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Review Article

From Particle Attributes to Biological Performance: An Integrated Evaluation Framework for Next-Generation Nanocosmetics

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Abstract

Development of Nanocosmetics commonly relies on particle size, polydispersity, surface charge, morphology and encapsulation efficiency to identify optimized formulations. No doubt, these attributes are indispensable for quality control, stability, and manufacturing reproducibility, they cannot independently predict skin disposition or biological effectiveness. Nanocarriers with comparable particle sizes may produce substantially different release, retention, and biological responses because of differences in composition, structural organization, surface properties, and interactions with the skin barrier. This article argues for an integrated, claim-directed evaluation framework that connects physicochemical attributes with skin disposition, molecular and cellular responses, functional skin outcomes, and consumer-visible benefits. Relevant endpoints may include barrier integrity, hydration, extracellular matrix preservation, oxidative stress reduction, inflammatory modulation, pigmentation control and tolerability. Implementing this approach will require validated skin models, standardized biological endpoints, and stronger translation of mechanistic findings into human outcomes. Therefore, the next generation of Nanocosmetics should be defined not by achieving the smallest particle size but by reproducible evidence linking rational nanoscale design to biological performance, safety, and meaningful skin benefits.

Keywords: Nanocosmetics, Biological performance, Physicochemical characterisation, Skin delivery, Nanocarriers, Claim substantiation, Nanocosmetics precision, Organ-on-chip technology, Artificial intelligence

List of Abbreviations: AI: Artificiale Intelligence; AU: Arbitrary Units; C. acnes: Cutibacterium acnes; DCFH-DA: 2',7'-Dichlorodihydrofluorescein Diacetate; IL: Interleukin; IC_{50}: Half-Maximal Inhibitory Concentration; MDA: Malondialdehyde; MITF: Microphthalmia-Associated Transcription Factor; MMP: Matrix Metalloproteinase; MMP-1: Matrix Metalloproteinase-1; MMP-3: Matrix Metalloproteinase-3; MMP-9: Matrix Metalloproteinase-9; MTT: 3-(4,5-Dimethylthiazol-2-yl)-2,5-Diphenyltetrazolium Bromide Assay; mRNA: Messenger Ribonucleic Acid; NF-κB: Nuclear Factor Kappa B; NLC: Nanostructured Lipid Carrier; Nrf2: Nuclear Factor Erythroid 2-Related Factor 2; OECD: Organisation for Economic Co-operation and Development; PDI: Polydispersity Index; PEG: Polyethylene Glycol; Ra: Average Surface Roughness; ROS: Reactive Oxygen Species; R2: Gross Elasticity Parameter; R5: Net Elasticity Parameter; R7: Biological Elasticity Parameter; rRNA: Ribosomal Ribonucleic Acid; S. epidermidis: Staphylococcus epidermidis; SCCS: Scientific Committee on Consumer Safety; SEM: Scanning Electron Microscopy; SLN: Solid Lipid Nanoparticle; SOD: Superoxide Dismutase; TEWL: Transepidermal Water Loss; TEM: Transmission Electron Microscopy; TNF-α: Tumor Necrosis Factor Alpha; UV: Ultraviolet; VISIA: Visual Imaging Skin Analysis System; WST-1: Water-Soluble Tetrazolium Salt-1 Assay

Introduction

In the past 20 years, the global cosmetic industry has seen tremendous technological progress, as evidenced by the adoption of nanotechnology in the production and formulation of many product categories, including skin, hair, anti-aging, sun protection, and dermatological products. Nanocosmetics are defined as products containing nanoscale materials or nanocarrier systems that enhance the delivery, stability, and efficacy of active ingredients in formulations and typically have a size range of 1–1000 nm [1]. Among the most common methods for nano-delivery vehicles are liposomes, nanoemulsions, Solid Lipid Nanoparticles (SLN), Nanostructured Lipid Carriers (NLC), polymeric nanoparticles, dendrimers, and nanocrystals [2]. These vehicles provide significant advantages in product formulation, such as enhanced solubility of poorly water-soluble materials, protection from oxidative or light-induced degradation of bioactives, controlled release, enhanced retention in the skin, and better sensory properties [3]. While this innovation is significant, the field has become far too reliant on particle size alone as an indicator of success in the development and formulation process of nanocosmetics [4]. Through a review of the scientific literature, it appears that the majority of research studies evaluate success based on achieving small particle sizes, narrowly defined polydispersity, desirable zeta potential, and high encapsulation efficiency. While these metrics are critical for determining quality control, they have become surrogate indicators of biological effectiveness [5].

This reductionist approach has created a significant translational gap: products that perform impressively on physicochemical benchmarks often fail to deliver consumer-visible skin improvements that are both reproducible and mechanistically explicable. Skin biology is substantially more complex than any single particle dimension can capture [6]. Clinical outcomes, such as wrinkle reduction, pigmentation control, barrier repair, and elasticity improvement, are governed by intricate molecular events, including collagen transcription, ceramide synthesis, Reactive Oxygen Species (ROS) scavenging, and cytokine modulation, none of which can be predicted from nanometer-scale size data alone [7]. The scientific community has begun to acknowledge this limitation. Currently, guidance on nanomaterials mainly focuses on safety, exposure, and physicochemical characterization. Consequently, the suggested framework for biological performance should be considered an addition to current safety standards, aimed at enhancing scientific assessment and supporting cosmetic claims, rather than being viewed as a mandatory regulatory approval criterion [8]. Existing reviews of nanocosmetics have primarily focused on the types of nanocarriers, formulation benefits, physicochemical properties, and safety. However, comparatively less emphasis has been placed on establishing a structured relationship between critical nanoparticle attributes, skin-specific biological responses, and clinically observable cosmetic outcomes. Therefore, this article proposes an integrated evaluation framework that retains physicochemical characterization as the foundation for product quality while incorporating mechanistic, functional, and clinical endpoints to establish biological performance. The framework aims to support more reproducible formulation development, stronger claim substantiation, and improved translation of nanocosmetic systems from laboratory studies to consumer use. This conceptual shift from a particle-centric to a biology-centric framework is the central argument of the present article, as summarized in Table 1.

Table 1: Evaluation Criteria in Nanocosmetics Research: Traditional versus emerging approach.

Traditional Physicochemical Approach	Emerging Biology-Centric Approach
Particle size	Barrier repair efficacy
Polydispersity index (PDI)	Collagen and elastin synthesis
Zeta potential	Oxidative stress reduction
Encapsulation efficiency	Cytokine and inflammatory modulation
Morphology (TEM/SEM)	Microbiome restoration and balance
Storage stability	Clinically observable skin improvement
Drug loading capacity	Long-term safety and tolerability

Nanocosmetics: Major Benefits and Scientific Importance

Cosmetic formulation design has been greatly transformed by nanotechnology, which provides a means overcomes the limitations associated with traditional topical delivery systems. The scientific benefits of nanocosmetic systems can be categorized into five areas of significance. The primary science-based advantage associated with nanocarrier-based formulations is increased solubility and stability [9]. Many active components commonly used in cosmetics, such as retinol, coenzyme Q10, curcumin, resveratrol, vitamin E, bakuchiol, and ascorbic acid, have poor aqueous solubility and are unstable in the environment. By encapsulating the active component in a nanocarrier, the solubility of the active component is improved through solubilization, the shelf life is extended, and the active component is protected against photodegradation, oxidation, and hydrolysis [10].

The second major benefit of nanocarriers is the controlled and sustained release of the active component from the nanocarrier to the skin. Unlike traditional lotions and creams, where the

active component is deposited only on the surface of the skin, nanocarrier systems provide controlled release profiles for the active components, allowing them to remain active for a longer period in the target tissue and produce less irritation due to high peak concentrations of the active components than would be observed with traditional formulations. This also allows for the use of retinoids and acids at concentrations that would otherwise be too aggressive for cosmetic use [11]. Another area of significance is improved retention of the active components in the skin and enhanced follicular targeting. Rather than merely improving gross percutaneous penetration, modern nanocarriers are designed to improve the retention of active components at the level at which they provide benefits to the skin and hair follicles [12].

The ability of hair follicles to store nanoparticles makes it possible for any active ingredients in those nanoparticles to be released over a long time into the surrounding tissues around the hair follicle, a discovery that has major ramifications for anti-aging, androgenic alopecia, and the scalp microbiome [13]. The fourth advantage is the optimal consumer and sensory experience characteristics. Compared to their equivalent conventional emulsions, nano formulations have been shown to be more spreadable, have less greasy residue, have an improved sensory feel on the skin, and have greater aesthetic appeal, all of which have a direct impact on product effectiveness and customer acceptance by increasing compliance with application protocols [14].

The multifunctional nature of nanocarriers distinguishes them from traditional delivery systems. Advanced delivery systems can combine multiple functions in one product. For example, tocopherol and tocopheryl acetate-loaded nanostructured lipid carrier systems have been reported to create an occlusive film on the skin, enhancing skin moisture, elasticity, and local skin retention, providing antioxidant, UV protection, and anti-aging effects, all of which are consistent with the complexity of the biological nature of human skin [15]. These outcomes cannot be predicted using traditional metrics such as particle size, zeta potential, or encapsulation efficiency. Table 2 outlines the primary cosmetic nanocarrier systems, their primary functional advantages, and application examples currently utilized in the cosmetics industry.

Table 2: Major Nanocarrier Systems in Cosmetics: Advantages and Applications.

Nanocarrier System	Key Advantages	Representative Cosmetic Applications
Liposomes	Biocompatibility, biomimetic phospholipid bilayer, enhanced skin penetration, versatile encapsulation of hydrophilic and lipophilic actives	Anti-aging serums, moisturisers, sensitive skin formulations
Nanoemulsions	Improved thermodynamic stability, transparent appearance, high surface area, enhanced solubilisation capacity	Sunscreens, lightweight serums, tinted moisturisers
Solid Lipid Nanoparticles (SLNs)	Controlled and sustained release, occlusive film formation, skin hydration enhancement, protection of labile actives	Anti-aging creams, UV-protective formulations
Nanostructured Lipid Carriers (NLCs)	Higher loading capacity than SLNs, reduced drug expulsion during storage, superior skin retention	Retinoid delivery, anti-pigmentation products
Polymeric Nanoparticles	Targeted delivery, versatile surface functionalisation, sustained release over extended periods	Skin rejuvenation, peptide and growth factor delivery
Nanocrystals	Enhanced saturation solubility, increased skin adhesion, high drug content per particle	Antioxidant formulations, poorly soluble active delivery
Dendrimers	Precisely defined architecture, multivalent surface groups, capacity for co-encapsulation of multiple actives	Experimental anti-aging and gene-delivery cosmetics

Current Limitations and Challenges

Despite their significant potential, nanocosmetic systems continue to face challenges that limit widespread clinical adoption and consumer confidence. Safety remains a primary concern, particularly regarding nanoparticle accumulation in skin tissues, potential reactive oxygen species generation following UV exposure, and the long-term effects of repeated applications. Furthermore, the toxicological profiles of many novel nanocarrier materials remain insufficiently characterized across different exposure routes, skin conditions, and population groups [16].

Regulatory fragmentation is another major obstacle. Different regions have varying definitions, notification requirements, safety assessments, and labelling standards for cosmetic nanomaterials. Although the European Union Cosmetics Regulation (EC) No. 1223/2009 requires nanomaterial notification, standardized biological efficacy evidence is not yet mandatory. Manufacturing scalability and batch-to-batch consistency also remain significant challenges for commercialization, as laboratory-scale formulations often fail to maintain particle characteristics and stability during industrial production. Another limitation is the lack of clinical translatability. Many published studies focus primarily on physicochemical parameters, such as particle size, Polydispersity Index (PDI), and zeta potential, with limited assessment of biological activity through cell-based, ex vivo, or in vivo models. This disconnect highlights the urgent need to integrate biological performance evaluation with traditional physicochemical characterization to ensure meaningful and clinically relevant nanocosmetics development.

Why Conventional Nanocosmetic Evaluation Is Incomplete

A common belief in the scientific research of nanocosmetics is that the smaller the nanoparticles, the more deeply they penetrate the skin, and the more active they are in biological systems. But over time, more and more, there is an indication that this is not a simple relationship. The stratum corneum is a highly efficient biological barrier that slows down the penetration of nanoparticles, regardless of their size [17]. Research has shown that most of the intact nanoparticles are found in the outer layers of the skin or hair follicles and that biological effects in deeper tissues are mediated by the release of the active ingredient from the encapsulated nanoparticles and not by the penetration of the nanoparticles [18]. Therefore, in addition to particle size, carrier flexibility, release kinetics, lipid composition, and surface chemistry may be more important in determining efficacy than particle size.

The use of Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs) also illustrates that formulations with similar particle sizes (150–200 nm) show significantly different skin retention, occlusive properties, and delivery efficacy as a result of the difference in lipid crystalline structure, type of surfactants used, and solid-to-liquid lipid ratio [10,19]. Likewise, the penetration properties of liposomes of similar size can be different, contingent on the composition of the bilayer, surface charge, and structural organization [20]. Surface properties, such as charge, polyethylene glycol coating, functionalization with ligands, and interactions with lipids, can have a more profound effect on biological outcomes than particle size. The surface properties, in addition to size, influence follicular penetration and cellular uptake [21.

The future of nanocosmetics lies in biology-driven, mechanism-based evaluation that delivers measurable, meaningful, and consumer-relevant outcomes, as illustrated in Figure 1.

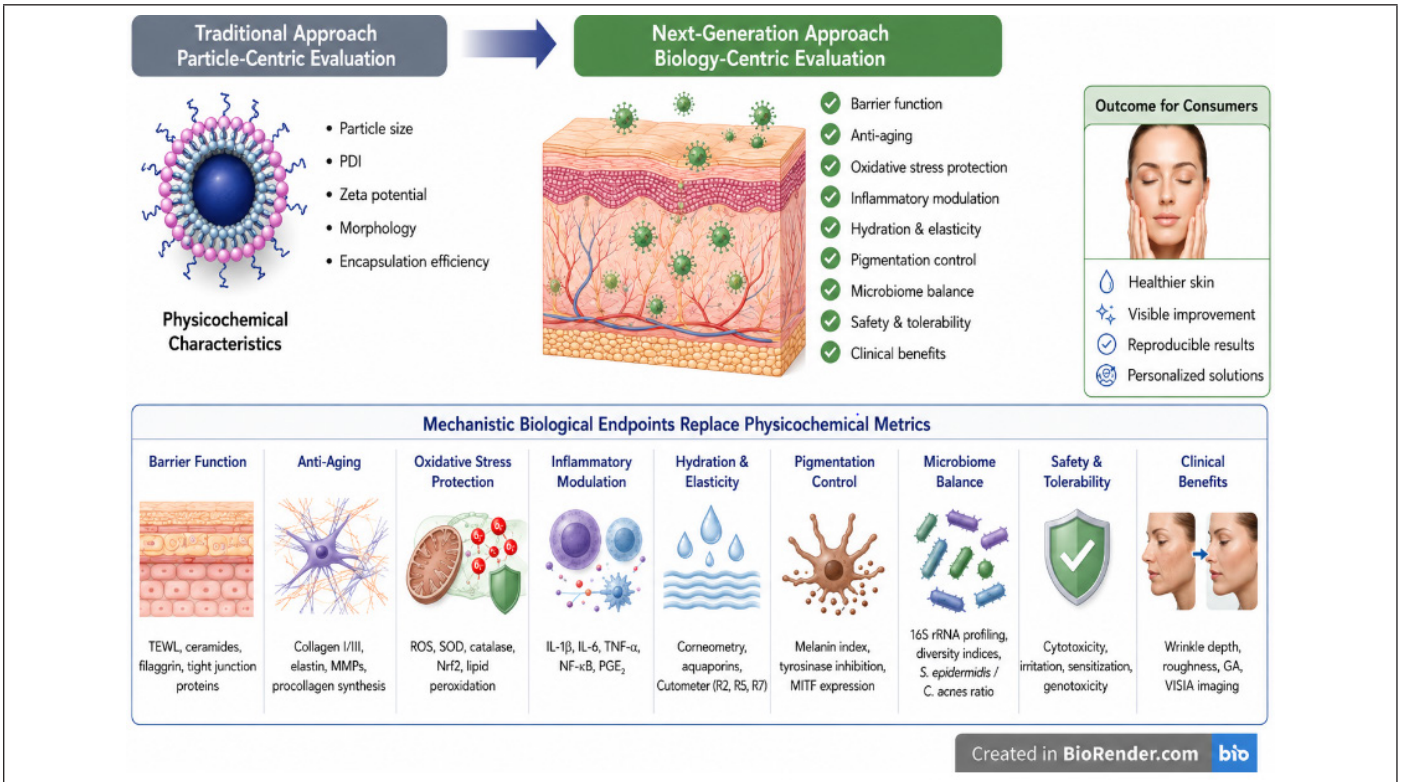

Figure 1: Transition from traditional Particle centric evaluation to biology driven assessment in relevant outcomes.

Furthermore, skin conditions play a significant role in penetration dynamics. Damaged, inflamed, atopic, or aged skin shows altered barrier function, lipid composition, and protein expression, which allow them to exhibit different behaviors in the skin to nanocarriers, which cannot be adequately predicted by physicochemical measurements alone [22]. Thus, particle size is a quality characteristic but cannot be used as a good predictor of biological activity. Future development of nanocosmetics should consider the development of biological performance metrics that are directly linked to clinically and cosmetically relevant outcomes [23].

Critical nanocarrier Attributes and Their Biological Consequences

In a study by [24], it was determined that visible improvements to skin health, such as better hydration, elasticity, pigmentation control, wrinkle reduction, and barrier function recovery, are more important to a consumer than simply the size of a nanoparticle. There are various ways to measure barrier function, including Transepidermal Water Loss (TEWL) and biomarker levels of ceramides, filaggrin, involucrin, and tight junction proteins [25]. The antiaging efficacy of a nanocosmetic can be measured by the level of fibroblast activation, collagen and elastin production, and inhibition of the matrix metalloproteinases that degrade the dermal matrix [26]. Biological measures of antioxidant activity can involve the measurement of Reactive Oxygen Species (ROS), antioxidant enzymes, glutathione, and activation of the Nrf2 pathway [27]. Melanin-related biomarkers, inhibition of the enzyme tyrosinase,

and levels of IL-1β, IL-6, IL-8, and TNF-α are used as biological measures for pigmentation control and anti-inflammation. Use of these types of biological metrics will provide meaningful evidence of the efficacy of a given product. The underlying biological mechanisms for specific cosmetic outcomes are presented in Table 3.

Table 3: Biological Mechanisms Underlying Key Cosmetic Outcomes.

Desired Cosmetic Outcome	Underlying Biological Mechanism
Skin hydration	Aquaporin-3 and aquaporin-9 upregulation; natural moisturising factor synthesis
Epidermal barrier repair and permeability regulation	Ceramide I/III/VI synthesis; filaggrin and involucrin expression; tight junction protein restoration (claudin-1, occludin)
Anti-aging (collagen)	Fibroblast activation; collagen type I and III transcription; MMP-1, MMP-3, and MMP-9 inhibition
Skin elasticity	Elastin preservation; lysyl oxidase activity; tropoelastin synthesis
Pigmentation control	Tyrosinase inhibition; MITF downregulation; melanosome transfer blockade; reduction of melanin index
Antioxidant protection	ROS scavenging; SOD and catalase activity enhancement; Nrf2 pathway activation
Anti-inflammatory activity	IL-1β, TNF-α, and IL-6 suppression; NF-κB pathway inhibition; prostaglandin modulation
Microbiome balance	Restoration of S. epidermidis / C. acnes ratio; microbial diversity indices; defensin stimulation

Advanced Models and Analytical Technologies

Historically, scientists have relied heavily on physicochemical endpoints when testing nanocarriers because of the limitations of our biological evaluation tools; however, many of these constraints are quickly diminishing as new technologies emerge that will allow us unprecedented levels of precision when evaluating the interactions between nanocarriers and skin tissues at both the molecular/cellular and tissue levels. The most important techniques are briefly described below and depicted in Figure 2.

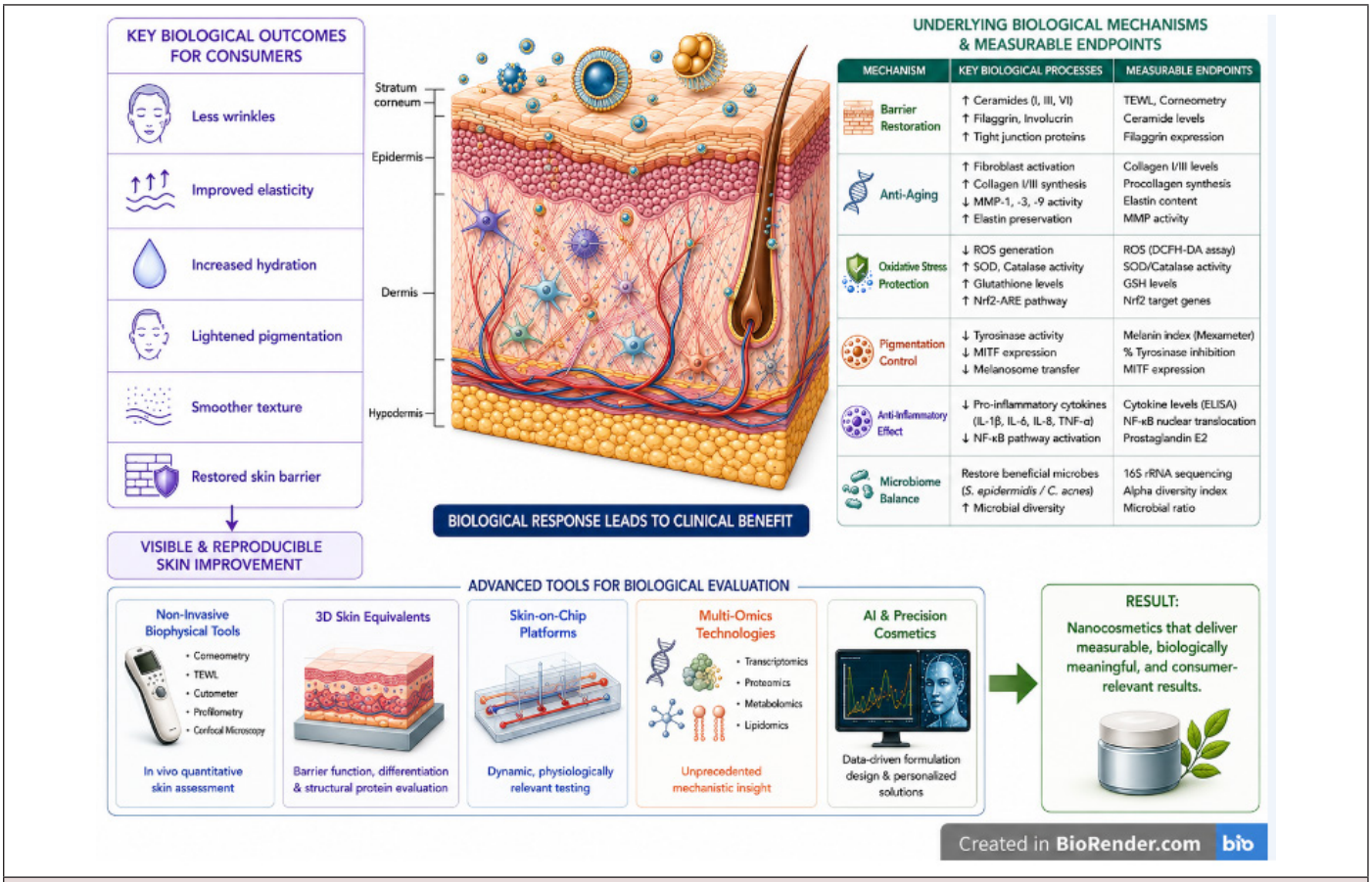

Figure 2: Biological mechanism underlying key cosmetic outcomes and the advanced tools used to evaluate them.

Non-Invasive In Vivo Biophysical Measurement

Quantitative evaluation of skin biological functions can be performed using noninvasive biophysical tools without the need for a biopsy. Some of the measurements of these different tools include corneometry, which measures hydration of the skin (Transepidermal Water Loss (TEWL), which measures barrier integrity; Cutometer, (measures elasticity) profilometry, (evaluates wrinkle depth and roughness); and reflectance confocal microscopy, (visualizes structures found in the epidermis and collagen). In addition, if used together with molecular biomarkers, these non-invasive biophysical evaluation tools can create a thorough consumer-relevant biological evaluation [25].

Three-Dimensional Human Skin Equivalents

Reproductions of human epidermidis and full-thickness skin systems can replicate human skin. They allow us to assess barrier functions, epidermal differentiation, structural proteins, and other attributes of these types of tissues. OECD-validated platforms will be increasingly used in the future for efficacy and safety assessments and regulatory submissions [28].

Skin-on-Chip Platforms

Dynamic skin microenvironments can be recreated in microfluidic skin-on-chip systems by providing fluid flow, mechanical stimulation, and immune interaction. These types of systems provide a realistic way to investigate potential safety issues associated with the use of nanoparticles for longer durations [29].

Multi-Omics Technologies

The use of integrated approaches across different fields of myology will help scientists (and the public) better understand how nanomaterials affect biology through transcriptomic, proteomic, metabolomic, and lipidomic studies. These scientific methods show how nanomaterials can change the fundamental way we produce collagen, our skin barrier function, and how they cause a cellular response within our body. Therefore, they provide a better mechanistic picture of their effects than our currently accepted physical or chemical characterization [30].

Artificial Intelligence and Precision Cosmetics

AI provides an accelerated approach to identify the best formulation for a specific individual by predicting the likely outcome of a specific nanosized delivery system using biological metrics, such as collagen stimulation, rate of Trans-Epidermal Water Loss (TEWL), and many other biological variables. To create an accurate individualized skin map for a targeted and effective formulation, precision cosmetics require the use of skin imaging technology, genetic information, microbiome data, and environmental factors. The ethical issues surrounding data privacy, informed consent, and algorithm bias must be properly addressed to ensure consumer confidence in the industry is maintained [31]. Predictions indicate that the use of AI will guide the biological optimization of nanosized delivery systems by 2035 for the development of nanocosmetics, with an emphasis on selecting nanosized delivery systems based on biological effectiveness versus size alone.

Safety, Regulatory and Cosmetic Claim Substantiation

Nanocosmetics are now being regulated with a focus not only on physicochemical characteristics but also, increasingly, on scientifically based biological assessments. While some of the standards, such as particle size, zeta potential, and efficiency of encapsulation, are still fundamental for quality assurance of products, regulatory agencies are becoming aware that these parameters alone are insufficient to predict biological effectiveness or long-term biological fate and persistence. As such, regulators will be looking for mechanistic evidence of how nanocarrier systems impact skin biology (barrier repair, antioxidant properties, anti-inflammatory properties, enhanced collagen synthesis, and microbiome balance) [32]. There have been many recent discussions regarding the regulation of cosmetics, focusing on the need to combine validated biological endpoints (to demonstrate biological effectiveness) with traditional safety (risk) assessments (to substantiate the science of which to base the effectiveness of products). As a result of these discussions, platforms for advanced type testing with at least human 3D skin models, skin chips (i.e., microfluidic chips containing human skin cells), and multi-omics methodologies are all being viewed as excellent resources for producing biological information about products while reducing the need for animal testing [33]. Additionally, harmonized international standards are expected to promote consistent methods of quantifying the biomarkers used to measure efficacy, tolerability, and visible results in consumers. It is anticipated that successful nanocosmetic products will have to include a comprehensive biological data package (which links the properties of each formulation with measurements of skin responses) over the next several years. This change represents a major paradigm shift (Promise) in regulatory science, where product approval and acceptance will increasingly be based on demonstrated statistical data demonstrating biological performance rather than simply meeting threshold values or limits established by the current (or previous) regulatory systems.

Future of Biology-Driven Nanocosmetics Design

The shift to biologically based nanocosmetics manufacturing will be increased by the use of AI and machine learning technologies to help researchers and manufacturers view the relationship between the formulation's physical/chemical properties and how these properties influence the biologically relevant outcomes

seen across all types and applications of skin products [34], While traditional methods may provide limited insights into the formulation's physical/chemical makeup and the biological impact on the skin, next-generation AI will allow for an advanced level of analysis of both historical and current formulation datasets to identify links between formulation composition, processes, and biological responses that would be overlooked by existing methods [35] (Table 4).

Table 4: Recommended Biological Performance Metrics for Next-Generation Nanocosmetics Evaluation.

Evaluation Category	Recommended Biological Performance Metrics
Barrier Function	TEWL ($g/m^2/h$), ceramide I/III levels, filaggrin and involucrin expression, tight junction proteins (claudin-1, occludin)
Anti-Aging	Collagen type I/III mRNA and protein, elastin content, MMP-1/-3/-9 activity, procollagen synthesis
Oxidative Stress	Intracellular ROS (DCFH-DA assay), SOD and catalase activity, Nrf2 target gene expression, lipid peroxidation (MDA)
Inflammation	IL-1β, IL-6, IL-8, TNF-α expression ; NF-κB nuclear translocation ; prostaglandin E2
Skin Hydration	Corneometry (AU), aquaporin-3/-9 expression, natural moisturising factor quantification
Skin Elasticity	Cutometer parameters R2 (gross elasticity), R5 (net elasticity), R7 (biological elasticity)
Pigmentation	Melanin index (mexameter), tyrosinase inhibition (%), MITF expression, melanosome transfer assay
Microbiome	Alpha-diversity (Shannon index), S. epidermidis / C. acnes ratio, 16S rRNA profiling
Safety	MTT/WST-1 cytotoxicity (IC_{50}), OECD 442C/D sensitisation, OECD 439 skin irritation, genotoxicity (Ames test)
Clinical Benefit	Wrinkle depth (profilometry), skin roughness (Ra/Rz), Investigator Global Assessment, VISIA imaging

Future Research Priorities (2026–2035)

Collaborations between academia, industry, and government should focus on developing universally accepted frameworks for the biological evaluation of nanocosmetics in the next decade. One of the difficulties is that there is still no agreement on what is necessary in a biological data package to assess the efficacy and safety of the nanocosmetics. The use of standardized procedures with cross-laboratory validation studies and centralized biological performance databases will play a key role in generating reproducible and comparable results [25]. Advanced 3D skin models have been proposed as an alternative test method for long-term safety evaluation, providing more clinically relevant information than conventional testing methods. The formulation design will be artificial intelligence-driven and will require a large amount of biological data from various institutions. To minimize the historical research biases, future personalized nanocosmetics should include skin models of different ethnic groups. Beyond that, strong clinical validation (with standardized biological endpoints rather than safety-focused endpoints), metrics of efficacy based on the microbiome, and more harmonized international regulatory frameworks will be vital to the success of products on the market, despite the increased cost and complexity of microbiome-based evaluations [36-38].

Conclusion

Nanotechnology in cosmetics has fundamentally altered cosmetic science (and how we define and evaluate the effectiveness of products). In previous definitions of topical nano-delivery, particle size was the primary determinant of a product's efficacy. Relying primarily on particle size has led to an insufficient assessment of the biological performance of nanocosmetics and their benefits to the skin. A paradigm shift away; from a particle-centric approach to a biology-centric approach; is needed, where the proof of efficacy will be measured using biological (rather than physical) output. Although particle size is an important consideration, however, it does not provide a consistent basis for predicting performance. Many of the best-known cosmetic claims, such as "repairing the skin barrier" and "reducing the effects of oxidative stress," depend on biological mechanisms defined at the molecular level. Recent advancements in three-dimensional skin models, organ-on-chip technology, and precision phenotyping have made it possible to directly measure biological mechanisms. Regulatory agencies are now demanding biological evidence to be used during the evaluation of product safety, as the market moves towards biologically credible claims for cosmetics. As such, many of the more successful nanocosmetics will continue to demonstrate reproducible improvements in biological endpoints in a variety of skin types with clear mechanisms and consistent data supporting their safety. Therefore, the entire industry must shift from a particle-centric model to the one focused on skin biology. Regulatory science emphasizes biological evidence of nanomaterial safety. Future successful nanocosmetics will show reproducible clinical benefits and safety, prioritizing skin biology over merely small particle sizes.

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Ethical Approval

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Consent to Publication

The authors confirm that this manuscript is original, has not been published previously in any language or format, and is not under consideration for publication elsewhere.

Conflict of Interest

The authors declare no conflict of interest.

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