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Skin aging and barrier dysfunction: bridging current therapies with future genetic and nanotechnological interventions

Starzenie się skóry i zaburzenia funkcji bariery skórnej: połączenie obecnych metod leczenia z przyszłymi rozwiązaniami genetycznymi i nanotechnologicznymi

ABSTRACT

Genetic cosmeceuticals powered by nanotechnology offer a new path to customized anti-ageing skincare. Recent developments in nano-formulations have enabled precise, effective delivery to skin cells anti-ageing genetic elements, such as the SIRT1 and FOXO3 genes, which are essential for controlling cellular senescence and promoting skin regeneration. Nanocarriers such as lipid nanoparticles, polymeric nanoparticles, and exosomes shield genetic payloads from degradation and allow for regulated intracellular release, and yet their surface functionalization improves targeting of dermal fibroblasts and keratinocytes and minimizes off-target effects.

This literature review aimed to analyze current anti-aging therapy options in the context of their efficacy and to examine the possibilities for newer genetic and nanotech anti-aging treatment options. Additionally covered is the synergistic function of nano-formulations in reducing oxidative stress and enhancing skin health when paired with growth factors and antioxidants.

All things considered, genetic cosmeceuticals driven by nanotechnology present a paradigm shift toward targeted, minimally invasive, and customized anti-aging treatments.

Keywords: nanotechnology, anti-aging, FOXO3 gene, nano-carrier, gene delivery, SIRT1 gene.

STRESZCZENIE

Kosmeceutyki genetyczne oparte na nanotechnologii otwierają nową drogę do spersonalizowanej pielęgnacji przeciwstarzeniowej. Najnowsze osiągnięcia w dziedzinie nanoformulacji umożliwiły precyzyjne i skuteczne dostarczanie do komórek skóry genetycznych składników przeciwstarzeniowych, takich jak geny SIRT1 i FOXO3, które są niezbędne do kontrolowania starzenia się i wspomagania regeneracji skóry. Nanonośniki – takie jak nanocząsteczki lipidowe, polimerowe oraz egzosomy – chronią ładunek genetyczny przed degradacją i umożliwiają jego kontrolowane uwalnianie wewnątrzkomórkowe. Dodatkowo funkcjonalizacja ich powierzchni poprawia ukierunkowanie na fibroblasty skóry właściwej i keratynocyty oraz ogranicza działania niepożądane.

Celem niniejszego przeglądu literatury była analiza aktualnych opcji terapii przeciwstarzeniowych pod kątem ich skuteczności oraz zbadanie możliwości wprowadzenia nowych genetycznych i nanotechnologicznych metod leczenia przeciwstarzeniowego. Dodatkowo omówiono synergiczne działanie nanoformuł w redukcji stresu oksydacyjnego i poprawie zdrowia skóry w połączeniu z czynnikami wzrostu i przeciwutleniaczami.

Podsumowując, kosmetyki genetyczne oparte na nanotechnologii stanowią przełom w kierunku celowanych, minimalnie inwazyjnych i spersonalizowanych terapii przeciwstarzeniowych.

Słowa kluczowe: nanotechnologia, działanie przeciwstarzeniowe, gen FOXO3, nanonośnik, dostarczanie genów, gen SIRT1.

INTRODUCTION

An overview of anti-aging gene therapy

Anti-aging gene therapy is a cutting-edge technique for combating the biological mechanisms that cause aging and age-related diseases. This ground-breaking therapy uses genetic alteration to target critical biochemical pathways that are responsible for cellular senescence, oxidative stress, and tissue degradation over time. Anti-aging gene therapy seeks to improve longevity and quality of life by focusing on certain genes and pathways [1]. The Forkhead Box O3 (FOXO3) gene, also known as the "longevity gene," is an important target in anti-aging gene therapy. This gene has been associated to cellular stress tolerance, deoxyribonucleic acid (DNA) repair, and oxidative stress management. Improving its expression through gene therapy can greatly postpone cellular aging and protect against age-related illnesses. Sirtuin 1 (SIRT1) and other sirtuin family genes influence mitochondrial activity and metabolic functions, forming another essential pathway. Activating these genes have shown promise in terms of increasing skin suppleness and minimizing cellular damage [2]. Anti-aging gene therapy frequently employs viral vectors, such as adeno-associated viruses (AAVs), to introduce genetic material into target cells. These vectors ensure effective transfection while reducing immunological reaction. For example, some experiments have used telomerase reverse transcriptase (TERT) to lengthen telomeres, which normally shrink with age, so postponing cellular aging. Despite its potential, anti-aging gene therapy faces ethical issues, off-target consequences, and exorbitant costs. Advances in Clustered Regularly Interspaced Short Palindromic Repeats-CRISPR associated protein 9 (CRISPR-Cas9) technology and other gene-editing techniques are assisting in addressing these difficulties by providing accuracy and lowering hazards. Gene therapy is on track to move from experimental treatments to mainstream anti-aging interventions, altering the landscape of modern healthcare and cosmeceuticals [3].

Emergence of genetic cosmeceuticals

A significant advancement in dermatology is the emergence of genetic cosmeceuticals that customize skincare based on individual genetic profiles. These products contain active ingredients targeting genetic expressions related to skin traits, drawing on genomic testing to address collagen degradation, antioxidant capacity, and melanin production [4, 5]. Recent bioinformatics, transcriptomics, and CRISPR technologies enhance these solutions by actively influencing gene pathways, utilizing botanical extracts and peptides to modulate inflammation and promote healing. The incorporation of epigenetic modulators brings potential anti-aging benefits [6-8]. At-home DNA-based diagnostics allow consumers to identify genetic skin vulnerabilities, promoting personalized skincare regimens. While genetic cosmeceuticals remain in research phases, with regulatory approval limited to medical gene-delivery therapies for conditions like psoriasis, their development must adhere to safety and ethical standards established by current medical practices [9, 10].

This review aimed to provide a detailed explanation of the mechanisms involved in skin aging and the disruption of the barrier function, along with a critical evaluation of the current treatment options and discussing new developments in the area of genetic and nanotechnology-based therapies. This article also atempted to fill the void between traditional therapies and the emerging modalities, such as gene therapy for cosmeceuticals and nano-technology based delivery.

MAJOR ANTI-AGING GENES AND THEIR MECHANISMS OF ACTION

Anti-aging genes, notably FOXO3, SIRT1, and telomerase, are pivotal in research focused on longevity and cellular health [11, 12]. FOXO3 enhances lifespan by improving stress resistance and promoting autophagy while its variants are linked to longevity in various populations. SIRT1, the "longevity enzyme," regulates aging and metabolism by influencing gene expression and mitochondrial function, with significant roles in age-related diseases [13-16]. Its activation by resveratrol mirrors caloric restriction benefits, highlighting therapeutic potential. Telomerase, crucial for extending cellular longevity, counters telomere shortening. Activating telomerase may restore function in aged cells and extend life, although cancer risks persist. Integrating advancements in gene editing and nanotechnology opens up new possibilities for anti-aging treatments [17-22].

NANOCARRIERS TYPES FOR GENE DELIVERY

Gene delivery utilizes advanced strategies to address genetic disorders, cancer, and other complex conditions. The integration of nanotechnology has significantly enhanced gene therapy efficacy through nano-formulations that use various nanocarriers for the safe transport of genetic material to targeted cells. These carriers, such as liposomes and polymeric nanoparticles, improve the stability and absorption of nucleic acids like DNA, ribonucleic acid (RNA), and CRISPR-Cas, while facilitating controlled release. Each type of nanocarrier has distinct properties and challenges: liposomes are biocompatible but have stability limitations; polymeric nanoparticles like poly(lactic-co-glycolic acid) (PLGA) offer controlled release but pose cytotoxicity risks; dendrimers have high surface areas but complex synthesis and toxicity concerns. Inorganic nanoparticles enable stable delivery with imaging but raise long-term toxicity questions, while exosomes are biocompatible carriers with scalability difficulties [23, 24]. Carbon nanotubes and solid lipid nanoparticles show strength and low toxicity yet face challenges in aggregation and loading. Nanogels are responsive carriers suitable for gene therapy, though they lack mechanical strength in physiological conditions. Virus-like particles (VLPs) are effective for gene delivery, especially for CRISPR and mRNA applications, but large-scale production and immunogenicity are limitations. Metal-organic frameworks (MOFs) offer high porosity for large biomolecule accommodation, beneficial for cancer gene therapy, but their biocompatibility remains a concern. Peptide-based nanocarriers are biodegradable and low-toxic, facilitating cell membrane penetration for small interfering ribonucleic acid (siRNA) and CRISPR delivery, though their cargo protection can be compromised by enzymatic degradation. Lastly, hydrogel-based nanocarriers provide high biocompatibility and sustained release for regenerative medicine but typically suffer from low mechanical strength [25].

MECHANISMS OF NANOCARRIER-MEDIATED GENE ENCAPSULATION AND RELEASE

Nanocarriers are developing as sophisticated therapeutic gene delivery vehicles due to their capacity to preserve genetic material, increase cellular absorption, and regulate release at precise places. Encapsulation and release mechanisms are critical to their success because they govern the therapeutic effectiveness, stability, and specificity of gene delivery [26].

Mechanisms for gene encapsulation

Electrostatic interactions enable nanocarriers like cationic liposomes and polymers to encapsulate genetic materials (e.g., plasmid DNA, siRNA, messenger ribonucleic acid (mRNA)) by allowing negatively charged nucleic acids to bond with positively charged carriers, enhancing stability and cellular uptake [27, 28]. Hydrophobic interactions in amphiphilic nanocarriers, such as lipid nanoparticles, protect nucleic acids from degradation and improve stability, often utilizing helper lipids for better complex formation. Covalent conjugation involves the attachment of genetic materials to carriers via functional groups, enhancing stability and allowing controlled release, with PEGylation enhancing circulation time. Physical encapsulation involves trapping genes within nanostructures during nanoparticle creation, utilizing methods like emulsion and solvent evaporation for high efficiency. Layer-by-layer assembly alternates layers of polyelectrolytes with genetic material and nanocarriers to prevent degradation and enable controlled release [29-31].

Mechanisms of gene release

Gene delivery nanocarriers are designed for stimuli-responsive release, allowing for the targeted delivery of genetic materials. pH-responsive carriers, utilizing polymers like poly(L-histidine) or ionizable lipids, operate in acidic environments such as tumors or endosomes, where they disassemble to release RNA or DNA. Redox-responsive systems leverage intracellular reducing agents like glutathione to disrupt disulfide bonds, facilitating gene release in the cytoplasm [32]. Enzyme-responsive carriers, including biodegradable polymers like PLGA, release their contents as they degrade in the presence of specific enzymes such as nucleases or matrix metalloproteinases. Thermo-responsive platforms, represented by thermosensitive hydrogels or liposomes, respond to localized heat or ultrasound for controlled gene release. Furthermore, light-triggered and mechanically responsive carriers can release genes when exposed to ultraviolet/near-infrared (UV/NIR) light or mechanical stress, enhancing precision in targeting tissues and adapting to dynamic environments [33].

UTILIZATION OF NANO-BASED GENE DISTRIBUTION SYSTEMS IN GENETIC COSMETICS

Genetic cosmeceuticals address the genetic and molecular causes of skin aging, moving beyond mere symptom treatment. They utilize gene-based technologies, including gene delivery and editing, to offer personalized skincare solutions aimed at rejuvenation, wrinkle reduction, and minimizing photoaging and oxidative stress. The approach involves a regulatory cascade initiated by external agents like botanical extracts, influencing regulatory genes that manage downstream expressions. Advanced technologies such as CRISPR-Cas9 and RNA interference enable direct modifications to genes, enhancing essential proteins for skin health and leading to improvements in collagen synthesis and barrier protection [34]. Fig. 1 is provided to clarify the interaction between external regulators and gene editing, illustrating their roles in skin health and cosmetology.

Skin rejuvenation and reduced wrinkles

The regeneration of aged skin is a key focus in cosmetic dermatology, addressing changes such as loss of collagen, elastin, and hyaluronic acid that lead to wrinkles and sagging. Traditional anti-aging treatments only target symptoms and not the underlying genetic causes. Genetic cosmeceuticals represent a novel approach, utilizing gene therapy to enhance the production of essential proteins like collagen and elastin through gene delivery techniques that focus on dermal cells. This method not only aids in skin renewal but can also protect against premature cell aging. Tailoring gene therapy to individual genetic profiles promises more effective treatments that significantly reduce wrinkles and enhance youthful appearance [35].

Addressing photoaging through gene delivery

Photoaging, the premature aging of the skin caused by persistent exposure to UV radiation, is a primary contributor to visible skin aging symptoms such as wrinkles, pigmentation, and loss of suppleness. UV light causes a cascade of molecular reactions in the skin, including the breakdown of collagen and elastin fibers, the creation of reactive oxygen species (ROS), and the activation of inflammatory pathways that hasten the

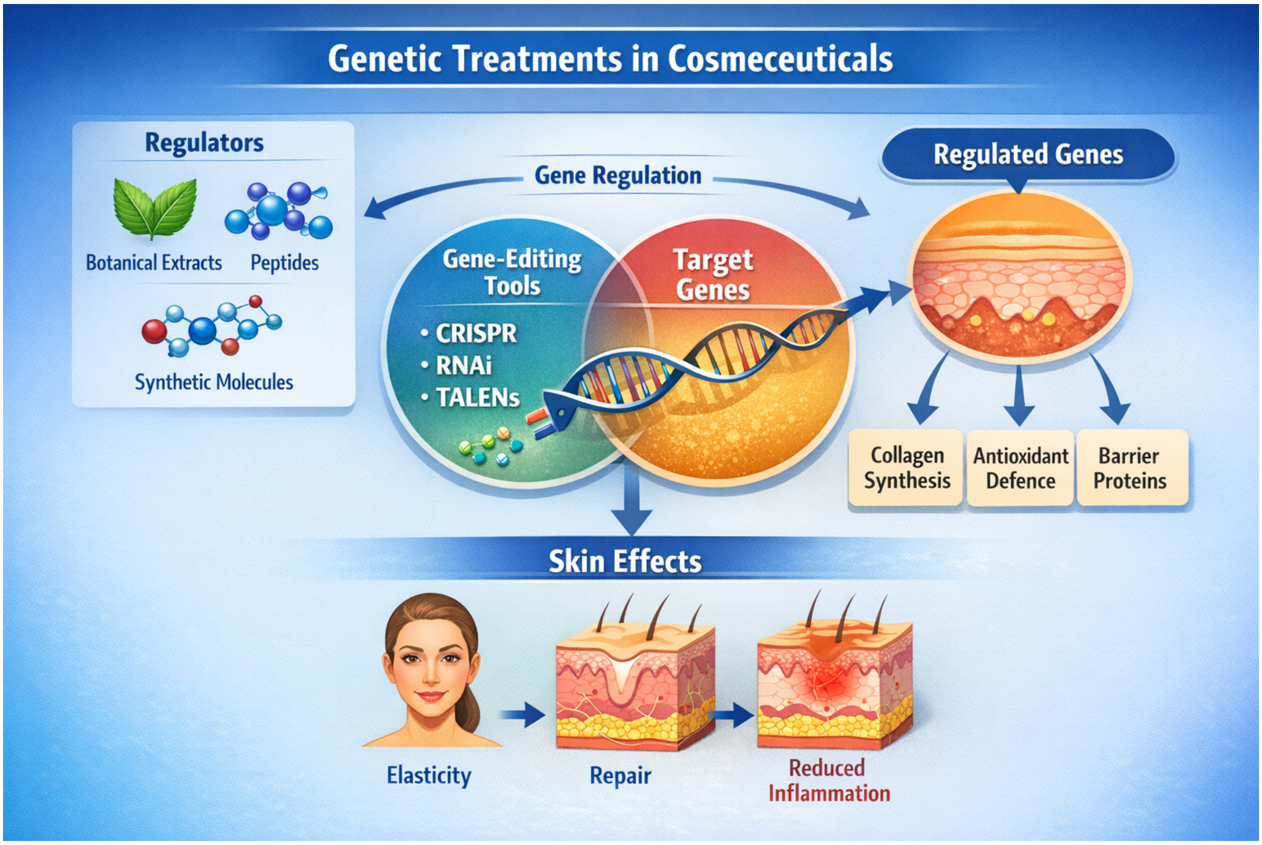

Fig. 1. Scheme of genetic treatments in cosmeceuticals. Regulators such as botanical extracts, peptides, and synthetic molecules act through regulating genes, while gene-editing tools (CRISPR, RNAi, TALENs) can directly target regulating or regulated genes. The regulated genes influence collagen synthesis, antioxidant defence, and barrier proteins, leading to skin effects including elasticity, repair, and reduced inflammation. **Source:** Own elaboration.

aging process. While sunscreens and topical antioxidants have long been used to prevent and treatment photoaging, they are generally ineffective for long-term protection or correcting existing damage. Genetic cosmeceuticals represent an advanced strategy to combat photoaging by targeting the molecular mechanisms involved in UV-induced skin aging. Utilizing gene delivery technology, these treatments can introduce specific genes that encode beneficial enzymes or proteins for skin restoration [36, 37]. For instance, they may deliver antioxidant enzymes like superoxide dismutase (SOD) or catalase to neutralize ROS and prevent cellular damage. Additionally, they can provide genes that produce collagenase inhibitors to mitigate collagen degradation caused by UV radiation. Gene delivery can also enhance the production of DNA repair enzymes to address UV-induced genetic damage, potentially reducing visible signs of aging and improving skin health on a genetic level. Moreover, personalized therapies may be developed based on an individual's genetic predispositions to UV damage, allowing for tailored approaches that enhance skin protection and repair processes in response to photoaging [38].

Managing oxidative stress

Oxidative stress significantly contributes to skin aging, manifesting as wrinkles, loss of suppleness, and pigmentation changes due to an imbalance between ROS production and antioxidant elimination. While topical antioxidants like vitamins C and E offer limited, unstable protection, genetic cosmeceuticals present a more durable solution by enhancing the skin's innate antioxidant defences through gene delivery of enzymes such as SOD and catalase. These therapies potentially improve protection against oxidative damage, particularly in sensitive skin cells like keratinocytes and fibroblasts. Additionally, combining gene delivery with topical antioxidants may provide immediate and long-term protection. Personalized treatments based on genetic susceptibilities to oxidative stress are also possible [39, 40]. In prior sections, longevity-associated genes like FOXO3 and SIRT1 were highlighted for their roles in aging and oxidative stress responses. However, it is crucial to differentiate these from structural genes essential for maintaining skin barrier integrity and resilience, which are implicated in various skin disorders. By drawing this distinction, it becomes clearer that the earlier discussion of FOXO3, SIRT1, and telomerase activation serves to illustrate the emerging scientific horizon of genetic cosmeceuticals. Together, these complementary perspectives, one futuristic and one established, provide a holistic understanding of how genetics contributes both to skin barrier health and to the future of anti-aging cosmetology [40].

ADVANCEMENTS IN NON-VIRAL GENE DELIVERY TECHNOLOGIES

Rapid advancements in non-viral gene delivery technologies in recent years have made them safer, more adjustable, and more effective than viral vectors for use in cosmetic and therapeutic purposes. To transfer genetic information like DNA, mRNA, or siRNA into target cells without triggering robust immune reactions, non-viral techniques use nanoparticles, liposomes, dendrimers, polymers, and peptides [41]. Since direct gene modification can treat conditions like psoriasis or eczema without causing systemic adverse effects, these technologies hold special promise for topical and dermatological applications. The creation of intelligent nanocarriers that improve cellular absorption, shield genetic material from deterioration, and permit tailored gene expression with low cytotoxicity is essential to these developments [41].

CRISPR-Cas systems in topical applications

An innovative development in precision dermatology is the incorporation of CRISPR-Cas systems into non-viral topical gene delivery platforms. Highly specific gene editing is made possible by CRISPR technology, which directs the Cas9 nuclease to select DNA sequences. Recent research has demonstrated that lipid nanoparticles or polymeric micelles can effectively distribute topically administered CRISPR-Cas components to modify genes linked to skin problems [42]. For instance, research restored skin barrier function in a mouse model by using lipid-based CRISPR delivery to fix a mutation in the filaggrin gene that causes atopic dermatitis. Another novel application involves using CRISPR interference (CRISPRi) to suppress hyperpigmentation genes like tyrosinase (TYR) and microphthalmia-associated transcription factor (MITF) via topical hydrogels embedded with CRISPR constructs. These techniques provide very selective and minimally off-target gene modification methods that are non-invasive [43].

Plasmid DNA and siRNA-based nanoformulations

To prevent enzymatic breakdown and promote cellular absorption in the skin, plasmid DNA (pDNA) and siRNA are increasingly being encased in dendrimer complexes, solid lipid nanoparticles (SLNs), chitosan nanogels, and nanostructured lipid carriers (NLCs). Genes implicated in inflammation, melanogenesis, and carcinogenesis can be downregulated by siRNA-based formulations, which are very helpful in gene silencing. For example, a cationic nanogel with siRNA, that targets IL-17, was developed, and when applied topically, it dramatically decreased erythema and inflammation in psoriasis-affected skin. In diabetic ulcer models, cationic liposomes have also been used to carry pDNA encoding for Vascular Endothelial Growth Factor (VEGF) in order to promote angiogenesis and quicken wound healing. Skin-targeting ligands and penetration enhancers are being used to refine these delivery methods in order to guarantee transdermal effectiveness without compromising the integrity of the epidermal barrier [43].

Safety and biocompatibility concerns

Safety and biocompatibility are crucial in the clinical translation of non-viral gene delivery methods, which require careful assessment of nanoparticle accumulation, cytotoxicity, and immunogenicity. While materials like polyethylenimine (PEI) can be effective for gene transfection, they pose significant risks at high doses. New formulations employ biocompatible carriers such as PEGylated carriers, biodegradable polymers like PLGA, and natural substances like hyaluronic acid to promote safety and cellular homeostasis. Regulatory bodies are increasingly focusing on the safety and effectiveness of these novel carriers, particularly in cosmetic applications and treatments for chronic skin conditions. The regulatory environment is complex, as the classification of products varies across jurisdictions, often leading to inadequate oversight. To address these challenges, there is a pressing need for harmonized international guidelines that clearly delineate cosmetic from therapeutic products, establish standardized safety testing protocols, and consider the ethical implications of biomedical innovations in cosmetics. Current advancements in self-degrading and stimuli-responsive nanocarriers may pave the way for safer topical gene treatments in the future [44].

RECENT RESEARCH STUDIES AND CASE STUDIES

Table 1 summarizes research articles on the use of several types of nanomaterials for the targeted delivery of therapeutic genes to address aging-related disorders. Emerging technologies in genetic cosmeceuticals, nanocarrier-based formulations, and barrier-modulating agents are primarily supported by *in vitro* studies and animal experiments, providing valuable insights but lacking full human applicability. Preclinical models like murine and porcine have been used to investigate nanoparticle skin penetration and gene delivery, yet they cannot wholly mimic human skin. Human research is limited to small safety trials and efficacy studies, mainly on topical applications, indicating a need for extensive, controlled human studies to confirm safety and effectiveness. Consequently, claims of these technologies being ready for market may mislead consumers and practitioners due to insufficient clinical data.

Tab. 1. Latest research studies on gene delivery for anti-aging by nanocarriers **Source:** [45, 46].

Nanomaterial	Targeted Gene / Molecule	Target Area	Model	Methodology	Key Results	Conclusion
Lipid Nanoparticles (LNPs)	SIRT1	Skin cells	Human (clinical trial)	Topical delivery of SIRT1 gene	Enhanced skin regeneration via increased SIRT1 expression [45]	LNPs show potential in anti-aging gene therapy
Polymeric Nanoparticles (PNPs)	Telomerase Reverse Transcriptase (TERT)	Skin fibroblasts	Rat	Sustained release of TERT gene	Telomerase activity restored; telomere length increased [45]	PNPs can deliver anti-aging genes to fibroblasts for skin regeneration
Gold Nanoparticles (AuNPs)	p53	Aged human fibroblasts	Human (pilot study)	p53 gene injected into fibroblasts	Increased cell growth; delayed senescence [45]	AuNPs effectively transport p53 to boost fibroblast activity
Mesoporous Silica Nanoparticles (MSNs)	FOXO3A	Dermal fibroblasts	In vitro & limited animal studies	Targeted delivery using peptides	Increased FOXO3A expression; enhanced collagen production [45]	MSNs support targeted anti-aging gene delivery and cellular function
Nanostructured Lipid Carriers (NLCs)	NAD+ precursors	Skin cells	In vitro (keratinocytes)	Topical administration of NAD+ precursors	Increased NAD+ levels; improved mitochondrial function [45]	NLCs can potentially reverse cellular aging
RNA Nanocarriers	Anti-aging miRNAs	Skin cells	In vitro & murine model	miRNA delivery targeting aging markers	Improved skin elasticity; reduced wrinkle formation [46]	RNA nanocarriers efficiently deliver anti-aging miRNAs
Polymeric Micelles	CRISPR-Cas9 targeting aging genes	Skin & muscle	In vitro & small animal studies	Gene editing via CRISPR-Cas9	Successful gene editing; regenerated skin and muscle cells [46]	Polymeric micelles provide precise anti-aging gene editing
Liposomes	Growth Hormone Releasing Hormone (GHRH)	Bone & muscle	Murine	Systemic delivery via liposomes	Increased GH output; improved muscle regeneration [46]	Liposomes are effective for rejuvenation gene delivery

CHALLENGES AND FUTURE DIRECTIONS FOR NANOCARRIER-BASED ANTI-AGING GENE DELIVERY

Anti-aging gene therapy using nanocarriers shows potential for enhancing biological functions and longevity, yet faces significant challenges. Key obstacles include technological barriers in gene delivery that provoke immune responses or face degradation [46]. Developing nanocarriers tailored for aging tissues is essential, alongside addressing cost-effectiveness and scalability. Biocompatibility of nanocarriers is crucial to ensure safety in human applications, while the potential risks associated with genetic modifications necessitate thorough preclinical and clinical testing. Regulatory challenges further complicate the approval processes due to the complexity of gene therapies and emerging nanomaterials. Future integration of artificial intelligence may optimize gene delivery systems, enable personalized approaches and accelerate development toward viable anti-aging therapies [46].

GENETIC THERAPIES IN COSMETOLOGY: PROMISE, LIMITATIONS, AND FUTURE PROSPECTS

The integration of genetic techniques into cosmetology represents one of the most forward-thinking yet contentious frontiers in dermatological science. For decades, gene-based therapies were regarded as an unfulfilled promise, largely confined to the treatment of severe genetic disorders, cancers, or rare metabolic diseases. However, the successful approval of mRNA vaccines delivered by LNPs against COVID-19 has dramatically altered perceptions regarding the feasibility and scalability of nucleic acid-based therapeutics. Previously envisioned mainly for highly specialized applications such as personalized immuno-oncology, these platforms have now entered mainstream healthcare. This precedent invites the critical question: can genetically therapies, once considered prohibitively complex and costly, be realistically adapted for cosmetology, a field driven by consumer demand for safety, efficacy, and accessibility [47].

Lessons from approved genetic therapies

To evaluate this possibility, it is essential to analyse the trajectory of approved genetic therapies. The success of mRNA vaccines demonstrates that large-scale production, cold-chain logistics, and public acceptance of genetic medicines are achievable, provided there is clear therapeutic necessity and global coordination. Other approved therapies, such as onasemnogene abeparvovec for spinal muscular atrophy or chimeric antigen receptor T-cell (CAR-T) therapies for hematological cancers, further demonstrate the profound clinical potential of gene-based interventions. Yet, their exorbitant costs, often exceeding hundreds of thousands of dollars per treatment, remain a substantial barrier. In contrast, cosmetology is typically a consumer-driven market where affordability and broad accessibility dictate success. Thus, while genetic cosmeceuticals may inherit the technological breakthroughs of these therapies, they will need to overcome cost and scalability challenges to find widespread adoption [47].

Potential cosmetology applications of genetic therapies

Genetic therapies in cosmetology offer numerous applications such as skin rejuvenation, wrinkle reduction, pigmentation control, and hair restoration. By enhancing collagen and elastin production, gene delivery systems improve skin firmness. Fibroblast-targeted therapies may promote dermal renewal to combat signs of aging. Tools like CRISPR can modulate melanin production by targeting tyrosinase and MITF. Genetic approaches may also prevent photoaging through DNA repair enzyme delivery or antioxidant pathway activation, enhancing resilience against UV damage. Additionally, correcting filaggrin mutations could improve skin barriers, benefiting conditions like atopic dermatitis while enhancing overall skin appearance. These advancements link medical dermatology with cosmetology by addressing both aesthetic and molecular issues [47].

Ethical, safety, and regulatory dilemmas

Implementation of genetic therapies in cosmetology presents significant ethical and regulatory challenges. Unlike lethal conditions, the aesthetic focus mandates stricter safety measures due to potential risks like off-target genetic changes and long-term carcinogenicity. Genetic cosmeceuticals reside in a regulatory grey area, complicating their approval compared to traditional cosmetics, particularly since the United States Food and Drug Administration (FDA) and the European Medicines Agency (EMA) classify them differently, creating high barriers for cosmetic applications. Techniques such as CRISPR-Cas9 and siRNA offer promise for skincare, yet must navigate safety, ethics, and regulatory demands for thorough testing and manufacturing compliance. Personalized skincare solutions may emerge, necessitating harmonized international regulations to ensure safety in these innovations [48].

Cost and accessibility barriers

The financial dimension is equally pressing. While high-income consumers may drive initial market adoption, true scalability in cosmetology requires production methods that lower costs to levels comparable with premium skincare products rather than therapeutic biologics. Nanocarrier platforms, particularly LNPs, polymeric nanoparticles, and exosomes, provide hope by enabling efficient encapsulation, protection, and delivery of genetic materials at lower manufacturing costs. However, achieving reproducibility, stability, and long shelf-life in over-the-counter formulations remains a formidable challenge [48].

Societal perceptions and consumer acceptance

Another layer of complexity involves consumer acceptance. While the success of COVID-19 vaccines normalized mRNA-based products, the idea of using similar tools for cosmetic purposes may provoke scepticism or ethical opposition. Concerns over “genetic tampering for vanity” could trigger societal debates similar to those surrounding genetic enhancement in athletes or designer babies. Public education and transparent labelling will therefore be crucial in shaping acceptance. The parallel rise of personalized skincare driven by genomics and AI-driven diagnostics suggests, however, that consumers are increasingly open to science-backed, individualized interventions [48].

Integration with personalized and preventive cosmetology

The most likely path forward lies in integrating genetic therapies with personalized skincare approaches. DNA-based diagnostic kits already analyse polymorphisms linked to collagen degradation, pigmentation, and oxidative stress responses. By coupling these diagnostics with targeted genetic interventions – such as siRNA silencing of pro-inflammatory genes (interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF-α)) or plasmid DNA encoding for protective antioxidants—cosmetology may shift from a reactive paradigm to one centred on prevention and repair at the molecular level. This aligns with the broader societal movement toward precision medicine and individualized wellness solutions [49].

The foreseeable timeline

The translation of genetic therapies into cosmetology is anticipated to progress gradually. In the short term (1-5 years), hybrid topical formulations using genetic materials like siRNA or plasmid DNA with traditional cosmetic actives are likely to emerge, categorized as advanced cosmetics or medical devices for easier market access. In the medium term (5-10 years), clinical trials may target specific issues such as photoaging and hyperpigmentation with non-viral nanocarrier systems. Countries like South Korea and Japan are expected to lead these innovations under strict regulations.

In the long term (beyond 10 years), genetic cosmetology may become highly personalized, supported by AI and precision delivery methods, transforming the management of aging, pigmentation, and hair issues through enhanced consumer acceptance and reduced costs [49].

Case illustrations from emerging research

Recent studies bridge medicine and cosmetology, showing that genetic therapies can have dual applications. A recent study indicated that CRISPR techniques corrected filaggrin mutations in mice, improving skin barrier function and offering potential for atopic dermatitis treatment. Additionally, siRNA-loaded nanogels demonstrate non-cytotoxic treatments for hyperpigmentation, while VEGF plasmid DNA could enhance recovery after cosmetic procedures. Despite the promise of genetic cosmeceuticals and personalized interventions, most findings remain preclinical, raising concerns about long-term safety, ethical use of technologies like CRISPR-Cas9, and regulatory clarity. Caution is advised to avoid unrealistic expectations before these advances are widely adopted in cosmetics [50].

CONCLUSIONS

The use of nano-formulations to deliver anti-aging genes constitutes a significant development in the field of genetic cosmeceuticals. Nanotechnology, such as nanoparticles, nanogels, and lipid-based carriers, can be used to precisely deliver therapeutic genes to skin cells, improving rejuvenation and correcting aging symptoms. This technique has various benefits, including increased stability, regulated release, and fewer adverse effects. Despite ongoing problems in assuring biocompatibility, scalability, and regulatory approval, the potential for tailored anti-aging therapy is enormous. As research advances, nano-formulations are set to become a potent weapon in age-defying skincare, providing highly effective and tailored treatments that address the underlying molecular causes of aging while also improving skin health.

REFERENCES / LITERATURA

1. Saad FA. Gene therapy for skin aging. *Curr Gene Ther.* 2025;25(1):2-9. https://doi.org/10.2174/0115665232286489240320051925
2. Yu J, Li T, Zhu J. Gene therapy strategies targeting aging-related diseases. *Aging Dis.* 2023;14(2):398-412. https://doi.org/10.14336/AD.2022.00725
3. Kitaeva KV, Solovyeva VV, Blatt NL, Rizvanov AA. Eternal youth: a comprehensive exploration of gene, cellular, and pharmacological anti-aging strategies. *Int J Mol Sci.* 2024;25(1):643. https://doi.org/10.3390/ijms25010643
4. Malik S, Muhammad K, Waheed Y. Nanotechnology: a revolution in modern industry. *Molecules.* 2023;28(2):661. https://doi.org/10.3390/molecules28020661
5. Hegde AR, Kunder MU, Narayanaswamy M, et al. Advancements in sunscreen formulations: integrating polyphenolic nanocarriers and nanotechnology for enhanced UV protection. *Environ Sci Pollut Res.* 2024;31:1-22. https://doi.org/10.1007/s11356-024-33712-0
6. Cao G, Lin M, Gu W, et al. The rules and regulatory mechanisms of FOXO3 on inflammation, metabolism, cell death and aging in hosts. *Life Sci.* 2023;328:121877. https://doi.org/10.1016/j.lfs.2023.121877
7. Hardiany NS, Putra MAR, Penantian RM, Antarianto RD. Effects of fasting on FOXO3 expression as an anti-aging biomarker in the liver. *Heliyon.* 2023;9(2):e13223. https://doi.org/10.1016/j.heliyon.2023.e13144
8. Park SH. Role of phytochemicals in treatment of aging and cancer: focus on mechanism of FOXO3 activation. *Antioxidants.* 2024;13(9):1099. https://doi.org/10.3390/antiox13091099
9. Cui Z, Zhao X, Amevor FK, et al. Therapeutic application of quercetin in aging-related diseases: SIRT1 as a potential mechanism. *Front Immunol.* 2022;13:943321. https://doi.org/10.3389/fimmu.2022.943321
10. Li Y, Tian X, Luo J, et al. Molecular mechanisms of aging and anti-aging strategies. *Cell Commun Signal.* 2024;22(1):285. https://doi.org/10.1186/s12964-024-01663-1
11. Pandey BK, Pandey KB, Srivastava SK. Uses of nanotechnology in refining the anti-aging activities of plant bioactives. In: *Plant Bioactives as Natural Panacea Against Age-Induced Diseases.* Elsevier; 2023:387-403. https://doi.org/10.1016/B978-0-323-90581-7.00006-2
12. Yanamandala N, Kumar P. Polymeric micelles and dendrimer drug delivery. In: *Nanocosmetics: Delivery Approaches, Applications and Regulatory Aspects.* Elsevier; 2023:205-226. https://doi.org/10.1201/9781003319146-10
13. Dowaidar M. Drug delivery based exosomes uptake pathways. *Neurochem Int.* 2024;180:105835. https://doi.org/10.1016/j.neuint.2024.105835
14. Hwu JR, Tsay SC, Patil U, et al. Functionalized carbon nanotubes as gene carriers. In: *Advanced Materials for Multidisciplinary Applications.* Springer; 2023:105-129. https://doi.org/10.1007/978-3-031-39404-1_3
15. Ranjbar S, Emamjomeh A, Sharifi F, et al. Lipid-based delivery systems for flavonoids and flavonolignans. *Pharmaceutics.* 2023;15(7):1944. https://doi.org/10.3390/pharmaceutics15071944
16. Madgula K, Peddada LM, Pattathil SD. Biologically synthesized nanocarriers for targeted drug delivery applications. In: *Nanotechnology for Drug Delivery and Pharmaceuticals.* Academic Press; 2023:43-70. https://doi.org/10.1016/B978-0-323-95325-2.00009-2
17. Zhang T, Luo X, Xu K, Zhong W. Peptide-containing nanoformulations: skin barrier penetration and activity contribution. *Adv Drug Deliv Rev.* 2023;194:115139. https://doi.org/10.1016/j.addr.2023.115139
18. Tekinay SH. Nanomaterials for skin anti-aging. *Eur Polym J.* 2024;217:113311. https://doi.org/10.1016/j.eurpolymj.2024.113311
19. Prasanth MI, Sivamaruthi BS, et al. Role of epigenetic modulation in neurodegenerative diseases. *Antioxidants.* 2024;13(5):606. https://doi.org/10.3390/antiox1305060
20. Cord D, Rîmbu MC, et al. Phytochemicals as epigenetic modulators in chronic diseases. *Molecules.* 2025;30(21):4317. https://doi.org/10.3390/molecules30214317
21. Liang C, Yi Y, Li J, et al. Unveiling exosomes in combating skin aging. *Stem Cell Res Ther.* 2025;16(1):474. https://doi.org/10.1186/s13287-025-04620-y
22. Mitali, Singh MK, Mishra AK. Nanotechnology-based approaches for combating skin aging. *Curr Aging Sci.* 2025. https://doi.org/10.2174/0118746098384581250904035955
23. Khobragade R, Chaudhary AA, Ali MA, et al. Nanotechnology-enhanced sunscreens. *Pharmaceutics.* 2025;17(8):1080. https://doi.org/10.3390/pharmaceutics17081080
24. Shilovsky GA, Sorokina EV, Akhaev DN. Anti-aging medicine: mitochondria-targeted antioxidants and physical activity. *Biol Bull Rev.* 2024;14(4):426-433. https://doi.org/10.1134/S2079086424600188
25. Singh B, Kumar G, Vandana, et al. Bioactive-based nanocarriers for cosmeceuticals. In: *Bioactive-Based Nanotherapeutics.* 2025:339-367. https://doi.org/10.1002/9781394287345.ch10
26. Aloenida YP, Dewi MK, Muhaimin M, Chaerunisaa AY. Nanoparticles as a promising approach for improving skin anti-aging activity. *Nanotechnol Sci Appl.* 2026:571010. https://doi.org/10.2147/NSA.S571010
27. Devi V, Deswal G, Grewal AS, et al. Phytoextracts as natural anti-aging agents. *Curr Aging Sci.* 2025. https://doi.org/10.2174/0118746098363055250218040726
28. Kumar S, Gupta R, Sharma A. Nanotechnology-based cosmeceuticals. *Colloids Surf B Biointerfaces.* 2022;210:112231. https://doi.org/10.1016/j.colsurfb.2021.112231
29. Liu Y, Fang M, Tu X, et al. Dietary polyphenols as anti-aging agents. *Nutrients.* 2024;16(19):3305. https://doi.org/10.3390/nu16193305
30. Faraji SN, Karami-Darehnaranji M, Takallu S, et al. Advances of gold and silver nanoparticles for skincare. In: *Nanotechnology in Cosmeceuticals.* Academic Press; 2026:103-112. https://doi.org/10.1016/B978-0-443-30184-1.00010-7

31. Gilbert MM, Mathes SC, Mahajan AS, et al. The role of sirtuins in dermal fibroblast function. *Front Med.* 2023;10:1021908. https://doi.org/10.3389/fmed.2023.1021908
32. Pozos-Nonato S, Domínguez-Delgado CL, Campos-Santander KA, et al. Novel nanotechnological strategies for skin anti-aging. *Curr Pharm Biotechnol.* 2023;24(11):1397-1419. https://doi.org/10.2174/1389201024666221223095315
33. Nadeem W, Ahmad S, Rahman MU, et al. Nanostructured lipid carriers in cosmeceuticals. *Prospects Pharm Sci.* 2025;23(2):74-83. https://doi.org/10.56782/pps.315
34. Wang W, Zhu H, Jiang Q, et al. FOXO: a key target in aging. *Biogerontology.* 2026;27(1):38. https://doi.org/10.1007/s10522-025-10380-2
35. Kang Y, Zhang S, Wang G, et al. Nanocarrier-based transdermal drug delivery systems. *Pharmaceutics.* 2024;16(11):1384. https://doi.org/10.3390/pharmaceutics16111384
36. Ramaraj JA, Narayan S. Anti-aging strategies and topical delivery. *Curr Aging Sci.* 2024;17(1):31-48. https://doi.org/10.2174/1874609816666230320122018
37. Yan Z, Zhang S, Wu G, et al. Advances in nanotechnology-based topical delivery systems. *Pharmaceutics.* 2026;18(1):63. https://doi.org/10.3390/pharmaceutics18010063
38. Khan Y, Bisht AS, Ashique S, et al. Innovative anti-aging strategies targeting WNT pathway. *Hum Gene.* 2025;44:201397. https://doi.org/10.1016/j.humgen.2025.201397
39. Alves PL, Nieri V, Moreli FD, et al. Advancing technologies in cosmeceuticals. *Molecules.* 2024;29(20):4890. https://doi.org/10.3390/molecules29204890
40. Verma D, Jain A, Singh A. Phytosomes as delivery systems. *J Drug Deliv Sci Technol.* 2022;74:103554. https://doi.org/10.1016/j.jddst.2022.103554
41. Pan X, Zhong Z, Hu X, et al. Nanotechnology in anti-aging cosmetics. *Polym Bull.* 2025;82(14):8635-8725. https://doi.org/10.1007/s00289-025-05903-3
42. Yihan W, Jinjin D, Yingqi W, et al. Advances in plant essential oils for skincare. *Front Pharmacol.* 2025;16:1578280. https://doi.org/10.3389/fphar.2025.1578280
43. Parga AD, Ray B. Nanocarrier systems for dermatologic delivery. *Int J Nanotechnol Nanomed.* 2025;10(1):1-12. https://doi.org/10.33140/IJNN.10.01.01
44. Thakur M, Bala R. Cosmeceutical regulations: global perspective. *Int J Toxicol.* 2025. https://doi.org/10.1177/10915818251399664
45. Prajapati A, Kumar R. Nanoparticles in cosmeceutical science. *J Pharma Insights Res.* 2024;2(3):30-37. https://doi.org/10.69613/rckvna64
46. Li D, Huang Y, Chen J. Hydrogel-based delivery systems for skin anti-aging. *J Control Release.* 2023;353:1122-1135. https://doi.org/10.1016/j.jconrel.2022.12.003
47. Shaker LM, Al-Amiery A. Next-generation antioxidant strategies. *cScience.* 2026;2(1):e70013. https://doi.org/10.1002/csc3.70013
48. Rohilla S, Rohilla A, Narwal S, et al. Global trends of cosmeceuticals in nanotechnology. *Pharm Nanotechnol.* 2023;11(5):410-424. https://doi.org/10.2174/2211738511666230508161611
49. Shree D, Patra CN, Sahoo BM. Herbal nanocarriers for dermatological disorders. *Pharm Nanotechnol.* 2022;10(4):246-256. https://doi.org/10.2174/2211738510666220622123019
50. Chauhan SB, Singh I, Singh M, Singh M. Hybrid cosmeceutical innovations for aging skin. *Curr Aging Sci.* 2025. https://doi.org/10.2174/0118746098369285250902044905

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