

# pH-Optimized Formulation Design: Bridging Dermatological Physiology And Topical Innovation.

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## ABSTRACT

The pH of skincare products plays a pivotal role in maintaining skin barrier function, microbiome balance, and overall skin health. Although its importance is well established, pH remains an under-integrated parameter in topical formulation design. This review explores the role of skin surface pH in supporting barrier integrity and introduces a conceptual design framework for developing pH-optimized skincare products aligned with the skin's physiological pH range (4.1–5.8). Key formulation considerations, including ingredient compatibility, buffering systems, preservatives, and packaging, are addressed within this framework. By integrating pH as a core design principle, this approach bridges formulation science with skin biology and clinical relevance.

**Keywords:** Acid mantle; Skin surface pH; pH-optimized formulation; Skin microbiome; Topical formulation; Transepidermal water loss; Personalized skincare..

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## INTRODUCTION

The skin surface maintains a mildly acidic environment, commonly referred to as the acid mantle, with pH values typically ranging from 4.1 to 5.8, influenced by the anatomical site, ethnicity, age, and environmental exposure [1–4]. This surface acidity plays a critical role in skin health by supporting key biological functions, including barrier homeostasis, lipid processing, epidermal cohesion, and microbial regulation [3,5,6]. Although the concept of the acid mantle was first introduced nearly a century ago, its dermatological significance has gained broader recognition in recent decades, driven by advances in skin biology and microbiome science [3,6]. The acid mantle is now understood as a dynamic biochemical interface that modulates enzyme activity, innate immunity, and microbial colonization [3,4,6,7].

While intrinsic physiology determines the baseline pH, topical products play a decisive role in modifying it. Many soaps and cleansers are formulated at neutral or alkaline pH levels due to surfactant chemistry, preservative compatibility, or consumer lather expectations [8]. Repeated use of products formulated outside the skin's physiological pH range can disrupt the acid mantle, increase transepidermal water loss (TEWL), and foster microbial dysbiosis [9–11]. Formulations designed to acidify the skin have shown promise in restoring pH balance and microbial resilience, particularly in sensitive and disease-prone skin. For instance, lactic acid-based products formulated between pH 3.7 and 4.0 have been reported to improve hydration and

accelerate barrier recovery, reinforcing the functional benefits of acidic formulations [12].

Despite growing evidence, pH remains largely absent from product labeling and formulation design standards. Unlike SPF, which benefits from standardized testing protocols and clear on-pack labeling, product pH is rarely disclosed and lacks regulatory oversight, leaving consumers vulnerable to product formulations that disrupt the skin's physiological balance [10,13]. In response, this review introduces a conceptual framework rooted in dermatological physiology and formulation science to guide the design of skincare products that preserve skin-compatible pH through ingredient selection, effective buffering, and packaging strategies. It also highlights the research gaps and scientific opportunities to support the next generation of pH-optimized formulation design.

## Skin Physiology and the Acid Mantle

The stratum corneum (SC), the outermost layer of the epidermis, is composed of flattened corneocytes embedded in a lipid matrix rich in ceramides, free fatty acids, and cholesterol [4,6,14]. This layered structure functions as the skin's primary barrier, regulating TEWL, shielding against environmental insults, and modulating microbial colonization, thereby supporting both biochemical defense and skin renewal [3,15,16].

Under normal physiological conditions, the skin maintains a surface pH of approximately 4.1–5.8, with more acidic values in sebaceous-rich regions (e.g., forehead, upper back) and more alkaline values in moist, occluded, or friction-prone areas (e.g., axillae, groin, palms) [3,17]. Skin

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surface pH also varies across physiological states, shifting in neonates, older adults, and disease-prone skin [17,18]. For example, aging skin tends to shift toward a more alkaline pH due to reduced sebum production, which can impair barrier function and increase susceptibility to irritation [1,3,6]. In newborns, the skin is near-neutral (~7.0) at birth and acidifies gradually over the first few weeks. These physiological and pathological variations are summarized in Table 1.

The acid mantle is now understood as a mildly acidic buffer system localized primarily within the stratum corneum, with evidence suggesting it is concentrated in the middle SC layers [3,19]. Skin surface acidity is thought to result from a combination of endogenous and exogenous acidifying mechanisms. Endogenous contributors include keratinocyte-driven processes such as filaggrin breakdown, proton extrusion via NHE1, and lipid metabolism, while exogenous influences include sebaceous and sweat gland secretions as well as microbial metabolism [3,4,19].

A vertical pH gradient also exists through the stratum corneum, increasing toward near-neutral values in the viable epidermis and dermis [3,19]. This gradient enables the compartmentalized activity of enzymes necessary for

lipid processing and skin renewal. Key enzymes, such as acid sphingomyelinase and  $\beta$ -glucocerebrosidase, which catalyze the formation of barrier-reinforcing ceramides, require an acidic environment for optimal functioning. A shift in skin pH toward neutrality diminishes their activity, leading to impaired lipid organization, reduced hydration, and weakened barrier integrity [20,21,22]. Simultaneously, an elevated pH leads to the overactivation of serine proteases, such as kallikrein-5 and -7, which can disrupt corneocyte cohesion and amplify inflammatory cascades. These imbalances are implicated in conditions such as atopic dermatitis, where elevated pH correlates with both barrier dysfunction and microbial dysbiosis [12].

Furthermore, the acid mantle plays a key role in influencing the composition of the skin microbiome by favoring the proliferation of acid-tolerant commensals while inhibiting opportunistic pathogens. This pH-dependent microbial selectivity supports barrier integrity and immune balance [23–25]. Disruption of the acid mantle raises the skin surface pH. Such shifts in pH have been associated with delayed barrier recovery, increased TEWL, microbial imbalance, and inflammatory skin disorders, linking pH modulation to skin pathophysiology [4,12]

**Table 1: Physiological and pathological variations influencing skin pH**

Observed Skin pH Range (approx.)	Factor	Biochemical and Barrier Impacts	Associated Clinical Outcomes	Reference
<i>Intrinsic Factors</i>				
7.08 → ~5.7 at birth	Neonatal physiology	↑ Serine proteases; ↓ $\beta$ -glucocerebrosidase sphingomyelinase	Delayed barrier development; risk of diaper dermatitis, eczema	[12,18,25]
>6 in elderly	Aging	↑ Alkaline ceramidase → ↓ ceramides	Impaired barrier; increased dryness	[26]
4.1–5.8 (optimal)	Normal physiology	Optimal for $\beta$ -glucocerebrosidase, sphingomyelinase	Maintains barrier and microbial balance	[3,27]
>6 in axillae, groin, palms	Anatomical site variation	↑ Microbial colonization in moist, occluded areas	Higher risk of irritation, infection	[28]
4.6 vs 5.0	Pigmentation differences	↓ Serine protease activity in darker skin	Stronger barrier in darker phototypes	[29]
6–6.5	Acne-prone condition	Elevated pH supports <i>C. acnes</i> growth and inflammation	Exacerbation of acne lesions	[30]
>6 in Atopic Dermatitis, psoriasis	Inflammatory skin disease	↓ Antimicrobial peptide (AMP) activity; ↑ serine protease activity	Barrier dysfunction, microbial dysbiosis	[31,32]
<i>Extrinsic Factors</i>				
>6.5 after washing	Alkaline cleansing products	Strips natural acids; ↑ TEWL; ↑ inflammation	Barrier disruption, dysbiosis, eczema flare-ups	[27,33]

>5.5 in dry environments	Environmental dryness	↓ Stratum corneum hydration; ↑ pH; ↓ lipid-processing enzymes	Dryness, irritation, atopic dermatitis flares	[34,35]
>6 post-UV exposure	UV radiation exposure	↑ pH; ↓ hydration; lipid disorganization	Barrier erosion, elevated inflammation risk	[36,37]

### pH and the Skin Microbiome

The skin microbiome is composed of a diverse array of microorganisms, including bacteria, fungi, and viruses that inhabit the epidermis [38]. These microorganisms contribute significantly to cutaneous health by reinforcing the skin barrier, modulating immune responses, and offering protection against pathogenic organisms. Among the various environmental factors that shape microbial composition, skin surface pH plays a fundamental role in regulating microbial diversity and activity [17,23,24]

An acidic skin environment (typically pH 4.1–5.8) preferentially supports the colonization of acid-tolerant commensals such as *Staphylococcus epidermidis*, while inhibiting the growth of opportunistic pathogens, including *Staphylococcus aureus*, *Candida albicans*, and *Escherichia* species [4,25]. Disruptions to this acidic balance can lead to microbial dysbiosis, a shift in the microbial community that has been linked to various inflammatory skin conditions [17].

For example, elevated skin pH has been associated with increased colonization of *Staphylococcus aureus* in atopic dermatitis and with fluctuations in *Cutibacterium* abundance during acne flare-ups [3,4]. These microbial changes often coincide with a reduction in the production of antimicrobial peptides, modifications to lipid composition, and upregulation of pro-inflammatory cytokines. Collectively, such alterations compromise the skin barrier and exacerbate immune dysfunction [3,12].

Recent studies have provided evidence for the microbiome-modulating potential of pH-targeted skincare products. In a 2024 randomized controlled trial, Janssens-Böcker et al. demonstrated that formulations buffered below pH 5 significantly increased microbial diversity and reduced the abundance of *Corynebacterium kroppenstedtii*, a pro-inflammatory species linked to odor and irritation in postmenopausal women [39]. Further studies show that acidic products help preserve beneficial skin microbiota and maintain barrier function, whereas alkaline products disrupt the microbial landscape and increase TEWL [40,41].

Microbial composition also varies across different body sites, reflecting the anatomical and biochemical differences in pH. Sebaceous-rich zones, moist intertriginous regions, and dry areas each harbor distinct microbial communities with different sensitivities to pH fluctuations [3,27,42]. These site-specific variations suggest that tailored pH formulation strategies may enable more targeted and effective dermatological care.

Advances in microbial profiling and sequencing offer deeper insights into how skin pH may influence microbial gene expression, including pathways related to microbial

adhesion, metabolism, immune signaling, and biofilm formation [42,43]. These findings underscore the importance of maintaining an acidic skin environment, not only to support beneficial microbes but also to sustain the complex interplay between host and microbiota.

### Impact of Product pH on Skin Parameters

The pH of a product influences multiple aspects of skin barrier function, with its effects amplified in individuals with compromised epidermal integrity or chronic sensitivity. While the role of pH in disrupting the acid mantle is well established, its specific impact on physiologically relevant parameters, such as TEWL, hydration, irritation, and lipid organization, remains a critical focus for formulation design [6,9,33,44]. These effects are particularly pronounced in product categories such as cleansers and moisturizers, where pH can directly modulate stratum corneum function, enzyme activity, and barrier recovery [9,12,45].

Products formulated outside the physiological pH range may also overwhelm the skin’s intrinsic buffering capacity, especially in aged or diseased skin, contributing to prolonged disruption and delayed repair [6,46].

### Transepidermal Water Loss and Barrier Integrity

Elevated skin pH weakens intercellular cohesion within the stratum corneum by enhancing the activity of serine protease, particularly kallikreins, which accelerate the degradation of corneodesmosomes. This leads to compromised barrier integrity and increased TEWL [11,20,47,48]. In a controlled patch-test study, four commercially available soaps, three with alkaline pH values (~10–10.5) and one mildly acidic syndet (pH 5.5), were tested on healthy volunteers. The traditional alkaline soap caused the highest and most sustained increase in TEWL at 72 hours, while the syndet showed no significant change, indicating lower barrier disruption [9]. These findings are consistent with broader evidence that mildly acidic syndets preserve stratum corneum integrity more effectively than alkaline soaps [49].

Beyond surface effects, product pH may also influence deeper SC homeostasis by altering pH-sensitive microdomains, which are localized acidic gradients near the stratum granulosum–corneum interface that regulate enzyme activity, lipid synthesis, and barrier maturation [6,12].

### Skin Irritation and Sensitivity

Increased pH can enhance the penetration of irritants and allergens by altering lipid organization and corneocyte structure [50,51]. These changes can denature structural

proteins and trigger inflammatory cascades, intensifying symptoms such as stinging, burning, and pruritus [50,51]. Individuals with pre-existing sensitivity, including those with rosacea, atopic dermatitis, or aging skin, are particularly susceptible to adverse reactions from high-pH products [50,51,52]. Even with these known risks, many commercial cleansers still have pH values above 7, which may contribute to cumulative sensitivity or subclinical inflammation with chronic use [53,54].

**Moisture Retention and Hydration**

Acidic moisturizers (pH 4.0–5.0) have demonstrated superior performance in improving skin hydration and reducing the clinical signs of dryness, particularly in aged

or xerotic skin [4,55]. In a longitudinal trial, elderly nursing home residents who used a pH 4.0 moisturizer for several weeks exhibited better hydration and fewer skin lesions than those who used a pH 6.0 product [56]. Other studies suggest that acidic formulations enhance lamellar lipid organization and support ceramide synthesis, further contributing to barrier repair [57].

This hydration benefit is partly attributed to the more efficient processing of filaggrin into natural moisturizing factors (NMFs), which occurs optimally at an acidic pH [58]. Additionally, mildly acidic formulations may help normalize corneocyte desquamation by modulating protease activity, thereby preventing barrier thinning or hyperproliferation [12,59].

**Table 2: Summary of Product pH Effects on Skin Outcomes**

Skin Parameter	Effect of Alkaline pH	Effect of Acidic pH	Representative Studies
Transepidermal Water Loss (TEWL)	Increases TEWL by disrupting lipid matrix and corneocyte cohesion via protease activation	Maintains low TEWL by preserving lipid structure and enzyme balance	[6,9,60]
Hydration	Reduces hydration due to impaired NMF formation and disrupted lipid layers	Enhances hydration and NMF production, especially in xerotic or aging skin	[6,33]
Skin Irritation	Increases irritation risk by enhancing allergen penetration and inflammatory response	Reduces irritation potential in sensitive or compromised skin	[6,9,60]
Barrier Recovery	Slow repair after disruption due to enzyme imbalance and impaired lipid renewal	Accelerates recovery via optimized enzyme activity and lipid reorganization	[6,60]
Corneocyte Desquamation	Disrupts desquamation by increasing kallikrein activity and breaking down corneodesmosomes	Supports normal epidermal turnover through controlled protease regulation	[6,60,61]
Microbial Balance	Shifts microbiota toward pathogenic species due to elevated pH	Supports commensal dominance and microbial diversity	[39]

**Clinical Implications of Topical Product pH**

Mounting evidence highlights the significance of product pH as a modifiable factor in dermatological care, particularly in conditions marked by barrier impairment, inflammation, and microbial imbalance [6]. Formulations designed to maintain the skin’s physiological acidity have been shown to alleviate symptoms and promote sustained barrier integrity.

*Atopic Dermatitis:* Atopic Dermatitis is characterized by elevated surface pH, reduced ceramide levels, and increased colonization by *Staphylococcus aureus* [48,59]. Alkaline conditions exacerbate protease activity and disrupt the lipid matrix, contributing to inflammation and impaired barrier repair. Clinical studies have shown that moisturizers with a

pH below 5 can help restore acid mantle integrity, reduce flare frequency, and improve TEWL outcomes [4,48,55].

*Acne Vulgaris:* Elevated pH levels can favor the proliferation of *Cutibacterium acnes* and aggravate inflammation in acne-prone skin [3,30,62]. Conversely, acidic formulations, particularly those maintaining a pH between 4.0 and 5.0, have been shown to reduce lesion counts and support barrier function [11]. Additionally, low-pH formulations may also enhance the efficacy and bioavailability of actives such as salicylic acid by minimizing their conversion into less absorbable forms.

*Psoriasis:* Psoriatic skin is marked by abnormal keratinocyte proliferation, disrupted barrier function, and immune dysregulation [3,4,63]. Contributing factors

include altered lipid organization, microbiome imbalance, decreased hydration, and changes in skin surface pH [4]. While pH findings in psoriatic skin are mixed, with some studies reporting lower values in lesions, pH alterations may still influence processes like desquamation and barrier integrity [3,4,63]. pH-balanced skincare regimens, including acidic cleansers and moisturizers, are increasingly recommended to support barrier integrity and alleviate symptoms [4]. Moreover, the pH of topical formulations influences the bioavailability, tolerability, and therapeutic efficacy of anti-psoriatic actives such as salicylic acid, corticosteroids, and vitamin D analogs [63].

### Formulation Strategies for pH-Optimized Skincare

The formulation of pH-optimized skincare products requires deliberate integration of dermatological physiology, ingredient chemistry, and formulation engineering principles. While the biological rationale for an acidic product pH is well established, translating this into stable, effective, and consumer-acceptable formulations presents multiple design challenges. This section outlines a conceptual framework for pH optimization across key stages of formulation development, including ingredient compatibility, buffering strategies, preservative efficacy, and packaging design. The process is summarized in the pH-Optimized Formulation Framework (Figure 1), which highlights pH-critical checkpoints from concept to final product.

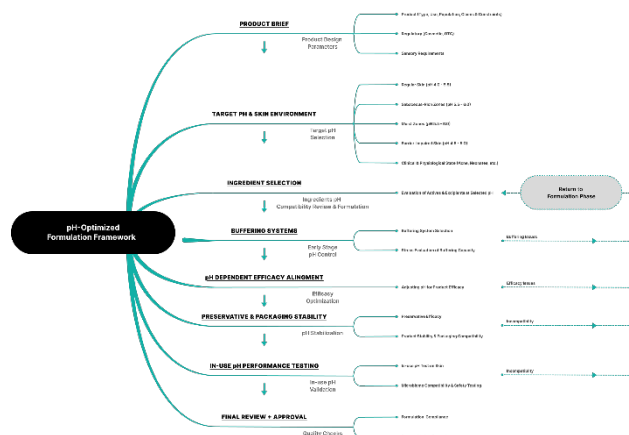
#### pH-Optimized Formulation Framework

Formulating pH-optimized skincare products begins with defining the product's intended function, target skin condition, and anatomical site. Each of these variables informs the appropriate physiological pH range, typically between 4.1 and 5.8, for which the formulation must be tailored.

After establishing a pH target, ingredients must be selected not only for their efficacy and sensory attributes, but also for their chemical behavior within the desired pH range. Particular attention must be given to actives, preservatives, and excipients that may degrade, lose efficacy, or interact unfavorably outside their optimal range.

Buffering systems are then incorporated to preserve the pH stability throughout the product lifecycle. These systems are especially critical in water-based formulations, where environmental stressors (e.g., heat, air exposure, and microbial contamination) may trigger pH drift.

Throughout the development, *in vitro* and *in vivo* testing, including pH stability studies, skin compatibility assessments, and packaging interactions, should be conducted to validate that pH integrity is maintained from manufacturing to consumer use. This iterative process ensures that pH is not treated as a post-hoc adjustment but as a foundational parameter embedded across the formulation design.



**Figure 1: pH-optimized formulation framework summarizing critical stages in developing pH-compatible products.**

#### Ingredient Selection and Compatibility

Active ingredients, excipients, and delivery systems exhibit distinct pH-dependent profiles that govern their solubility, chemical stability, and biological efficacy. For instance, alpha hydroxy acids (e.g., glycolic acid) require a pH between 3.0 to 5.0 to exert optimal exfoliating effects, whereas niacinamide may hydrolyze into nicotinic acid outside the pH range of 4 to 7, potentially increasing the risk of skin flushing and irritation [64,65].

Similarly, ascorbic acid in topical formulations demonstrates maximal percutaneous absorption below pH 3.5, whereas certain peptides may lose their structural integrity under acidic conditions [66]. For example, epidermal growth factor (EGF) exhibits optimal stability between pH 6.0 and 8.0, with conformational changes and aggregation occurring near its isoelectric point around pH 4.6 [67]. These constraints necessitate meticulous ingredient screening, particularly when designing multifunctional or synergistic formulations.

To resolve potential incompatibilities, formulators may employ strategies such as microencapsulation, dual-phase systems, or pH-responsive delivery technologies. Early phase compatibility testing, encompassing both chemical stability and functional efficacy, is critical to ensure the targeted delivery of actives without compromising formulation performance or pH stability.

#### Buffering Capacity and Stabilization

Establishing a target pH at the time of manufacture is insufficient unless that pH remains stable throughout the product's shelf life and typical usage conditions. Formulations without adequate buffering capacity are prone to pH drift caused by ingredient degradation, temperature variation, environmental exposure, or consumer handling. Buffer systems, typically comprising weak acid–base conjugates such as citric acid/citrate or lactic acid/lactate, help maintain product pH stability by neutralizing minor acid or base fluctuations [68]. In a 4-week clinical study, buffered topical formulations with pH ≤ 4.5 effectively acidified the skin surface and maintained physiological skin pH [69]. Such systems are particularly important in leave-

on products, pediatric applications, and formulations containing pH-sensitive actives.

The evaluation of buffering capacity entails more than a single-point pH measurement. This requires testing the resistance of the formulation to pH shifts under stress conditions, including accelerated aging, repeated container opening, and UV exposure. Buffer integration should be considered a proactive design element essential for ensuring consistent product performance, safety, and efficacy over time.

#### ***Preservatives and Packaging Interactions***

Preservative efficacy is intrinsically linked to pH, as ionization state governs antimicrobial activity [70]. Organic acid preservatives, such as benzoic and sorbic acids, are most effective in their protonated (undissociated) forms at acidic pH values, typically below their pKa, where they can diffuse across microbial membranes, disrupt intracellular pH, and impair metabolic function. In contrast, phenoxyethanol and certain alcohols maintain broad-spectrum activity across a wider pH range, offering greater formulation flexibility [71].

The preservative performance can also be influenced by interactions with emulsifiers, thickeners, and active ingredients, which may reduce the availability of the preservative in the aqueous phase through partitioning or other physical interactions [72,73]. Therefore, preservative efficacy testing, including challenge testing and real-time microbial assays, should be conducted at the final formulation pH value.

Packaging plays a central role in preserving pH integrity and preservative efficacy over time. Certain packaging polymers, such as low-density polyethylene (LDPE) and polypropylene (PP), have been shown to absorb lipophilic actives and preservatives, leading to reduced potency over time. In a 2010 study evaluating ophthalmic formulations, LDPE absorbed 72% of benzyl alcohol and 96% of chlorbutol, while PP absorbed 8% of benzyl alcohol and 23% of chlorbutol over a three-month period [74].

Conversely, packaging materials may also leach additives such as plasticizers or residual monomers into the formulation. These leachables, such as phthalates or bisphenol A (BPA), can alter pH, destabilize actives, or interact with preservatives [75]. The risk of such interactions necessitates the importance of early-stage compatibility assessments between formulation and packaging.

Barrier packaging solutions, including multilayer laminate tubes, airless pumps, and opaque containers, can help mitigate these risks by minimizing oxygen ingress, UV exposure, and material exchange. These strategies are especially critical for formulations with narrow pH ranges, sensitive actives, or low preservative margins.

#### **Research Gaps and Implementation Barriers**

Although the biological importance of maintaining an acidic skin surface is well established, the translation of this knowledge into consistent formulation practices and clinical guidelines remains limited. This section outlines the

key scientific, regulatory, and practical gaps that hinder the broader adoption of pH-optimized skincare.

#### ***Lack of Standardized Labeling and Reporting***

Currently, there are no regulatory mandates requiring manufacturers to disclose the pH of topical products. This lack of transparency limits consumer awareness, complicates clinical recommendations, and hinders cross-brand comparisons. In addition, the absence of standardized pH testing protocols, such as when and how pH is measured (in concentrate, diluted, or after application), further undermines reproducibility across different studies.

#### ***Limited High-Quality Clinical Trials***

Many available studies on pH-optimized skincare are limited by short follow-up periods, small cohorts, or lack of control groups, restricting conclusions on long-term effects [39]. Robust peer-reviewed clinical trials evaluating long-term skin outcomes, especially in high-risk populations such as infants, elderly individuals, and patients with chronic dermatological conditions, are scarce. Moreover, few trials directly compare formulations of identical compositions that vary only in pH, making it challenging to isolate the effects of pH as an independent formulation variable.

#### ***Underexplored Buffering and In-Use pH Dynamics***

Product pH is often reported as a static value; however, it may drift significantly during storage or in use. The buffering capacity of a formulation is rarely measured or disclosed, even though it has the potential to affect stability, bioavailability, and skin response [3,76]. Future studies should incorporate dynamic pH assessments, including in vivo skin pH measurements post-application and throughout the product's life cycle.

#### ***Insufficient Research on Personalized pH Targeting***

While there is growing interest in personalized skincare, research on pH variability across anatomical sites, age groups, ethnicities, and disease states remains sparse. The development of pH-targeted regimens requires a deeper understanding of physiological and pathological pH ranges, as well as practical methods for matching formulation pH to individual needs.

#### ***Translational Barriers in Formulation Practice***

Even when pH science is well understood, implementation can be constrained by real-world formulation challenges. These include ingredient incompatibility at low pH, preservative system limitations, and the lack of commercial buffering agents that are both effective and cosmetically acceptable. Additionally, there is commercial hesitation to pursue low-pH formulations due to potential irritation risks or sensory changes, particularly in leave-on products.

#### **Discussion and Future Perspectives**

As the relationship between product pH and skin health becomes increasingly evident, the next frontier lies in translating these insights into standardized formulation

practices and measurable clinical outcomes. This includes the development of pH-optimized products across all topical categories, from cleansers and moisturizers to barrier repair solutions and therapeutic treatments. Incorporating buffering systems and ensuring pH stability across a product's lifecycle will be essential for maintaining efficacy, particularly in contexts where sweat, water, and microbiota may shift the surface pH after application.

The skin microbiome represents a particularly promising domain for pH-optimized formulations. Future investigations integrating pH modulation with metagenomic and transcriptomic profiling could clarify how local acidity shapes microbial behavior and immune signaling [43]. Such insights could guide the development of formulations that not only preserve commensal ecosystems but also actively promote skin-microbiome symbiosis.

From a regulatory perspective, standardized pH labeling, similar to SPF rating, could empower dermatologists and consumers to make more informed product selections. Combined with public education initiatives, such labeling could help bridge the gap between dermatological science and everyday consumer skin care.

Technological innovations may further accelerate the integration of pH-optimized design into personalized and preventive skin health strategies. Wearable pH sensors, home-use diagnostics, and AI-assisted skin analyses have the potential to enable personalized pH modulation strategies tailored to individual physiology, lifestyle, and disease risk. These developments align with the broader movement toward precision dermatology and proactive skin health.

Looking forward, advancing pH science will require integration across microbiome ecology, barrier physiology, and formulation chemistry. Such interdisciplinary approaches can inform more precise and responsive strategies for both therapeutic and topical dermatological applications.

## CONCLUSION

pH-optimized formulation design represents a compelling opportunity to align dermatological and topical formulation innovation with skin physiology. Embracing pH as a core design parameter may enable more effective, microbiome-compatible, and scientifically transparent skincare solutions.

## DISCLAIMER

The perspectives shared herein are those of the author and do not in any way reflect the official policy or position of any affiliated institutions or organizations.

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## CONFLICT OF INTEREST

None.

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