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Review Article

Nanotechnology-Based Cosmeceuticals: Recent Advances In Skin Delivery Systems And Future Perspectives

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ABSTRACT

Cosmeceuticals represent a rapidly developing category of personal-care products that combine cosmetic functions with biologically active ingredients intended to improve the appearance and condition of the skin. Many cosmetic actives, however, are limited by poor water solubility, chemical instability, rapid degradation, or inadequate localization within the skin. Nanotechnology has emerged as an important formulation strategy for addressing several of these limitations. Nanometer-scale delivery systems can improve dispersion, protect sensitive compounds, influence release kinetics, and promote controlled deposition within selected skin layers. Major nanocarriers investigated for cosmetic applications include liposomes, niosomes, nanoemulsions, solid lipid nanoparticles, nanostructured lipid carriers, ethosomes, transfersomes, polymeric nanoparticles, nanocapsules, and dendritic systems. Recent research has expanded toward phytochemical-loaded nanosystems, multifunctional and hybrid carriers, follicular delivery, stimulus-responsive systems, and more sustainable manufacturing approaches. These technologies have potential applications in anti-aging, photoprotection, skin brightening, moisturization, antioxidant protection, and acne-oriented formulations. At the same time, nanoparticle safety, long-term exposure, environmental fate, regulatory classification, manufacturing reproducibility, and scale-up remain important challenges. This review summarizes the role of nanotechnology in cosmeceuticals, major nanocarriers used for topical delivery, recent advances, and future perspectives. The future development of nanocosmeceuticals will depend on achieving a balance between improved delivery performance, demonstrated safety, regulatory compliance, and sustainable production.

1. INTRODUCTION

The skin is the largest external organ of the human body and performs essential functions including protection against physical and chemical stresses, prevention of excessive water loss, temperature regulation, and interaction with the external environment.

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From a cosmetic perspective, maintaining skin hydration, elasticity, pigmentation balance, and protection against environmental stress is a major objective. Conventional cosmetic formulations can provide useful effects, but delivery of many biologically active compounds remains difficult because the stratum corneum forms a highly effective barrier. [5], [6], [7]

The increasing demand for products with measurable biological effects has contributed to the development of cosmeceuticals. The term generally describes cosmetic products containing biologically active ingredients intended to provide benefits beyond simple cleansing or beautification. Examples include antioxidants, vitamins, peptides, botanical extracts, moisturizers, exfoliating agents, and photoprotective ingredients. [15]

Nanotechnology has introduced new possibilities for improving the performance of such ingredients. Nanostructured delivery systems can modify the physical properties of active substances and influence their distribution, stability, and release after topical application. Research has investigated nanocarriers for improving skin penetration, skin retention, controlled release, and protection of sensitive compounds from environmental degradation. [1], [2], [3]

The application of nanotechnology to cosmetics has therefore developed into the field commonly described as nanocosmeceuticals. Nanocarriers have been investigated for anti-aging products, sunscreens, anti-acne preparations, moisturizing systems, pigmentation-control products, and hair-care formulations. Despite their potential, nanocosmeceuticals should not be considered automatically superior to conventional products. Particle size, composition, surface characteristics, concentration, route of exposure, and formulation design can influence both efficacy and safety. [1], [4], [5]

2. OVERVIEW OF COSMECEUTICAL

2.1 Definition of Cosmeceuticals

Cosmeceuticals are products positioned between conventional cosmetics and pharmaceutical preparations. They contain active substances intended to provide functional benefits to the skin, although the precise legal definition and regulatory status of the term differ between countries. Typical cosmeceutical ingredients include vitamins and vitamin derivatives, antioxidants, peptides, alpha-hydroxy acids, botanical extracts, polyphenols, retinoid-related cosmetic ingredients, moisturizing agents, skin-conditioning compounds, and sunscreen-related ingredients. [15]

2.2 Major Applications

- Anti-aging: reduction of the appearance of fine lines and improvement of skin texture.
- Photoprotection: protection against ultraviolet-associated oxidative and structural damage.
- Skin brightening: management of uneven pigmentation and improvement of skin tone.
- Moisturization: improvement of water retention and barrier function.
- Anti-acne care: delivery of ingredients intended to reduce excessive sebum, inflammation, or follicular blockage.
- Antioxidant protection: delivery of compounds that counteract oxidative stress.
- Hair and scalp care: delivery of active ingredients to follicles and scalp tissue.

3. NANOTECHNOLOGY USED IN COSMECEUTICAL

3.1 Advantages of Nanotechnology in Cosmeceuticals

- Increased apparent solubility of poorly water-soluble compounds. [1], [2], [3]
- Improved physical and chemical stability.
- Protection against light, oxygen, and environmental degradation.

- Enhanced skin deposition and controlled localization.
- Controlled or sustained release.
- Improved dispersion of active ingredients.
- Increased surface area for interaction with the skin.
- Potential targeting of selected skin structures.
- Improved sensory properties of some formulations.

3.2 Mechanism of Improved Skin Delivery

The skin barrier is mainly associated with the stratum corneum, which restricts the movement of many molecules. Nanocarriers may influence topical delivery through increased contact area, improved hydration, controlled release, protection of sensitive actives, and follicular localization. Some lipid-based nanoparticles produce an occlusive film that reduces water loss and may increase hydration of the stratum corneum. However, improved penetration is not always desirable. For many cosmetic applications, deposition in the upper skin layers rather than systemic penetration is the preferred outcome. Modern formulation development therefore increasingly emphasizes controlled localization rather than simply maximizing penetration. [6], [7], [13]

4. NANO CARRIER USED IN COSMECEUTICAL

Table 1. Major nanocarriers used in cosmeceutical skin delivery

Nanocarrier	Basic structure	Major advantages	Typical cosmetic applications
Liposomes	Phospholipid bilayer vesicles	Biocompatibility; carry hydrophilic and lipophilic actives	Vitamins, antioxidants, anti-aging
Niosomes	Non-ionic surfactant vesicles	Good versatility and stability	Botanicals, vitamins, antioxidants
Nanoemulsions	Very small oil/water droplets	High interfacial area; good dispersion	Essential oils, lipophilic actives
SLNs	Solid lipid matrix	Protection, occlusion, controlled release	Sunscreens, moisturizers, anti-aging
NLCs	Solid + liquid lipid matrix	Higher loading potential; flexible release	Antioxidants, vitamins, photoprotection
Ethosomes	Flexible phospholipid vesicles with ethanol	Enhanced deformability and topical delivery	Actives requiring enhanced penetration
Transfersomes	Highly deformable phospholipid vesicles	Flexible skin delivery	Topical and transdermal actives
Polymeric nanoparticles	Polymer matrix or core-shell structure	Controlled release and protection	Antioxidants, botanicals, targeted delivery
Dendrimers	Highly branched polymeric structures	Functionalizable surface	Emerging cosmetic delivery platforms

4.1 Liposomes

Liposomes are vesicular systems composed primarily of phospholipid bilayers surrounding an aqueous compartment. Their amphiphilic structure allows them to accommodate both hydrophilic and lipophilic compounds. They have been widely investigated for delivery of vitamins, antioxidants, botanical compounds, and other cosmetic actives. [1], [10], [14]

4.2 Niosomes

Niosomes are vesicular carriers formed mainly from non-ionic surfactants and cholesterol or related stabilizing components. They are structurally similar to liposomes but can provide different stability and formulation characteristics. They have been studied for delivery of antioxidants, vitamins, plant-derived compounds, and other skin-care ingredients. [1], [14]

4.3 Nanoemulsions

Nanoemulsions consist of very small oil and water droplets stabilized by surfactants or related interfacial components. Their high interfacial area can improve dispersion of poorly water-soluble compounds and make them attractive for essential oils, botanical compounds, and lipophilic antioxidants. [1], [2], [13]

4.4 Solid Lipid Nanoparticles

Solid lipid nanoparticles (SLNs) are colloidal carriers containing a solid lipid matrix. They can protect incorporated substances and provide controlled release. SLNs have been studied for sunscreen, anti-aging, and antioxidant applications. Their occlusive properties may also contribute to increased skin hydration. [9], [10]

4.5 Nanostructured Lipid Carriers

Nanostructured lipid carriers (NLCs) are second-generation lipid nanoparticle systems that generally combine solid and liquid lipids, creating a less ordered lipid matrix than SLNs. This structure can increase loading capacity for some active compounds and reduce limitations associated with highly crystalline lipid matrices. [9], [10]

4.6 Ethosomes

Ethosomes are flexible vesicular systems containing relatively high concentrations of ethanol. Ethanol can increase membrane fluidity and contribute to skin permeation. These systems have been investigated for delivery of compounds that require enhanced topical penetration. [12]

4.7 Transfersomes

Transfersomes are highly deformable vesicles containing phospholipids and edge activators. Their flexibility enables them to pass through narrow pathways within the skin more readily than conventional rigid vesicles. They have potential for improving topical delivery of selected active compounds. [11]

4.8 Polymeric Nanoparticles and Nanocapsules

Polymeric nanoparticles can be designed as matrix systems or core-shell structures. Their properties can be modified through polymer selection, particle size, and surface chemistry. They offer opportunities for controlled release, improved stability, protection of sensitive compounds, surface modification, and potential site-specific delivery. [2], [6]

4.9 Dendrimers

Dendrimers are highly branched, regularly organized nanoscale polymers. Their surfaces contain numerous functional groups that can be modified to interact with active substances. Their controlled architecture makes them an emerging platform for advanced cosmetic delivery. [2], [3]

4.10 Inorganic Nanoparticles

Nanoscale zinc oxide and titanium dioxide have important applications in photoprotective products. Their optical properties can provide ultraviolet protection while potentially improving the cosmetic appearance of formulations. Nevertheless, nanoscale inorganic materials require careful safety evaluation because their biological and environmental behavior can differ from larger particles. [2]

5. RECENT ADVANCES

Nanotechnology-based skin delivery is progressing from simple encapsulation systems toward multifunctional, targeted, and responsive platforms. Recent reviews emphasize advances in lipid nanoparticles, nanoemulsions, vesicular systems, nanofibers, phytochemical-loaded systems, and other engineered nanostructures. [1], [2], [3], [16], [18], [19], [20]

5.1 Advanced Lipid Nanocarriers

Recent research has placed substantial emphasis on SLNs and NLCs because of their potential for skin hydration, occlusion, photoprotection, and controlled delivery. NLCs may offer advantages over SLNs when higher loading or improved release characteristics are required. [9], [10], [17]

5.2 Phytochemical-Loaded Nanocarriers

Plant-derived compounds such as polyphenols and flavonoids are attractive cosmetic actives but may suffer from poor solubility, oxidation, and photoinstability. Nanotechnology can help protect these compounds and improve their formulation performance. Liposomes, SLNs, NLCs, nanoemulsions, and other systems have therefore been explored for phytochemical delivery. [1], [16], [20]

5.3 Nanocarriers for Anti-Aging Products

Oxidative stress, ultraviolet exposure, and age-related changes in extracellular matrix components contribute to visible skin aging. Nanocarriers can potentially improve delivery of antioxidants, peptides, vitamins, and other actives while protecting them from degradation. The objective is increasingly shifting from simply increasing penetration toward maintaining an appropriate active concentration at a desired location for an adequate period. [1], [15], [16]

5.4 Advanced Photoprotection

Nanotechnology has been investigated to improve sunscreen formulations and the dispersion of ultraviolet-protective materials. Nanostructured systems may contribute to improved formulation uniformity and photoprotective performance. Safety assessment remains essential, particularly for nanoparticles capable of interacting with biological tissues. [2], [17]

5.5 Follicular and Site-Oriented Delivery

Hair follicles represent potential reservoirs for topical delivery. Particle size and surface characteristics can influence follicular localization. This approach may be useful for cosmetic applications involving scalp care, sebum regulation, and follicle-associated skin concerns. [7], [16]

5.6 Hybrid and Multifunctional Systems

One important research direction is the combination of different delivery technologies into a single platform. Examples include lipid-polymer hybrid nanoparticles and combinations of vesicles with penetration-enhancing components. Such systems aim to combine stability, loading capacity, controlled release, and improved topical localization. [2], [17]

5.7 Stimuli-Responsive Delivery

Stimuli-responsive systems are designed to alter their behavior in response to environmental factors such as pH, temperature, enzymes, or other biological conditions. Although still emerging in cosmeceutical development, these systems could provide more precise control over when and where an active ingredient is released. [16], [18]

5.8 Nanofibers and Emerging Structures

Nanofibrous materials have attracted attention as advanced topical platforms because their high surface area and porous architecture may support incorporation and gradual release of active compounds. Emerging research is also investigating nanocrystals and other engineered nanostructures for skin and hair applications. [18], [19]

5.9 Safety and Toxicological Advances

The biological behavior of a nanoparticle depends on size, morphology, surface charge, composition, aggregation, and exposure conditions. Potential issues include irritation, oxidative stress, unintended penetration, long-term exposure, environmental release, and interactions with biological barriers. Consequently, efficacy studies should be accompanied by appropriate toxicological and physicochemical characterization. [2], [17], [18]

Table 2. Selected recent directions in nanocosmeceutical research

Recent direction	Potential benefit	Key challenge
Phytochemical nanocarriers	Protect unstable natural actives and improve delivery	Chemical stability and reproducibility
NLC/SLN systems	Controlled release, occlusion and skin hydration	Loading capacity and long-term stability
Follicular targeting	Localized delivery around hair follicles	Controlling particle localization
Hybrid nanoparticles	Combines advantages of different carrier classes	Complex formulation and scale-up
Stimuli-responsive systems	On-demand or condition-dependent release	Predictable response in real skin
Green nanotechnology	Lower environmental and manufacturing burden	Maintaining performance while reducing processing impacts
AI-assisted formulation	Faster optimization and prediction	Quality of training data and validation

6. FUTURE PERSPECTIVES

6.1 Personalized Nanocosmeceuticals

Individual differences in skin type, age, pigmentation, hydration, barrier condition, and environmental exposure influence cosmetic requirements. Future formulations may therefore be designed for specific skin profiles rather than using a single formulation for a broad consumer population. [16]

6.2 Precision Skin Delivery

Future nanocarriers may be engineered to deliver active substances preferentially to the epidermis, dermis, hair follicle, or other selected skin structures. The objective will be controlled localization rather than unrestricted penetration. [7], [16]

6.3 Smart and Stimuli-Responsive Systems

Smart nanoparticles capable of responding to pH, temperature, enzymes, or other local conditions could provide more controlled release. Such systems may reduce unnecessary exposure of the active ingredient and improve formulation efficiency. [16], [18]

6.4 Green Nanotechnology

Sustainable production is expected to become increasingly important. Future research may emphasize biodegradable carriers, naturally derived lipids, plant-based materials, low-energy manufacturing, reduced solvent use, and environmentally responsible packaging. [18], [20]

6.5 Improved Safety Evaluation

Long-term consumer exposure is an important consideration because cosmetic products may be applied repeatedly over many years. Future research should establish standardized approaches for assessing skin penetration, systemic exposure, local toxicity, phototoxicity where relevant, immunological effects, and environmental fate. [2], [17], [18]

6.6 Regulatory Development

The regulatory status of nanomaterials can vary according to jurisdiction and intended use. As the technology develops, clearer characterization requirements, standardized testing, and appropriate labeling frameworks will become increasingly important. [2], [18]

6.7 Industrial Scale-Up

Laboratory-scale preparation does not automatically translate into successful commercial production. Particle aggregation, batch-to-batch variation, contamination, stability loss, and production cost must be addressed. Future manufacturing strategies should focus on reproducible processes that maintain critical particle characteristics at larger scale. [1], [2], [17]

6.8 Artificial Intelligence and Formulation Design

Artificial intelligence and computational modeling may assist researchers in predicting interactions among carrier composition, particle characteristics, active ingredients, and skin properties. Such approaches could shorten formulation-development cycles and support rational design of next-generation nanocosmeceuticals. [18], [20]

7. CONCLUSION

Nanotechnology has become an important platform for the development of advanced cosmeceuticals and topical skin-delivery systems. Conventional cosmetic formulations can be limited by poor solubility, instability, degradation, and inadequate localization of active ingredients. Nanocarriers such as liposomes, niosomes, nanoemulsions, SLNs, NLCs, ethosomes, transfersomes, and polymeric nanoparticles provide different strategies for overcoming these challenges. [1], [2], [3], [5]

The major potential benefits of nanotechnology include protection of sensitive compounds, improved dispersion, controlled release, increased skin deposition, and the possibility of more precise delivery. Recent developments are moving toward multifunctional lipid systems, phytochemical-loaded nanoparticles, follicular delivery, hybrid carriers, and responsive nanostructures. [1], [6], [9], [10], [11], [12]

However, the development of nanocosmeceuticals must proceed with appropriate consideration of safety. Increased delivery should not be treated as an objective by itself; the desired outcome is safe and controlled localization of active ingredients. Long-term toxicological assessment, standardized characterization, environmental evaluation, regulatory clarity, and scalable manufacturing remain important challenges. [2], [17], [18]

Future nanocosmeceuticals are likely to become increasingly sophisticated, personalized, and sustainable. Integration of nanotechnology with biotechnology, green chemistry, and computational formulation design may create a new generation of skin-care products with improved stability and controlled performance. Successful translation will ultimately depend on demonstrating that the advantages of nanoscale delivery are accompanied by reliable safety, reproducibility, and meaningful consumer benefits. [16], [18], [20]

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