

## Review Article



# Microbiome-Based Interventions for Skin Aging and Barrier Function: A Comprehensive Review

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## ABSTRACT

The skin microbiome, a dynamic ecosystem of microorganisms, is essential for maintaining skin health by protecting against pathogens, modulating immunity, and enhancing barrier function. External factors such as pollutants, harsh skincare products, and aging disrupt microbial balance, leading to compromised skin health and accelerated aging. Aging-related changes, including reduced microbial diversity, loss of beneficial metabolites, and increased oxidative stress, contribute to inflammaging. Microbiome-supportive skincare, incorporating probiotics, prebiotics, and postbiotics, offers promising solutions to restore microbial balance, strengthen the skin barrier, and delay aging. These formulations work by reducing inflammation, enhancing antioxidant defenses, and regulating skin pH. However, challenges in microbiome research and product development persist, including individual variability in microbial composition, formulation complexities, and a limited understanding of microbe-skin interactions. Future innovations such as personalized microbiome skincare, genetically engineered probiotics, and advanced diagnostic tools could enable more targeted and effective interventions. Long-term clinical trials and detailed mechanistic studies are crucial to validate the efficacy of microbiome-focused skincare and optimize formulations for diverse populations. By addressing these challenges and advancing research, microbiome-supportive skincare has the potential to revolutionize approaches to skin health, preserving resilience and combating aging through tailored microbial interventions.

**Keywords:** Barrier; Prebiotics; Probiotics; Skin aging; Skin microbiome

## INTRODUCTION

The skin microbiome, a diverse community of bacteria, fungi, and viruses, plays a pivotal role in maintaining the health and function of the skin. This complex ecosystem exists in a delicate balance, contributing to a protective barrier that defends against pathogens, regulates immune responses, and supports skin homeostasis<sup>1</sup>. The diversity of the microbiome varies across different skin sites, and its composition is influenced by numerous factors, including genetics, environment, age, and lifestyle choices<sup>2,3</sup>. Emerging

research has shown that disruptions in the microbiome, often termed dysbiosis, can compromise skin health, leading to various dermatological conditions, including eczema, acne, and psoriasis. Furthermore, these persistent dysbiosis and skin conditions are closely related to mental health conditions such as anxiety and depression<sup>4</sup>.

The skin barrier, primarily composed of the stratum corneum, serves as the first line of defense against external damage. This barrier function is largely maintained by a matrix of lipids, proteins, and natural moisturizing factors that prevent transepidermal

water loss (TEWL) and protect the skin from environmental aggressors. A healthy microbiome supports this barrier by promoting the production of ceramides and antimicrobial peptides (AMPs), both of which are crucial for maintaining skin integrity. When the skin microbiome is balanced, it regulates the skin's pH, mitigates oxidative stress, and promotes repair mechanisms essential for barrier maintenance<sup>5,6</sup>.

As skin ages, both the barrier function and the microbiome undergo significant changes. The natural decline in skin lipids, combined with reduced cellular turnover, compromises the skin's ability to retain moisture, leading to dryness, wrinkles, and increased susceptibility to external damage. This weakening of the skin barrier is exacerbated by age-related shifts in the microbiome, characterized by reduced microbial diversity and increased colonization by potentially pathogenic species<sup>7,8</sup>. The resulting dysbiosis can drive chronic, low-grade inflammation, often referred to as "inflammaging," which further accelerates the aging process and contributes to skin barrier dysfunction<sup>9</sup>.

Microbiome-supportive skincare, which includes the use of prebiotics, probiotics, and postbiotics, offers a promising approach to combat these effects. By fostering a healthy microbial environment, these products aim to restore the skin's natural defenses, enhance barrier function, and potentially delay the visible signs of aging. Recent studies have demonstrated that probiotic formulations can improve skin hydration, reduce TEWL, and alleviate signs of inflammation, suggesting that microbiome-targeted therapies may play a key role in maintaining youthful, resilient skin<sup>10,11</sup>.

These findings underscore the growing recognition of the skin microbiome's pivotal role in dermatology, particularly in maintaining skin barrier function, mitigating aging-related changes, and addressing inflammation-driven conditions. This review aims to synthesize current knowledge on microbiome-friendly skincare approaches, exploring their mechanisms, benefits, and potential for innovation in promoting skin health and resilience.

## THE SKIN MICROBIOME AND ITS RELATIONSHIP WITH SKIN HEALTH

### Composition of the skin microbiome

The skin microbiome is a multifaceted and dynamic ecosystem composed of bacteria, fungi, viruses, and mites that reside on the skin's surface. These microorganisms collectively influence skin physiology and act as a protective shield against environmental insults. The primary bacterial genera include *Staphylococcus*, *Corynebacterium*, *Cutibacterium*, and *Micrococcus*, while fungi such as *Malassezia* dominate the skin mycobiome. Viruses, including bacteriophages, and mites like *Demodex*, also form part of this complex community.

### Roles of the skin microbiome in health

#### 1) Protection against pathogens

Commensal bacteria, such as *Staphylococcus epidermidis*, produce AMPs, including phenol-soluble modulins, that inhibit the colonization and growth of pathogenic organisms like *Staphylococcus aureus* and *Streptococcus pyogenes*. The microbiome also exerts its protective effects through competitive exclusion, whereby commensals outcompete pathogens for nutrients and adhesion sites, thereby preventing dysbiosis<sup>12,13</sup>.

#### 2) Modulation of inflammation

The microbiome interacts with immune cells, such as Langerhans cells and keratinocytes, to regulate inflammatory responses. For instance, *Cutibacterium acnes* modulates Toll-like receptor 2 signaling, which can mitigate inflammation and prevent the onset of chronic conditions like acne vulgaris. Additionally, specific strains of *S. epidermidis* produce lipoteichoic acid, which has been shown to suppress TLR3-mediated inflammation, thereby promoting skin homeostasis<sup>14,15</sup>.

#### 3) Immune defense

The microbiome supports the skin's immune barrier by enhancing the production of immunoglobulins, particularly immunoglobulin A, and modulating cytokine signaling pathways. *S. epidermidis*-derived AMPs and metabolites, such as short-chain fatty acids (SCFAs), help strengthen the epidermal barrier by stimulating the expression of filaggrin and ceramide production. These metabolites also act as signaling molecules, influencing the differentiation of regulatory T-cells and balancing pro- and anti-inflammatory cytokines, crucial for maintaining immune homeostasis<sup>16,17</sup>.

#### 4) Barrier function enhancement

SCFAs, produced by microbes like *Cutibacterium* and *Staphylococcus*, play a crucial role in maintaining the acid mantle of the skin, which prevents pathogen colonization. These metabolites also regulate keratinocyte differentiation and lipid synthesis, which are essential for maintaining skin hydration and integrity<sup>11,18</sup>.

These intricate interactions between the skin microbiome, immune system, and skin barrier highlight the pivotal role of a balanced microbiota in maintaining skin health and protecting against dermatological diseases. Integrating microbiome-targeted therapies, such as probiotics, prebiotics, and postbiotics, into skincare regimens offers promising avenues for enhancing skin resilience and mitigating inflammation-driven conditions.

### Disruption of the microbiome

Several external and internal factors can disturb the skin microbiome, leading to compromised skin health and barrier function.

### 1) Pollutants and environmental stressors

Environmental pollutants, such as particulate matter 2.5, heavy metals, and ultraviolet (UV) radiation, can induce oxidative stress, leading to an imbalance in the skin microbiome. These stressors disrupt microbial diversity by fostering the growth of pro-inflammatory and pathogenic species while reducing commensal populations<sup>19</sup>. Oxidative stress from pollutants not only accelerates skin aging but also impairs the skin barrier by damaging keratinocytes and altering lipid composition. For instance, studies have shown that long-term exposure to urban pollution increases the colonization of *Cutibacterium* species and alters the skin's immune response<sup>20</sup>. The research by Boonpethkaew et al.<sup>21</sup> demonstrates that exposure to high levels of air pollution reduces microbial diversity, disrupts beneficial microbiome correlations with skin barrier parameters, and promotes the overgrowth of pathogenic microorganisms, thereby impairing skin barrier integrity. For instance, *Streptococcus parasanguinis*, enriched in less polluted environments, was associated with lower skin pH and higher stratum corneum hydration. In contrast, *Malassezia* spp. and *Aureobasidium* spp., prevalent in polluted areas, correlated with increased TEWL and reduced hydration, respectively.

### 2) Aging

Aging profoundly affects the skin microbiome, characterized by reduced microbial diversity and increased colonization by opportunistic pathogens such as *S. aureus*. This shift is often accompanied by a decline in sebum production and lipid content, essential components for maintaining microbial balance and barrier integrity. Furthermore, aging exacerbates inflammaging—a state of chronic, low-grade inflammation driven by microbial dysbiosis. This state contributes to barrier dysfunction, increased TEWL, and a heightened risk of inflammatory skin conditions<sup>7,22</sup>. The relationship between skin aging, microbial dysbiosis, and its effects on barrier function and inflammaging will be discussed in greater depth in subsequent sections of this review.

### 3) Harsh skincare products

The frequent use of skincare products with high pH, strong surfactants, or preservatives can disturb the skin's natural balance by stripping away protective oils and altering the microbial community. For example, soaps and cleansers with an alkaline pH can increase TEWL and disrupt the acid mantle, allowing harmful species like *S. aureus* to proliferate while depleting beneficial bacteria such as *S. epidermidis*. Similarly, some preservatives used in cosmetics can inhibit the growth of commensal bacteria, further compromising the skin's microbial equilibrium<sup>23,24</sup>.

## SKIN AGING AND THE MICROBIOME

### Aging-related changes in the microbiome

As the skin ages, the composition and functionality of its microbiome undergo significant alterations, which detrimentally affect its barrier function and overall health. Aging is typically accompanied by follows.

#### 1) Reduced microbial diversity

Studies highlight a decline in beneficial commensals such as *C. acnes* and *S. epidermidis*, while pathogenic species like *S. aureus* gain dominance. This microbial imbalance compromises skin health, diminishing its ability to fend off pathogens and environmental insults<sup>3,25</sup>.

#### 2) Decreased sebum production

Aged skin produces less sebum, reducing the availability of lipids required to sustain a diverse microbiome. This lipid deficiency hinders microbial metabolism and promotes dryness<sup>26,27</sup>.

#### 3) Reduced hydration and epidermal thinning

Aging-associated dehydration and a thinner epidermis reduce the hospitable environment for commensal bacteria, further limiting their abundance and protective roles<sup>3,7</sup>.

#### 4) Loss of microbial metabolites

Beneficial byproducts such as SCFAs, known for fortifying the skin barrier and modulating immune responses, are diminished, leading to higher TEWL and weaker defenses<sup>28,29</sup>.

These cumulative changes render aged skin more prone to conditions such as dryness, sensitivity, eczema, and rosacea. For instance, the reduced diversity and functionality of the microbiome in aged skin correlate with a compromised barrier function and an increase in pro-inflammatory states<sup>30,31</sup>.

### Dysbiosis & inflammaging

The concept of "inflammaging" describes the chronic, low-grade inflammation associated with aging, which drives tissue degeneration, including in the skin. Dysbiosis of the microbiome plays a crucial role in perpetuating this condition.

#### 1) Pathogenic colonization

Pathogenic species such as *S. aureus* and *Corynebacterium striatum* release toxins and inflammatory signals, stimulating a sustained immune response<sup>32</sup>.

#### 2) Cytokine activation

Cytokine dysregulation is believed to play a key role in the remodeling of the immune system at older age, with evidence pointing to

an inability to fine-control systemic inflammation, which seems to be a marker of unsuccessful aging. Pro-inflammatory cytokines like interleukin-1 $\beta$  and tumor necrosis factor- $\alpha$  are upregulated, while pattern recognition receptors (e.g., Toll-like receptors) are excessively activated, amplifying inflammatory pathways<sup>33</sup>. Inflammaging has been linked with increased levels of systemic cytokines, exacerbated by the imbalance in gut microbiota, and can affect not only metabolic and neurological diseases but also cardiovascular and autoimmune conditions<sup>34</sup>.

### 3) Structural protein degradation

Chronic inflammation plays a critical role in the degradation of structural proteins like collagen and elastin, both of which are key components of the skin's extracellular matrix (ECM). This degradation can lead to diminished skin elasticity, wrinkle formation, and impaired wound healing<sup>35</sup>. Specific microbial species can trigger inflammatory pathways, leading to increased production of matrix metalloproteinases (MMPs) that break down collagen and elastin. Studies indicate that the imbalance in microbial populations enhances the activation of immune cells and inflammatory cytokines, which subsequently accelerate ECM degradation<sup>18,36</sup>.

This feedback loop between inflammation and dysbiosis exacerbates skin aging by thinning the dermis, impairing the stratum corneum, and accelerating visible signs of aging.

### Microbiome and oxidative stress

Oxidative stress is a hallmark of the aging process and is heavily influenced by the state of the skin microbiome. For example, studies have shown that microbial imbalances in aged skin increase pro-oxidative enzymes, heightening the susceptibility of the skin to hyperpigmentation, fine lines, and loss of elasticity<sup>22,37</sup>. Dysbiosis fosters the proliferation of pathogenic microbes that generate reactive oxygen species (ROS). Excess ROS overwhelms the skin's antioxidant defenses, damaging lipids, proteins, and DNA<sup>34</sup>. On the other hand, the microbiome also plays a role in reducing oxidative stress. Harel et al.<sup>38</sup> identified two bacterial families, *Sphingomonas* and *Erythrobacteraceae*, as potentially protective against UV radiation. These bacteria produce compounds that may shield the skin from solar damage. Further investigation of *Sphingomonas* strain demonstrated its impressive resistance to UV irradiation and its ability to reduce ROS levels in human keratinocytes. These findings suggest that the skin microbiome plays a crucial role in protecting against the harmful effects of UV

exposure, opening new possibilities for microbial-based skin protection strategies<sup>37</sup>. Andersson et al.<sup>39</sup> identified a protein, RoxP, secreted by *C. acnes*, which possesses strong antioxidant properties. This protein plays a key role in modulating oxidative stress both on the skin and within human cells. In vitro and in vivo experiments showed that RoxP enhances the viability of monocytes and keratinocytes exposed to oxidative stress, suggesting its protective role in maintaining skin health. Additionally, a reduction in RoxP levels was observed in skin affected by oxidative diseases like actinic keratosis and basal cell carcinoma. This decline in RoxP correlated with microbial dysbiosis, specifically a reduced prevalence of *C. acnes*, underscoring the potential of RoxP as a biopharmaceutical candidate for managing oxidative skin damage. These findings emphasize the contribution of skin microbiota, particularly *C. acnes*, in protecting the skin from oxidative stress.

Understanding the relationship between the microbiome, inflammaging, and oxidative stress is crucial for developing targeted skincare strategies that support microbial balance and reinforce the skin's natural defenses. By incorporating microbiome-supportive ingredients that promote beneficial bacteria and reduce dysbiosis, it is possible to mitigate these aging-related changes and preserve skin health and resilience<sup>40,41</sup>.

## MICROBIOME-SUPPORTIVE SKINCARE PRODUCTS

### Probiotics, prebiotics, and postbiotics in skincare

Microbiome-supportive skincare focuses on maintaining a balanced skin microbiota by incorporating probiotics, prebiotics, and postbiotics (Table 1).

#### 1) Probiotics

These are live microorganisms, typically bacteria, that can provide health benefits when applied topically. In skincare, probiotics such as *Lactobacillus* and *Bifidobacterium* species help to reinforce the skin's natural defenses by promoting the growth of beneficial microbes, inhibiting pathogenic bacteria, and modulating the skin's immune response<sup>42</sup>. Emerging evidence highlights the therapeutic potential of probiotics in managing a spectrum of dermatological conditions, including acne vulgaris<sup>43</sup>, atopic dermatitis, eczema<sup>44</sup>, and psoriasis<sup>45</sup>. By restoring dysbiosis within the skin microbiome and attenuating pro-inflammatory

**Table 1.** Key benefits from microbiome-supportive skin care ingredients

| Category    | Examples                                      | Mechanism                                                       | Skin benefits                               |
|-------------|-----------------------------------------------|-----------------------------------------------------------------|---------------------------------------------|
| Probiotics  | <i>Lactobacillus</i> , <i>Bifidobacterium</i> | Balances skin microbiota, prevents pathogen colonization        | Improves hydration, reduces acne            |
| Prebiotics  | Inulin, fructooligosaccharides                | Fuels beneficial microbes, enhances microbiome diversity        | Supports barrier function                   |
| Postbiotics | Lactic acid, peptides                         | Provides antimicrobial peptides, improves microbial environment | Promotes skin renewal, soothes inflammation |
| Ferments    | Rice ferment, kombucha                        | Delivers bioactive compounds, enhances skin elasticity          | Brightens skin, reduces signs of aging      |

pathways, probiotic interventions provide a biologically inspired, non-invasive strategy for improving clinical outcomes. Their role in modulating host-microbial interactions underscores a promising avenue for advancing holistic and sustainable treatments for cutaneous disorders<sup>46,47</sup>.

## 2) Prebiotics

Prebiotics are non-digestible ingredients that serve as food for beneficial bacteria, promoting their growth and activity on the skin. Ingredients like inulin, alpha-glucan oligosaccharide, and certain plant extracts are commonly used as prebiotics in skincare. By nourishing the skin's commensal bacteria, prebiotics help maintain microbial diversity, protect against harmful organisms, and support a healthy skin barrier<sup>48-51</sup>.

## 3) Postbiotics

Postbiotics are the metabolic byproducts or compounds produced by probiotics during fermentation. These include substances like SCFAs, peptides, enzymes, and bacteriocins, which can have direct benefits for skin health. Postbiotics can help regulate skin pH, enhance moisture retention, and exert anti-inflammatory and antioxidant effects, supporting the skin's resilience and reducing signs of aging<sup>42,51</sup>.

## 4) Ferments

Fermentation is a biological process that utilizes microorganisms such as bacteria and yeast to break down organic materials into simpler compounds. In skincare, this process transforms ingredients into smaller, more bioavailable molecules, enhancing their absorption and efficacy. Fermented ingredients are rich in beneficial compounds like amino acids, antioxidants, and vitamins, which can improve skin health by strengthening the skin barrier, enhancing hydration, and providing anti-inflammatory effects<sup>52</sup>.

Recent clinical studies and product developments have demonstrated the tangible benefits of microbiome-based skincare interventions targeting skin aging and barrier function<sup>53</sup>. For example, a randomized, double-blind, placebo-controlled trial involving *Lactobacillus plantarum*, *Lactobacillus reuteri*, and *Lactobacillus rhamnosus* strains in combination with topical ectoin showed significant improvements in skin hydration, elasticity, and wrinkle reduction. Another study on fermented lysates (VHProbi® Mix R) containing *Lactocaseibacillus rhamnosus* and *Lactobacillus paracasei* also reported enhanced skin barrier function and reduced TEWL following topical application<sup>54</sup>. Furthermore, topical postbiotic formulations, such as *Lactiplantibacillus plantarum* LB244R®, have been clinically validated to improve skin elasticity and reduce visible signs of aging<sup>55</sup>.

In the commercial domain, several products have translated this science into accessible skincare solutions. TULA Skincare

incorporates probiotic and prebiotic extracts across its product line, including hydrating creams and cleansers. Gallinée offers a youth serum that combines probiotics, prebiotics, and postbiotics to support skin microbiota and improve radiance. Similarly, Bliss's Mighty Biome™ collection features moisturizers and serums fortified with prebiotics and postbiotics, marketed to enhance the skin's natural barrier. These developments illustrate the growing evidence base and practical applications of microbiome-based skincare in dermatology.

## Mechanisms of action

Microbiome-supportive skincare products support skin health through several mechanisms that help restore microbial balance, improve barrier function, and delay the aging process (Table 2).

### 1) Restoring microbial balance

By introducing beneficial microbes (probiotics) or feeding existing beneficial species (prebiotics), microbiome-supportive products help to re-establish a balanced skin microbiota. This balance is crucial for preventing overgrowth of pathogenic bacteria that can cause inflammation, infection, and skin conditions like acne, eczema, and rosacea<sup>42,56</sup>.

### 2) Promoting a healthy skin barrier

A balanced microbiome plays a critical role in maintaining a strong stratum corneum, which serves as the skin's first line of defense. Microbiome-friendly products enhance barrier function by promoting the production of essential lipids like ceramides. Ceramides are a key component of the skin barrier, helping to retain moisture and protect against external aggressors. By supporting ceramide production, these products help reduce TEWL and improve skin hydration and elasticity. For example, the commensal bacteria *S. epidermidis* has been found to promote ceramide production by secreting the enzyme sphingomyelinase, which aids in ceramide synthesis. In contrast, pathogenic bacteria like *S. aureus* can degrade ceramides, contributing to a weakened skin barrier and disorders such as eczema and acne<sup>49,57</sup>.

### 3) Reducing inflammation

Probiotic and postbiotic compounds play a significant role in reducing skin inflammation by interacting with the skin's innate immune system. These compounds help regulate the immune response, inhibiting the release of pro-inflammatory cytokines and promoting the production of anti-inflammatory molecules. This action is particularly beneficial in managing chronic skin conditions like eczema, rosacea, and acne, which are often exacerbated by inflammation. Research shows that postbiotics, especially SCFAs like butyrate, can help reduce levels of pro-inflammatory cytokines, alleviating skin redness, swelling, and

**Table 2.** Mechanisms of microbiome-supportive skincare products in enhancing skin health

| Mechanism of action              | Description                                                                                                                                                                                                                                                                                                   | References |
|----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Restoring microbial balance      | Microbiome-friendly products introduce beneficial microbes (probiotics) or feed existing beneficial species (prebiotics) to restore a balanced skin microbiota. This balance prevents overgrowth of pathogenic bacteria that cause inflammation, infection, and conditions such as acne, eczema, and rosacea. | 42, 47     |
| Promoting a healthy skin barrier | A balanced microbiome supports the production of essential lipids like ceramides, which strengthen the stratum corneum. This improves barrier function by reducing TEWL, enhancing moisture retention, and boosting skin elasticity.                                                                          | 44, 48     |
| Reducing inflammation            | Probiotics and postbiotics modulate immune responses, reducing the release of pro-inflammatory cytokines and promoting anti-inflammatory molecules. This lowers chronic inflammation, improving conditions like eczema and rosacea, while preventing skin aging.                                              | 45, 49,50  |
| Antioxidant effects              | Postbiotics such as SCFAs and peptides possess antioxidant properties that neutralize ROS. By reducing oxidative stress, they prevent collagen degradation, protein oxidation, and lipid peroxidation, which contribute to wrinkles, sagging, and pigmentation.                                               | 42, 51     |
| Skin pH regulation               | Postbiotics help maintain the skin's slightly acidic pH, which is crucial for microbial balance and skin barrier integrity. The acidic environment prevents pathogenic bacterial growth and supports enzymes involved in skin renewal and repair processes.                                                   | 29, 42, 46 |

TEWL: transepidermal water loss, SCFA: short-chain fatty acid, ROS: reactive oxygen species.

irritation<sup>58</sup>. Additionally, studies indicate that probiotics and their metabolites can enhance the skin barrier, reducing inflammation and improving conditions like eczema and acne<sup>50,59</sup>.

#### 4) Antioxidant effects

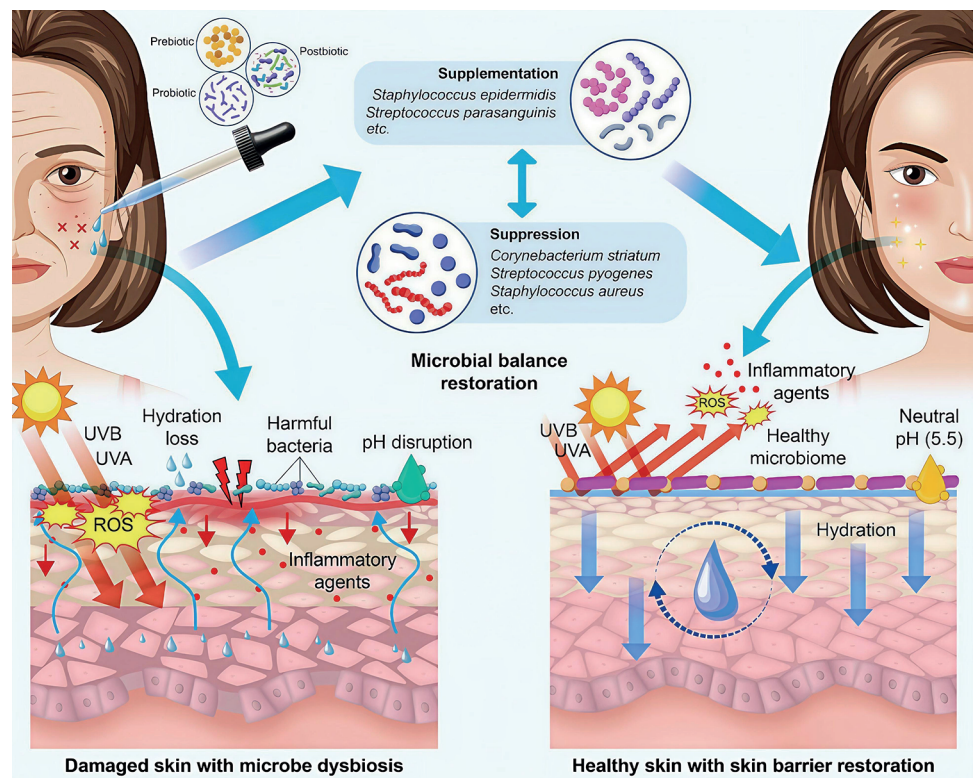
Postbiotics such as SCFAs and peptides produced by beneficial microbes exhibit antioxidant properties that help neutralize ROS. By reducing oxidative stress, these products prevent collagen degradation, protein oxidation, and lipid peroxidation, all of which contribute to visible signs of aging such as wrinkles, sagging, and pigmentation<sup>42</sup>. The study by Lee et al.<sup>60</sup> investigated the protective effects of the postbiotic *Levilactobacillus brevis* BK3, derived from fermented Kimchi, against oxidative damage in skin cells. The postbiotic demonstrated significant antioxidant activity, as evidenced by its ability to neutralize ROS and enhance the expression of key antioxidant enzymes, such as superoxide dismutase, catalase, and glutathione peroxidase. Additionally, BK3 was shown to regulate collagen-related proteins, including MMP-1 and collagen type I alpha 1, which are involved in collagen degradation and synthesis.

#### 5) Skin pH regulation

Many postbiotics help to maintain the slightly acidic pH of the skin, which is essential for microbial balance and barrier integrity. This acidic environment discourages

the growth of pathogenic bacteria and supports the activity of enzymes involved in skin renewal and repair processes<sup>29,42,51</sup>.

In summary, microbiome-supportive skincare products offer a promising approach to maintaining skin health, reinforcing the skin barrier, and combating the signs of aging. By leveraging the benefits of probiotics, prebiotics, and postbiotics, these formulations create a more supportive environment for the skin's natural microbiome, helping to delay aging and improve overall skin resilience (**Fig. 1**).

**Fig. 1.** Microbiome skincare workflow.

UVB: ultraviolet B, UVA: ultraviolet A, ROS: reactive oxygen species.

## CHALLENGES AND FUTURE DIRECTIONS

### Challenges in microbiome research and skincare development

Despite the growing interest in microbiome-supportive skincare, several challenges remain in advancing this field. First, one of the major difficulties lies in isolating and characterizing the vast number of microbial species that live on the skin. Many of these species are difficult to culture in laboratory settings, limiting our understanding of their precise roles in skin health. Additionally, the complex interactions between different microbes and how they collectively influence skin function remain largely underexplored, making it difficult to determine which specific species are most crucial for maintaining a balanced and healthy microbiome<sup>61</sup>. Second, individual variability in the skin microbiome poses another challenge. The composition of the microbiome differs significantly among people due to factors such as age, genetics, environment, lifestyle, and even geographical location. This variability complicates the development of universal microbiome-friendly skincare products, as what may benefit one person's microbiome might not work for another. Personalized skincare solutions, though promising, are still in their early stages<sup>3,62-64</sup>. Lastly, there are significant formulation challenges. Many preservatives and chemical ingredients in conventional cosmetics can negatively affect the skin microbiota, leading to imbalances. Creating formulations that are stable, safe, and effective while supporting the growth of beneficial microbes is technically difficult. Moreover, ensuring the viability of live probiotics in these formulations adds another layer of complexity for manufacturers<sup>65,66</sup>.

### Innovations in skincare

Looking to the future, several innovations have the potential to transform microbiome-supportive skincare.

#### 1) Personalized microbiome skincare

With the advent of new technologies such as next-generation sequencing, personalized skincare solutions tailored to an individual's unique skin microbiome could soon become a reality. These personalized approaches would allow for targeted interventions to restore microbial balance based on the specific needs of an individual's skin microbiota. Skincare companies could analyze users' skin microbiome profiles and design products that promote the growth of beneficial microbes while minimizing harmful species<sup>67,68</sup>.

#### 2) Genetic-based microbiome interventions

Advances in microbiome research and genetic engineering could lead to the development of genetically modified probiotics specifically designed to enhance skin barrier function or combat

pathogenic species. These engineered microbes could be incorporated into skincare formulations to provide more precise and effective interventions for skin health and aging<sup>69,70</sup>.

#### 3) New microbiome testing methods

Emerging diagnostic tools, such as at-home microbiome testing kits, could allow consumers to monitor the state of their skin microbiome over time. This data could be used to optimize skincare routines and adjust product formulations based on changes in microbial composition, environmental factors, and lifestyle habits. These innovations would not only empower consumers but also provide researchers with valuable data for further improving microbiome-friendly skincare products<sup>62</sup>.

### Future research directions

While microbiome-supportive skincare shows significant potential, more research is required to fully understand its long-term benefits and mechanisms. Most current studies are short-term, offering limited insights into how these products affect skin aging over extended periods. To establish stronger evidence for their efficacy, long-term, placebo-controlled clinical trials are necessary to evaluate sustained improvements in skin barrier function, microbial balance, and visible signs of aging. A notable limitation in current research is the lack of definitive evidence clarifying whether alterations in the skin microbiome act as a causal factor or are merely a consequence of skin aging and barrier dysfunction. While correlations between dysbiosis and these dermatological changes are well-documented, mechanistic studies demonstrating causality remain limited. Future research should aim to delineate the directionality of this relationship through longitudinal studies and controlled experimental models. Additionally, more detailed mechanistic studies are needed to clarify how probiotics, prebiotics, and postbiotics interact with the skin microbiota and immune system on a molecular level. Such research would aid in optimizing formulations for specific skin conditions and aging processes. Lastly, the link between the skin microbiome and aging, particularly in relation to inflammaging and oxidative stress, remains underexplored. Future studies should focus on how microbial imbalances evolve with age and how restoring a healthy microbiome can prevent or reverse these aging-related changes. Ultimately, further research and innovation are essential to overcoming current challenges and maximizing the potential of microbiome-friendly skincare in preserving skin health and delaying aging.

## CONCLUSIONS

In conclusion, the skin microbiome plays a critical role in maintaining the integrity of the skin barrier and preventing premature

aging by modulating immune responses, reducing inflammation, and supporting healthy microbial balance. Microbiome-supportive skincare, incorporating probiotics, prebiotics, and postbiotics, offers a promising, non-invasive approach to preserving skin health, promoting hydration, and mitigating oxidative stress—key factors in delaying the visible signs of aging. As our understanding of the skin microbiome continues to evolve, further research is essential to optimize these products and fully realize their potential as preventative tools in anti-aging skincare.

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### CONFLICTS OF INTEREST

The authors have nothing to disclose.

### DATA SHARING STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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