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Nanomaterials in Dermatology: A New Frontier for Anti-Aging Therapies

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ABSTRACT

Nanomaterials represent an emerging frontier in biomedical applications, demonstrating significant potential across diverse therapeutic domains, including dermatology and aesthetic medicine. The integumentary system serves as a focal point for these interdisciplinary fields, offering opportunities for both protective interventions and

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therapeutic enhancement. The skin functions as a dual-interface organ, facilitating transdermal drug delivery to systemic circulation, simultaneously serving as a target for localized therapeutic interventions. The convergence of nanotechnology with clinical medicine presents novel approaches for skin rejuvenation and functional optimization, addressing both therapeutic and cosmetic objectives within the broader context of human health and well-being. This review synthesizes contemporary research findings and foundational studies to elucidate the advancement of nanomaterial applications in dermatological science. We examine the current challenges surrounding clinical translation, with particular emphasis on environmental sustainability, human safety profiles, and the optimization of both cosmetic efficacy and therapeutic outcomes in nanomedicine-based interventions.

Introduction

Nanotechnology encompasses the design and utilization of materials at the nanometer scale, which exhibit unique physicochemical properties that differ substantially from their bulk counterparts due to increased surface area-to-volume ratios and altered molecular interactions with biological systems [1]. The incorporation of active pharmaceutical ingredients into nanoscale delivery vehicles has become a prominent strategy for enhancing drug development and therapeutic innovation, with particular success in topical applications where nano-pharmaceuticals and nano-cosmeceuticals have demonstrated clinical efficacy in treating various dermatological conditions including atopic dermatitis [2], cutaneous malignancies [3], thermal injuries and wound healing [4,5], and providing photoprotection against ultraviolet radiation exposure [6,7,8,9,10]. The formulation of skincare products using nanotechnology platforms represents a significant advancement in dermatological therapeutics, particularly in addressing limitations of conventional ultraviolet filters through nanoparticle formulations of inorganic compounds such as titanium dioxide and zinc oxide [11], as well as organic photoprotective agents like benzophenone-3 [7,12], thereby improving both efficacy and consumer acceptability [8,10]. The encapsulation of sunscreen agents within nanocarrier systems may provide synergistic photoprotective effects, as the nanomaterials themselves can contribute additional UV-blocking properties [13]. However, the reduced particle dimensions that confer therapeutic advantages may also present potential safety concerns, as nanomaterials can exhibit enhanced reactivity and may promote reactive oxygen

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species generation, leading to inflammatory cascades, DNA damage, protein oxidation, membrane disruption, and cellular stress responses [14, 16]. Assessment of nanomaterial safety typically involves evaluation of lipid peroxidation markers and cellular viability assays as standard methodological approaches [15, 17, and 18]. The bioavailability of pharmaceutical agents, defined as the proportion of administered drug that reaches systemic circulation and becomes available for therapeutic action, is influenced more significantly by formulation characteristics and chemical composition than by the intrinsic physical properties of the active ingredient, though physical parameters do affect the required dosage [24]. The incorporation of active ingredients into nanocarrier systems represents an established strategy for enhancing bioavailability, particularly for compounds with poor aqueous solubility, while the increased surface area contact may facilitate enhanced dermal penetration. Beyond bioactivity considerations, particle size critically influences the pharmacokinetic profile, stability, and overall therapeutic effectiveness of nanopharmaceutical products.

Types of Nanomaterials Used in Cosmetic Formulations

Owing to its broad particle size, the surface is a fascinating route of drug administration for many APIs. The benefits of oral drug distribution also include feasibility of overcoming the risks involved to oral administration (e.g. discomfort, infection), preventing the first-time processing related to opioid administering drugs, the potential to extend care over even a prolonged period of time, enabling its use of medications with short biological quarter, and thus minimizing digestive intake. The significant challenge facing the shipping of APIs via the skin would be to resolve the various physiological strands of different polarisation. Skin is recognized to offer protection from xenobiotics that also may not only be toxic operatives and infectious agents, and also drugs, whilst also making sure the removal of biological membranes for homeostasis. Because as permeability of the skin to the API decreases its penetration, the bioaccumulation of systemically applied APIs is lower compared to intravenous and oral paths Various forms of nanomaterials (such as Nanoemulsions, Solid Lipid Nanoparticles (SLNs) and Nanocomposite Lipid Carriers (NLCs), Nanocristals, Dendrimers, Dendrimers, Dendrimers, Metal Nanoparticles, Polymer Nanoparticles, Carbon Nanoparticles, Polymers, Polymers, etc are being suggested to resolve the issues experienced in the skin implementation of APIs.

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Nanotechnology Applications in Age-Prevention Dermatological Products

The integration of nanotechnology platforms into cosmeceutical formulations has emerged as a significant sector within the dermatological product market, with various commercial preparations now incorporating nanoscale delivery systems for enhanced therapeutic efficacy. These advanced formulations provide protection against ultraviolet radiation and environmental oxidative stressors while supporting structural integrity and functional capacity of cutaneous tissues, ultimately promoting dermal health through preservation of extracellular matrix architecture and maintenance of barrier function. The primary molecular targets of anti-aging interventions include collagen (the predominant structural protein in skin, hair, and nail tissues) and elastin (a critical extracellular matrix component responsible for tissue elasticity and resilience). Commercial products such as Agera Nano Eye Lift incorporate peptide-based signaling molecules, retinol derivatives, and retinyl palmitate to stimulate collagen biosynthesis and dermal cellular proliferation, resulting in reduction of fine lines and rhytides. Bionova-Nano Skin Innovation systems utilise co-encapsulation strategies to deliver multiple bioactive compounds including vitamins, proteins, botanical extracts, and pharmaceutical agents within protective nanocarriers designed for controlled release under varying environmental conditions. Mineral-based formulations containing zinc oxide and titanium dioxide nanoparticles represent particularly significant developments in photoprotection, offering enhanced skin compatibility with reduced oiliness, minimal sensory perception, and improved cosmetic acceptability [26]. Solid lipid nanoparticles, nanoemulsions, liposomes, and niosomes demonstrate superior capacity for maintaining cutaneous hydration through prolonged moisture retention, making them valuable components in moisturizing formulations. The anti-aging cosmetics sector extensively employs nanospheres, lipid vesicles, nanosomes, and nanocapsules as delivery vehicles for active ingredients targeting dermal rejuvenation [27]. In hair care applications, nanomaterial systems function by retaining moisture within the hair cuticle structure, reducing inter-follicular friction and scalp irritation while establishing protective film barriers. Contemporary hair treatment products incorporating nanoemulsions, microemulsions, nanocapsules, nanospheres, and lipid carriers are specifically formulated to repair damaged cuticle structures, maintain hair morphology and luminosity, and achieve improved manageability with reduced oiliness and enhanced damage resistance [28].

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Clinical Benefits of Nanoscale Drug Delivery Platforms

Nanoscale drug delivery systems demonstrate exceptional capability in overcoming physiological barriers encountered during oral administration, including acidic gastric environments, mucus layer impedance, and selective intestinal epithelial transport mechanisms. The therapeutic performance of these delivery platforms is fundamentally governed by three critical physicochemical parameters: particle dimensions, surface properties, and drug loading capacity, which collectively influence synthesis protocols, tissue distribution patterns, cellular uptake mechanisms, and elimination pathways [31]. Particle size represents the primary determinant of pharmacokinetic behaviour, governing cellular penetration rates and immunological recognition processes, while surface characteristics dictate hydrophilic-lipophilic balance and subsequent biological interactions including cellular internalisation, plasma protein adsorption, tissue distribution, and immune system activation [30]. Drug loading parameters constitute another essential factor influencing both cellular uptake efficiency and cytotoxicity profiles of nanocarrier systems [32]. The protective capacity of nanomaterials enables preservation of encapsulated bioactive compounds against degradation during gastrointestinal transit and metabolic processing, facilitating controlled release into target tissues including the gastrointestinal tract, systemic circulation, or specific organ systems [33]. The ultimate therapeutic efficacy of these delivery platforms depends on the complex relationship between their intrinsic physicochemical characteristics and the anatomical site of drug release, highlighting the importance of rational design approaches for clinical applications. Strategic modification of nanoparticle surface characteristics enables precise targeting of therapeutic agents to specific anatomical sites and cellular populations, facilitating enhanced drug delivery efficacy through both passive and active targeting mechanisms [34, 35]. Active targeting approaches utilise ligand-mediated recognition systems where therapeutic payload release occurs through controlled degradation or diffusion of the carrier matrix [36], enabling site-specific drug delivery through incorporation of targeting moieties including nucleic acids, carbohydrates, lipids, proteins, and small molecular ligands that exhibit selective affinity for target tissues [37]. Advanced targeting strategies employ stimulus-responsive materials that undergo structural or chemical changes in response to external triggers such as magnetic fields, electrical stimulation, photonic activation, pH variations, hyperthermia, ultrasonic waves,

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or interaction with specific ionic environments and enzymatic activity, thereby providing temporal and spatial control over therapeutic release [38]. Metallic nanoparticle systems, including gold, silver, and iron oxide formulations, demonstrate particular utility as drug delivery platforms due to their surface modification potential and responsive properties, though biocompatible nanomedicines are generally preferred owing to their superior safety profiles and tuneable physicochemical properties achieved through manipulation of chemical composition, morphology, size distribution, and surface fictionalization [39]. The therapeutic efficacy of nano-delivery systems correlates inversely with molecular weight of the encapsulated agents, as larger molecules typically exhibit reduced delivery efficiency and decreased bioavailability due to transport limitations [40]. Clinical outcomes depend on the complex interplay between carrier characteristics, drug properties, and therapeutic objectives, with different delivery platforms offering distinct advantages based on these parameters [41]. Compared to conventional formulations, nanomedicines provide multiple therapeutic advantages including enhanced epithelial permeability, improved chemical stability, extended circulation half-life, increased tissue penetration and bioavailability, superior target binding affinity, and reduced systemic toxicity profiles [42].

Nanoliposomes

Nanoliposomes represent spherical vesicular structures comprising phospholipid bilayers that form spontaneously in aqueous environments, creating discrete compartments capable of encapsulating both hydrophilic and lipophilic therapeutic agents. These colloidal delivery systems typically exhibit particle sizes ranging from 50 to 450 nanometers and function as oil-in-water emulsions with enhanced stability and bioavailability profiles [43]. Manufacturing protocols for nanoliposomal formulations include thin-film hydration methodologies, wherein dried lipid films deposited from organic solvents undergo controlled aqueous rehydration to form multilamellar vesicles, and mechanical dispersion techniques involving ultrasonication or high-pressure homogenisation to achieve size reduction and uniform distribution [44]. Alternative production approaches encompass electroformation processes utilizing controlled electrical fields to generate giant unilamellar vesicles, reverse-phase evaporation methods for enhanced encapsulation efficiency, and microfluidic platforms enabling precise control over vesicle size distribution and lamellarity, with these diverse manufacturing strategies

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accommodating various formulation requirements including ionic surfactant stabilisation, phospholipid membrane composition optimisation, and biopolymer matrix integration for sustained release applications..

Industrial Implementation of Micellar Nanotechnology in Consumer Skincare Products

The integration of micelle nanotechnology into commercial cosmetic formulations has expanded significantly across multiple consumer product categories, with domestic and international manufacturers positioning these systems as advanced solutions for enhanced product performance and bioactive delivery. Nano-emulsion platforms serve as the primary technological foundation for micelle nanoparticle development, facilitating the encapsulation of bioactive compounds within structured delivery vehicles designed for controlled release and enhanced skin penetration in anti-aging applications. The commercial landscape includes various facial care products incorporating micelle nanotechnology, with notable developments including Tri-K Industries' proprietary nano-based gel systems manufactured in collaboration with Kemira for diverse cosmetic applications, demonstrating the growing industrial adoption of these advanced delivery platforms in consumer skincare products. The fluid is severity of the consequences as Kemira Nanogel reported to become a special nano-emulsion predominant component which has been developed utilizing a simple composition (45). Nanogel was created by a straightforward method to make a submicron emulsion comprising micelle bioactive nanomaterials. The key advantage of the commercialized gel would be to prevent the loss of skin water, improve the development of new skin cells, and easily transport the main chemical. These features are also proposed to be beneficial for the protection, moisturizing, and anti-aging sections of cosmetics. Also it mentioned that this really helps give skincare products a great skin feels during implementation (46). The commercial cosmetics industry has increasingly adopted micellar nanotechnology for dermatological applications, exemplified by Naturel Kiss's development of nano-emulsion-based facial cleansers and therapeutic mists containing bioactive compounds such as botanical extracts and essential oils, with claimed efficacy for makeup removal and treatment of hyperpigmentation, scarring, and photoaging [47]. L'Oréal S.A. has pioneered two distinct micellar platforms: a stable nano-emulsion system featuring oil-phase micelles below 100 nm diameter, comprising high molecular weight oils (>400 Da) dispersed in

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aqueous media with anionic surfactants including phosphoric acid derivatives and polyoxyethylene compounds at 2-10% oil-to-surfactant ratios, maintaining optical clarity despite substantial oil content and enabling multi-site applications across facial, hair, and mucosal tissues [48], and an advanced phase-separation system utilizing polyethylene oxide-polypropylene copolymer-stabilized oil-filled nanoparticles implemented in cleansers and ocular formulations [49]. While these innovations demonstrate technical feasibility, clinical validation of therapeutic claims remains limited, and the safety profile of chronic micellar nanoparticle exposure, particularly for periocular and mucosal applications, requires comprehensive evaluation given the varying regulatory frameworks governing cosmeceutical products across jurisdictions, highlighting the need for standardised safety protocols and comparative efficacy studies to guide clinical decision-making and consumer counseling.

Dermal Penetration of Nanoparticles

The skin, as the body's largest organ, comprises three distinct anatomical layers: the epidermis (outermost layer), dermis (containing vascular networks, hair follicles, and sebaceous glands), and subcutaneous tissue (hypodermis) composed of adipose and connective tissue. Within the epidermis, the stratum corneum represents the primary barrier to transcutaneous absorption, owing to its unique lipophilic architecture and tightly packed corneocyte structure [50]. Molecular transport across this barrier occurs via three principal pathways: intercellular (through lipid lamellae), transcellular (through corneocytes), and appendageal (via hair follicles and sweat ducts) routes [51].

The proliferation of nanotechnology-enabled cosmetic and pharmaceutical products has raised significant questions regarding the safety profile of topically applied nanomaterials. The extent of dermal penetration depends on multiple variables, including the physicochemical properties of the nanoparticles (size, surface charge, and hydrophobicity), vehicle composition, application conditions, and skin integrity [52]. Nanomaterials can be broadly classified into two categories based on their biodegradability: (1) biodegradable systems including lipid-based carriers and nano-emulsions, and (2) persistent materials such as titanium dioxide (TiO_2), fullerenes, and quantum dots.

Current evidence suggests that transcutaneous penetration of nanoparticles is generally limited under normal physiological conditions. However, compromised skin barrier

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function may alter this penetration profile. Most investigations demonstrate that topically applied nanoparticles primarily accumulate within hair follicles and skin appendages, with minimal detection beyond the stratum corneum [53]. Advanced imaging techniques, including confocal microscopy studies of fluorescently tagged particles (20-200 nm), have confirmed that intact or minimally compromised skin effectively prevents deeper penetration of most nanomaterials [54].

Human exposure studies have yielded mixed findings. Gulson and colleagues detected zinc in both urine and blood samples following application of ZnO-containing sunscreens to healthy volunteers under beach conditions, though the specific form (ionic versus particulate) remained undetermined [55]. Conversely, the Environmental Working Group's comprehensive review of over 400 studies concluded that zinc oxide and titanium dioxide formulations represent safe and effective photoprotective agents, with 16 dermal absorption studies consistently demonstrating negligible penetration through intact skin [69].

This apparent contradiction in the literature reflects the complexity of nanoparticle-skin interactions and highlights the need for standardised testing protocols. The Scientific Committee on Consumer Safety has emphasised that percutaneous absorption of TiO_2 and ZnO nanoparticles requires further investigation [56]. Future research priorities should focus on determining whether nanomaterials remain localized to superficial skin layers or achieve systemic distribution with potential for organ accumulation. Lipid focused nanomaterials also are dosed using skin penetration [57]

The clinical implications of these findings remain under active investigation, particularly regarding long-term exposure scenarios and vulnerable populations with compromised skin barrier function. Continued surveillance and mechanistic studies are essential to establish comprehensive safety profiles for nanotechnology-enabled dermatological products.

Conclusions

Nanomaterials have emerged as versatile agents across multiple biomedical applications, particularly in dermatological interventions. Both organic and inorganic nanoparticles, including hybrid formulations, demonstrate significant potential in protecting cutaneous tissue from oxidative damage and ultraviolet radiation—key contributors to photoaging processes. Effective prevention of skin aging requires maintenance of optimal lipid and

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protein homeostasis, which preserves barrier function and reduces susceptibility to environmental stressors. Clinical implementation of nanoparticle-based therapeutics necessitates careful consideration of biocompatibility, clearance mechanisms, and environmental impact, particularly regarding potential disruption of beneficial microbiota such as lactobacilli. The skin's role as a dynamic interface presents opportunities for transdermal nanotechnology applications that may influence systemic physiological responses. This rapidly evolving field continues to generate novel findings, with research developments occurring at an unprecedented pace in contemporary dermatological science.

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