

Biomimetic and Smart Delivery Systems in Advanced Cosmetics and Cosmeceuticals: Recent Advances, Applications, and Future Perspectives

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Abstract:

The cosmetic industry is increasingly moving toward multifunctional formulations that combine cosmetic benefits with the delivery of biologically active ingredients. However, the effective delivery of these ingredients to the skin can be challenging due to factors such as poor stability, degradation and limited skin penetration. This has encouraged the development of advanced delivery systems designed to improve the protection, stability and delivery of cosmetic actives. Biomimetic delivery systems, which are inspired by natural biological structures and processes, have gained attention in advanced cosmetics because they can help protect active ingredients and improve their delivery and performance in topical formulations. Various delivery platforms including liposomes, niosomes, nanoemulsions, solid lipid nanoparticles, nanostructured lipid carriers and polymeric nanocarriers have been investigated for cosmetic applications. In addition, smart or stimuli-responsive delivery systems have gained attention for their ability to respond to specific stimuli, such as pH, temperature, enzymes and light, thereby enabling controlled or triggered release of active ingredients. This review provides an overview of recent advances in biomimetic and smart delivery systems for cosmetics and cosmeceuticals, focusing on their mechanisms, applications, advantages, limitations, safety considerations and future perspectives.

Keywords: Biomimetic delivery systems; Smart delivery systems; Stimuli-responsive systems; Cosmetics; Cosmeceuticals; Nanocarriers; Topical delivery

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Introduction

The cosmetic and cosmeceutical industry has evolved rapidly with the increasing use of active ingredients that provide various benefits to the skin. Modern cosmetic formulations are not limited to improving skin appearance they may also contain active ingredients with antioxidant, anti-ageing, anti-acne, skin-brightening, and photoprotective properties [1]. However, the incorporation of an active ingredient into a cosmetic formulation does not necessarily guarantee its effective performance on the skin site. The effectiveness of many cosmetic ingredients may be influenced by factors such as poor stability, degradation, low solubility and limited penetration into the skin. In addition, the skin has a natural barrier that protects the body from external substances and can also restrict the movement of active ingredients into the desired skin layers. Therefore, simply incorporating an active ingredient into a conventional cosmetic formulation may not be sufficient to achieve its intended effect. These challenges highlight the need for effective delivery strategies that can improve the stability, protection and performance of cosmetic active ingredients in topical formulations [1,5].

One of the major challenges in topical delivery is the barrier function of the skin. The skin barrier helps to protect the body from environmental substances, but it can simultaneously restrict the movement of active ingredients into the desired skin layers. In particular, the stratum corneum forms the first and most important barrier for many substances applied to the skin. In addition to the properties of the skin, characteristics of the active ingredient, including molecular size, solubility, and lipophilicity, can influence its penetration and distribution. Therefore, achieving effective delivery of cosmetic actives to the intended skin site is an important consideration in the development of advanced topical formulations [1,4,5].

The limitations associated with conventional topical formulations have led to increasing interest in advanced delivery technologies for cosmetic and cosmeceutical applications. Nanotechnology has enabled several approaches for designing delivery systems that can improve the protection, stability and delivery of active ingredients. Liposomes, niosomes, nanoemulsions, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs) and

polymeric nanocarriers are among the systems explored for topical delivery [1-6,8-10,15].

Building on advances in delivery technologies, biomimetic and smart delivery systems are being investigated as approaches for improving the delivery of cosmetic active ingredients. Biomimetic systems are inspired by natural biological structures, materials or processes and are designed to achieve suitable interactions with the biological environment. Smart delivery systems are designed to respond to specific stimuli and modify their behaviour according to changes in the surrounding environment. Such stimuli may include pH, enzymatic activity, oxidative conditions, temperature and light. These responses can enable controlled or triggered release of active ingredients and may provide greater control over their delivery to the skin [11-14].

Despite the potential of these advanced delivery systems, several challenges still need to be addressed before their broader application in cosmetics and cosmeceuticals. Ensuring adequate formulation stability, safety, biocompatibility and reproducibility is essential for their successful development. Controlled release of active ingredients and scale-up of complex formulations may also present practical difficulties. In addition, regulatory requirements and the need for reliable long-term safety and efficacy data remain important considerations for translating these systems from laboratory research to practical cosmetic applications [11,14].

The present review focuses on biomimetic and smart delivery systems for cosmetics and cosmeceuticals, covering their principles, major delivery platforms, applications, advantages, limitations, safety considerations and future perspectives.

Biomimetic Delivery Systems: Biomimetic delivery systems are developed by drawing inspiration from natural biological structures and processes. These systems are designed to mimic selected biological features to improve the interaction of the delivery carrier with the skin. Depending on their design, biomimetic systems may enhance biocompatibility, protect sensitive active ingredients and improve their retention or delivery at the target skin site. Because of these properties, biomimetic approaches are being increasingly explored for advanced cosmetic and cosmeceutical formulations [13].

Natural biological membranes and vesicular structures have provided inspiration for the development of biomimetic delivery systems. Their structural and surface properties can be considered when designing carriers for topical delivery. By incorporating selected biological features, these systems may improve interaction with the skin and

help protect sensitive cosmetic actives. Such approaches are particularly relevant to the development of delivery systems for cosmetic and cosmeceutical actives [13].

A variety of biomimetic strategies are being investigated for delivering cosmetic and cosmeceutical active ingredients. These include carriers inspired by biological membranes and vesicles, as well as nanoparticulate systems designed to reproduce selected features of natural biological structures. Depending on their design, such systems can protect sensitive actives and influence their interaction with the skin, as well as their retention and release. The composition, size and surface characteristics of these carriers can be modified to meet the requirements of different cosmetic applications [13]. Examples include liposomes and niosomes, which are vesicular systems inspired by certain characteristics of biological membranes. Liposomes are made of phospholipid bilayers [16], and niosomes are made of non-ionic surfactants [6].

Biomimetic delivery systems are increasingly being investigated for various cosmetic and cosmeceutical applications, particularly when enhanced protection and delivery of active ingredients are required. They have potential applications in formulations containing antioxidant, anti-ageing, skin-brightening and skin repair actives. By improving the stability of sensitive ingredients and facilitating their interaction with the skin, biomimetic carriers may enhance the performance of topical formulations. Their versatility also provides opportunities for incorporating a wide range of cosmetic and cosmeceutical actives into advanced delivery systems [1,13].

Biomimetic delivery systems offer several potential benefits for cosmetic and cosmeceutical formulations, including improved protection of active ingredients, facilitated interaction with the skin and enhanced control over their delivery. However, their development may be associated with challenges related to formulation stability, manufacturing complexity, reproducibility and cost. The safety and compatibility of some biomimetic materials also require careful evaluation before their broader application. Therefore, further research is needed to establish their long-term safety, stability and effectiveness in commercial cosmetic formulations [13].

Smart/Stimuli-Responsive Delivery Systems: Smart or stimuli-responsive delivery systems are advanced carriers designed to respond to specific changes in their surrounding environment. Unlike conventional delivery systems, these carriers can alter their properties or release behaviour in response to specific stimuli. Depending on their

design, they may respond to stimuli such as pH, temperature, enzymes, light or oxidative conditions. This responsive behaviour can be utilized to achieve more controlled release of cosmetic active ingredients [11,14].

Based on the source of stimulation, smart delivery systems can be broadly divided into internally and externally triggered delivery systems. Internal stimuli originate from the local biological environment and may include variations in pH, enzymatic activity and oxidative conditions. External stimuli, on the other hand, are applied from outside and can include temperature, light, ultrasound and electric or magnetic fields. The response of the delivery carrier to these stimuli can be designed to modify its structure or permeability and thereby enabling controlled release of the active ingredient [11,14].

pH-responsive delivery systems are designed to change their behaviour in response to variations in the pH of the surrounding environment. Such changes can affect the ionization, swelling, solubility or permeability of the carrier and consequently influence the release of the incorporated active ingredient. By taking advantage of these pH-dependent changes, delivery systems can be designed to provide more controlled release under specific conditions. This approach has potential for improving the delivery of cosmetic actives while minimizing premature release before the carrier reaches the intended environment [11,14].

Temperature-responsive delivery systems use changes in temperature as a trigger to modify the

behaviour of the delivery carrier. Variations in temperature can cause changes in properties such as polymer conformation, phase behaviour, swelling, or permeability, which can subsequently influence the release of the active ingredient. By designing carriers that respond within a specific temperature range, controlled release can be achieved according to the surrounding conditions. Such systems may therefore provide useful opportunities for regulating the delivery of cosmetic actives in topical formulations [12].

Enzyme-responsive systems utilize the activity of specific enzymes as triggers for controlled release. These systems can incorporate enzyme-sensitive components that undergo structural or chemical changes when exposed to the relevant enzymatic environment. As a result, the carrier may become more permeable or undergo degradation, thereby allowing the incorporated active ingredient to be released. This biologically triggered response provides an additional approach for controlling the delivery of cosmetic actives under specific skin conditions [11,14].

Light-responsive systems use externally applied light stimuli to trigger changes in the carrier and regulate the release of active ingredients. Oxidative-responsive systems respond to changes in the local oxidative environment, which can induce chemical or structural changes in the carrier and influence the release of active ingredients. These approaches provide additional opportunities for controlled delivery of cosmetic actives [11,14].

Table 1: Major delivery platforms used in cosmetics and cosmeceuticals.

Delivery Platform	Basic structure	Key Advantages	Cosmetic Applications
Liposomes	Phospholipid bilayer with aqueous core	Can encapsulate hydrophilic and lipophilic actives, improving their stability and delivery	Anti-ageing, moisturizing, antioxidants and skin-repair formulations [16]
Niosomes	Non-ionic surfactant bilayer	Good stability and potential for controlled or prolonged release	Anti-ageing, moisturizing, skin brightening, hair care [6]
Nanoemulsions	Nano sized oil-in-water or water-in-oil droplets	Improved dispersion and delivery of poorly water-soluble actives	Creams, lotions, sunscreens, and other skin-care formulations [8-10,15]
Solid Lipid Nanoparticles (SLNs)	Nanoparticles containing a solid lipid matrix	Protection of active ingredients, controlled release, potential occlusive and moisturizing effects	Sunscreens, moisturizers, anti-ageing formulations [2-5]
Nanostructured Lipid Carriers (NLCs)	Lipid matrix containing a mixture of solid and liquid lipids	Higher loading capacity and improved release characteristics compared with SLNs	Sunscreens, antioxidants formulations and other skin-care products [2-5,7]
Polymeric Nanocarriers	Nanocarriers composed of biocompatible polymers	Controlled and modified release of active ingredients	Delivery of antioxidant, anti-ageing and other cosmetic actives [17]

Major Delivery Platforms: Several delivery platforms have been investigated to improve the stability, protection and delivery of cosmetic active ingredients. Important systems include liposomes, niosomes, nanoemulsions, solid lipid nanoparticles, nanostructured lipid carriers and polymeric nanocarriers. These platforms differ in their composition, structure and mechanisms of active incorporation, which influences their stability, their interaction with the skin and release behaviour. Their versatility has supported their application in a wide range of cosmetic and cosmeceutical formulations [2-6,8-10,15-17].

Applications in Cosmetics and Cosmeceuticals: Biomimetic and advanced delivery systems have been explored for a wide range of cosmetic and cosmeceutical applications. Their ability to improve the stability, skin delivery, and controlled release of active ingredients makes them useful in the following areas:

1. **Anti-ageing and wrinkle care:** Delivery of active ingredients intended to support skin appearance, reduce the effects of skin ageing, and improve skin condition [1,3,4].
2. **Antioxidant delivery:** Encapsulation and delivery of antioxidant compounds can help improve the stability and topical delivery of sensitive active ingredients [1,3,5].
3. **Sun protection and photoprotection:** Lipid nanoparticles and other nanocarriers have been investigated for the delivery of sunscreen agents and for improving photoprotective performance [1-5,7].
4. **Skin repair and barrier support:** Lipid-based carriers have potential applications in formulations designed to support skin-barrier function and maintain skin condition [2-5].
5. **Topical skin care and dermatological applications:** Advanced delivery systems can facilitate the topical delivery of active ingredients used in various skin-care and dermatological cosmetic formulations [1,4,5].
6. **Hair and scalp care:** Nanocarrier-based cosmetic formulations have also been explored for hair and scalp applications, including hair-care and scalp-care products [1,6].

Challenges and Future Perspectives: Although biomimetic and smart delivery systems provide promising approaches for improving the delivery of cosmetic and cosmeceutical active ingredients, several challenges need to be addressed before their wider application. Maintaining formulation stability during storage is important because changes in carrier characteristics may affect the protection and release of active ingredients. Safety and compatibility with the skin also require careful

evaluation, particularly when novel materials or nanocarriers are intended for repeated use. The cost of specialized materials, equipment and characterization techniques may further limit their large-scale development. Appropriate regulatory evaluation and safety assessment are also necessary to support their successful introduction into cosmetic products [11,14].

Future research should focus on developing safe, stable, cost-effective, and scalable delivery systems with well-established safety and performance profiles [11,14].

Conclusion

Biomimetic and smart delivery systems have emerged as promising approaches for improving the stability, protection, and delivery of cosmetic and cosmeceutical active ingredients. Biomimetic systems can facilitate interaction with the skin, while smart delivery systems offer opportunities for controlled release in response to specific stimuli. These advanced delivery approaches have potential applications in a wide range of cosmetic and cosmeceutical formulations. However, challenges related to safety, stability, manufacturing, scale-up and regulatory evaluation remain. Continued research focused on safe, efficient, and scalable systems may support the development of next-generation cosmetic and cosmeceutical products [1,11,13,14].

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