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Nanobiotechnology to Make Innovative Pro-Aging Cosme-Nutraceuticals

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Abstract

The aging process is a complex succession of biological phenomena that, among others, cause epidermal thinning with a slowdown of its turnover. Concurrently, the dermis loses collagen and elastin, leading to the appearance of fine lines and wrinkles on the faces of both women and men who desire to maintain a youthful appearance and achieve a longer life. Consequently, there is a widespread pursuit of rejuvenation through the use of cosmeceuticals and nutraceuticals, aligning with the concept of "Beauty from Within". This approach involves the contemporary use of the same active ingredients, applied topically via cosmetics and ingested orally through dietary supplements. This paper, by examining the structure and functions of the skin and mucous membranes and their associated aging phenomena, emphasizes the necessity of developing products that are effective and safe. Such products must possess the capacity to cross the barriers of these biological structures without provoking any side effects. To this end, novel tissue-carriers, fabricated from biodegradable polymers, are proposed as an integrated solution, creating advanced cosme-nutraceuticals that are not only highly effective and skin-friendly but also address the critical environmental challenge of plastic waste.

Keywords: skin; mucous membranes; aging phenomena; penetration enhancers; cosmeceuticals; nutraceuticals; carrier; active ingredients

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Introduction

The aging process is a complex set of biological phenomena that cause epidermal thinning and a slowdown in cellular turnover. Simultaneously, the dermis loses collagen and elastin, leading to the appearance of wrinkles and fine lines. As a youthful appearance begins to fade, people are living longer and increasingly wish to look younger[1]. In fact, the market for the population aged 60 and above has reached USD 28.04 billion (19.8%) in 2022, while the market for those aged 65 and over accounted for USD 209.78 billion (14.9%)[2,3]. Moreover, the global population aged 60 and older is projected to increase from 1.1 billion in 2023 to 2.4 billion by 2030 (Fig. 1)[4].

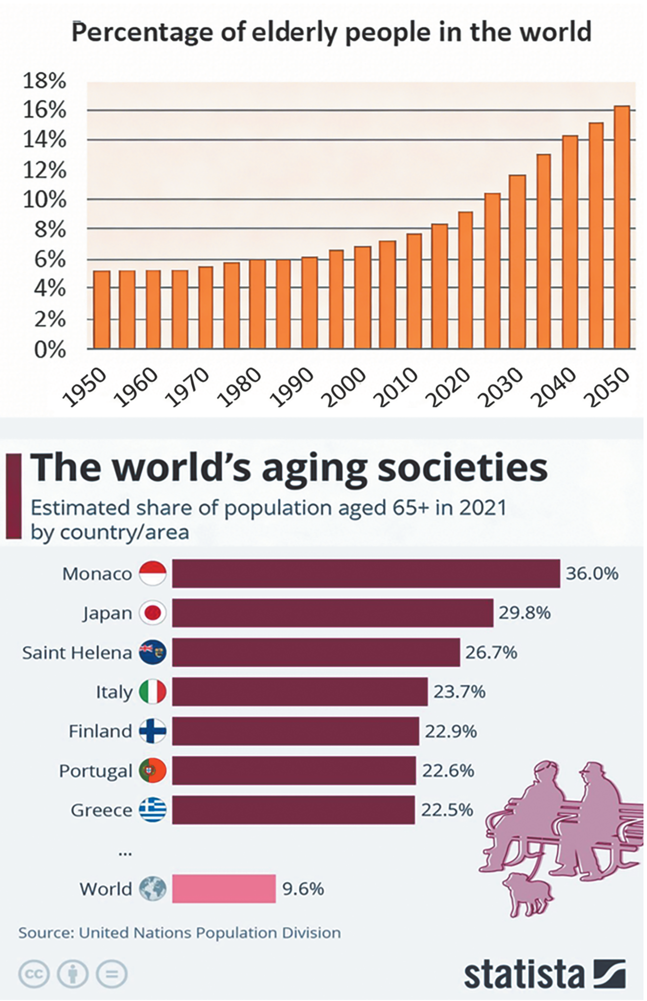


Figure 1: The global percentage of elderly 65+ in different countries by 2022 (courtesy of Chernburmroog et al.[2] and Zandt[3]).

To better understand these new denominations, it is necessary to consider their definition. "Pro-aging" or "pro-age" products are defined as "all the products that, referring to the holistic approach to aging phenomena, are focused on maintaining health and quality of life throughout the lifespan rather than solely preventing or reversing the aging process"[5]. For these reasons, consumers are increasingly requesting and prioritizing the purchase of cosmetics and dietary supplements considered to have this "pro-aging" activity. Consequently, particularly among younger generations such as Millennials (aged 30–45) and Gen Z (aged 14–29), people are seeking cosme-nutraceuticals that are believed to address the molecular hallmarks of aging and may enhance both health and beauty, thereby increasing longevity[6].

Furthermore, consumers prefer high-quality, science- and nature-oriented products that are also supported by social media and opinion leaders. In this context, cosmeceuticals and nutraceuticals are considered to possess effectiveness and safety due to their content of selected active ingredients and carriers. Naturally, both effectiveness and safety must be scientifically validated through biological and clinical tests. It is necessary to underline, however, that the younger generations represent 25% of consumer expenditure on wellness, accounting for 40% of the market spend[6,7].

This review, therefore, posits that the next generation of pro-aging solutions must address a dual challenge: not only achieving superior clinical efficacy through advanced delivery systems but also aligning with growing consumer and regulatory demands for environmental sustainability. We will argue that nanobiotechnology, specifically through the development of biodegradable, tissue-based carriers, offers an integrated solution to this dual challenge. The following sections will first establish the physiological basis for pro-aging interventions and the limitations of current carriers, then explore how novel nanocarriers can enhance the delivery of key active ingredients, and finally, contextualize this technological advancement within the urgent need to mitigate the environmental impact of the cosmetics industry, particularly plastic pollution.

Skin and mucous membranes: structure, functions, and aging

Skin

The skin is the largest organ of the human body, composed of three distinct layers: the epidermis, dermis, and hypodermis. It performs crucial functions, including thermoregulation, sensation, absorption, excretion, and vitamin D synthesis[8]. The epidermis, the outermost layer, is further subdivided into five strata, with the stratum corneum (SC) acting as the primary physicochemical barrier against external aggressions. This cornified layer is critical for preventing excessive water loss and regulating the penetration of substances. The continuous renewal of the SC, a process involving the transformation of keratinocytes into corneocytes over a 40–56-day cycle, is vital for maintaining homeostasis (Fig. 2)[9].

The barrier function of the SC is largely attributed to its unique molecular structure, often described as a "lamellar body". This structure consists of a keratinized network containing a mixture of lipids—primarily ceramides, cholesterol, and free fatty acids—organized in a crystalline matrix (Fig. 3 and Fig. 4)[8–12]. The transition of this lipid organization from a crystalline to a liquid state is considered a key mechanism for enabling the permeation of active ingredients. As the skin ages, a modified cellular turnover and thinning of its layers are accompanied by a reduction in water content and lipid integrity, leading to the visible appearance of fine lines and wrinkles.

Mucous membranes

Unlike the skin, which is protected by an acidic lipid-water coating, the mucous membranes of the oral and vaginal tracts are specialized epithelial tissues covered by a protective and lubricating mucus[13]. This mucus, a mixture of polymeric glycoproteins, acts as a selective barrier, trapping pathogens and inhaled particles while enabling the entry of small molecules, a process regulated by enzymes, van der Waals forces, and hydrogen bonding. It also plays a vital role in immunity through the production of specific immunoglobulins and maintains physiological equilibrium via the local microbiota[13,14].

The aging of mucous membranes involves modifications to the local microbiota and detrimental metabolic

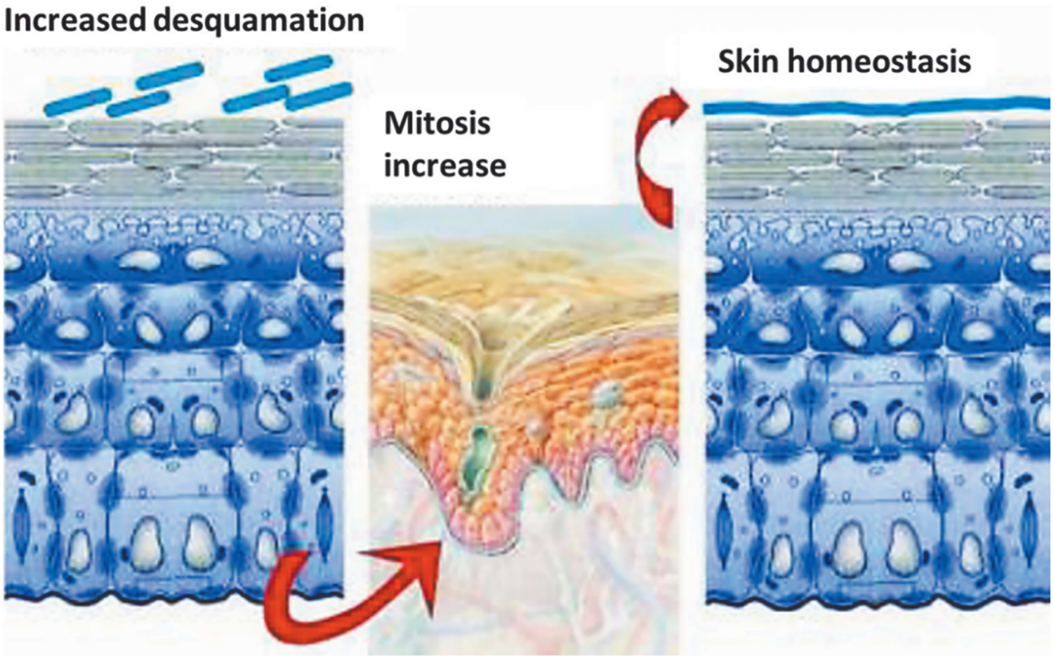


Figure 2: The skin turnover and desquamation process to maintain the body's homeostasis (courtesy of Morganti et al.[9]).

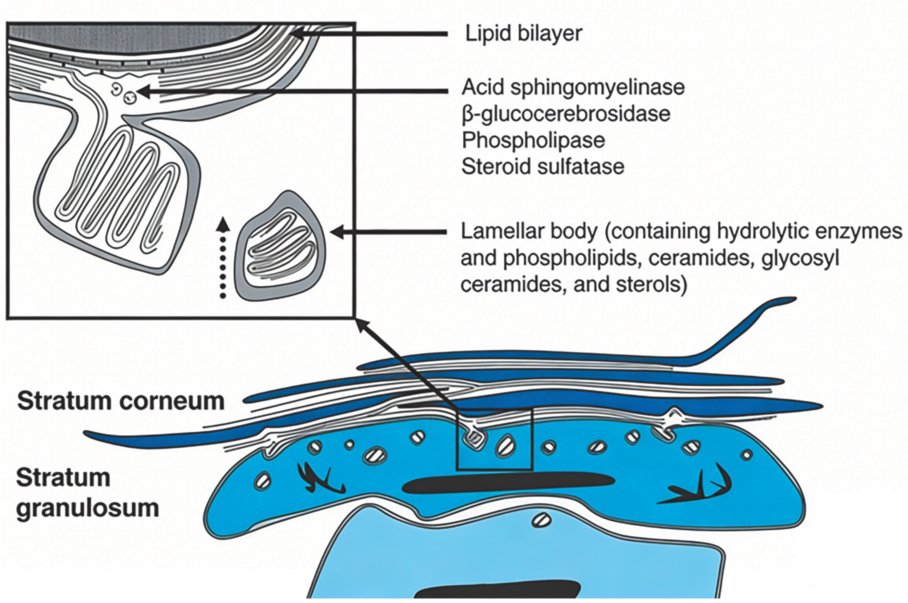


Figure 3: Lamellar body and its lipid content (courtesy of Morganti et al.[9]).

changes, which contribute to age-associated declines in immune function and lead to conditions such as dryness[15,16]. Consequently, the goal of pro-aging cosme-nutraceuticals is to slow these degenerative phenomena in both skin and mucous membranes, often by employing the same active ingredients both topically and orally to achieve the so-called "Beauty from Within".

Carriers and active ingredients

Carriers

In the pursuit of next-generation cosme-nutraceuticals, carriers (or vehicles) are of fundamental importance for addressing the dual challenges of efficacy and sustainability. These ingredients, once selected and embedded into different structures, play a crucial role in their function on the skin and mucous membranes. Specifically, carriers must load, transport, and release the ingredients at the level of the epidermis and mucous membrane layers, at the programmed time and dose. According to scientist J.W. Wiechers, this activity depends on the so-called "4R's delivery", that is, Right chemical, Right concentration, Right site, Right time. Thus, the proposed role of a delivery system is "to ensure that the right concentration of the right chemical reaches the right site in the body for a sufficiently long and correct period of time"[17]. By doing so, it is possible to achieve the effectiveness and safety of the ingredients selected for the formulation of drugs and/or cosme-nutraceuticals. For this purpose, many different carriers can be used in various topical formulations, such as gels, oils, O/W (oil-in-water) and W/O (water-in-oil) macro- and microemulsions, or through the innovative tissues reported and discussed below, as suggested by our group in various studies[18–23]. However, all carriers should possess the necessary physicochemical and biological characteristics, for example, to mimic the basic structure of the skin and mucous membranes, thereby permeating the different cutaneous and mucous barriers via various transit pathways (Fig. 5)[24].

Therefore, carriers must be studied, formulated, and controlled to achieve the optimal capacity for loading and transporting selected active ingredients, releasing them into different body sites at the programmed dose and time[17]. The penetration of the skin and mucous membranes is influenced by many factors, such as the condition of the skin/mucous membranes (healthy or diseased), the physicochemical and biological characteristics of both ingredients and carriers, the influence of the formulation design, the optimization of skin penetration modality, the dosing condition, and the product's modality of use[21]. For this purpose, the

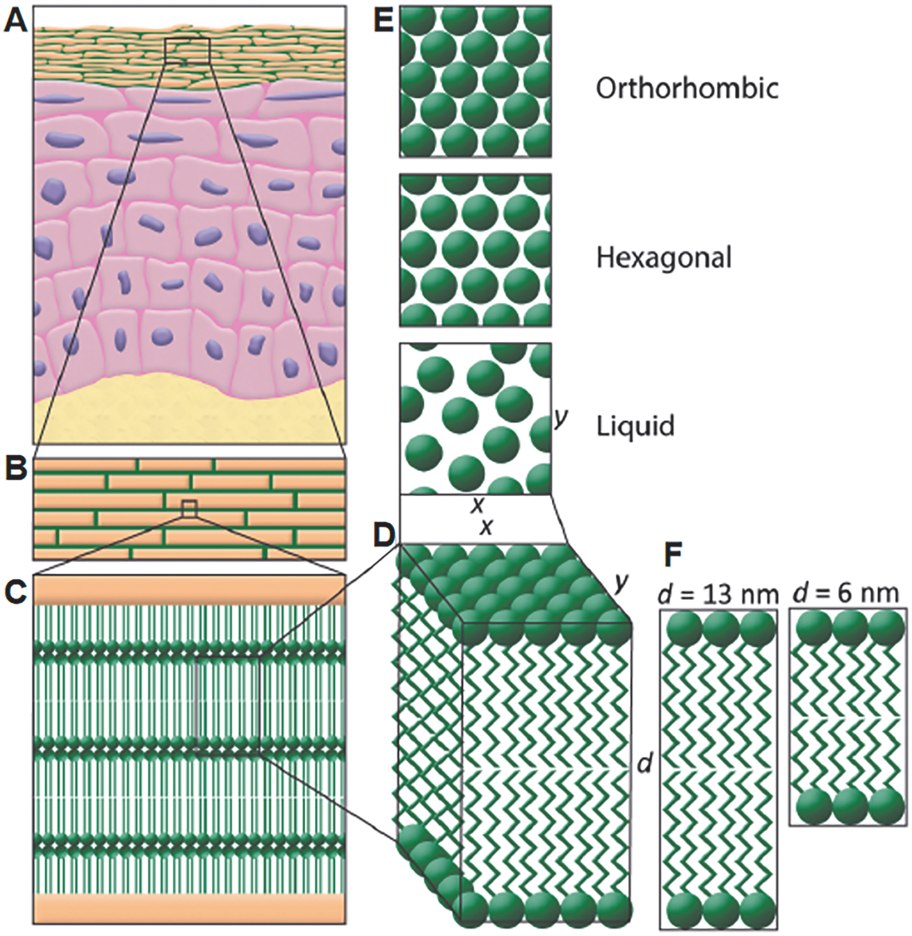


Figure 4: Different structures of the stratum corneum crystalline/liquid matrix (courtesy of Berkers et al.[11]).

(A) Schematic overview of the skin. (B) The brick-and-mortar structure mimics the corneocytes embedded in the lipid matrix. (C) In between the corneocytes, the lipids are stacked in lamellae. (D) Detail of the lipid lamellae. (E) Perpendicular to the lamellae, the lipids are organized in a lateral packing. This can be either orthorhombic, hexagonal, or liquid (top view). (F) The lipid lamellae are stacked on top of each other with a repeat distance (d) of either 13 nm (long periodicity phase) or 6 nm (short periodicity phase). The 13 nm LPP, illustrated here in a simplified manner, is formed by a complex "sandwich-like" repeating unit comprising multiple lipid layers, whereas the 6 nm SPP corresponds to a simpler lipid bilayer structure.

selected encapsulation of ingredients, the micro/nano size of the carrier's components, and the embedded active ingredients provide great flexibility in the choice of delivery mechanisms. This is the reason for our proposal to use specialized tissues as carriers, as an alternative to current emulsions.

Beyond the technical aspects of efficacy and safety, the translation of nanocarrier-based products from the laboratory to the market faces significant regulatory challenges. Regulatory bodies worldwide, including the U.S. Food and Drug Administration (FDA) and the European Commission's Scientific Committee on Consumer Safety (SCCS), have established specific frameworks for nanomaterials in cosmetics and food supplements. Key hurdles include the lack of a globally harmonized definition of a "nanomaterial", which can create ambiguity. Furthermore, products containing nanomaterials often require a more rigorous safety assessment dossier, including data on physicochemical characterization, toxicokinetics (absorption, distribution, metabolism, and excretion), potential for bioaccumulation, and long-term effects. For instance, in the European Union, cosmetic products containing nanomaterials must be explicitly notified to the authorities and listed in the ingredients declaration with the suffix "(nano)". These regulatory requirements, while essential for consumer protection, add complexity and cost to the product development

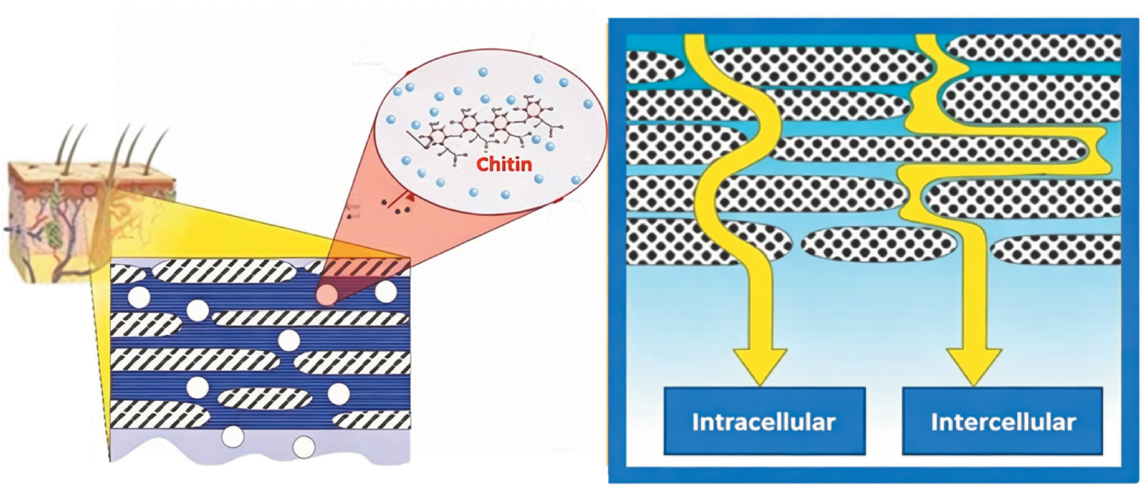


Figure 5: The main transit ways of penetration through the skin (courtesy of Morganti et al.[24]).

lifecycle, and must be a central consideration for any entity aiming to commercialize nanocarrier technology.

Beyond the regulatory hurdles for the nanomaterials themselves, the choice of final product packaging and its environmental footprint represents another critical dimension of sustainability, which will be discussed in a later section.

Fabrication of tissue carriers

The proposed tissue-carriers are fabricated from natural, biodegradable polymers such as chitin—often sourced from renewable crustacean shell waste—using electrospinning and air-spraying technologies. Initially, the active ingredients are selected and encapsulated into a complex of chitin nanofibrils/nanolignin (CN-NL). The obtained microcapsules are then air-sprayed and added to the electrospinning gel/suspension. This gel, carefully controlled for its density, is electrospun with the precisely dosed energy to obtain the designed tissue, characterized by a structure similar to the physiological extracellular matrix (ECM) (Fig. 6)[22,23].

These novel nanobiotechnological tissue-vehicles, embedding and activated by the selected and encapsulated ingredients, have been characterized by different technologies such as fourier transform infrared (FTIR) spectroscopy, thermogravimetric analysis (TGA), dynamic light scattering (DLS), cell viability assays, and other analytical methods. While this review does not present primary data, our previous work, cited herein, has characterized these critical parameters. For instance, fabrication is typically conducted using specific electrospinning parameters (e.g., polymer solution concentrations of 5%–10% w/v, applied voltages of 15–25 kV, and flow rates of 0.1–0.5 mL/h) to achieve desired fiber morphology and porosity[22,23]. Our studies have consistently demonstrated high encapsulation efficiency (> 90%) for various active ingredients within the CN-NL complex. Stability data from TGA confirm that the encapsulation provides significant protection against thermal degradation, increasing the decomposition temperature of active ingredients by as much as 50–100 °C compared to their free form[25]. Furthermore, *in vitro* release profiles typically exhibit a beneficial biphasic pattern: an initial burst release for immediate effect, followed by a sustained release over 8–12 h as the active ingredient gradually diffuses from the nanofiber matrix. Crucially, direct comparative studies have validated the superiority of this system, showing that these tissue-carriers can release active ingredients more rapidly and in significantly higher quantities compared to conventional O/W emulsion formulations[9]. Therefore, it has been possible to control the encapsulation range, thermal stability, compatibility, composition, effectiveness, and safety of the obtained formulations (Fig. 7)[25]. By doing so, innovative cosmeceuticals and nutraceuticals have been realized, enriched by the selected and encapsulated active ingredients necessary to characterize their effectiveness and safety. Encapsulation, in fact, protects them from environmental oxidative effects, increasing the

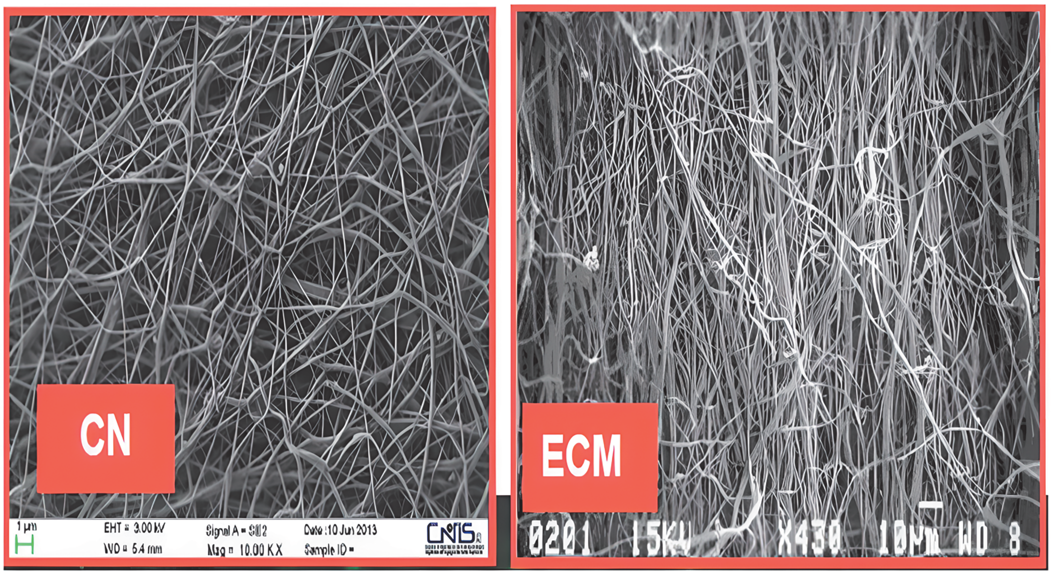


Figure 6: Chitin nanofibrils-nanolignin tissue has a network similar to the skin matrix (courtesy of Morganti et al.[19]).

ingredients' penetrability through the skin and mucous barriers[18–20,22,23,25–28].

Moreover, these novel vehicles, unlike emulsions, are free of preservatives, emulsifiers, fragrances, and other chemicals, which often cause allergic and/or sensitization phenomena.

Active ingredients

Among the natural pro-aging ingredients frequently utilized by our group are nicotinamide, ascorbic acid, allantoin, and lutein. The selection of these agents is based on their well-documented biological activities. However, a critical evaluation reveals that their practical efficacy in conventional formulations is often hampered by significant challenges related to stability, penetration, and controlled bioavailability. This section discusses these limitations and posits how the proposed nanocarrier technology offers a mechanistic solution to overcome them, thereby translating theoretical benefits into tangible clinical outcomes.

Nicotinamide

Nicotinamide mononucleotide (NMN), an amide form of vitamin B3, is a celebrated precursor to the essential coenzyme nicotinamide adenine dinucleotide (NAD^+), which is vital for cellular metabolism, DNA repair, and mitigating inflammatory responses[29–31]. However, a critical challenge for topical NMN is its delivery. As a relatively large and hydrophilic molecule, its ability to independently permeate the lipophilic SC in sufficient quantities to effect a meaningful increase in intracellular NAD^+ is a subject of ongoing scientific debate. Simple topical application often results in a low bioavailability, limiting its true pro-aging potential.

The proposed CN-NL tissue-carrier mechanistically addresses this delivery challenge. The nanofibrous structure, mimicking the ECM, creates a large surface area for intimate contact with the skin, acting as a penetration enhancer by transiently modulating the lipid barrier. More importantly, the inherent bioadhesive properties of chitin ensure prolonged residence time on the skin surface, creating a sustained concentration gradient that drives the diffusion of NMN into the epidermis. This system ensures that a significantly higher payload of NMN reaches the viable epidermal cells where it is needed, moving beyond a superficial, low-bioavailability application to a truly effective delivery strategy[25].

Vitamin C

Ascorbic acid (vitamin C) is a potent antioxidant that protects against reactive oxygen species (ROS)/reactive

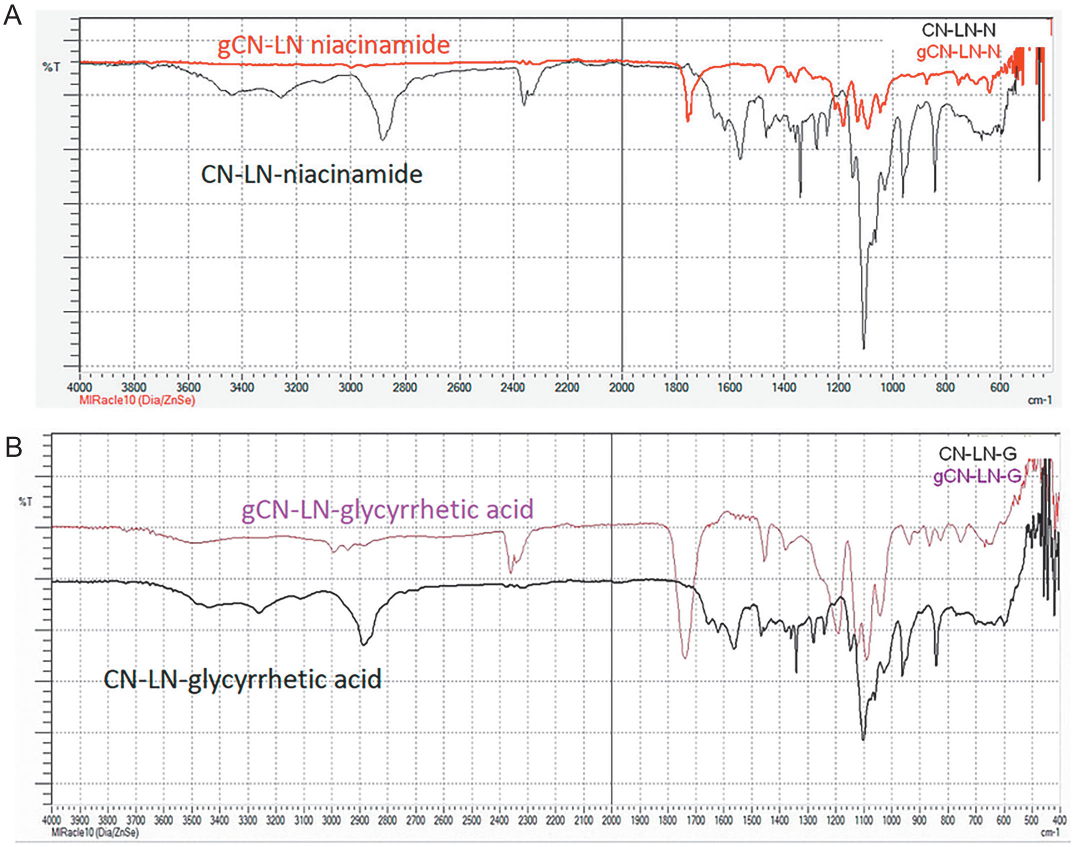


Figure 7: **Active ingredients encapsulated into the complex CN-NL controlled by the FTIR spectra (courtesy of Danti et al.[25]).**

FTIR spectrum of: (A) chitin–lignin complex (CN-LN) and polylactic acid (PLA)-grafted chitin–lignin complex (gCN-LN) with niacinamide; (B) chitin–lignin complex (CN-LN) and PLA-grafted chitin–lignin complex (gCN-LN) with glycyrrhetic acid.

nitrogen species (RNS) damage and is an essential cofactor for collagen synthesis[31–33]. Its primary limitation, however, is its extreme instability. It readily oxidizes when exposed to air, light, and certain pH levels, rendering it inactive. While more stable derivatives (e.g., sodium ascorbyl phosphate) exist, they often exhibit lower conversion rates to active ascorbic acid in the skin, presenting a trade-off between stability and efficacy.

Our nanocarrier system resolves this stability-efficacy paradox. By encapsulating the highly active, yet unstable, pure ascorbic acid within the dense, cross-linked matrix of the CN-NL complex, the molecule is physically shielded from oxidative environmental stressors. The antioxidant properties of nanolignin itself provide an additional layer of protection, creating a localized antioxidant-rich microenvironment. This ensures that vitamin C remains in its most potent form until it is released within the skin, thus delivering maximum antioxidant and collagen-boosting benefits without compromising stability.

Allantoin

Allantoin is well-regarded for its soothing, moisturizing, and anti-collagenase properties, making it valuable in formulations designed to ameliorate stress-induced aging phenomena[34]. The critical challenge for allantoin is not penetration, but rather optimizing its therapeutic window. Its efficacy is dependent on maintaining a consistent, therapeutic concentration at the target site. In conventional formulations, it can be quickly wiped away or absorbed, leading to a short duration of action that requires frequent reapplication.

The nanofiber tissue-carrier is uniquely suited to solve this by providing advanced controlled-release kinetics. Instead of a single, rapid release, the allantoin is physically entrapped within the polymer matrix of the nanofibers. This creates a reservoir system that exhibits a biphasic release profile: an initial burst for immediate soothing, followed by a prolonged, zero-order sustained release as the molecule slowly diffuses out over several hours. This maintains the desired therapeutic concentration on the skin for a significantly longer period, maximizing its anti-collagenase and healing effects from a single application.

Lutein

Lutein, a carotenoid, offers crucial protection against high-energy blue light and ultraviolet (UV) radiation, mitigating oxidative stress and lipid peroxidation[35]. Its significant formulation challenge is its lipophilic nature. This makes it difficult to disperse homogeneously in typically water-based cosmetic serums, leading to potential issues with product stability and aesthetics. Furthermore, delivering a lipophilic molecule through the aqueous-lipophilic maze of the epidermis is inefficient.

The CN-NL nanocarrier acts as a versatile delivery vehicle that overcomes this lipophilicity barrier. The amphiphilic nature of the chitin-lignin complex allows for the effective encapsulation and stabilization of lutein within the carrier matrix, ensuring a uniform formulation. Upon application, the carrier adheres to the skin and acts as a delivery shuttle. The nanofibers facilitate the transport of the lipophilic lutein across the different polarity layers of the epidermis, ensuring it reaches the viable cell layers where it can effectively absorb high-energy light and exert its protective antioxidant functions, thus improving skin hydration and elasticity from within.

Penetration through human barriers

As previously reported, both skin and mucous membranes possess physiological barriers that impede the permeation of any environmental substance, whether occasionally or deliberately contacting their surfaces, as well as the penetration of any carriers and active ingredients applied to these surfaces to allow for cosmeceutical and nutraceutical activity. On the one hand, the extent of product penetration depends on the physicochemical and biological properties of the selected nanosized carriers and the active ingredients loaded, carried by their structures, and released at the skin/mucous level. On the other hand, their effectiveness depends on the structural biological organization of the skin lipids and the mucous membranes' glycoproteins, which vary due to environmental conditions and/or different disease phenomena[36–38]. For this purpose, various nanoparticles (NPs), especially metal ones, have attracted great attention for their potential applications in medicine, cosmetics, and dietary supplements. They are characterized by easy preparation, surface reactivity, and control, coupled with better optical and biocompatibility[36–38]. Thus, for example, the activity of metal NPs can be easily detected by their surface, enhanced by the interesting optical function of surface-enhanced Raman scattering (SERS)[39].

Another aspect of nanobiotechnology is the use of polymeric nanofibers as carrier-tissues that, fabricated by electrospinning technology, can be utilized to transport and release various active ingredients at the level of the skin and mucous membrane layers, as proposed by our group[17–20,22,23,26,27].

However, it is important to remember the difficulty in achieving uniformity of fiber and tissue structures, necessitating careful control of all parameters, such as their compressive strength and water absorption capacity, as well as the size, surface charge, and physicochemical properties of the selected microparticles/NPs[36–38]. For this purpose, the use of chitin nanofibril tissues is particularly interesting in the medical, cosmetic, and food fields due to their skin- and eco-friendly characteristics, as demonstrated by various studies conducted by our research group[17–20,22,23,26,27].

Thus, specialized chemical enhancing biomolecules and physical methods are normally used to allow and increase the transepidermal and transdermal penetration, release, and delivery of selected active ingredients[38]. Among the most commonly used biomolecules are hydrophilic peptides and proteins, primarily obtained by the enzymatic activity of fish collagen. Moreover, regarding physical methods, it is necessary to remember, among others, the use of iontophoresis, electroporation, electrophoresis, and microneedle devices[38,39]. In any case, both chemical and physical methods are utilized to improve skin permeability, owing to their demonstrated capacity to form temporary micropores on its surface, which also influences skin moisture retention[39]. Therefore, the chitin nanofibers, produced and used by our research group as a positively charged polymer and part of the nanocapsulated tissue-carrier, seem to induce the formation of the reported micropores, overcoming the negatively charged SC barrier when applied to wet skin and massaged softly with fingers[38].

The sustainability challenge: plastic pollution and the role of eco-friendly carriers

The development of advanced cosme-nutraceuticals, as discussed, does not occur in a vacuum. A critical component of a product's lifecycle and its ultimate sustainability is its packaging, which is currently dominated by plastics. These polymers, in fact, reached a production of 390.7 million metric tons in 2021 and, accounting for about 400 million metric tons/year, are forecast to triple by 2060 with an annual increase of 1.6% (Fig. 8)[40–42].

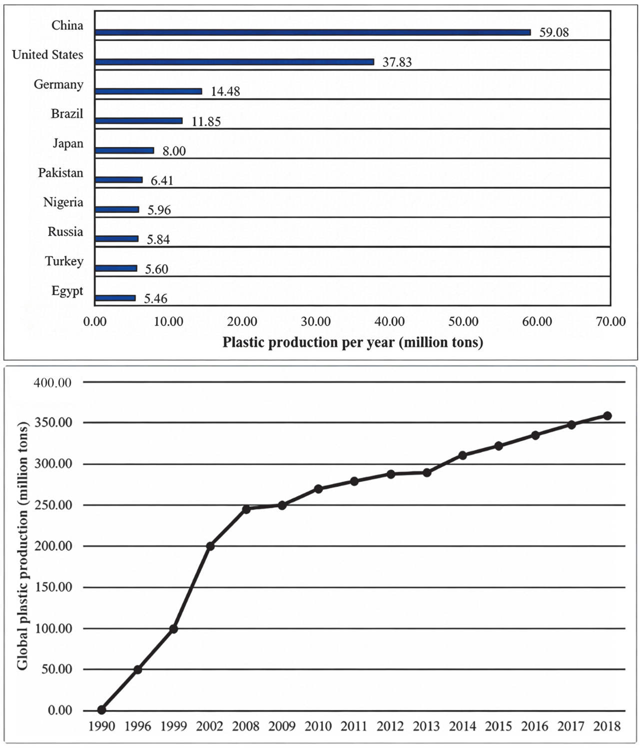


Figure 8: Global plastic production in different countries by 2018 (courtesy of Sani & Sharma[43]).

Regarding global consumption, it was estimated at 464 million metric tons by 2020 and is projected to reach up to 884 million metric tons by 2050[40–42]. The majority of plastic (around 40%) is used for cosmetic, food, and consumer packaging, which, reaching 216 million tons in 2015, represents the biggest driver of this use (Fig. 8)[40]. Thus, there is a need to reduce the production and consumption of current non-biodegradable plastics and promote the use of degradable bioplastics, even if the latter are currently insufficient to cover today's industrial and consumer necessities.

Unfortunately, only 10% of plastics are actually recycled, while 79% end up in landfills and 12% are incinerated, creating environmental waste pollution[41,42]. However, 9–15 million metric tons of plastics enter the oceans every year, making up 80% of all marine debris. The majority of this waste is transformed into micro/nanoparticles due to the activity of sun rays and microorganisms[43–45]. These resulting very tiny and toxic particles, becoming food for fish, birds, and sea mammals, have been recovered in tea bags[46], human blood[47], the feminine placenta[48], the brain[49], and DNA[50], inducing damage to other organs as well[51].

It is within this context of overwhelming plastic pollution that the proposed bio-based tissue-carriers find their second critical application. A significant portion of cosmetic plastic waste comes from single-use product formats, such as sheet masks, sachets, and sample packaging. Our proposed CN-NL tissue-carriers, being fully biodegradable and derived from renewable resources, offer a direct, one-to-one replacement for these disposable plastic-based products. By functioning as both the active ingredient delivery system and the product format itself, they eliminate the need for a separate, non-biodegradable plastic substrate. Adopting such a technology would therefore represent a tangible step for the cosmetics industry to mitigate its plastic footprint, directly addressing the environmental crisis detailed in this section.

Conclusions and future perspectives

This review, guided by the visionary concepts of nanotechnology pioneers like Drexler[52], has underscored the growing demand for effective pro-aging cosme-nutraceuticals, driven by a holistic “Beauty from Within” lifestyle[53–60]. We have highlighted the limitations of conventional delivery systems and proposed a novel approach centered on nanobiotechnology: the use of tissue-based, eco-friendly carriers fabricated via electrospinning. These carriers, particularly those based on chitin nanofibrils, demonstrate superior potential for delivering active ingredients, releasing them more rapidly and in greater quantities compared to traditional emulsions[9]. By mimicking the skin’s ECM and offering a chemical-free, biodegradable alternative, these innovative vehicles not only enhance the efficacy and safety of pro-aging formulations but also align with the urgent global need to reduce plastic waste and environmental pollution.

The market impetus for such innovations is clear, with the global wellness economy projected to approach USD 9 trillion by 2029, a significant portion of which is driven by the cosme-nutraceutical sector (Fig. 9)[61]. While the promise of these tissue-carriers is significant, their advent opens up several critical avenues for future research.

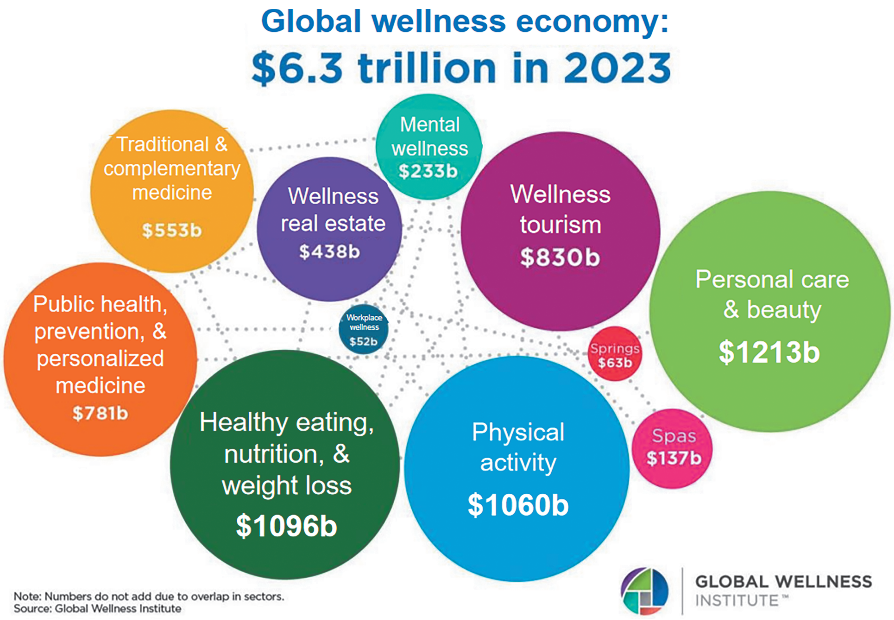
Future research should focus on:

(1) **Mechanism of penetration enhancement:** elucidating the precise molecular mechanisms by which these nanofiber carriers interact with and permeate the SC and mucosal barriers. Studies could investigate how carrier properties, such as fiber diameter, porosity, and surface charge, influence the transient disruption of lipid lamellae or the opening of micropores.

(2) **Controlled release kinetics:** optimizing the release profiles of various active ingredients from the tissue-carriers. Research is needed to tailor the polymer composition and encapsulation techniques (e.g., core-shell vs. matrix dispersion) to achieve sustained, targeted, or triggered release in response to physiological cues like pH or temperature.

(3) **Long-term clinical validation:** conducting large-scale, long-term clinical trials to rigorously validate the pro-aging efficacy and safety of cosme-nutraceuticals formulated with these carriers. Comparative studies against market-leading conventional products would be essential to quantify their superior performance in improving skin hydration, elasticity, and wrinkle reduction.

(4) **Synergistic “Beauty from Within” systems:** developing integrated systems that combine topical tissue-carriers with orally administered nutraceuticals



Note: Numbers do not add due to overlap in sectors.
Source: Global Wellness Institute

Figure 9: Global wellness economy report (courtesy of global wellness institute (GWI)[61]).

based on the same carrier technology. This would require investigating the gastrointestinal stability, mucoadhesion, and bioavailability of these carriers for systemic pro-aging effects.

The practical implications of this technology extend far beyond the laboratory. From a commercial standpoint, it enables the creation of a new generation of high-performance, preservative-free, and waterless products, which are highly sought after in the current wellness market. This could lead to the development of personalized cosme-nutraceuticals, where carriers are loaded with active ingredients tailored to an individual's specific needs. Furthermore, the use of natural biopolymers like chitin, often sourced from industrial by-products, establishes a foundation for a more circular and sustainable economy within the cosmetics industry. Ultimately, the widespread adoption of these advanced, skin- and eco-friendly tissue-vehicles offers a tangible pathway toward a future where personal care is not only more effective but also in greater harmony with our planet's health.

Author contributions

Pierfrancesco Morganti, Marco Palombo, and Giovanna Donnarumma conceived the idea of the manuscript. Pierfrancesco Morganti drafted and edited the manuscript. Pierfrancesco Morganti, Marco Palombo, Hong-Duo Chen, Vladimir E. Yudin, and Giovanna Donnarumma supervised the work. All authors reviewed, edited, and approved the final version of the manuscript and agreed to its publication.

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Ethics statement

Not applicable.

Data availability statement

Not applicable.

AI statement

The authors declare that no generative artificial intelligence (AI) or AI-assisted technologies were used in the preparation, analysis, or writing of this manuscript.

Conflicts of interests

Hong-Duo Chen serves as a member of the Editorial Board of this journal. He was not involved in the editorial review or decision-making process for this manuscript. All editorial decisions were made independently by other members of the Editorial Board who have no conflicts of interest.

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