicrobial efficacy [100]. Postbiotics obtained from the fermentation of *Lactobacillus acidophilus* (*L. acidophilus*), LGR-1, *Bifidobacterium animalis* (*B. animalis*), and *Streptococcus thermophilus* were applied to determine their antimicrobial activity, particularly against pathogenic bacteria *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Escherichia coli* (*E. coli*), *Enterococcus hirae*, and *Candida albicans* [100]. Agar disc diffusion experiments revealed positive inhibition zone diameters (mm) of lipogelosomal postbiotics to non-encapsulated postbiotic lysates counterparts, with a notable increase in antimicrobial effect on *E. coli* strains [100]. No significant decrease in the diameter of the inhibition zones was observed. The microdilution method was performed to quantify the minimum inhibitory concentration (MIC) values of the lipogelosomal postbiotics and the postbiotics lysates; the MIC values of all lipogelosomal bacteria were lower compared to the non-encapsulated postbiotics, with S. aureus and E. coli experiencing the most significant decrease in MIC values of 7.0% and 10.0% respectively. This highlights encapsulation as a key strategy for maximising postbiotic performance [101,102].

6. Challenges in Incorporating Biotics in the Cosmetic Industry

6.1. Definition Ambiguity

The absence of specific regulations and clearly defined terminology for biotics within the cosmetic industry has significant implications for product development, marketing, and consumer understanding. A summary of the current definitions is reported in Table 2.

Table 2. Definition of each classification of biotic based on the ISAPP definitions for prebiotics, probiotics, and postbiotics.

Biotic Classification	Definition
Prebiotic	A substrate that is selectively utilised by host microorganisms and confers a health benefit [38].
Probiotic	Live microorganisms which, when administered in adequate amounts, confer a health benefit on the host [31].
Postbiotic	A preparation of inanimate microorganisms and/or their components that confers health benefits on the host [39].

The definitions provided by the ISAPP are primarily applicable to the gut microbiome and nutricosmetics [103]. To date, an equivalent framework for topical skin biotics has not been formally established [103]. Although there is growing evidence supporting the beneficial effects of biotics on the skin microbiome, the absence of skin-specific guidance contributes to inconsistent terminology and ambiguity in cosmetic labelling [104–110].

Within the cosmetic industry, many products are promoted as "microbiome-friendly" or as having "prebiotic effects" (see Table 3 for examples of commercially available products) [49]. While some formulations genuinely incorporate true prebiotics that meet the established criteria, others leverage the broader concept of microbiome modulation without fulfilling the definition of a prebiotic [31]. For example, a study investigating the enzyme-assisted extraction (EAE) of blackcurrant demonstrated favourable shifts in the skin microbial balance and described the ingredient as exhibiting prebiotic potential [48]. However, the study did not assess the selective microbial utilisation of the extracted carbohydrate fractions as nutrient substrates. In the absence of mechanistic evidence demonstrating the selective utilisation, such effects cannot be accurately classified as prebiotic activity [31]. Similarly, the definition of probiotics specifies that they must be live microorganisms [38]. However, many cosmetic products marketed as probiotic-containing formulations include non-viable bacterial derivatives [53], such as ferments or lysates, which are more accurately categorised as postbiotics as these are dead microorganisms [39]. The term "postbiotic" itself has been inconsistently defined across the literature, where it may refer to heat-inactivated microbes, cell extracts, cell-free supernatants, or isolated microbial metabolites individually [39]. This broad and overlapping usage leads to over-generalisation and presents challenges in cosmetic legislation and claim substantiation [53,107]. The lack of clear differentiation between probiotic and postbiotic ingredients can mislead consumers and complicate regulatory oversight, particularly when evaluating product claims.

Table 3. Examples of commercially marketed cosmetic products containing prebiotics, probiotics and postbiotic strains and their classification according to the ISAPP definition.

Product Name	**Marketed Biotic Active**	**Marketed as**	**Biotic Classification Based on ISAPP Definition**
Aveeno Dermexa Daily Emollient Cream [105]	*Avena sativa* (oat) kernel extract, *Avena sativa* (oat) kernel oil, *Avena sativa* (oat) kernel oil.	Prebiotic	Prebiotic
La Roche-Posay Toleriane Sensitive Skin Moisturiser [106]	La Roche-Posay thermal spring water.	Prebiotic	N/A
Biossance Squalane + Probiotic Gel Moisturiser [107]	*Lactobacillus* ferment.	Probiotic	Postbiotic
Haruharu Wonder Black Rice Probiotics Barrier Essence [108]	*Galactomyces* Ferment Filtrate, *Bifida* Ferment Filtrate, *Aspergillus* Ferment, *Oryza sativa* (rice) Lees extract.	Probiotic	Prebiotic and Postbiotic
Lancôme Advanced Génifique Youth Activating Serum [109]	*Bifida* Ferment Lysate *Lactobacillus*, *Faex* Extract/Yeast Extract, *Polymnia sonchifolia* Root Juice, Alpha-glucan Oligosaccharide, Mannose.	Prebiotic and Probiotic	Postbiotic
Avène XeraCalm Lipid-replenishing Cleansing oil [110]	I-modulia®, obtained from *A. dolomiae* fractions.	Postbiotic	Postbiotic

Despite inconsistent terminology, several widely marketed products incorporate ingredients that function as prebiotics, probiotics, and postbiotics (Table 3). Many cosmetic products marketed as "probiotic" formulations contain non-viable ferments or lysates which align more closely with the ISAPP definition of postbiotics rather than true probiotics.

6.2. Regulatory Gaps

Prebiotics and postbiotics are non-viable substances so there are no specific biological regulations detailing their use in cosmetic products [111–113]. In contrast, probiotics consist of live microorganisms, which introduce greater regulatory complexity [103] (see Figure 6 for a summary on the regulatory status of biotics (probiotics and related biotic ingredients) in cosmetic products across different jurisdictions).

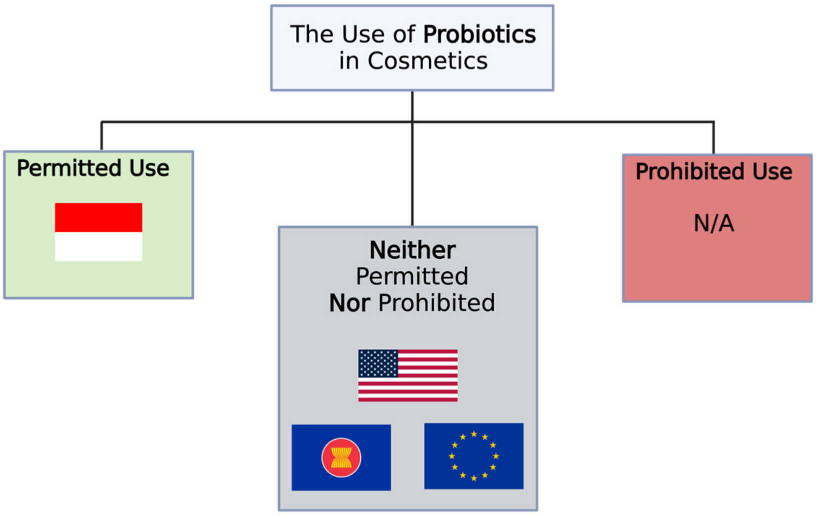

Figure 6. Regulatory status of biotics (probiotics and related biotic ingredients) in cosmetic products across different jurisdictions. The diagram illustrates regions where the use of biotics in cosmetics is permitted (e.g., Indonesia), neither permitted nor prohibited (e.g., United States, European Union, and ASEAN countries), and prohibited, for which no specific examples are currently identified. Regulatory interpretation varies by region and is influenced by local definitions, safety requirements, and product classification. Created in BioRender. Borello, M. (2026) https://BioRender.com/7j4goup.

Under the EU Cosmetic Regulation (EC) No. 1223/2009, biotics are regulated primarily in terms of consumer safety rather than biological activity [114]. Article 2 defines a cosmetic product as "any substance or mixture intended to be placed in contact with the external parts of the human body with a view exclusively or mainly to cleaning them, perfuming them, changing their appearance, protecting them, keeping them in good condition or correcting body odours" [114]. There is no specific section addressing biotic ingredients or defining formulation boundaries for cosmetics containing live microorganisms. Consequently, cosmetic products incorporating biotic technologies may still be classified as cosmetics, provided they meet the general definition. In the United States, there are currently no regulations specifically governing the use of biotics in cosmetics, nor are probiotic ingredients included in the list of prohibited or restricted cosmetic substances. However, as per ISO 17516:2014, microbiological safety regulations exist to control contamination, stipulating limits of 1×10^2 CFU/g for eye-area products and 1×10^3 CFU/g for non-eye-area products [115,116]. However, these limits were established to address unintended microbial contamination and do not account for the intentional inclusion of live probiotics intended to confer skin benefits. For products containing live bacteria to be launched, the Cosmetic Product Safety Report (CPSR) must document the viable CFU/g count to comply with the ISO standard. Hence, companies must ensure that the CFU/g of the finished product is under the limit, regardless of whether the final viable count includes contaminants or beneficial bacteria.

In ASEAN countries, regulations regarding probiotics are primarily focused on food, health supplements, and nutricosmetics. While no ASEAN member state explicitly regulates probiotics in cosmetics, countries such as Indonesia, Malaysia, the Philippines, and Thailand have established frameworks for probiotics in related sectors [117]. In Indonesia, the National Agency of Food and Drug Control, Badan Pengawasan Obat dan Makanan (BPOM), previously regulated probiotics in cosmetics under BPOM Regulation No. 23 Year 2019, which limited live probiotic counts to 1000 CFU/g or mL for general cosmetic products and 500 CFU/g or mL for paediatric cosmetics. This regulation was revised in October 2025 (BPOM Regulation No. 17 Year 2025) to oversee probiotics in food and health supplements, excluding cosmetics [118]. As a result, the earlier regulation remains the primary reference for probiotic use in cosmetics, highlighting the need for regulatory revision. These inconsistencies underscore the challenges of establishing a harmonised regulatory framework for biotics within ASEAN, not to mention at an international level. Although ASEAN ministers signed a harmonised cosmetic regulatory scheme in 2003 [119], the framework does not address probiotics or CFU limits in finished cosmetic products, indicating the need for updated legislation [117,119,120]. The lack of regulatory clarity contributes to overgeneralisation in labelling and marketing, potentially misleading consumers and limiting informed decision-making.

6.3. Limitations of Clinical Studies

Several studies suggest that topical prebiotics, probiotics, and postbiotics may improve skin barrier function and help address a range of skin concerns. However, many of these studies are limited by small sample sizes, short study durations, and an emphasis on laboratory-based endpoints rather than real-world clinical outcomes [83]. For instance, a 2023 study employed ex vivo and in vitro models to investigate the effects of live bacteria on *Acne vulgaris*, using human skin samples to assess bacterial growth, tissue viability, and metabolic activity over a three-week period [121]. Similarly, a 2020 randomised, double-blind, placebo-controlled clinical trial evaluated a serum containing galacto-oligosaccharides (GOS) in 60 healthy adult participants [122]. While informative, such small-scale studies may overestimate effect sizes due to limited population heterogeneity, thereby increasing the margin of error. Consequently, findings from these studies should be interpreted with caution, considering variability in skin type, age, and ethnicity.

Some larger-scale studies have also been conducted. For example, a 2024 study involving 1317 participants, including infants, children, and adults, evaluated the effects of a cream containing *A. dolomiae* extract [83]. The study reported promising outcomes in minor wound healing, with participants indicating high tolerability (98.5%) and high user satisfaction for instant relief from symptoms such as perioral dermatitis, non-oozing diaper rash, and superficial wounds and burns. These findings suggest that postbiotic extracts may provide noticeable beneficial effects on the skin. Nevertheless, the intervention period was limited to three weeks, which restricts conclusions regarding long-term efficacy [83]. Furthermore, the results of the study were derived from a consumer acceptance questionnaire. To further substantiate the claims of postbiotic benefits, researchers can include objective and measurable outcomes such as skin hydration and TEWL values [82]. While controlled clinical studies provide valuable preliminary data, their findings should be complemented by investigations conducted under realistic, at-home usage conditions. Consequently, the ability to substantiate cosmetic claims and draw robust conclusions remains limited, highlighting the need for larger, more diverse, and reproducible clinical trials. In addition, more detailed reporting of test methods and participant characteristics would facilitate future validation by other researchers.

Developing our understanding of postbiotics may also be limited by the conflict between commercial and scientific interests. This was recently demonstrated by a study to determine the antimicrobial effects of novel lipogelosomal postbiotics without detailing the postbiotic components used in their formulation [101]. Such practice underscores the need to balance progressing our understanding of biotics with economic incentives and the need for the protection of trade secrets.

6.4. Barriers to Stable and Effective Formulations

For cosmetic products containing prebiotics, probiotics, and postbiotics, formulation challenges are largely similar to regular cosmetic products on the market which must adhere to EU cosmetic safety regulations [114]. This includes physicochemical stability (pH, temperature), compatibility, and preservative system selection for prebiotics, postbiotics and encapsulated probiotic formulations [123].

Postbiotics pose an additional challenge due to recent findings which indicate that cosmetic production processes such as fermentation and downstream processing can influence preservative requirements. A 2024 study reported that postbiotic and fermented vegetable extracts may retain preservative residues following fermentation [124]. Quantifying these residues is essential, as they can impact the additional preservative systems required in the final formulation and must remain within regulatory limits [114,115].

In contrast, formulations containing live probiotics present significant challenges. Traditional preservatives may reduce probiotic viability, adversely affecting product efficacy and shelf-life [125]. For example, conventional preservative systems have been shown to decrease the CFU/mL of *Propionibacterium acnes* in topical formulations [125]. Advanced approaches such as lipid microencapsulation have been explored to maintain probiotic viability, but these techniques increase formulation complexity due to additional viability tests required [126,127].

The extraction, preparation, and incorporation of probiotic strains suitable for cosmetic use require careful control of viability, stability, and safety. Techniques such as freeze-drying, encapsulation, and oil-based delivery systems are viable options but demand precise environmental conditions [53]. Live bacterial strains are highly sensitive to pH changes that could occur during manufacturing, temperature fluctuations that could occur during transport and storage, and exposure to moisture that could be introduced during consumer use and storage [53]. These sensitivities present additional challenges during scale-up, as observed in nutricosmetic manufacturing, where productivity is limited by high costs, stringent conditions, and specialised training requirements [128]. Similar barriers apply to the cosmetic industry.

7. Future of Biotics in the Cosmetic Industry

The general probiotic market was valued at USD 87.70 billion in 2023 [129]. In 2024, the global dietary probiotic supplement market size was estimated at USD 9.71 billion [130]. The current forecast predicts an increase in this market to USD 14.72 billion by 2030 [130]. Within this broader context, microbiome-focused cosmetic formulations represent a rapidly emerging sub-sector. From an industry perspective, global market analysts estimate that the skin microbiome cosmetics sector was valued at approximately USD 435 million in 2024 and is projected to expand at a compound growth rate of ~12% to reach over USD 830 million by 2030 [131], reflecting growing investment and market interest in microbiome-focused formulations. This rapid growth suggests expanding demand, consumer knowledge, and awareness, which present various business opportunities, including in cosmetics. Sustainability practices, such as the use of biodegradable ingredients, incorporating green chemistry methodologies and ethical bacterial sourcing, solidify the continuation of biotic usage in cosmetics. Moreover, there is potential in further cosmetic biotic research and development based on current contemporary procedures in the industry, the available market statistics and clinical findings, and widespread perception.

7.1. Need for Standardised Certification Criteria

Third-party certification plays a critical role in substantiating cosmetic claims related to biotics. Currently, MyMicrobiome [132] is the only organisation offering certification for "microbiome-friendly" claims [49,132]. However, this certification does not specifically address products containing true biotics. The development of standardised certification criteria tailored to biotic-based cosmetic formulations would enhance transparency, reinforce consumer trust, and support accurate claim substantiation.

7.2. AI-Customised Skincare via Microbiome Sequencing

As the cosmetic market becomes increasingly saturated, demand for personalised skincare continues to grow. Next-generation sequencing (NGS) enables detailed profiling of the skin microbiome by providing culture-independent identification and relative quantification of microbial taxa based on their DNA sequencing, facilitating the identification of dysbiotic patterns associated with specific skin disorders [133]. Databases such as the Probiotics Database (PBDB) and the Probiotic Strains Database provide extensive genomic libraries that could support personalised skincare strategies [134,135]. However, selecting the most appropriate strains for specific skin concerns remains challenging. Artificial intelligence (AI) offers a potential solution by enabling the analysis and integration of large-scale microbiome and omics datasets [136].

Omics technologies are a group of analytical approaches used to comprehensively study biological systems at the molecular level. In skin microbiome research, these methods generate extensive molecular data by capturing information on microbial DNA (genomics), gene activity (transcriptomics), and small molecules produced during metabolism (metabolomics) [136]. Collectively, these approaches result in high-dimensional and highly interconnected datasets of thousands of genes, transcripts, and metabolites, which cannot be reliably interpreted using manual analytical approaches [136]. Multi-omics is an approach which combines multiple omics technologies to provide a more holistic understanding of probiotic properties [136]. AI models such as machine learning could be trained on these datasets to help accelerate microorganism classification and predict interactions between cosmetic ingredients and the skin microbiome, paving the way for the development of personalised skincare formulations [136]. This enables formulators to develop and tailor future cosmetic products according to individual microbiome profiles rather than conventional skin-type classifications. Such microbiome-informed personalisation has the potential to improve product efficacy and long-term skin health [136]. However, further validation and standardisation will be required to translate sequencing-driven insights into robust cosmetic formulations.

7.3. Unlocking Synergy Through Synbiotics

Synbiotics combine prebiotics and probiotics to produce synergistic benefits for the host. ISAPP defines synbiotics as "a mixture comprising live microorganisms and substrate(s) selectively utilised by host microorganisms that confers a health benefit on the host" [137]. Complementary synbiotics deliver independent benefits, while synergistic synbiotics function cooperatively. Preliminary skincare studies suggest that synbiotic formulations can modulate microbial balance, enhance barrier function, and reduce pathogenic bacteria [138,139]. Prebiotics may also improve probiotic survival within formulations by supporting microbial stability, potentially offering greater microbiome modulation than probiotics alone [139]. Further large-scale studies are required to substantiate these findings and develop robust, efficacious synbiotic cosmetic products.

7.4. Sustainability

7.4.1. Biodegradable Ingredients and Formulations

A key player of the ever-growing sustainability movement in cosmetics is ingredient waste reduction. Several approaches have been considered to formulate cosmetics with biodegradable excipients. Chitosan, a non-toxic polymer derived from chitin found in the shells of crustaceans, exhibited an enhanced performance in *L. casei* microencapsulation, while providing a breathable, moisture-retaining occlusive agent on the skin [60].

However, the broad-spectrum antimicrobial properties of chitosan must be considered for formulators to maintain the microbial viability of the encapsulated strains [140]. Tapioca starch showed a synergistical performance alongside alginate in providing structural matrix integrity and thermal stability of *Lacticaseibacillus rhamnosus GG-*, *Lacticaseibacillus casei-*, and *Lactiplantibacillus plantarum*-loaded microspheres [141]. Although this practice is currently performed in the food and supplement industry, it could be applied in the cosmetic industry to produce more stable and biocompatible microspheres. Similarly, pectin, the polysaccharide that makes up the cell walls of citrus fruits [142], showed the matrix stability of *L. acidophilus*- and *B. animalis*-loaded sodium alginate hydrogels, as well as microbiota degradation [143,144].

7.4.2. Green Chemistry Approaches

Sustainability has become a central focus within the cosmetic industry. A 2021 study demonstrated efficient postbiotic production through fermentation using cheese whey and alternative substrates such as milk permeate and lignocellulosic biomass [145]. These renewable feedstocks reduce raw material costs and minimise waste, supporting environmentally conscious postbiotic production and aligning with sustainable cosmetic innovation. Alginite, a mineral-rich volcanic soil containing extinct unicellular algae [146], displayed several skin benefits when incorporated during the fermentation process of five *Lactobacilli* (LAB) strains, including *Lactobacillus rhamnosus*, *L. acidophilus*, *Limosilactobacillus reuteri*, and *Lactococcus lactis*, and a non-LAB probiotic strain *Bifidobacterium adolescentis* [147,148]. The alginite findings showed promising figures of increased skin moisturisation, but a decrease in antioxidant activity. Interestingly, when fermented alongside alginite, LGR-1 and *B. adolescentis* exhibited negative tyrosinase activity values of around 94% and 135% respectively, indicating a skin tanning effect. The supplementation of deposit-rich and naturally occurring biomass in probiotic fermentation provides the potential for greener ingredient sourcing for skin tanning cosmetics.

7.4.3. Sustainable Sourcing of Biotics

Companies such as Silab Saint-Viance, France, BASF Personal Care Monheim am Rhein, Germany, and Ultra Chemical Inc. Red Bank, New Jersey, USA have successfully created patents for plant-based biotics [149,150].

LACTOBIOTYL®, created by Silab France and composed of Maltodextrin and *Lactobacillus arizonensis* postbiotic ferment, is achieved by the bioguided fermentation of the *lactobacillus* strain and jojoba-derived substrates [149]. As the fermentation process mimics the environment of jojoba, it comes with strong claims for tackling dry skin.

BIOLIN/P, a natural prebiotic created by French biotechnology company Sweetech, utilises inulin and alpha-glucan oligosaccharides extracted from the fermentation of chicory root to selectively support skin commensal bacteria [150].

Relipidium® from BASF is described as a yeast extract modified by yeast biotechnology that helps restore the skin barrier and rebalance the skin's microbiome [151,152]. It is obtained by fermenting a yeast substrate with *L. plantarum*. Mechanistically, it stimulates the synthesis of epidermal lipids such as ceramides and cholesterol, speeds up barrier recovery, reduces TEWL, and supports a healthier balance between beneficial bacteria like *S. epidermidis* and pathogenic *S. aureus*, improving hydration and comfort over about two weeks of use [153]. Phytofirm®, sold as Phytofirm Biotic by BASF, is derived from soybean extract that has been fermented with the bacterium *L. plantarum* to mimic the performance of probiotics on the skin [154]. The fermentation turns non-GMO, traceable European soy into a liquid rich in peptides and lactic acid, which has been shown extensively in the literature to boost collagen I and V and elastin production [155,156].

8. Conclusions

Overall, the growing understanding of the skin–gut microbiome axis presents significant opportunities for incorporating biotics into cosmetic products (see Figure 7 for a summary). However, challenges related to definition ambiguity, regulatory gaps, clinical evidence limitations, and formulation stability currently restrict broader application. Addressing these issues through harmonised regulations, improved clinical validation, and technological innovation, as seen in Figure 7, will enable the development of substantiated, personalised, and sustainable biotic-based cosmetic solutions.

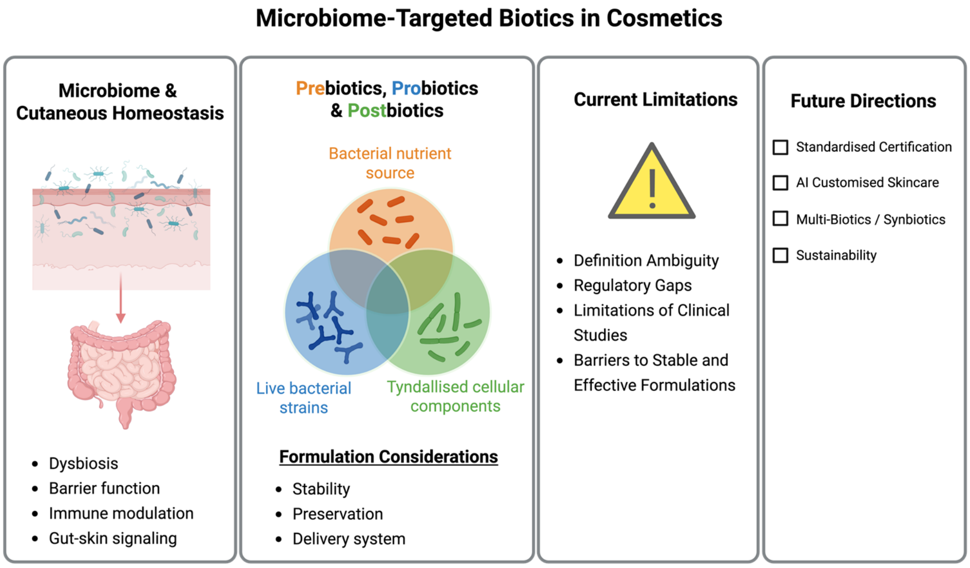

Figure 7. Skin microbiome-targeted cosmetic strategies: current concepts, challenges, and future directions. Overview of the role of the skin microbiome in cutaneous homeostasis, highlighting the impact of dysbiosis on barrier function, immune modulation, and gut–skin signalling. Microbiome-targeted cosmetic approaches include prebiotics, probiotics, and postbiotics, which each have key formulation considerations. Current limitations in this field, together with emerging future directions are outlined. Created in BioRender. Borrello, M. (2026) https://BioRender.com/ciijm9i.

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Abbreviations

The following abbreviations are used in this manuscript:

A. dolomiae	*Aquaphilus dolomiae*
AMPs	antimicrobial peptides
BPOM	Badan Pengawasan Obat dan Makanan
C. acnes	*Cutibacterium acnes*
CFU	colony-forming unit
CPSR	cosmetic product safety report
E. coli	*Escherichia coli*
EAE	enzyme-assisted extraction
EPS	exopolysaccharides
FAO	Food and Agriculture Organization of the United Nations
FOS	fructo-oligosaccharides
Gas6	growth arrest-specific protein 6
GOS	galacto-oligosaccharides
GSA	gut–skin axis
ISAPP	International Scientific Association for Probiotics and Prebiotics
LGR-1	*Lactobacillus reuteri*
LRC-14	*Lactobacillus rhamnosus*
MAPK	mitogen-activated protein kinase
MGP	matrix Gla protein
NF-κB	nuclear factor kappa B
NGS	next-generation sequencing
NLRs	NOD-like receptors
O/W	oil-in-water
PBDB	probiotics database
PI3K/Akt	Phosphatidylinositol 3-kinase/Protein Kinase B
PRRs	pattern recognition receptors
ROS	reactive oxygen species
S. aureus	*Staphylococcus aureus*
S. epidermidis	*Staphylococcus epidermidis*
SCFAs	short-chain fatty acids
TEWL	transepidermal water loss
TFU	total fluorescent unit
TLRs	toll-like receptors
VDR	vitamin D receptor
WHO	World Health Organization

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