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Review Paper

Nano Technology in Cosmetic and Cosmeceutical Formulation

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ABSTRACT

Nanotechnology has the potential to generate advancements and innovations in formulations and delivery systems. This fast-developing technology has been widely exploited for diagnostic and therapeutic purposes. Today, cosmetic formulations incorporating nanotechnology are a relatively new yet very promising and highly researched area. The application of nanotechnology in cosmetics has been shown to overcome the drawbacks associated with traditional cosmetics and also to add more useful features to a formulation. Nano cosmetics and nano cosmeceuticals have been extensively explored for skin, hair, nails, lips, and teeth, and the inclusion of nanomaterials has been found to improve product efficacy and consumer satisfaction. This is leading to the replacement of many traditional cosmeceuticals with nano cosmeceuticals. However, nanotoxicological studies on nano cosmeceuticals have raised concerns in terms of health hazards due to their potential skin penetration, resulting in toxic effects. This review summarizes various nanotechnology-based approaches being utilized in the delivery of cosmetics as well as cosmeceutical products, along with relevant patents. It outlines their benefits, as well as potential health and environmental risks. Further, it highlights the regulatory status of cosmeceuticals and analyses the different regulatory guidelines in India, Europe, and the USA and discusses the different guidelines and recommendations issued by various regulatory authorities. Finally, this article seeks to provide an overview of nano cosmetics and nano cosmeceuticals and their applications in cosmetic industries, which may help consumers and regulators to gain awareness about the benefits as well as the toxicity related to the continuous and long-term uses of these products, thus encouraging their judicious use.

INTRODUCTION

Nanotechnology is defined as the science and engineering involved in manipulating matter at the nanoscale, typically within the size range of 1–100 nanometres (nm), to develop materials, structures, and devices with novel physicochemical properties. At this scale, materials exhibit unique

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characteristics such as increased surface area, enhanced reactivity, and improved mechanical, optical, and biological properties that differ significantly from their bulk counterparts. Owing to these distinctive features, nanotechnology has emerged as one of the most revolutionary technologies of the modern era and has found extensive applications across diverse fields, including medicine, electronics, energy, pharmaceuticals, and cosmetics.

In recent years, nanotechnology and nano-delivery systems have gained remarkable attention in the cosmetic and cosmeceutical industries. These technologies encompass the design, characterization, manufacturing, and application of nanoscale materials and systems to improve product performance and consumer benefits. The incorporation of nanotechnology into cosmetic science has significantly transformed conventional formulations, leading to enhanced efficacy, stability, and targeted delivery of active ingredients.

Global Market Trends and Growth of Nanomaterials

The rapid advancement of nanotechnology has greatly contributed to the global market share of pharmaceuticals and cosmetics. Nanomaterials, in particular, have emerged as key components in innovative cosmetic formulations. According to market estimates, the international nanomaterials market size was valued at approximately USD 8.5 billion in 2019 and is projected to grow at a compound annual growth rate (CAGR) of about 13.1% between 2020 and 2027. This substantial growth reflects the increasing adoption of nanotechnology-based products and the rising awareness of their advantages over traditional cosmetic formulations. Although nanomaterial such as gold and silver nanoparticles have been utilized in cosmetics for several decades, the scope and intensity of their applications have expanded significantly in recent years.

Nanoparticles: Characteristics and Classification

In cosmetic and pharmaceutical applications, nanoparticles are primarily employed as delivery systems for active pharmaceutical ingredients (APIs), cosmetic actives, and bioactive compounds. Their small size enables enhanced penetration through the skin, improved bioavailability, and protection of sensitive ingredients from chemical or enzymatic degradation.

Nanoparticles differ from bulk materials due to their unique properties, particularly their high surface area-to-volume ratio. This characteristic allows for greater interaction with biological membranes and facilitates controlled, site-specific, and sustained release of active ingredients. Common types of nanoparticles used in cosmetic and cosmeceutical formulations include lipid-based nanoparticles, polymeric nanoparticles, liposomes, solid lipid nanoparticles, nanostructured lipid carriers, and quantum dots.

Based on their structural organization, nanoparticles are broadly classified into two main categories: nanospheres and nano capsules.

Nanospheres

Nanospheres are matrix systems in which the active ingredient is uniformly and physically dispersed throughout a continuous polymeric network. In this system, the drug or cosmetic active is either dissolved or entrapped within the polymer matrix. Nanospheres provide controlled and prolonged release of actives and are particularly useful for improving the stability of sensitive ingredients such as vitamins, antioxidants, and botanical extracts.

Nano capsules

Nano capsules are vesicular systems characterized by a core-shell structure. In these systems, the active ingredient is confined within a central cavity that is surrounded by a distinct polymeric or lipid membrane. This membrane acts as a barrier that controls the release rate of the encapsulated compound. Nano capsules are especially advantageous for targeted delivery, protection of unstable ingredients, and enhancement of skin penetration while minimizing irritation and toxicity. [1, 2]

Cosmetics: Definition and Regulatory Perspective

Cosmetics are among the oldest consumer products used by humans, primarily for beautification, personal hygiene, and regenerative purposes. Cosmetics can be defined as preparations intended for external application to the human body and may be formulated from single or multiple substances derived from natural, synthetic, or semi-synthetic sources.

According to the United States Food and Drug Administration (USFDA), cosmetics are defined as "articles intended to be applied to the human body for cleansing, beautifying, promoting attractiveness, or altering the appearance, without affecting the body's structure or functions." Similarly, under the Drugs and Cosmetics Act, 1940 and Rules, 1945 (India), a cosmetic is defined as "any article intended to be rubbed, poured, sprinkled, or sprayed on, or introduced into, or otherwise applied to the human body or any part thereof for cleansing, beautifying, promoting attractiveness, or altering the appearance, and includes any article intended for use as a component of cosmetics."

Cosmeceuticals: Bridging Cosmetics and Pharmaceuticals

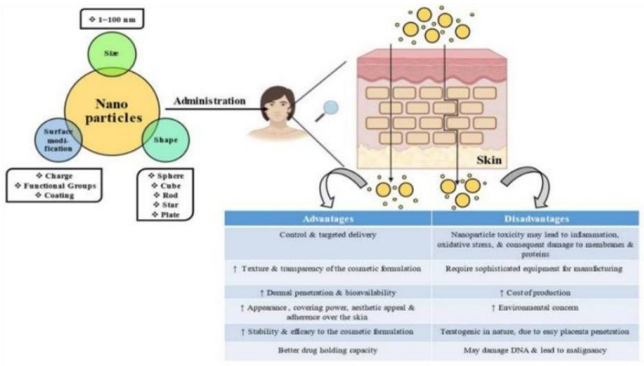
Cosmeceuticals represent a unique category of products that lie at the interface between cosmetics and pharmaceuticals. These formulations contain biologically active ingredients that provide therapeutic or preventive benefits while being applied topically like conventional cosmetics.

Cosmeceutical products are widely used for the management and improvement of various conditions such as photoaging, wrinkles, hyperpigmentation, uneven skin tone, dryness, acne, hair damage, and scalp disorders. By delivering active compounds such as antioxidants, peptides, retinoids, growth factors, and botanical extracts, cosmeceuticals aim to restore, protect, and enhance skin and hair health.

Nanotechnology has played a pivotal role in the advancement of cosmeceutical formulations by enabling improved penetration of active ingredients into deeper skin layers, enhanced stability, and sustained release profiles. [1, 3]

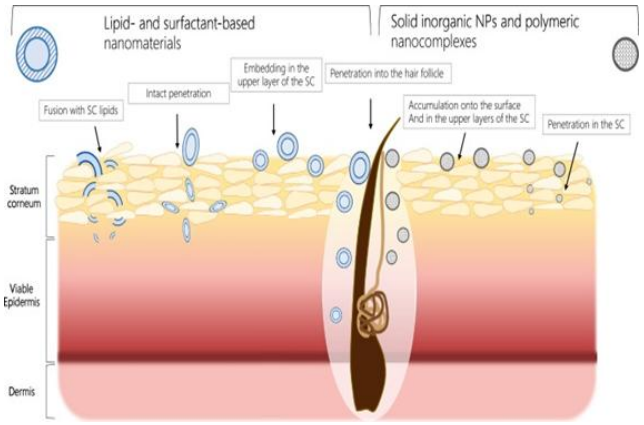
Future Prospects of Nano-Cosmeceuticals

Currently, cosmeceuticals represent one of the fastest-growing segments of the personal care industry, with a rapidly expanding global market. The increasing demand for high-performance, multifunctional, and scientifically validated products has driven extensive research and development in nano-cosmeceuticals. Continued advancements in nanotechnology, combined with growing consumer awareness and regulatory support, are expected to further accelerate innovation in this field.



Nanoparticle Penetration Through Skin

Skin penetration of nanoparticles is influenced by particle size, surface charge, composition, and formulation vehicle. While most nanoparticles accumulate in the stratum corneum or hair follicles, very small particles (<10 nm) may reach deeper layers. Lipid-based nanocarriers are particularly effective in enhancing penetration while minimizing systemic exposure. [4]

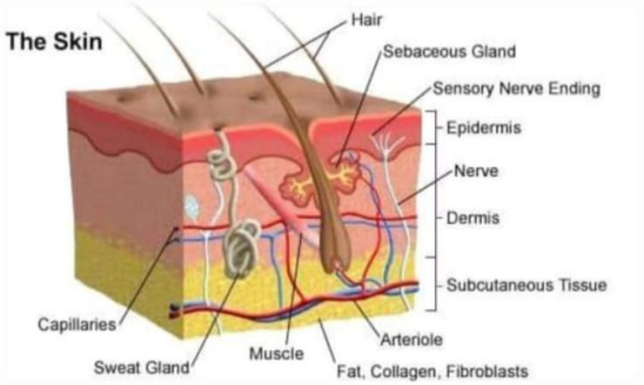


Skin

Skin Structure and Barrier Function

The skin is the largest organ of the human body and serves as a protective barrier against environmental insults. It consists of three main layers: epidermis, dermis, and hypodermis. The outermost stratum corneum is the principal barrier to penetration of active ingredients.

Nanotechnology-based systems are designed to overcome this barrier by enhancing penetration through transcellular, intercellular, or appendageal pathways while maintaining skin integrity. [5]



EXTRACTION PROCEDURE OF HERBAL COSMETICS

Maceration: Examples: Extract essential oils, active chemicals from plant matter[liquids]
Percolation: Examples: Extract tinctures[liquids]
Soxhlet extraction: Examples: Alkaloids, flavonoids, essential oils, liquids, powders
Decoction: Examples: Water soluble, heat stable compounds[liquids], volatile oils
Counter-current extraction: Examples: Solids, semisolids, liquids, powders
Supercritical fluid extraction: Examples: Liquids, Nano formulations, Solids, Semisolids
Ultrasound extraction (sonication) Examples: Polyphenols, Flavonoids, Alkaloids, Polysaccharides
Hydrodistillation: Examples: Essential oils from heat sensitive herbal drugs, liquids [Arka]
Digestion: Examples: Raw coarsely powdered herbal materials that can withstand moderate heat [Arista, Asava]
Infusion: Examples: Herbal tea [liquid herbal dosage form]
Microwave-assisted extraction: Examples: tinctures, cosmetics, tablets, and capsules [6]

Nanotechnology-Based Delivery Systems in Cosmetics

-Liposomes and Ethosomes:

These vesicular systems encapsulate hydrophilic and lipophilic actives, improving stability and skin delivery.

-Solid Lipid Nanoparticles (SLN) and Nanostructured Lipid Carriers (NLC):

SLNs and NLCs provide controlled release, occlusion, and enhanced skin hydration.

-Nanoemulsions:

Nanoemulsions improve product texture, transparency, and bioavailability of actives.

-Inorganic Nanoparticles:

Titanium dioxide and zinc oxide nanoparticles are widely used in sunscreens for efficient UV protection.[7]

Herbal Nano formulations:

Herbal cosmetics utilize plant-derived bioactive compounds. Nano formulation enhances their stability, bioavailability, and skin penetration. Extraction methods include maceration, percolation, Soxhlet extraction, decoction, supercritical fluid extraction, ultrasound-assisted extraction, and microwave-assisted extraction. Post-extraction processing ensures quality, consistency, and suitability for cosmetic bases. [8]
Synthetic Nano formulations:
Synthetic nanomaterials such as silica, carbon black, gold and silver nanoparticles, hydroxyapatite, and organic UV filters are widely used in modern cosmetics. These materials provide functional benefits including antimicrobial activity, UV protection, pigmentation, and anti-aging effects. [9]

Methods of Preparation of Nanoparticles:

Common preparation techniques include solvent evaporation, nanoprecipitation, double emulsion, high-pressure homogenization, ultrasonication, and microwave-assisted extraction. The choice of method depends on the nature of the active ingredient and desired product characteristics. [10]

Challenges in formulating herbal cosmetics and cosmeceuticals:

Herbal cosmetics and cosmeceuticals face challenges due to variability in natural raw materials, lack of fixed standardization, and inconsistent regulatory guidelines. Environmental (ethnic) factors such as light, temperature, humidity, altitude, rainfall, and soil significantly influence plant growth and the concentration of

bioactive constituents, affecting product efficacy. Scarcity of cultivable land limits large-scale production of medicinal plants. Additionally, poor-quality raw materials caused by soil degradation and excessive use of pesticides and fertilizers lead to unintentional adulteration. These factors collectively impact the stability, safety, quality control, and therapeutic effectiveness of herbal cosmetic formulations. [11]

CURRENT MARKET TRENDS IN NANOTECHNOLOGY

The global market for nanotechnology-based cosmetics and cosmeceuticals is expanding rapidly due to consumer demand for high-performance and personalized skincare solutions. [12] Key trends include enhanced delivery systems, sustainable nanomaterials, brand innovation, and increased patent activity. Significant growth is projected in both cosmetic nanotechnology and cosmeceutical market. [13]

Market Growth and Financial Outlook:

Market size and growth: The global nanotechnology in cosmetics market is projected to grow from $8.36 billion in 2024 to $9.73 billion in 2025, reflecting a 16.4%CAGR.By 2029, the market is expected to reach $17.73 billion, driven by advancements in product efficacy, consumer demand foe personalized solutions, and increased regulatory approvals.

Cosmeceutical market Expansion: The cosmeceuticals market is anticipated to grow from $80.56 billion in 2025to$110.32 billion by 2030, at a 6.49%CAGR, fueled by rising consumer interest in science-backed skincare and therapeutic formulations. [14]

REGULATORY AUTHORITIES [15]

Country/Region	Regulatory Approach	Definition of Nanomaterial	Pre-Market Requirement	Labelling Requirement
EU **European Union (EU)**	**Highly Prescriptive & Precautionary.** Most restrictive regime globally.	**Statutory:** Insoluble/bio-persistent, $\mathbf {1\text {to }100\text {nm}} $, intentionally manufactured.	**Mandatory Authorization** for UV-filters, colorants, and preservatives. **Mandatory Notification** (6 months prior) for all others.	**Mandatory:** Must label with " $$nano$$ " After the ingredient name (e.g., Titanium Dioxide $$nano$$)
US **United States (US)**	**Existing Framework.** Relies on manufacturer's responsibility for safety.	**No Formal Regulatory Definition.** Relies on general FDA guidance.	**No Pre-Market Approval** (except for colour additives). Safety is the manufacturer's responsibility.	**Not Explicitly Required.** Must list ingredients by standard name; no mandatory "nano" designation.
CA **Canada**	**Hybrid Approach.** Primarily relies on existing acts but has a definition for environmental/chemical control.	**Draft/Guidance:** Health Canada uses a functional definition based on novel properties and size.	**Notification/Assessment** under the *New Substances Notification Regulations* if the nanoform is considered a "new substance."	**No Mandatory Nano-Specific Labelling** for cosmetics currently.

AU **Australia**	**Adapting Framework.** Regulation is split across agencies (NICNAS/TGA).	**Non-statutory working definitions** based on the material's properties and potential hazards.	**Mandatory Notification/Assessment** for all new industrial chemicals, including nanomaterials, via the Australian Industrial Chemicals Introduction Scheme (AICIS).	**No Mandatory Nano-Specific Labelling** for cosmetics.
KR **South Korea**	**Risk-Based/Hybrid.** Strong focus on safety assessment.	**Statutory/Formal:** Defined for various regulatory purposes (e.g., *Act on the Registration and Evaluation of Chemical Substances*).	**Mandatory Reporting** of nanomaterial use, often tied to a risk assessment, before marketing.	**Mandatory Labelling** requirement for certain nanomaterials (e.g., Titanium Dioxide, Zinc Oxide) if their safety has been confirmed.

BR Brazil	Emerging/Guidance. ANVISA (National Health Surveillance Agency) has provided specific guidance.	Functional Definition based on size (usually $\mathbf {1\text {to} 100\text {nm}} $) and novel properties.	Specific Technical Information on the nanomaterial (including characterization and safety data) must be submitted during product registration/notification.	No Mandatory Nano-Specific Labelling currently.
IN India	Emerging/In Development. Relies on the Drugs & Cosmetics Act.	No Specific Regulatory Definition for nanomaterials in cosmetics yet.	No Specific Pre-Market Approval for nano-ingredients. General cosmetic import/manufacturing rules apply.	No Mandatory Nano-Specific Labelling currently.
CN China	Adapting. Governed by the Cosmetic Supervision and Administration Regulation (CSAR).	No specific definition in CSAR, but the National Medical Products Administration (NMPA) requires nano-specific safety data.	Mandatory Registration/Filing with additional data requirements for nanomaterials used as new ingredients.	No Mandatory Nano-Specific Labelling currently, but data on particle size is required for NMPA filing.

Safety Consideration in nano cosmetics

Nanocosmetics offer improved performance, but safety remains a major concern. Most nanoparticles do not penetrate intact skin; however, very small particles (<10 nm) may reach deeper skin layers. Lipid-based nanoparticles enhance the delivery of active ingredients, which improves efficacy but may increase the risk of systemic absorption. Toxicity concerns include oxidative stress due to reactive oxygen species

(ROS), skin irritation, inflammation, and possible tissue accumulation. Metal nanoparticles such as silver and titanium dioxide require special attention because of their potential cytotoxic and genotoxic effects. Formulation stability is crucial, as aggregation or changes in particle size can affect safety and efficacy, making stability testing under different light, temperature, and pH conditions essential. Nanoparticles may also interact with preservatives, UV filters, or other ingredients, altering product safety. Risk management strategies include controlling particle size, encapsulation, extensive in vitro and in vivo testing, transparent labelling, consumer education, and post-marketing surveillance. Emerging regulations focus on stricter evaluation and global standardization. [16]

CONCLUSION

Currently, nanotechnology is regarded as a promising and revolutionizing field and is being utilized and appreciated in the areas of cosmetics, cosmeceuticals, dermatology, biomedical applications, etc. The introduction of newer advancements and novel drug delivery systems make cosmetics and cosmeceuticals more popular with increased market share. Today, these cosmetics are an indispensable part of the daily routine; further, the introduction of nanotechnology to cosmetics has enhanced its acceptance among users all around the world. However, its associated toxicity owing to its penetrability is a major concern that is often overlooked, leading to adverse health issues. Presently, novel nanocarriers such as liposomes, ethosomes, cubosomes, NLC, SLNs, nano emulsions, niosomes, etc., are exploited to formulate various cosmetics and cosmeceuticals with enhanced outcomes. Nano systems carry and deliver these formulations across the skin by diverse mechanisms and impart several functions, such as sun protection, moisturization, wrinkle reduction, etc. Even though these nanomaterial products are gaining impressive market value, there is tremendous debate concerning their safety and toxicity in humans, demanding more careful investigations. Hence, the cosmetic legislation should provide a specific list of references as well as the ingredients that produce unintended environmental effects for all users of cosmetic products, such as consumers and professional users, thus ensuring the safety of the usage of cosmetic products. Long-term toxic or carcinogenicity studies of cosmetics, including nano cosmetics and nano cosmeceuticals (and their ingredients), should be conducted before the commercialization of these products. Nano cosmeceuticals should be manufactured in such a way that they add value to the health of consumers. Moreover, careful clinical trials of cosmeceuticals should be conducted, such as those performed for drugs, to assure the safety of the formulations in humans. Additionally, stringent regulations should be imposed on the manufacturing, storage, import, and marketing of cosmeceuticals and nanoparticles incorporated therein. Universal collaborative efforts among researchers as well as global regulatory agencies are required to develop standard rules and regulations for using nano systems in cosmetics and help address the existing gaps in the related data. Non-governmental organizations and government bodies should work in a coordinated manner to develop and propagate effective education materials for consumers. They should establish special programs, such as written and video materials, through multimedia or seminars with the aim to provide education for the wise use of cosmetics containing nano cosmetics and nano cosmeceuticals. Finally, there is a need to harmonize regulations internationally to establish a better regulatory framework for safety, efficacy, and marketing, which ultimately helps the cosmetic industries and also protects consumers from potential hazards. Moreover,

awareness among consumers can also help to improve this situation by enabling informed choices of products.

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