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NANOSTRUCTURES IN COSMETIC FORMULATIONS

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Abstract: The beginnings of nanotechnology date back to 1959, when Richard Feynman gave his famous lecture that has inspired many scientists. The development of methods of obtaining results (top-down and bottom-up) over the following years has meant that a multitude of nanometric structures are now known, and knowledge about their properties and application possibilities is also broader.

Today, cosmetics manufacturers choose nanostructures for several reasons, namely: penetration through the skin, targeted delivery of active ingredients, achieving stability, and obtaining new color elements.

This article is a review of the latest knowledge about the properties of nanostructures and their application potential for cosmetic formulations.

Keywords: nanomaterials, cosmetics, quality, liposomes.

1. INTRODUCTION

Richard Feynman's famous lecture "There's plenty of room at the bottom" from 1959 initiated the development of nanotechnology. The dynamic progress of nanotechnology is indicated by the increase in the field of nanomaterials of patents granted in the world, from 224 in 1991 to 12,776 in 2008 [Chávez-Hernández et al., 2024]. The development of "top-down" and "bottom-up" methods of obtaining nanometric structures has resulted in their wide application use. Literature data indicate that a particularly large number of nanomaterials are being introduced into the formulation of personal care and cosmetic products [Sharma et al., 2023]. Over the past twenty years, the cosmetics industry in the world has developed dynamically, achieving an average annual growth of 4.5%. This is one of the factors driving the implementation of cosmetic product innovations, including those related to the use of nanomaterials [Liu et al., 2022].

2. NANOMATERIALS IN COSMETICS FORMULATION

Currently, nano systems are used in cosmetic products for two main reasons: they can improve the properties of cosmetic ingredients and can increase skin penetration. The effect of improving the properties is achieved through prolonged release, increased physicochemical stability, reduced irritability, improved texture quality, and improved dispersion/distribution properties of the active cosmetic ingredients. Nanomaterials can also play a protective role and improve the physicochemical stability of sensitive ingredients of the cosmetic composition and thus the entire formulation. The reduction in size is also correlated with the improvement of utility properties, i.e., product spread ability [Ferraris et al., 2021].

For nanoparticles, a high surface-to-volume ratio is observed as well as a change in the chemical potential difference between the particles and the surrounding medium; these factors make nanomaterials useful for transdermal administration. So far, three routes of nanoparticle penetration through the skin have been described, namely intercellular, intracellular, and trans appendageal. Nanoparticles diffuse through the lipid matrix surrounding corneocytes in the stratum corneum (SC) via the intercellular route and then partition between the lipid bilayers and the aqueous domain. The intracellular route involves transfer directly through corneocytes in the SC and keratinocytes beneath the SC. Nanoparticles can also penetrate hair follicles (trans appendageal route) [Maeda et al., 2024].

LIPOSOMES

The simplest structural liposomes are formed by a phospholipid bilayer that forms a vesicle. The bilayer is amphiphilic, with polar heads directed toward the aqueous phase. The substrate for creating liposomes dedicated to cosmetic applications is most often phosphatidylcholine, but also lysophosphatidylcholine, phosphatidylinositol, phosphatidylethanolamine, and phosphatidylglycerol. The widespread use of liposomes in cosmetic formulations is due to their beneficial properties, including biocompatibility, versatility, ability for targeted delivery and release, and ease of preparation. The biocompatibility of liposomes results from the structural similarities between the phospholipids that make up cell membranes and the phospholipids that build the liposome bilayer. In turn, the amphiphilic structure of liposomes entails versatility in the ability to encapsulate both hydrophilic and hydrophobic particles. Over the years, procedures have been developed for constructing and modifying liposome structures, enabling targeted delivery and release. Thus, liposomes have become structures capable of being released at a specific time and place [Chaves et al., 2023].

Nowadays, dermatologists emphasize that the first anti-aging action is the use of sunscreens. The available literature presents numerous results indicating the possibility of using liposomes in products aimed at sun protection. One of the first studies showing a positive correlation between liposomes and sunscreens was

presented by Golmohammadzadeh et al. They proved that the SPF value for products containing liposomes carrying octyl methoxycinnamate (OMC) was higher compared to emulsions containing the corresponding concentrations of OMC. The authors also indicated the penetration of liposomal systems containing OMC into deeper layers of the skin in comparison with an o/w emulsion containing OMC [Golmohammadzadeh et al., 2008]. In recent years, the growing popularity of products containing peptides as active substances reducing the effects of skin photoaging can be observed among consumers. Liposomes were also used in systems with a controlled peptide release profile for up to 24 hours, obtaining an optimized formulation [Shahi & Athawale, 2010].

One symptom of excessive sun exposure is uneven skin pigmentation, while the frequently used agents to lighten skin discolorations are hydroquinone, arbutin, and vitamin C. The inclusion of these substances in a cosmetic formulation may be associated with certain limitations. Hydroquinone is susceptible to oxidation, but its liposomal form shows improved stability. In addition, the combination of hydroquinone and kojic acid in the liposomal form allowed for a synergistic effect of lightening discolorations and minimizing side effects [Aparajita & Ravikumar, 2014]. In turn, the encapsulation of arbutin in liposomes resulted in an increased deposition in the epidermal layers, which suggests increased whitening activity [Wen et al., 2006]. Vitamin C also affects skin pigmentation by reducing melanin synthesis. In addition, ascorbic acid is a recognized ingredient in cosmetic formulations as it provides antioxidant protection and increases collagen synthesis. However, the poor stability and high hydrophilic nature of its protonated form mean that the absorption of vitamin C by the skin is limited. The latest studies indicate that the use of elastic cationic liposomes improves the efficiency of vitamin C encapsulation and increases its delivery to the skin layers [Caritá et al., 2023]. Encapsulated derivatives of vitamin C were also tested, e.g., sodium ascorbyl phosphate, which is considered an effective free radical scavenger. In this case, the liposomal form penetrated the skin more deeply [Foco et al., 2005].

It seems that vitamin A and its derivatives are considered the gold standard in limiting the processes of ageing and photoaging. It has been proven that retinoids affect the proliferation of keratinocytes, the synthesis of collagen fibers and elastin, and limit the degradation of collagen, thus supporting the reduction of wrinkles, discolorations, and hence slowing the ageing processes. However, the use of retinoids is associated with limitations resulting from their poor solubility in water, photosensitivity, and irritating effect on the skin. These effects can be reduced by using, for example, deformable liposomes. These liposomes are known under the name Penetration Enhancing Vesicles (PEV). Their activity is based on a temporary reduction barrier property of the skin but also on increasing the mobility and elasticity of the lipid bilayer of the vesicles. PEV also allows for the gradual release of retinoids, which limits irritation [Zhong et al., 2024].

Despite the frequent use of liposomes and the constant improvement of their production technology, there are still challenges associated with the transition to the stage of industrial production. Not all methods can be scaled up; the most common causes include problems with hydration of the large lipid layer, foaming, and product degradation. Industrial conditions require strict control to maintain the consistency of several key characteristics: particle size, lamellar structure, and encapsulation efficiency. It is recognized that scaling up liposome production is resource-intensive [Basak & Das, 2025; Shah et al., 2020].

NIOSOMES

Niosomes take the form of nanometric vesicles, the membrane of which is formed by a bilayer [Moammeri et al., 2023]. The main building block of the niosome bilayer is non-ionic surfactants, which have an amphiphilic structure with a polar head and a non-polar tail. In most niosome structures, cholesterol is also an essential building block, which affects the stability of the niosome membrane. It is estimated that cholesterol, interacting with non-ionic surfactants, also affects the stiffness of the bilayer [Fadaei et al., 2024; Mawazi et al., 2022]. Currently, niosomes together with liposomes are the most used delivery systems in cosmetics. This is due to several advantages of niosomes: low toxicity, biocompatibility, lack of immunogenic effect, chemical stability, and stability in variable pH. The ease of obtaining it, accompanied by low costs, is also important [Lens, 2025; Purohit et al., 2022]. Work on niosomes dedicated to cosmetic applications has been carried out since the 1970s; the first cosmetic company to patent a product with niosomes was L'Oréal [Sharma et al., 2023]. The available literature reports indicate that niosomes, in some cases have better application properties than liposomes. An example of this is the fact that tretinoin encapsulated in niosomes showed a higher level of retention in the skin than was the case with liposomal tretinoin [Zhong et al., 2024].

It was also proven that niosomes can be carriers of antioxidants that generally show low adsorption capacity in the skin. Such use of niosomes can improve adsorption and increase bioavailability, reducing irritation [Lens, 2025].

The sun protection activity of ZnO nanoparticles and the same particles encapsulated in niosomes was also compared. The results indicated that the system consisting of niosomes and ZnO nanoparticles showed a prolonged protective effect [El-Saadony et al., 2024].

In recent years, *Centella asiatica* has enjoyed undisputed popularity as an ingredient in cosmetic formulations. Asiaticoside and madecassoside are primarily responsible for the dermatological and pharmacological activity of *Centella asiatica* extracts. A way to fully utilize the activity of *Centella asiatica* extracts is to improve the penetration of asiaticoside and madecassoside into the stratum corneum of the epidermis. Studies have shown that niosomes containing *Centella asiatica* extract

improved the penetration of asiaticoside through the stratum corneum and increased its retention in the dermis of animals [Wichayapreechar et al., 2020].

Manosroi et al. also observed improved transepidermal absorption for a gel containing niosomal papain compared to a product based on free papain. Furthermore, niosomal papain demonstrated better chemical stability [Manosroi et al., 2013].

It is assumed that niosomes have higher chemical stability and flexibility compared to liposomes [Starzyk et al., 2008], but their use is associated with certain challenges. The most significant are the risks of sedimentation, accumulation, fusion, or leakage of the entrapped component during storage. Some methods for obtaining niosomes require refinement to shorten the preparation time. Furthermore, niosome preparation is associated with the risk of incomplete hydration of surfactants during the hydration process [Khokale et al., 2026].

DENDRIMERS

Another class of nanostructures used in modern cosmetic formulations are dendrimers. These are particles with a highly symmetrical and hyperbranched structure, resembling a tree. The architecture of dendrimers is unique, distinguished by a core to which "branches" are attached, with their structure being characterized by branching points and cavities. The peripheral surface of the dendrimer is rich in functional groups. The structure of dendrimers is characterized by repeating architecturally identical groups known as dendrons [Bacha et al., 2023]. The highly symmetric architecture of dendrimers requires methods of preparation that allow for control of the structure throughout the process. In the techniques of their synthesis, two approaches dominate: divergent and convergent. The divergent method involves synthesis from the core towards the periphery. This technique consists of a sequence of repeated steps: coupling of monomers and then activation of their end groups. To counteract the growth limitation resulting from this method, an alternative convergent synthesis strategy was developed. This method involves synthesis starting from the outer surface; the resulting dendrons are connected to a core-forming molecule. The divergent technique is particularly advantageous in the formation of dendrimers with asymmetric or mixed structures [Patel et al., 2022a]. Regardless of their chemical structure, dendrimers are said to have the ability to self-organize, be polyvalent, and be monodisperse, but their most important feature is the ability to encapsulate and transport chemical substances. The encapsulation process is influenced by several factors, including surface charge, the nature of the terminal groups, core structure, and pH [Gupta et al., 2022; Patel et al., 2022b].

In cosmetic formulations, dendrimers and their ability to encapsulate are primarily used to protect active substances from factors that may affect their stability, e.g., pH, temperature, and oxidation. Revlon has used Polyamidoamine dendrimers (PAMAM) to encapsulate salicylic acid in cosmetic and personal care products. These systems are further stabilized by ionic interactions between the carboxyl group of

salicylic acid and the amine group of the dendrimer. The salicylic acid-PAMAM complex has also been used in color cosmetics, where its presence allows for the elimination of interactions with iron oxide pigments [Ammala, 2013]. Encapsulation with dendrimers can also overcome solubility problems, as has been reported for riboflavins, while also achieving improved transepidermal diffusion [Filipowicz & Wołowiec, 2011]. Another approach to the use of dendrimers was reported in a patent by L'Oréal; namely, it was proposed to use the activity of dendrimers to absorb odors in deodorants [Ammala, 2013]. Dendrimers can also be classified as polymers, but their viscosity distinguishes them from traditional polymers. It is believed that dendrimers achieve the highest viscosity for the 4th generation; further increasing the number of generations will be accompanied by a decrease in the viscosity value. This relationship is not observed for traditional polymers, for which an increase in molecular weight is usually correlated with an increase in the viscosity value. L'Oréal has developed an innovation aimed at overcoming the problems resulting from the use of high molecular weight polymers. This innovation assumes the use of dendrimers in low-viscosity products and obtaining the expected results after contact with the skin [Patel et al., 2022a].

Dendrimers that act as antioxidants on their own also appear to have potential applications. Agbemade and co-workers obtained syringaldehyde-based antioxidant dendrimers built on a D-mannitol scaffold. Their results indicated that the dendrimers exhibited higher DPPH radical scavenging activity compared to the starting materials: syringaldehyde and BHT [Agbemade et al., 2025].

Recent years have also seen research into the use of dendrimers as agents that improve bioavailability and extend half-life. An example of this is the functionalization of caffeic acid and cinnamic acid with polyamidoamine dendrimers. The resulting compounds positively influenced the wound healing process and activated the molecular mediators of the wound healing process [Castro et al., 2025].

The use of dendrimers is not without its challenges, including the synthesis of higher generations, low synthesis efficiency, and the potential toxicity of cationic dendrimers [Roszkowski & Durczynska, 2025].

3. CONCLUSIONS

The available literature on the application potential of nanomaterials in cosmetics is very extensive. Many nanomaterials have already been included in cosmetic applications, others are recommended, while many are in the research phase. This article presents the application potential of liposomes, niosomes, and dendrimers. These materials have been extensively researched, and it seems that the knowledge about their applications in cosmetics is the greatest so far. The analysis of the literature indicates that in the future, more patent applications in the field of cosmetics will concern the use of carbon nanotubes, fullerenes, graphene, or nanospheres.

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