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Application of biomimetic materials in next generation cosmetic science: A review

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Abstract
The growing demand for effective, safe, and sustainable cosmetic products has driven significant advancements in cosmetic science, particularly through the integration of biomimetic materials. Biomimetic materials are engineered to imitate natural biological structures and processes of human skin, enabling improved compatibility and targeted performance. In next-generation cosmetics, these materials are designed to replicate intrinsic skin functions such as barrier repair, hydration maintenance, cellular communication, and protection against environmental stressors. Biomimetic peptides, lipids, ceramides, and natural moisturizing factor (NMF) analogues closely resemble endogenous skin components, thereby enhancing dermal–epidermal junction integrity, reducing trans epidermal water loss, and promoting visible anti-aging effects. Furthermore, biomimetic delivery systems, including lipid-based vesicles and nanocarriers, facilitate controlled release and deeper penetration of active ingredients, improving product efficacy and sensory attributes. The incorporation of eco-inspired biomimetic designs also supports sustainability by replacing conventional synthetic ingredients with bioequivalent alternatives that align with biological functions while minimizing environmental impact.
This review provides a comprehensive overview of the principles, mechanisms, applications, benefits, challenges, and future prospects of biomimetic materials in next-generation cosmetic formulations, highlighting their potential to bridge biological science and cosmetic innovation.

Keywords: Biomimetic materials, cosmetic science, biomimetic peptides, skin barrier repair, sustainable cosmetics, next-generation cosmetics

Introduction
The cosmetic industry has undergone a significant transformation in recent decades, driven by advances in skin biology, material science, and biotechnology, as well as increasing consumer demand for effective, safe, and sustainable products. Modern cosmetic formulations are no longer designed solely for aesthetic enhancement but aim to interact intelligently with the skin to support its natural structure and functions. This shift has led to the emergence of biomimetic materials as a promising strategy in the development of next-generation cosmetic and cosmeceutical products (Baran and Maibach, 2019) [1].
Biomimetic materials are engineered substances inspired by natural biological structures, processes, and mechanisms. In cosmetic science, biomimicry involves designing ingredients and formulations that closely resemble the skin's own components or physiological pathways, enabling improved compatibility and functionality (Vincent *et al.*, 2016) [48]. Unlike conventional cosmetic ingredients that often act superficially, biomimetic materials function in harmony with the skin's biological systems, resulting in enhanced efficacy, reduced irritation, and improved long-term skin health (Schagen, 2017) [39].
Human skin is a highly complex organ responsible for protection, hydration, thermoregulation, and sensory perception. The stratum corneum, composed of corneocytes embedded in a lipid matrix of ceramides, cholesterol, and fatty acids, plays a critical role in maintaining barrier integrity and preventing trans epidermal water loss (TEWL). Disruption of this barrier due to aging, environmental exposure, or inappropriate cosmetic use can lead to dryness, sensitivity, inflammation, and premature aging (Draelos, 2020) [8]. Biomimetic lipids and moisturizing systems are designed to replicate this natural lipid architecture, thereby restoring barrier function and improving hydration levels in a physiologically relevant manner (Müller *et al.*, 2021).
Among biomimetic ingredients, peptides have gained considerable attention for their role in skin rejuvenation and anti-aging applications. Biomimetic peptides are short chains of amino acids designed to mimic naturally occurring signaling molecules involved in collagen synthesis, extracellular matrix regulation, and cellular communication. These peptides can stimulate fibroblast activity, enhance dermal matrix production, and improve skin firmness and elasticity, making them valuable components in anti-aging cosmetic formulations. Their targeted mode of action and favorable safety profile further support their growing use in cosmetic and cosmeceutical products (Robinson *et al.*, 2018; Schagen, 2017) [37, 39].
In addition to active ingredients, biomimetic principles are increasingly applied to cosmetic delivery systems and formulation design. Advanced delivery technologies such as lipid-based carriers, lamellar emulsions, and nano-structured systems are engineered to mimic biological membranes, enhancing the penetration, stability, and controlled release of active compounds (López *et al.*, 2017). Furthermore, tactile sensing models inspired by the biomechanical properties of human skin are used to optimize sensorial

attributes such as spread ability, softness, and after-feel, which significantly influence consumer perception and product acceptance (Wiechers and Kelly, 2019) [51].

Overall, the integration of biomimetic materials represents a paradigm shift in cosmetic science, bridging the gap between natural biological systems and advanced formulation technologies. As understanding of skin biology continues to deepen, biomimetic strategies are expected to play an increasingly important role in the development of innovative, high-performance, and sustainable cosmetic products. This review aims to explore the principles, applications, and future prospects of biomimetic materials in next-generation cosmetics.

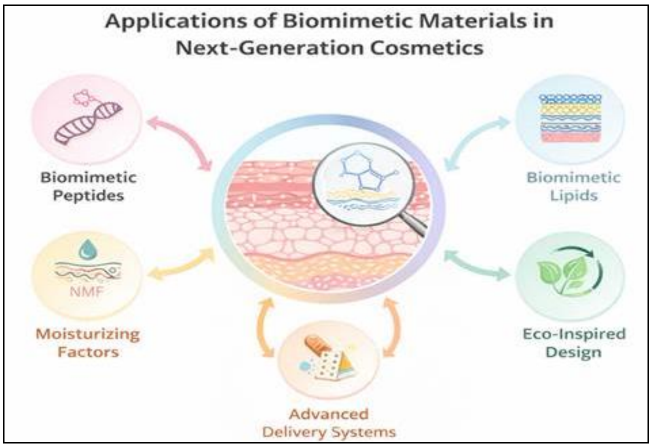

Fig 1: Schematic representation of biomimetic material application in cosmetic science

Evolution of Biomimetic Cosmetics

The evolution of biomimetic cosmetics reflects the broader shift of the cosmetic industry from traditional aesthetic driven formulations to biologically intelligent and function-oriented product design. Early cosmetic products primarily focused on surface beautification, relying on occlusive agents and synthetic compounds with limited interaction with skin biology. With advances in dermatological research and a deeper understanding of skin structure and physiology, cosmetic science began incorporating ingredients that resemble natural skin components, marking the initial phase of biomimetic cosmetic development (Baran and Maibach, 2019) [1]. The introduction of biomimetic lipids, such as ceramide analogues, represented a major milestone by enabling restoration of the skin barrier through mechanisms similar to those occurring naturally in the stratum corneum (Draleos, 2020). Subsequently, the development of biomimetic peptides that mimic endogenous signaling molecules further advanced the field by targeting cellular communication pathways involved in collagen synthesis, repair, and anti-aging processes (Schagen, 2017; Robinson *et al*., 2018) [37, 39]. In recent years, biomimetic concepts have expanded beyond active ingredients to include delivery systems, lamellar emulsions, and sensorial optimization models that emulate biological membranes and skin biomechanics (López *et al*., 2017; Wiechers and Kelly, 2019) [51]. More recently, sustainability-driven innovation has integrated eco-inspired biomimetic design, emphasizing functional efficiency and environmental compatibility, thereby aligning cosmetic performance with ecological responsibility (Vincent *et al*., 2016 [48]; Müller *et al*, 2021). This progressive evolution highlights biomimetic cosmetics as a cornerstone of next-generation cosmetic science, bridging natural biological mechanisms with advanced formulation technologies.

Principles of Application of Biomimetic Materials in Next-Generation Cosmetics

The application of biomimetic materials in next-generation cosmetics is fundamentally guided by the principle of replicating natural skin structure and biological function to achieve enhanced compatibility and efficacy. One key principle is biological similarity, where materials are designed to closely resemble endogenous skin components such as lipids, proteins, and signaling molecules, allowing them to integrate seamlessly with skin physiology and reduce the risk of irritation or adverse reactions. (Baroni *et al*., 2012; Elias, 2014). Another important principle is functional mimicry, which focuses on imitating natural skin processes including moisture retention, barrier repair, cellular communication, and self-renewal, thereby supporting skin health rather than merely masking cosmetic concerns. These biomimetic approaches promote long-term improvement in skin function and resilience. (Lodén & Maibach, 2016 [57]; Draelos, 2018). Skin barrier reinforcement is a central principle, as biomimetic lipids and ceramides help restore the highly organized lamellar structure of the stratum corneum and minimize transepidermal water loss. This reinforcement enhances skin hydration, elasticity, and protection against external aggressors. (Elias & Feingold, 2006; Bouwstra & Ponec, 2006) [3]. Additionally, targeted delivery and controlled release principles are applied through biomimetic carriers that mimic skin lipid architecture, thereby improving the penetration, bioavailability, and stability of active ingredients within cosmetic formulations. (Prow *et al*., 2011; Fernandes *et al*., 2020) [11, 34]. The principle of homeostasis maintenance ensures that cosmetic formulations support the skin's natural balance, adaptive responses, and microbiome rather than disrupting physiological processes. This approach aligns cosmetics with dermatological wellness and preventive skin care (Kong & Segre, 2012; Dreno *et al*.). Finally, eco-biomimicry and sustainability guide the selection of biodegradable, bio-engineered, or green-synthesized materials, aligning cosmetic innovation with environmental responsibility and regulatory expectations. Together, these principles establish biomimetic materials as the scientific foundation of next-generation cosmetic products that are effective, safe, and sustainable. (Anastas & Eghbali, 2010; Ribeiro *et al*., 2021)

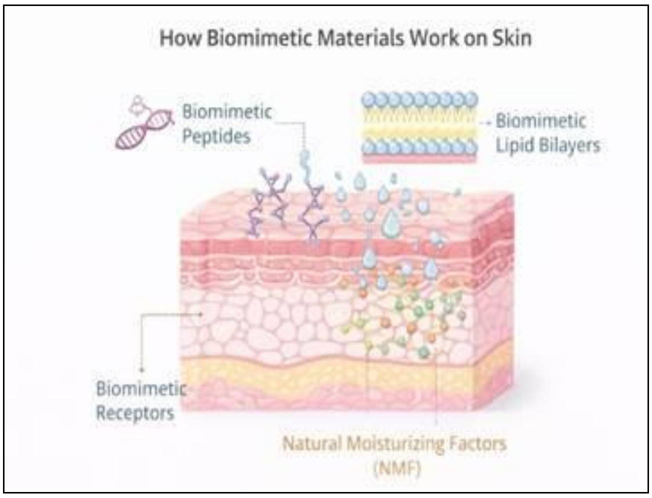

Fig 2: Schematic diagram showing of how biomimetic material works on skin

Types

Types of Biomimetic Materials in Next-Generation Cosmetics

1. Biomimetic Lipids

Biomimetic lipids are among the most extensively used biomimetic materials in cosmetic formulations due to their close resemblance to the natural lipid matrix of the stratum corneum. Human skin barrier function relies on a highly organized lamellar structure composed mainly of ceramides, cholesterol, and free fatty acids. Disruption of this structure, caused by aging, environmental stress, or harsh cosmetic products, leads to increased trans epidermal water loss and skin sensitivity. Biomimetic lipids are engineered to replicate both the composition and arrangement of these natural skin lipids, thereby restoring barrier integrity and enhancing moisture retention (Elias & Feingold, 2006; Bouwstra & Ponec, 2006 [3]; Lodén, 2012). Their application improves skin softness, elasticity, and resilience while reducing irritation, making them particularly beneficial in moisturizers, barrier repair creams, and sensitive-skin formulations (Draelos, 2020 [8]; Müller *et al*., 2021).

2. Biomimetic Peptides

Biomimetic peptides are short chains of amino acids designed to mimic endogenous peptides involved in skin signaling pathways. These peptides play a critical role in regulating collagen synthesis, cellular communication, wound healing, and inflammation control. With aging, the production of natural signaling peptides decreases, leading to reduced collagen levels and loss of skin firmness. Biomimetic peptides compensate for this decline by stimulating fibroblast activity and extracellular matrix production, resulting in visible anti-aging effects such as wrinkle reduction and improved skin tone (Schagen, 2017 [39]; Lupo & Cole, 2007; Robinson *et al*., 2018) [37]. Their specificity, low toxicity, and ability to target defined biological pathways have made biomimetic peptides key components in advanced anti-aging and cosmeceutical formulations (Schagen, 2017; Robinson *et al*., 2018) [37, 39].

3. Biomimetic Moisturizing Factors

Biomimetic moisturizing factors are developed to imitate the skin's natural moisturizing factor (NMF), a complex mixture of hygroscopic substances including amino acids, urea, lactates, and inorganic salts. These components play an essential role in maintaining water balance within the stratum corneum. Reduced NMF levels, commonly observed in dry and aged skin, result in roughness, flakiness, and impaired barrier function. Biomimetic NMF components bind and retain water in the outermost layers of the skin, leading to prolonged hydration and improved skin texture. Their incorporation into cosmetic products enhances moisturization without disrupting skin physiology, making them suitable for daily skincare and dermatologically sensitive formulations (Baran and Maibach, 2019) [1].

4. Biomimetic Delivery Systems

Biomimetic delivery systems are designed to emulate biological membranes and transport mechanisms to improve the efficacy of cosmetic actives. Traditional cosmetic formulations often face limitations such as poor penetration, instability, or uncontrolled release of active ingredients. Biomimetic delivery systems, including lamellar emulsions, lipid nanoparticles, and membrane-mimicking vesicles, overcome these challenges by facilitating targeted delivery and sustained release. These systems enhance the bioavailability of active compounds while minimizing irritation and degradation. By closely resembling natural lipid bilayers, biomimetic carriers integrate seamlessly with the skin, resulting in improved performance and reduced adverse effects (López *et al*., 2017).

5. Biomimetic Sensorial and Tactile Materials

Sensorial and tactile properties play a significant role in consumer acceptance of cosmetic products. Biomimetic sensorial materials are developed to replicate the mechanical and tactile properties of human skin, such as elasticity, smoothness, and friction behavior. These materials improve spread ability, after feel, and overall sensory experience during product application. Advanced tactile sensing models inspired by skin biomechanics are increasingly used to design formulations that feel more natural and pleasant on the skin. Enhanced sensory performance not only improves consumer satisfaction but also influences perceived product efficacy, making sensorial biomimicry an important aspect of modern cosmetic design (Wiechers and Kelly, 2019) [51].

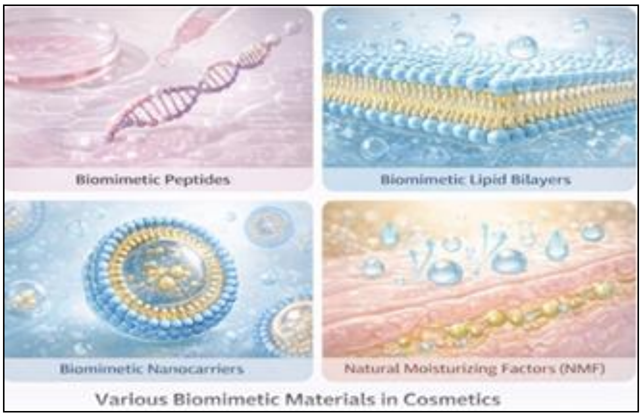

Fig 3: Classification of Biomimetic Materials and Their Functional Roles in cosmetic.

Mechanism

Biomimetic materials exert their effects in cosmetic formulations by closely interacting with the skin's natural biological structures and physiological pathways, thereby enhancing efficacy while maintaining high biocompatibility. The primary mechanism involves structural mimicry, where biomimetic lipids integrate into the stratum corneum and reorganize into lamellar structures similar to native skin lipids, restoring barrier integrity and reducing trans epidermal water loss. At the cellular level, biomimetic peptides function by imitating endogenous signaling molecules that bind to specific cell receptors on keratinocytes and fibroblasts, triggering intracellular pathways responsible for collagen synthesis, extracellular matrix remodeling, and skin repair processes, leading to improved firmness and reduced signs of aging (Schagen, 2017; Robinson *et al*., 2018) [37, 39]. Additionally, biomimetic moisturizing factors replicate components of the natural moisturizing factor, enhancing water-binding capacity within the stratum corneum and maintaining optimal hydration without disrupting skin homeostasis (Baran and Maibach, 2019) [1]. The efficacy of these actives is further enhanced by biomimetic delivery systems, such as lamellar emulsions and lipid-based carriers, which mimic biological membranes to facilitate controlled penetration, sustained release, and increased bioavailability of active ingredients while minimizing irritation (López *et al*., 2017). Furthermore, biomimetic sensorial materials interact with the mechanical and tactile receptors of the skin, improving spread ability and sensory perception, which indirectly influences consumer satisfaction and perceived efficacy (Wiechers and Kelly, 2019) [51]. Collectively, these interconnected mechanisms demonstrate how biomimetic materials operate synergistically to support skin function, promote repair, and deliver advanced cosmetic benefits in a physiologically aligned manner.

Applications of Biomimetic Materials in Next-Generation Cosmetics

Biomimetic materials are increasingly applied across a wide range of cosmetic and cosmeceutical products due to their ability to work in harmony with natural skin biology rather than merely improving surface appearance. One of their most important applications is in skin barrier repair and moisturization, where biomimetic lipids, ceramides, and natural moisturizing factor (NMF) analogues restore the structural organization of the stratum corneum, reduce trans epidermal water loss, and provide long-lasting hydration, particularly in dry, sensitive, and damaged skin conditions (Elias, 2018 [9]; Müller *et al*., 2021). In anti-aging skincare, biomimetic peptides act as signaling molecules that stimulate collagen and elastin synthesis, improve dermal matrix organization, and visibly reduce wrinkles and loss of firmness, offering deeper biological benefits compared to conventional anti-aging ingredients (Schagen, 2017; Robinson *et al*., 2018) [37, 39]. Biomimetic materials are also widely used in advanced delivery systems, such as lamellar emulsions and lipid-based nanocarriers, which mimic skin lipid architecture and enhance penetration, stability, and controlled release of active ingredients while minimizing irritation (López *et al*., 2017). In addition, biomimetic formulations play a key role in sensitive-skin and post-procedure products, where their high biocompatibility supports skin recovery, reduces inflammation, and maintains homeostasis (Draelos, 2020) [8]. Beyond performance, biomimetic approaches are increasingly applied in sustainable cosmetic development, where bioengineered peptides and lipids derived through green chemistry and fermentation replace petrochemical ingredients, reducing environmental impact while maintaining efficacy (Vincent *et al*., 2016) [48]. Together, these applications demonstrate that biomimetic materials are transforming cosmetic products into biologically intelligent systems focused on long-term skin health, safety, and sustainability.

- **Skin Barrier Repair and Moisturization**

Biomimetic lipids and natural moisturizing factor analogues are widely used to restore the lamellar lipid structure of the stratum corneum, strengthen the skin barrier, and reduce trans epidermal water loss. These applications are especially beneficial in dry, sensitive, and damaged skin conditions (Draelos, 2020 [8]; Müller *et al*., 2021).

- **Anti-Aging and Skin Rejuvenation**

Biomimetic peptides are applied in anti-aging formulations to mimic endogenous signaling molecules that stimulate collagen synthesis, improve extracellular matrix remodeling, and enhance skin firmness and elasticity, resulting in reduced wrinkles and fine lines (Schagen, 2017; Robinson *et al*., 2018) [37, 39].

- **Skin Repair and Regeneration**

Biomimetic materials support skin healing and regeneration by activating biological pathways involved in cell proliferation and tissue repair. These applications are common in post-procedure care products and cosmeceuticals aimed at restoring skin homeostasis (Baran and Maibach, 2019) [1].

- **Advanced Delivery Systems for Actives**

Biomimetic delivery systems such as lamellar emulsions, lipid nanoparticles, and membrane-mimicking carriers are used to enhance penetration, stability, and controlled release of active ingredients while minimizing irritation (López *et al*., 2017).

- **Improvement of Sensorial Properties**

Biomimetic sensorial and tactile materials are applied to improve spread ability, texture, softness, and after-feel of cosmetic products, thereby enhancing consumer perception and product acceptance (Wiechers and Kelly, 2019) [51].

- **Sustainable and Eco-Friendly Cosmetic Formulations**

Eco-inspired biomimetic materials are increasingly applied to replace conventional synthetic ingredients with bioequivalent alternatives, supporting sustainable product development with reduced environmental impact (Vincent *et al*., 2016) [48].

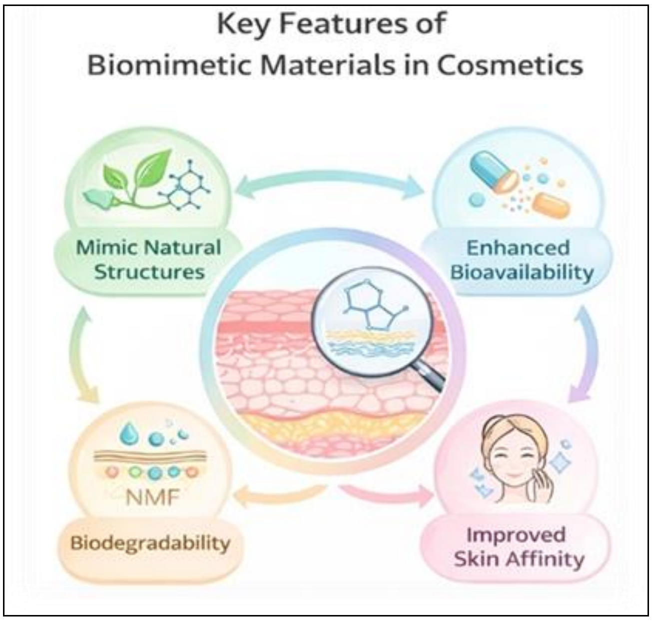

Fig 4: Schematic Representation of the Key Features of Biomimetic Materials in Cosmetics

Challenges

Despite the significant advancements and potential advantages of biomimetic materials in cosmetic science, several challenges continue to hinder their widespread adoption and commercialization. One of the primary challenges is the high cost of research, development, and production, as biomimetic peptides, lipids, and bioinspired delivery systems often require sophisticated synthesis techniques, biotechnological processing, and rigorous quality control, which substantially increase manufacturing expenses compared to conventional cosmetic ingredients (Robinson *et al*., 2018 [37]; López *et al*., 2017). Another critical challenge is stability, since many biomimetic compounds are inherently sensitive to environmental factors such as temperature fluctuations, light exposure, oxidation, and pH variations, leading to degradation and reduced efficacy over time if not properly stabilized within the formulation (Schagen, 2017; Draelos, 2020) [8, 39]. Skin penetration and bioavailability also pose considerable difficulties, particularly for large biomimetic molecules like peptides, which struggle to traverse the stratum corneum and therefore depend heavily on advanced delivery systems to achieve therapeutic concentrations at target sites (Elias, 2018) [9]. Furthermore, although biomimetic materials are designed to be biologically compatible, the risk of irritation, sensitization, or immunogenic responses cannot be entirely eliminated, especially in individuals with sensitive or compromised skin, necessitating extensive safety testing and clinical validation (Baran and Maibach, 2019) [1]. The complexity of formulation and scale-up represents another major obstacle, as maintaining the structural integrity and biological activity of biomimetic materials during large-scale manufacturing requires precise control of formulation parameters and processing conditions (Wiechers and Kelly, 2019) [51]. In addition, regulatory and standardization challenges remain significant, as global regulatory frameworks for novel biomimetic and nanostructured cosmetic ingredients are still evolving, often resulting in ambiguous approval pathways and delays in market entry (Vincent *et al*., 2016) [48]. Collectively, these challenges highlight the need for continued research, technological innovation, and regulatory harmonization to fully realize the potential of biomimetic materials in next-generation cosmetic products.

Table 1: Comparison of biomimetic materials in traditional ingredient

SR NO.	Biometric material	Traditional ingredients
1.	Inspired by natural skin components (peptides, lipids, ECM molecules	Derived from plants, minerals, oils or synthetic chemicals
2.	Mimic natural biological pathways, activate skin cells naturally	Mostly surface- level action, limited biological mimicry
3.	High efficacy due to cell targeted, receptor-based action	Mainly acts as moisturizes or protective agents
4.	Often enhanced through nanocarriers and biomimetic structures	Limited penetration; mainly remain on skin surface
5.	High biocompatibility but may cause sensitivity to some peptides	Generally safe, depends on ingredient type
6.	Less stable; sensitive to heat, PH and oxidation	More stable; longer shelf life
7.	High cost due to advanced synthesis	Generally cheaper, depends on ingredient type
8.	Cutting edge (peptides, nanocarriers, marine mimetics)	Conventional, widely used formulation
9.	Faster, targeted results: Antiaging, regeneration, barrier repair	Basic results: moisturization, cleansing
10.	Depends on source: biotech process can be energy heavy	Plant based ingredients often more sustainable
11.	Higher due to novel mechanisms and safety tests	Lower many ingredients already well studied
12.	Low to moderate	Traditional ingredients

Benefits

Biomimetic materials offer significant advantages in cosmetic formulations by closely imitating the structure and function of natural skin components. Their ability to interact harmoniously with skin biology results in improved performance, enhanced safety, and long-term skin health benefits. By supporting natural physiological processes rather than disrupting them, biomimetic materials have become a cornerstone of next-generation cosmetic innovation (Elias, 2018 [9]; López *et al*., 2017).

- **Enhanced Skin Compatibility and Safety**

Biomimetic materials are designed to closely resemble natural skin components such as lipids, peptides, and moisturizing factors, which improves biocompatibility and reduces the risk of irritation or adverse reactions. Their similarity to endogenous skin substances allows better tolerance, even for sensitive or compromised skin types (Draelos, 2020; Baran and Maibach, 2019) [1, 8].

- **Improved Skin Barrier Function**

Biomimetic lipids and ceramide analogues help restore the lamellar structure of the stratum corneum, strengthening the skin barrier and reducing trans epidermal water loss (TEWL). This leads to long-lasting hydration and protection against environmental stressors (Müller *et al*., 2021; Elias, 2018) [9].

- **Effective Anti-Aging Performance**

Biomimetic peptides mimic natural signaling molecules involved in collagen synthesis, elastin production, and cellular communication. Their application results in improved skin firmness, elasticity, and reduction of wrinkles and fine lines, making them highly effective anti-aging actives (Schagen, 2017; Robinson *et al*., 2018) [37, 39].

- **Targeted and Controlled Delivery of Actives**

Biomimetic delivery systems such as lipid-based carriers and lamellar emulsions enhance the penetration, stability, and controlled release of active ingredients. This targeted delivery increases efficacy while minimizing irritation and ingredient wastage (López *et al*., 2017).

- **Improved Sensory Attributes and Consumer Acceptance**

Biomimetic materials contribute to better texture, spread ability, and skin feel by mimicking the natural interaction between skin and topical formulations. Improved sensorial properties significantly enhance consumer satisfaction and perceived product quality (Wiechers and Kelly, 2019) [51].

- **Support for Skin Repair and Regeneration**

By imitating biological repair mechanisms, biomimetic materials support wound healing, post-procedure recovery, and maintenance of skin homeostasis. This makes them valuable in dermo cosmetic and cosmeceutical formulations (Baran and Maibach, 2019) [1].

- **Sustainability and Eco-Friendly Innovation**

Biomimetic approaches promote the use of bioequivalent and bioinspired alternatives to conventional synthetic ingredients, reducing environmental impact while maintaining high performance. This aligns cosmetic innovation with sustainability and green chemistry principles (Vincent *et al*., 2016) [48].

- **Future-Ready and Science-Driven Formulations**

The integration of biomimetic materials bridges biological science and cosmetic technology, enabling the development of advanced, multifunctional products that meet modern consumer demands for efficacy, safety, and sustainability (Elias, 2018 [9]; Müller *et al*., 2021).

Limitation

Although biomimetic materials have transformed modern cosmetic science by enabling biologically aligned and high-performance formulations, their application is associated with several notable limitations that restrict widespread industrial implementation. One of the most significant limitations is the high cost of research, development, and manufacturing, as biomimetic peptides, lipid analogues, and bioinspired delivery systems often require sophisticated synthesis techniques, biotechnological processes, and stringent quality control, making them less economically viable for large-scale and mass-market cosmetic products (Robinson *et al*., 2018 [37]; López *et al*., 2017). In addition, stability remains a critical concern, since many biomimetic ingredients are sensitive to environmental factors such as temperature, light exposure, oxidation, and pH variations, which can result in degradation, loss of biological activity, and reduced shelf life if appropriate stabilization strategies are not employed (Schagen, 2017; Draelos, 2020) [8, 39]. Another major limitation is restricted skin penetration, particularly for larger biomimetic molecules such as peptides and protein-based materials, which face difficulty crossing the stratum corneum and therefore require advanced carrier systems to achieve effective bioavailability (Elias, 2018) [9]. Despite being designed to mimic endogenous skin components, biomimetic materials may still pose a risk of irritation or sensitization in certain individuals, especially those with sensitive or compromised skin, emphasizing the need for extensive safety assessment and clinical validation (Baran and Maibach, 2019) [1]. Furthermore, the complexity of formulation and scale-up presents technical challenges during industrial production, as maintaining molecular integrity, reproducibility, and consistent performance demands precise control over formulation parameters and processing conditions (Wiechers and Kelly, 2019) [51]. Regulatory uncertainty also represents a significant limitation, since global regulatory frameworks for novel biomimetic and nano-enabled cosmetic ingredients are still evolving, often leading to delays in approval, lack of standardization, and challenges in international market access (Vincent *et al*., 2016) [48]. Collectively, these limitations highlight the necessity for continued technological innovation, cost-effective manufacturing strategies, improved stabilization techniques, and clearer regulatory guidelines to fully realize the potential of biomimetic materials in next-generation cosmetic formulations. 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Collectively, these limitations highlight the necessity for continued technological innovation, cost-effective manufacturing strategies, improved stabilization techniques, and clearer regulatory guidelines to fully realize the potential of biomimetic materials in next-generation cosmetic formulations (Dreno *et al*., 2016; Schagen, 2017; Fernandes *et al*., 2020 [11, 39]; Ribeiro *et al*., 2021)

Comparative Analysis

A comparative analysis of biomimetic materials and conventional cosmetic ingredients highlights a significant shift in formulation philosophy from surface-level treatment toward biologically aligned skin care. Conventional cosmetic ingredients, such as synthetic emollients, occlusives, and film-formers, primarily act by forming a superficial layer on the skin to improve appearance, texture, and short-term hydration, but they often do not actively interact with skin biology or support long-term barrier repair (Draelos, 2020) [8]. In contrast, biomimetic materials are specifically designed to mimic natural skin components and physiological processes, enabling them to integrate more effectively into the skin's structure and function. For example, while traditional moisturizers rely heavily on petrolatum or silicone-based occlusives, biomimetic lipids and ceramide analogues replicate the lamellar lipid organization of the stratum corneum, resulting in improved barrier restoration and sustained hydration (Elias, 2018 [9]; Müller *et al*., 2021). Similarly, conventional anti-aging formulations often depend on antioxidants or exfoliants to produce visible effects, whereas biomimetic peptides function as signaling molecules that stimulate collagen synthesis, elastin production, and cellular communication, offering deeper and more biologically relevant anti-aging benefits (Schagen, 2017; Robinson *et al*., 2018) [37, 39]. From a safety and compatibility perspective, conventional synthetic ingredients may cause irritation or long-term barrier disruption in sensitive skin when used excessively, while biomimetic materials generally demonstrate superior skin tolerance due to their structural similarity to endogenous substances (Baran and Maibach, 2019) [1]. However, this biological sophistication also introduces challenges, as biomimetic formulations are more complex, costly, and sensitive to environmental conditions compared to conventional cosmetics, which are often easier to manufacture and more stable (López *et al*., 2017). Additionally, in terms of sustainability, traditional cosmetic ingredients have historically relied on petrochemical sources, whereas biomimetic approaches increasingly emphasize bioinspired and eco-friendly alternatives that align with green chemistry principles, although scalability remains a concern (Vincent *et al*., 2016) [48]. Overall, while conventional cosmetics continue to dominate the market due to affordability and formulation simplicity, biomimetic materials represent a more advanced, science-driven approach that prioritizes long-term skin health, efficacy, and sustainability, positioning them as a cornerstone of next-generation cosmetic innovation (Elias & Feingold, 2006; Schagen, 2017 [39]; Ribeiro *et al*., 2021).

1. Mode of Action

Conventional ingredients mainly act on the skin surface by forming occlusive or film-forming layers that provide temporary moisturization and smoothness.

Biomimetic materials interact with skin biology by mimicking natural lipids, peptides, and signaling molecules, supporting physiological skin functions and long-term repair (Elias, 2018; Schagen, 2017) [9, 39].

2. Skin Compatibility and Safety

Conventional synthetic ingredients may sometimes disrupt the skin barrier or cause irritation with prolonged use, especially in sensitive skin.

Biomimetic materials show higher biocompatibility due to their structural similarity to endogenous skin components, resulting in better tolerance and safety profiles (Baran and Maibach, 2019; Draelos, 2020) [1, 8].

3. Efficacy and Performance

Conventional cosmetics primarily focus on aesthetic improvement and short-term effects.

Biomimetic materials provide enhanced and targeted efficacy, such as stimulation of collagen synthesis, barrier restoration, and cellular communication, leading to measurable functional benefits (Robinson *et al*., 2018 [37]; Müller *et al*., 2021).

4. Stability and Formulation Complexity

Conventional ingredients are generally more stable and easier to formulate.

Biomimetic materials often require controlled formulation conditions and advanced delivery systems to maintain stability and activity, increasing formulation complexity (López *et al*., 2017).

5. Cost and Commercial Feasibility

Conventional cosmetic ingredients are cost-effective and easily scalable.

Biomimetic materials involve higher research, development, and manufacturing costs, which can limit mass-market accessibility (Robinson *et al*., 2018) [37].

6. Sustainability and Environmental Impact

Many conventional ingredients are derived from petrochemical sources.

Biomimetic cosmetics increasingly adopt bioinspired and eco-friendly alternatives aligned with sustainability and green chemistry principles (Vincent *et al*., 2016) [48].

Advanced Technology

The advancement of biomimetic cosmetics has been strongly driven by the integration of cutting-edge technologies that enable precise imitation of biological structures, functions, and skin–material interactions. One of the most important technological developments is the use of biomimetic peptide engineering, where short, sequence-specific peptides are designed using molecular biology and bioinformatics tools to replicate natural signaling pathways involved in collagen synthesis, wound healing, and skin regeneration, thereby improving anti-aging efficacy (Schagen, 2017; Robinson *et al*., 2018) [37, 39]. Another major technological innovation is the development of advanced lipid-based and lamellar delivery systems, such as nanostructured lipid carriers and biomimetic emulsions, which mimic the organization of skin lipids in the stratum corneum and enhance penetration, stability, and controlled release of active ingredients (Müller *et al*., 2021; López *et al*., 2017). Nanotechnology-enabled biomimetic carriers, including liposomes and solid lipid nanoparticles, further improve bioavailability while reducing irritation and ingredient degradation, making them particularly valuable for sensitive skin formulations (Elias, 2018) [9]. In addition, 3D skin models and skin-on-chip technologies are increasingly employed to evaluate biomimetic cosmetic performance under physiologically relevant conditions, reducing reliance on animal testing while providing more accurate safety and efficacy data (Wiechers and Kelly, 2019) [51]. The incorporation of green chemistry and bio fabrication technologies, such as fermentation-derived peptides and bioengineered lipids, supports sustainable production of biomimetic materials with reduced environmental impact (Vincent *et al*., 2016) [48]. Collectively, these advanced technologies enable the precise design, evaluation, and optimization of biomimetic cosmetic formulations, positioning them at the forefront of next-generation cosmetic innovation.

- **Biomimetic Peptide Engineering**

Use of molecular biology and bioinformatics to design skin-signal-mimicking peptides. Enhances collagen synthesis, elasticity, and anti-aging performance (Schagen, 2017; Robinson *et al*., 2018) [37, 39].

- **Advanced Lipid and Lamellar Delivery Systems**

Nanostructured lipid carriers and lamellar emulsions mimic stratum corneum architecture. Improve barrier repair and long-term hydration (Müller *et al*., 2021; López *et al*., 2017).

- **Nanotechnology-Based Biomimetic Carriers**

Liposomes and solid lipid nanoparticles enhance penetration and stability. Reduce irritation and improve controlled release (Elias, 2018) [9].

- **3D Skin Models and Skin-on-Chip Technology**

Provide realistic evaluation of skin–formulation interaction. Improve safety, efficacy testing, and regulatory acceptance (Wiechers and Kelly, 2019) [51].

▪ **Green Chemistry and Bio fabrication**

Fermentation-derived peptides and bioengineered lipids. Support sustainable, eco-friendly cosmetic innovation (Vincent *et al.*, 2016) [48].

Fig 5: Overview of modern approaches in advanced cosmetic formulation

Case Studies on biomimetic materials

Several practical examples from the cosmetic industry clearly show how biomimetic materials have moved from scientific theory to real, effective products used by consumers worldwide. One of the most common and successful examples is the use of biomimetic ceramides in moisturizers developed for dry, sensitive, or damaged skin. Elias & Feingold, 2006; Lodén, 2012; Bouwstra *et al.*, 2003). These products work by copying the natural lipid structure of healthy skin, helping to repair the skin barrier, reduce water loss, and improve overall hydration, as confirmed by clinical studies (Elias, 2018 [9]; Müller *et al.*, 2021). Another widely accepted case is the use of biomimetic peptides in anti-aging skincare, where peptides designed to imitate natural skin signaling molecules stimulate collagen production and improve skin firmness, leading to visible reduction in wrinkles over time (Schagen, 2017; Robinson *et al.*, 2018) [37, 39]. Biomimetic technology has also proven effective in advanced emulsions and delivery systems, such as lamellar creams that resemble the layered structure of skin lipids, allowing active ingredients to penetrate better and work for longer durations compared to traditional formulations (López *et al.*, 2017). In products designed for sensitive skin, biomimetic natural moisturizing factor (NMF) analogues have been shown to maintain hydration while minimizing irritation by mimicking the skin's own moisture-retention system (Draelos, 2020) [8]. In addition to performance benefits, biomimetic approaches are increasingly used to support sustainability, where fermentation-derived peptides and bioengineered lipids replace petrochemical ingredients, delivering similar or better results with reduced environmental impact (Vincent *et al.*, 2016) [48]. Together, these case studies demonstrate that biomimetic materials are not just innovative concepts but practical, effective, and consumer-relevant solutions shaping modern cosmetic products (Schagen, 2017 [39]; Draelos, 2018; Ribeiro *et al.*, 2021).

Various case studies are:

1. **Biomimetic Ceramides in Moisturizers**
   - Used in products for dry and sensitive skin
   - Repair the skin barrier by copying natural skin lipids
   - Help reduce water loss and improve long-term hydration. (Elias, 2018 [9]; Müller *et al.*, 2021)

2. **Biomimetic Peptides in Anti-Aging Products**
   - Mimic natural skin signals that stimulate collagen
   - Improve firmness and reduce wrinkles over time
   - Supported by clinical studies (Schagen, 2017; Robinson *et al.*, 2018) [37, 39].

3. **Skin-Like Lamellar Creams and Emulsions**
   - Designed to resemble natural skin lipid layers
   - Improve penetration and performance of active ingredients
   - More effective than conventional emulsions (López *et al.*, 2017).

4. **Biomimetic NMF Analogues for Sensitive Skin**
   - Maintain moisture using skin-like hydration mechanisms
   - Reduce irritation and improve comfort
   - Ideal for post-procedure and sensitive skincare (Draelos, 2020) [8].

5. **Sustainable Biomimetic Ingredients**
   - Fermentation-derived peptides and lipids
   - Reduce environmental impact
   - Maintain high cosmetic performance (Vincent *et al.*, 2016) [48].

Conclusion

Biomimetic materials represent a transformative approach in next-generation cosmetic science by shifting formulation strategies from surface-level enhancement to biologically intelligent skin care. By closely mimicking natural skin components and physiological processes, these materials offer improved compatibility, enhanced efficacy, and long-term benefits such as barrier restoration, sustained hydration, and visible anti-aging effects. The integration of biomimetic peptides, lipids, moisturizing factors, and advanced delivery systems has enabled cosmetic formulations to interact more effectively with skin biology while minimizing irritation and improving consumer experience. Furthermore, the adoption of eco-inspired biomimetic design aligns cosmetic innovation with sustainability goals, supporting the development of environmentally responsible and ethically sourced products. Despite challenges related to cost, stability, and regulatory evaluation, ongoing advancements in biotechnology, material science, and formulation engineering continue to address these limitations. Overall, biomimetic materials bridge the gap between nature and technology, positioning them as essential contributors to the future of cosmetic and cosmeceutical development focused on skin health, safety, and sustainability.

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Authorship

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