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# Nano Beauty 2.0: Exploring Nanotechnology in Cosmetic Delivery—A Systematic Review

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## ABSTRACT

To increase the effectiveness of cosmetic goods, the cosmetic industry is closely examining the topic of nanotechnology. There are two possible outcomes from using nanoparticles in cosmetics: positive health impacts and negative ones. Nanotechnology enhances bioavailability, solubility, and release of products by reducing particle size. Nanocosmetics for skin, hair, nails, lips, and teeth have been extensively researched. It has been discovered that nanomaterials increase the effectiveness and customer satisfaction of products. Consequently, nanocosmetics is replacing several traditional cosmeceuticals. This overview compiles the various nanotechnology-based techniques utilized to supply cosmetic products. It enumerates their benefits together with any potential risks to the environment and public health. This article provides an overview of nanoparticles used in cosmetic goods along with their applications, which may help consumers acquire knowledge about the advantages as well as the toxicity associated with the prolonged usage of these items.

**Keywords:** Nanocosmetics, Solid lipid nanoparticles & nanostructured lipid carriers, Inorganic UV-filter nanoparticles, Transdermal skin penetration enhancement, Cosmetic nanotoxicology

## Introduction

Nanoscience includes particle study on a molecular or atomic scale, and nanometers are used to measure its size (1–100 nm). One nanometer is equivalent to one billionth of a meter. Thus, a group of methods for creating materials at the molecular level to create goods with superior physicochemical qualities above traditional products might be referred to as nanotechnology.<sup>1</sup> Utilization of nanotechnology in cosmetics helps in easy absorption of the product into the skin and improves efficacy. The effectiveness of nanotechnology-based cosmetics depends on various aspects, such as lipophilicity, molecular size, and ionization level.<sup>2</sup> The United States Food and Drug Administration (FDA) claims that cosmetics are “particles designed to be applied onto the human body or any part for beautifying, promoting attractiveness, cleaning, or modifying the appearance without influencing the structure or function of the body”.<sup>3</sup> “Any article intended to be rubbed, poured, sprinkled, or sprayed on, or introduced into, or otherwise applied to the human body for cleansing, beautifying, promoting attractiveness, or altering the appearance” is how the cosmetics are defined by the Drug and Cosmetics Act of 1940 and the rules of 1945.

Materials based on nanotechnology were originally used in the cosmetics industry. The ultimate goal of the cosmetics industry’s use of nanomaterials is to attain stability over the long run.<sup>4</sup> Due to their high

surface-to-volume ratio, which facilitates the efficient skin entry of the cosmetics, nanoparticles are being used in cosmetics at an increasing rate. Nowadays, skincare products are the most common application for nanomaterials, particularly sunscreens. Concerning the application of nanoparticles in cosmetic products, both the European Commission (EU) and the FDA have distinct regulations. The European Union Observatory for Nanomaterials has set forth registration compliance under the REACH framework, which stands for Registration, Evaluation, Authorization, and Restriction of Chemicals. It is essential to adhere to the REACH guidelines when utilizing nanoparticles.<sup>5</sup>

A brief synopsis of the various kinds of nanomaterials currently utilized in cosmetics is provided in this paper; various nanotechnology-based cosmetics, along with their benefits and drawbacks and their toxicity issues, are also discussed.

## History and Advancements

Around 4000 BC, the Greeks, Romans, and Egyptians were reported using hair dyes constituting natural nanoparticles.<sup>6</sup> Known as “the father of nanotechnology,” physicist Richard Feynman, in the 1950s, created the idea of modifying atoms and molecules to create parts that are so small that they are imperceptible to the naked eye. Since 1959, applications of nanotechnology have emerged in a number of disciplines, including science, physics, chemistry, and biology. Nevertheless, the word “nanotechnology” was coined in 1974 by Tokyo University professor Norio Taniguchi, who defined it as a procedure of breaking down, mixing, and shaping materials atom by atom or molecule-by-molecule. Christian Dior employed liposomes in cosmetics for the first time in 1986. He introduced Capture™, an antiaging cream. Subsequently, nanoparticles were adopted by several companies in the cosmetic industry. The renowned cosmetic producer L’Oreal S.A. has registered seven patents pertaining to the nanoparticle application in cosmetic formulation. In certain cosmetic products, nanoparticles such as titanium dioxide (TiO<sub>2</sub>), zinc oxide, carbon black, and silica are utilized.

Liposomes were discovered in the mid-1960s. Desai and Ferrari designed nanopores in 1997, composed of platelets that have high pore density (20 nm in diameter). In 1985, fullerenes, also called “buckyballs,” were discovered, and nanotubes were designed in 1991.<sup>7</sup>

## Methodology

A comprehensive literature search was carried out using keywords such as “nanotechnology in cosmetics,” “nanocarriers for cosmetic delivery,” “nanocosmetics,” “liposomes,” “nanogels,” and “solid lipid nanoparticles,” to find publications published between January

2010 and June 2025 in PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar. Studies confined to pharmaceutical drug delivery, non-English publications, and non-peer-reviewed sources were removed, while only peer-reviewed English papers concentrating on nanotechnology-based cosmetic formulations for skincare, haircare, sunscreens, antiaging, and dermal delivery were included. Of the 509 records found, 70 satisfied the final inclusion requirements for this evaluation after 305 duplicates were eliminated, 204 were screened, and 112 were selected. The complete screening procedure is represented in Figure 1.

**Nanosystems Used in Cosmetics**

Nanomaterials range from 1 to 100 nm. Therefore, the formulations that do not change after being applied to the skin are deliberated as nanomaterials. The review’s objective is to examine the advantages and applications of nanotechnology in cosmetics; we categorize formulations into two groups, as shown in Figure 2.

**Organic Nanoparticles**

1. **Liposomes:** Liposomes, spherical molecules with double phospholipid membranes, are used in cosmetics for delivering desired molecules and active ingredients.<sup>8</sup> They are nontoxic, biodegradable, and flexible, and can carry both hydrophilic and

hydrophobic substances.<sup>9</sup> Techniques include sonication and microfluidization. Extrusion was the first technique used to synthesize liposomes.

2. **Ethosomes:** Ethosomes, pliable vesicles with high ethanol and lipid concentrations, are used for cosmetic delivery through the transdermal route.<sup>10</sup> Research has found that Niacinamide and melatonin formulations enhance skin penetration. One of the studies done by Yucel et al. stated that ethosomes with rosmarinic acid show antiaging properties. Increased transdermal flux improves skin permeation.<sup>11</sup>

3. **Niosomes:** These nanovesicles, composed of non-ionic surfactants, self-assemble into unilamellar or multilamellar vesicles. They can contain lipids or cholesterol. Niosome synthesis techniques include ether injection, film method, Handjani-Vila sonication, reverse-phase evaporation, and heating.<sup>12,13</sup>

4. **Solid Lipid Nanoparticles and Nanostructured Lipid Carriers:** Solid lipid nanoparticles, submicrometer in size, are polymeric substances with a distinct outer shell and core containing fatty acids.<sup>14</sup> They are hydrophobic, preventing skin drying and retaining moisture. Sunscreens, antiacne, and antiaging ingredients are frequently transported via solid lipid nanoparticles and nanostructured lipid carriers.<sup>15</sup> For cosmetic applications, solid lipid

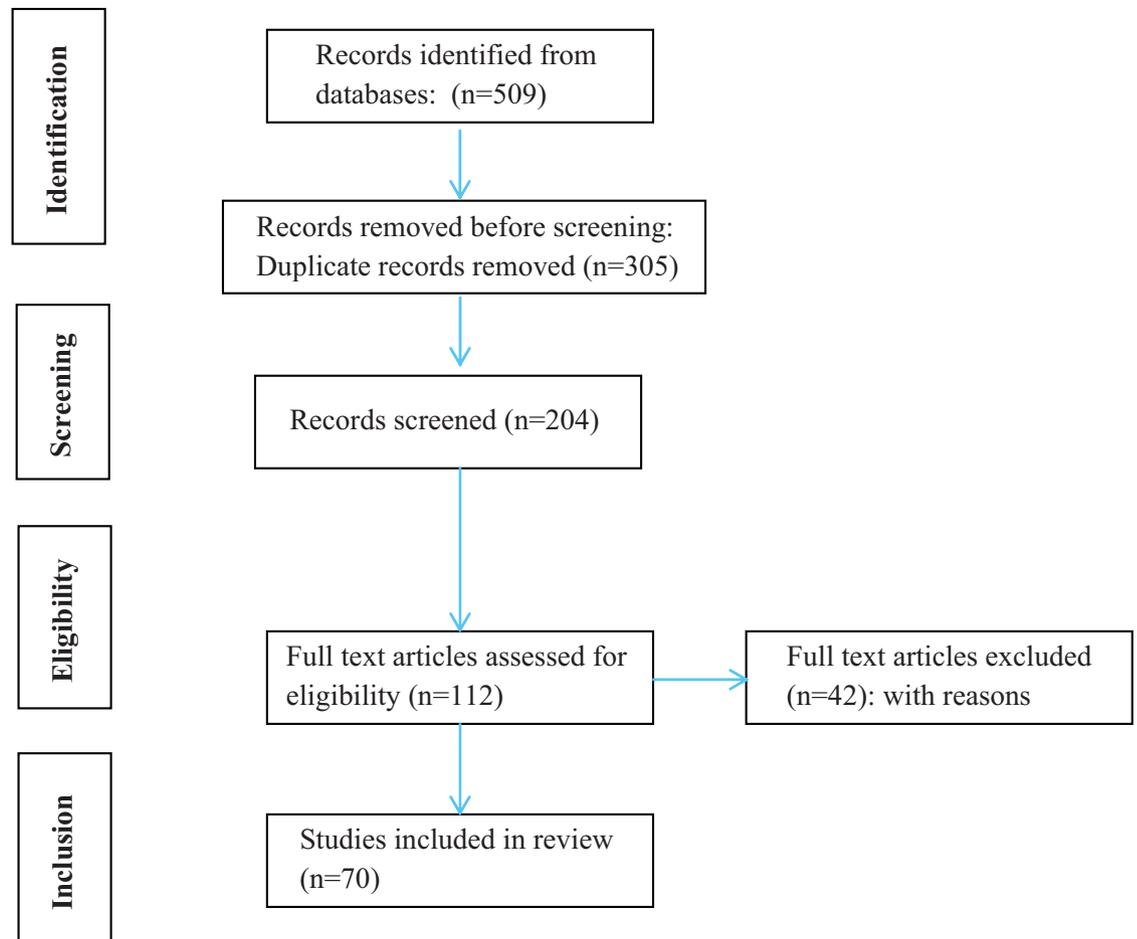


Fig 1 | PRISMA flow diagram for screening of articles for the study

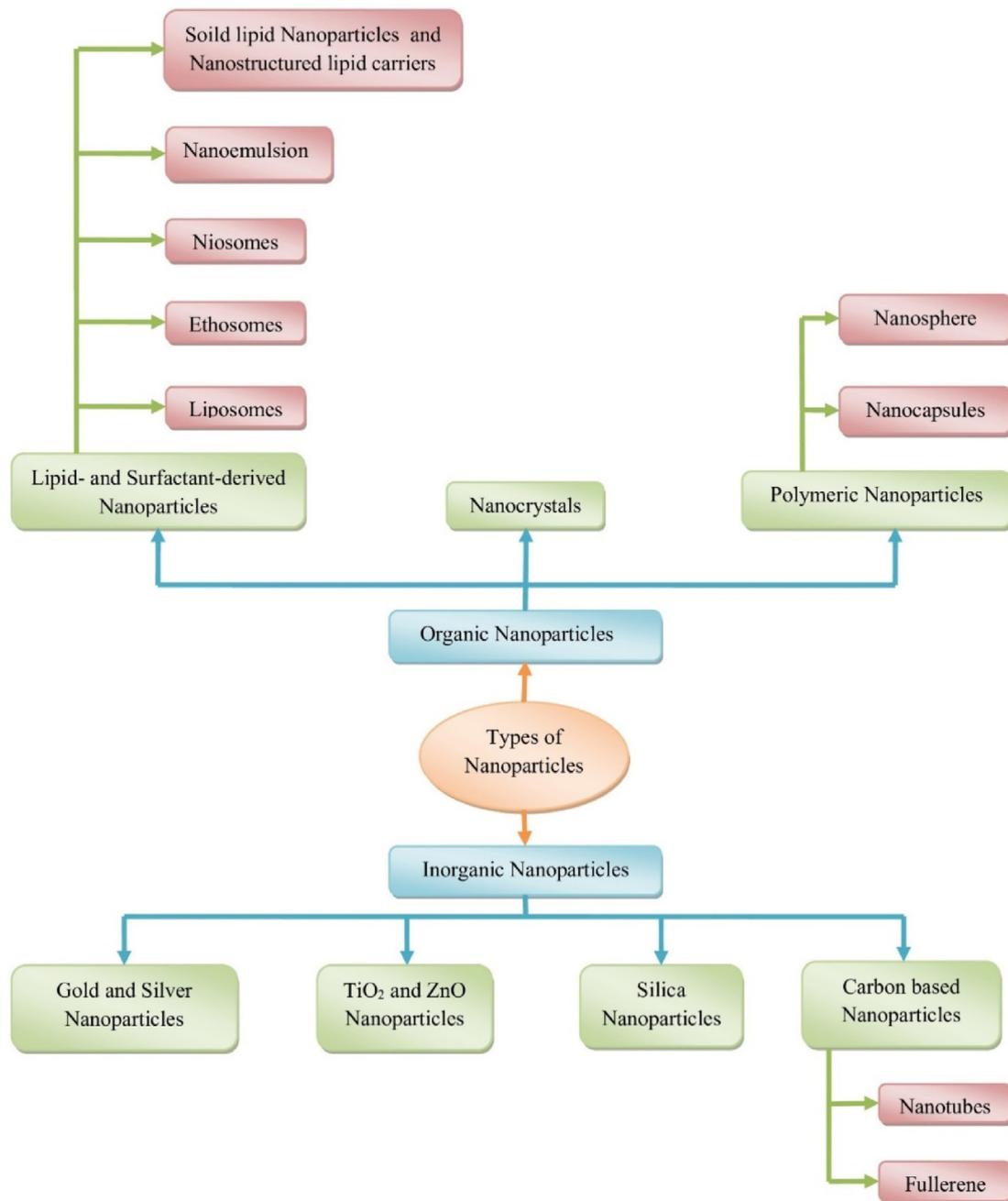


Fig 2 | Types of nanoparticles

nanoparticles and nanostructured lipid carriers exhibit numerous advantageous qualities, including occlusion, regulated active release, and an enhanced skin hydration impact. There are several known techniques for creating lipid nanoparticles, including the use of a high-pressure homogenization process.<sup>16</sup>

5. **Nanoemulsions:** Nanoemulsions, mixtures of water and oil containing nanoparticles, improve cosmetics' texture and shelf life. They have high surface area, low viscosity, stability, and solubility. Synthesis involves a two-stage process: a macroemulsion is first made, and in the second step, it is transformed into a nanoemulsion. Other techniques such as bubble bursting, high-pressure homogenization,

microfluidization, and evaporative ripening approach were put out by Fryd and Mason.<sup>17-19</sup>

6. **Nanospheres:** The spherical polymeric matrix encircles nanospheres, ranging from 10 to 200 nm in size. These biodegradable and nonbiodegradable nanospheres deliver active ingredients in cosmetics, including moisturizing, antiwrinkle, and antiacne lotions.<sup>20-22</sup> Poly(lactide-co-glycolic acid) nanospheres containing ubiquinone are stable, effective, and capable of regulating the release of active ingredients found in cosmetics. Hydrothermal methods, reduction mechanisms, and catalytically assisted chemical vapor deposition can also be used to create the nanospheres.<sup>23</sup>

7. **Nanocapsules:** Essential active ingredients in cosmetics are preserved in watery or oily states using poly-l-lactic acid nanoprecipitation with a diameter of 115 nm. Synthesized through chemical vapor condensation, mini-emulsion polymerization, and surfactant-assisted approaches, nanocapsules can entrap both hydrophilic and hydrophobic carrier types, allowing for bonding of proteins, polymers, and biomolecules. The use of cosmetic goods depending on nanocapsules was initially introduced by the L'Oréal cosmetic brand in 1995.<sup>24</sup>
8. **Nanocrystals:** Nanocrystals, ranging from 10 to 400 nm, are used to administer poorly soluble medications.<sup>25</sup> Juvena created "Juvedical" in 2000, featuring nanocrystals and rutin as a primary component. According to a study, rutin nanocrystals exhibited more bioactivity than regular rutin glycoside.<sup>26</sup>

### Inorganic Nanoparticles

1. **Gold Nanoparticles and Silver Nanoparticles:** Silver and gold nanoparticles are commonly used in cosmetics due to their antibacterial and antifungal properties.<sup>27</sup> They repair skin damage, enhance skin flexibility, and treat sunburn, hypersensitivity, and skin inflammation. Silver nanoparticles inhibit microorganisms and stabilize formulations for over a year without sedimentation. They do not penetrate human skin and show sufficient defense against microorganisms and their proliferation.<sup>28</sup>
2. **TiO<sub>2</sub> and Zinc Oxide Nanoparticles:** Sunscreens protect skin from harmful UVB, UVA-2, and UVA-1 radiation, often containing TiO<sub>2</sub> and zinc oxide, which shield the skin from the damaging rays of the sun. Nanoparticles offer advantages over larger materials, but excessive exposure can be harmful. Regular sunscreens are preferred for dermal application due to their safety and lack of toxicity issues.<sup>29</sup> TiO<sub>2</sub> is categorized as a Group 2B carcinogen by the International Agency for Research on Cancer.<sup>30</sup>
3. **Silica (SiO<sub>2</sub>) Nanoparticles:** Nanosilica enhances the surface, duration, and adequacy of cosmetic products, including lipsticks. These nanoparticles, ranging from 5 to 100 nm, carry hydrophilic and lipophilic entities, and are commonly found in leave-on and wash-off cosmetic products for the hair, skin, lips, face, and nails.<sup>31</sup>
4. **Fullerenes:** Carbon fullerene, a three-dimensional spherical compound with an odd number of carbon atoms, is widely used in cosmetics and cosmeceuticals due to its antioxidative properties. It helps reduce wrinkles and hyperpigmentation caused by ultraviolet (UV) damage.<sup>32</sup> Fullerene, often known as "buckyballs" or buckminsterfullerene. Fullerenes' hydrophobic nature has led to their increased use in medicinal applications.<sup>27,33</sup>

### Merits and Demerits of Nanotechnology in Cosmetics

The main reason for using different types of nanoparticles in cosmetics is to improve the efficacy and shelf life of products. The use of zinc oxide and TiO<sub>2</sub> in

sunscreen shields the skin from damaging UV rays, and they are odorless, colorless, and nonoily in nature and do not produce any whitish residue when applied on the skin. Due to the carrier nature of NPs, they are widely used as antiaging products.<sup>34,35</sup> Some of the advantages of the use of NPs in cosmetics are:

- They give cosmetics a softer texture.
- They work on the skin's surface.
- They are applied in small amounts.
- They improve the rate of absorption.
- They make products more soluble.
- They expand the product's surface area.
- They give cosmetics a longer shelf life.

In addition to this, the unprecedented efficacy of nanoparticles in cosmetic formulations is a result of enhanced skin penetration, targeted distribution, enhanced bioavailability, and controlled release mechanisms.

There are benefits and drawbacks of using nanoparticles in cosmetics. Because of their high penetration rate, nanoparticles with a high ratio of surface to volume are hazardous and can impact human body cells. Nanoparticles are not only dangerous to consumers but also to workers in the cosmetic industry who are in daily contact with them. NPs are very reactive, which results in the formation of a large number of reactive oxygen species (ROSs). The macromolecules found in proteins, DNA, and cell membranes are impacted by these ROS.<sup>36-38</sup> When zinc oxide and TiO<sub>2</sub> absorb UV light, they create free radicals that harm cells and cause skin cancer. Eventually, TiO<sub>2</sub> affects the brain. One investigation was carried out to look into the harmful in vitro effects of aluminum oxide and zinc oxide nanoparticles. In the study, aluminum oxide and zinc oxide generate free radicals. When these free radicals are investigated, they damage the blood-brain barrier, produce inflammation and toxicity to stem cells, and harm brain blood vessel cells, which can result in disorders such as atherosclerosis.<sup>39-41</sup> There should be no adulterations in the cosmetics utilized; they should be pure and active. About the application of nanoparticles in cosmetics, the FDA has distinct safety standards known as "Guidance for Industry: Safety of Nanomaterials in Cosmetic Products."<sup>42</sup> Table 1 illustrates the advantages and limitations of nanoparticles.

### Applications of Nanotechnology in Cosmetics

As already discussed, Nanoparticles are used as carriers and rheology modifiers for bioactive molecules, but their function remains unclear due to product labels only listing ingredients when manufactured specifically. Consequently, this section summarizes scientific literature from the latest commercial perspective.

**UV Filters:** UVA and UVB radiation poses health risks, causing matrix metalloproteinases to form, reducing skin suppleness. Inorganic filters such as zinc oxide and TiO<sub>2</sub> are commonly used in sunscreen formulation to absorb UVA and UVB radiation. TiO<sub>2</sub>

**Table 1 | Advantages and limitations of nanoparticles**

Nanoparticles	Advantages	Limitations
Liposomes	<ul style="list-style-type: none"> <li>They make it possible for the active substances to be released gradually, which results in longer-lasting effects and less frequent application.</li> <li>Composed of phospholipids that resemble the membranes of skin cells, which improves skin compatibility and lessens irritation.</li> </ul>	<ul style="list-style-type: none"> <li>The shelf life of liposomes is shortened by their susceptibility to oxidation, hydrolysis, and ingredient leakage.</li> <li>Although superior to traditional creams, penetration into deeper layers of the dermis is still limited.</li> </ul>
Ethosomes	<ul style="list-style-type: none"> <li>Unlike liposomes, ethosomes' ethanol fluidizes skin lipids to allow for a deeper penetration of active substances.</li> <li>Prolong the active ingredients' release, increasing their effectiveness and lowering the need for repeated applications.</li> </ul>	<ul style="list-style-type: none"> <li>Sensitive skin may become dry, red, or irritated by high ethanol concentrations.</li> <li>Even while ethosomes are more stable than liposomes, they may nonetheless deteriorate or leak over time.</li> </ul>
Niosomes	<ul style="list-style-type: none"> <li>Increase the permeability of hydrophilic and lipophilic active ingredients through the skin.</li> <li>Safe for cosmetic application; most surfactants are nontoxic and mild.</li> </ul>	<ul style="list-style-type: none"> <li>Prone to issues such as entrapped actives leaking, aggregating, or fusing while being stored.</li> <li>Sensitive skin may become dry or irritated by some surfactants.</li> </ul>
Solid lipid nanoparticles	<ul style="list-style-type: none"> <li>They provide a protective coating, which is beneficial for antiaging and sunscreen products.</li> <li>Minimizes transepidermal water loss, boosting skin hydration.</li> </ul>	<ul style="list-style-type: none"> <li>Solid lipids' crystalline form leaves less room for active ingredients.</li> <li>It is difficult to maintain consistency in large-scale production.</li> </ul>
Nanostructured lipid carriers	<ul style="list-style-type: none"> <li>Combinations of liquid and solid lipids produce matrix defects that enable the encapsulation of additional active ingredients.</li> <li>Because of the less organized matrix, there is a lower chance of drug leakage than with solid lipid nanoparticles.</li> </ul>	<ul style="list-style-type: none"> <li>Advanced methods increase the cost of the product.</li> <li>Sensitive skin may become irritated by certain lipid/surfactant combinations.</li> </ul>
Nanoemulsions	<ul style="list-style-type: none"> <li>They are aesthetically pleasant in lotions and serums due to their transparent or translucent look and nongreasy feel.</li> <li>Enhance skin moisture and give it an even texture.</li> </ul>	<ul style="list-style-type: none"> <li>Usually less viscous, gelling agents could be required to get the right texture.</li> <li>Sensitive to variations in pH and temperature, among other environmental conditions.</li> </ul>
Nanospheres	<ul style="list-style-type: none"> <li>Compared to traditional formulations, their small size allows for deeper penetration into the epidermis.</li> <li>Depending on the polymer matrix, they can transport both lipophilic and hydrophilic substances.</li> </ul>	<ul style="list-style-type: none"> <li>Demand exact control over the polymerization or nanoprecipitation processes as well as specific equipment.</li> <li>Sometimes the polymer matrix limits the amount of active chemical that can be contained.</li> </ul>
Gold nanoparticles	<ul style="list-style-type: none"> <li>They might increase the creation of collagen, which would increase the suppleness of the skin and lessen wrinkles.</li> <li>Gold nanoparticles are useful in formulations for sensitive skin because they can lessen skin redness and inflammation.</li> </ul>	<ul style="list-style-type: none"> <li>Gold nanoparticles are generally thought to be biocompatible; however, depending on their size, shape, concentration, and surface coating, they may have cytotoxic effects.</li> <li>Gold nanoparticles are costly to synthesize and stabilize, which raises the price of items containing them.</li> </ul>
Silver nanoparticles	<ul style="list-style-type: none"> <li>Beneficial for lowering microbial contamination and preventing skin infections in items such as lotions, creams, deodorants, and acne treatments.</li> <li>They are appropriate for sensitive or acne-prone skin since they can lessen redness and inflammation.</li> </ul>	<ul style="list-style-type: none"> <li>Higher quantities or extended exposure to silver nanoparticles may result in oxidative stress, cellular toxicity, or skin irritation.</li> <li>Safety issues arise because small nanoparticles have the potential to infiltrate the systemic circulation or penetrate deeper epidermal layers.</li> </ul>
TiO <sub>2</sub>	<ul style="list-style-type: none"> <li>It prevents sunburn, photoaging, and skin damage by blocking UVA and UVB rays.</li> <li>Compared to chemical sunscreens, it is generally harmless for delicate skin and less likely to trigger allergic reactions.</li> </ul>	<ul style="list-style-type: none"> <li>If not properly prepared, it may leave a whitish residue, particularly on darker skin tones.</li> <li>Needs to be carefully distributed in order to avoid clumping and provide even coverage in products.</li> </ul>
Zinc oxide	<ul style="list-style-type: none"> <li>Skin-friendly; ideal for infants, kids, and skin that is sensitive or prone to acne.</li> <li>Zinc oxide benefits with rashes, acne, and mild skin irritations because of its calming and antiinflammatory properties.</li> </ul>	<ul style="list-style-type: none"> <li>Surface coatings are frequently utilized to reduce the potential for oxidative stress caused by ROS produced by UV exposure.</li> <li>Aquatic life and ecosystems may be impacted by the buildup of zinc oxide nanoparticles in water bodies.</li> </ul>
Silica	<ul style="list-style-type: none"> <li>Silica provides a matte look by efficiently absorbing excess oil and sebum.</li> <li>Gives compositions more viscosity, which keeps ingredients from separating.</li> </ul>	<ul style="list-style-type: none"> <li>Overuse of silica can cause sensitive skin to become dry or irritated by its excessive absorption of skin oils.</li> <li>Because silica particles might aggregate, it is necessary to use appropriate formulation processes to ensure uniform dispersion.</li> </ul>
Fullerenes	<ul style="list-style-type: none"> <li>As excellent destroyers of free radicals, fullerenes shield skin cells from oxidative damage.</li> <li>They neutralize ROS to increase collagen formation and minimize fine wrinkles.</li> </ul>	<ul style="list-style-type: none"> <li>For efficient distribution, poor water solubility necessitates the use of appropriate carriers or encapsulating techniques.</li> <li>Not all nations have strict regulations; for nanosized fullerenes, labeling and safety testing might be necessary.</li> </ul>

absorbs UVB radiation, and zinc oxide absorbs UVA radiation.<sup>42</sup>

**Antifungal and Antibacterial Properties:** Antimicrobial drugs have drawbacks such as resistance and toxicity, leading to the use of metal-based and copper-based nanoparticles in cosmetics for antibacterial and antifungal properties.<sup>43</sup> Gold and silver nanoparticles are widely used in gels, creams, and personal care items due to their capacity to fight bacterial and fungal diseases, performing as well as or better than traditional antimicrobials.<sup>44</sup>

**Cleansing Agents:** The skin's hydrophilic layer, containing sebaceous and sweat gland secretions,

accumulates contaminants such as pollutants and pathogens. Cleansers such as micellar systems and nanoemulsions are used to remove impurities and odor.<sup>3,45</sup> Micellar water contains a small amount of water with a mild surfactant, which helps to remove dirt from skin.<sup>46</sup> Metal-based nanoparticles serve as disinfectants and decontaminants.

**Hydrating and Antiaging Agents:** Nanoparticles can enhance skin health by deeply penetrating the skin's surface, producing a moisturizing effect due to their hygroscopicity and metabolism. Unsaturated phospholipid-based liposomes penetrate the skin, causing osmolytes to maintain keratinocyte volume

and stop water loss.<sup>47</sup> Saturated phospholipid-based preparations, which resemble the lipidic matrix, provide a protective effect, making them an alternative for irritated, sensitive dry skin.<sup>48–50</sup>

**Rheology Modifier and Other Uses:** Rheology modifiers, such as clay and silica nanoparticles, are used in cosmetic products to enhance viscosity and sensory qualities, providing a sense of quality. These modifiers aggregate under mechanical pressure, providing an opaque finish and skin protection by absorbing and neutralizing hazardous compounds.<sup>51</sup>

### Comparison Between Traditional and Nanotechnology-Based Cosmetics

The following Table 2 represents a comparative overview between traditional and nanotechnology-based cosmetics:

### Latest Developments in Nanotechnology-Based Cosmetics Green Nanotechnology

As an innovative science that encompasses the design, characterization, production, and application of structures, devices, and systems by controlling shape and size at the nanometer scale, which spans the size range of 1–100 nm, green nanotechnology refers to the use of nanotechnology to improve the environmental sustainability of various processes.<sup>52</sup> Green nanotechnology is a cutting-edge field of technology that blends important ideas from green engineering and green chemistry. By saving raw resources, energy, and water, as well as by lowering greenhouse gas emissions and hazardous waste, it seeks to minimize the impact on the environment by limiting the use of fuel and energy where appropriate.<sup>53</sup>

A variety of nanomaterials can be used to create environmentally friendly cosmetics packaging. The most prevalent natural polymer on the planet is cellulose, which comes from plants and wood. It is biodegradable, harmless, and renewable. Despite being highly hydrophilic due to an abundance of hydroxyl groups, it is highly crystalline, degrades before melting, and is exceedingly difficult to dissolve in ordinary solvents. In order to regulate the final morphology, particular emphasis must be given to determining the best methods for producing cellulose nanofibers from solutions and, consequently, the circumstances in which they should operate. Cellulose nanofibers are used in the personal care sector to stabilize, thicken, and stabilize emulsions in the manufacture of gels, lotions, and creams. Their presence enhances these items' sensory qualities, stability, and texture.

Silver nanoparticles are another environmentally friendly nanomaterial that can be used in the packaging of cosmetic products. By extending the shelf life of cosmetic goods without the use of hazardous chemicals, silver nanoparticles provide a safe and efficient substitute for conventional preservatives. Cosmetics manufacturers can improve product stability, lower contamination risk, and use fewer chemical preservatives by adding silver nanoparticles to environmentally friendly packaging materials.<sup>54</sup>

Another kind of nanomaterial made from natural materials is clay nanocomposites. Hydrous silicates, also known as aluminum silicates, are essentially composed of silicon, magnesium or aluminum, oxygen, and hydroxyl, along with a variety of related cations. Clay nanoparticles are mixed with or integrated into other biodegradable polymers to improve a material's mechanical strength and barrier qualities.<sup>55</sup> Polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are examples of polymers. The sugars in plants such as corn and sugarcane are usually extracted to create PLA, a common biodegradable polymer, while microorganisms produce PHA.<sup>56</sup>

Microorganisms are used by “The Shell Works,” a firm that makes cosmetic items, to make their packaging. This covers both the outside packaging and the product containers. It is completely biodegradable and compostable, demonstrating that green nanotechnology can be successfully used in cosmetic packaging.

### Artificial Intelligence (AI) in Conjunction with Customized Nanocosmetics

In medicine, artificial intelligence (AI) technology is being utilized to assist with repetitive processes that require human knowledge, such as screening, diagnosis, treatment, and epidemiological analysis.<sup>57</sup>

Nanotechnology and AI are combining to change the way cosmetics are found, made, and customized. Among the noteworthy developments are:

1. AI-guided formulation and ingredient discovery;
2. In-home and in-clinic image and sensor-driven personalization;
3. The maturation of nanoenabled delivery systems (liposomes, solid lipid nanoparticles/ nanostructured lipid carriers, polymeric and hybrid carriers) as the foundation of customized dosing; and
4. Early “skin digital twins” that combine behavioral, environmental, and imaging data to forecast how an active will react.

**Table 2 | Traditional vs. Nanotechnology-based cosmetics**

Features	Traditional Cosmetics	Nanotechnology-Based Cosmetics
Skin infiltration	Restricted, frequently stays on the surface.	Extensive penetration within the layers of skin.
Compound stability	Many actives deteriorate due to oxidation, heat, and light.	Nanocarriers boost stability and offer shielding.
Mechanism of release	Quick release, brief duration.	Restricted and prolonged release.
Texture and elegance	It could feel thick or oily.	Clear, nonsticky, and lightweight.
Safety issues	Long-term, thoroughly researched evidence is available.	Insufficient long-term safety information.
Guidelines	Well-developed rules and guidelines.	Changing, not constant worldwide.

AI is involved in nanocosmetics in different ways:

- AI transforms multimodal signals (pictures, wearables, and weather) into customized regimens; nanocarriers enhance stability, targeting, and controlled release. The combination claims dynamic goods that adjust to the environment, microbiome, pigmentation, and skin barrier state.
- AI helps to predict which nanocarriers—liposomes, SLNs, NLCs, etc.—will best encapsulate and distribute an active ingredient, making it easier by AI models (deep learning [DL], Bayesian optimization). Predicts particle size, strength, zeta potential, and emission profile, which minimizes laboratory trial and error. For safe and efficient nanocarriers, generative AI recommends novel combinations of lipids, polymers, or surfactants.
- Due mostly to developments in computer technology, DL has emerged as a major field of research within machine learning (ML) in recent years. Numerous studies have demonstrated that DL outperforms conventional ML techniques in the medical field, especially in dermatology.<sup>58–60</sup>
- The proliferation of teledermatology and self-assessment smartphone apps can be attributed to the scarcity of dermatologists and advanced medical services. Furthermore, the needs of the COVID-19 epidemic fueled the quick uptake of teledermatology, where online dermatological consultations were considered a viable solution during the period of social distancing.
- Images from smartphones or dermatoscopes are analyzed by computer vision to check for wrinkles, pigmentation, acne, moisture, etc. AI systems suggest customized nanoformulations (such as liposomes for antioxidants, nanostructured lipid carriers for antiaging, or a nanoemulsion for hydration). Some startups use 3D-printed masks or patches that deliver nanoactives precisely where the skin needs them in conjunction with AI software.
- Wearable sensors, e-skins, and smart mirrors record sweat chemistry, UV exposure, sebum, and hydration. AI deciphers these signals and instantly modifies the nanocosmetic's type, frequency, or dosage. For instance, if your UV exposure is excessive, an AI app can advise you to use a sunscreen containing zinc oxide nanoparticles more often.
- AI creates a synthetic representation of your skin to mimic its reaction to particular active ingredients or nanocarriers. Accelerates Research and Development (R&D) by enabling scientists and businesses to test nanoformulations *in silico* before producing them.

### Regulatory Viewpoint

#### FDA Guidelines

The purpose of the guidance document is to help the industry and other interested parties recognize possible safety risks associated with nanomaterials in cosmetics and create a framework for assessing them. The FDA published a study written by its Nanotechnology

Task Force (the “Task Force”) in July 2007. The Task Force report evaluated scientific and regulatory factors pertaining to the efficacy and safety of FDA-regulated goods that incorporate nanomaterials and offered suggestions in light of these factors. The Scientific Committee on Consumer Safety (SCCS) “Guidance on the Safety Assessment of Nanomaterials in Cosmetics,” the Organization for Economic Co-operation and Development (OECD) Working Party on Manufactured Nanomaterials “Preliminary Review of OECD Test Guidelines for their Applicability to Manufactured Nanomaterials,” and pertinent ICCR reports, including “Currently Available Methods for Characterization of Nanomaterials” and “Principles of Cosmetic Product Safety Assessment,” are also cited in this guidance.

The use of nanomaterials in cosmetic items may raise concerns about the product's safety for its intended use because they can have different chemical, physical, and biological properties from larger-scale particles with the same chemical makeup. Data requirements and testing techniques should be assessed to address any special characteristics and functions of the nanomaterials used in the cosmetic products, as well as any unanswered questions regarding the suitability of conventional safety testing techniques for products involving nanotechnology, as is the case with any cosmetic product that has new or modified properties. The FDA advises that the safety evaluation of cosmetics containing nanomaterials should take into account a number of crucial elements, such as:

- The physicochemical characteristics
- Agglomeration and size distribution of nanomaterials under the conditions of toxicity testing and as expected in the final product
- Impurities
- Potential routes of exposure to the nanomaterials
- Potential for aggregation and agglomeration of nanoparticles in the final product
- Dosimetry for *in vitro* and *in vivo* toxicology studies
- *In vitro* and *in vivo* toxicological data on nanomaterial ingredients and their impurities, dermal penetration, potential inhalation, irritation (skin and eye) and sensitization studies, and mutagenicity/genotoxicity studies

Analyzing each ingredient's physicochemical characteristics and pertinent toxicological endpoints in light of the anticipated exposure from the final product's intended use is the best way to assess a cosmetic product's safety. If someone wants to incorporate a nanomaterial into a cosmetic product, they can use either a brand-new substance or a modified form of a component that is currently on the market.<sup>5</sup>

#### Scientific Committee on Consumer Safety (SCCS): Guidance on the Safety Assessment of Nanomaterials in Cosmetics

The Cosmetic Regulation (EC) No. 1223/2009, which defines a nanomaterial and mandates premarket notice, safety assessment, and labeling of cosmetics

containing nanomaterial constituents, explicitly addresses the use of nanoparticles in cosmetics in Europe. By making the process of creating safety dossiers easier for applicants, the guidance also seeks to support risk managers and assessors in putting the requirements of Article 16 of the Cosmetics Regulation (EC) No. 1223/2009 into practice.

The use of nanomaterials in cosmetic goods is expressly covered under Regulation (EC) No. 1223/2009. The following is a summary of this guidance's key ideas.

1. **Definition of Nanomaterial:** A Recommendation on a comprehensive definition of nanomaterial was accepted by the Commission in 2022 (2022/C 229/01). This recommendation states that a "nanomaterial" is any natural, incidental, or artificial material made up of solid particles that are present either alone or as distinguishable constituent particles in aggregates or agglomerates, and where at least 50% of these particles in the number-based size distribution meet at least one of the following requirements:

- a. One or more of the particle's external dimensions fall between 1 and 100 nm in size
- b. Two or more of the particle's external dimensions are smaller than 1 nm, and one is larger than 100 nm
- c. Particle has an elongated shape, like a rod, fiber, or tube; or the particle has a plate-like shape with one external dimension smaller than 1 nm and the other dimensions larger than 100 nm

2. **Material Characterization:** Unambiguous identification and thorough characterization of nanomaterials are crucial for safety assessment due to the possible changes in NMs' characteristics, behavior, and consequences. According to Cosmetics Regulation (EC) No. 1223/2009, Article 16 a) "identification of the nanomaterials," the characterization data must include information on the identity of the material or materials. It is crucial that the measurements be performed with widely recognized methods while taking nanoaspects into account and that thorough documentation be supplied. High-resolution electron microscopy must be one of the methods used to assess primary particle size, which is the common denominator for all nanomaterials. Characterization of nanomaterials must be done throughout the raw material stage, during the formulation of cosmetics, and during exposure for toxicity assessments.

3. **Exposure Assessment:** The process for evaluating the safety of nanomaterials is the same as that for nonnanosubstances, with particular attention paid to the nanoaspects. This will need estimating or determining the probability and magnitude of systemic and local exposure in relation to oral, cutaneous, and inhalation exposure pathways. Determining the possible translocation of nanoparticles across gastrointestinal, lung, or skin barriers while

simulating real-world application scenarios should be the main goal.

By analyzing the receptor fluid for nanoparticles in *in vitro* dermal absorption studies, one can estimate the potential systemic exposure for the dermal route. For all other potential uptake routes, and when available, one can analyze the data on occurrence in organs and/or blood from toxicokinetic or toxicological investigations. However, the techniques employed for this purpose must be widely accepted, cutting-edge, and have a detection limit low enough to show that there is no systemic exposure.

To ascertain the extent of systemic exposure through the appropriate absorption pathway, the fate and behavior of the nanomaterial (*in vitro*, *ex vivo*, or *in vitro-in vivo* extrapolation), and the anticipated target organs, ADME characteristics should be examined.

Skin sensitization, genotoxicity, local exposure, and local consequences must all be treated, regardless of the possibility of systemic exposure. Additional research should be done to determine if the absorbed substance was in particle form or in a solubilized/metabolized form when chemical analysis indicates systemic exposure.

4. **Hazard Identification/Dose Response Characterization:** According to the SCCS Notes of Guidance, information from toxicological studies for local toxicity, cutaneous sensitization, and genotoxicity, and, in the event of systemic absorption, systemic effects, will be needed. It is necessary to take into account the nanomaterial-related factors while testing nanomaterials for hazard identification and dosage response characterization. These include taking into account the forms of insoluble or partially soluble particles, how the particles aggregate and agglomerate, whether nanoparticles can pass through biological membranes, whether they can interact with biological entities locally or systemically, whether they can adsorb or bind to other substances on the surface, whether they can catalyze reactions on the surface, persistence, etc. All toxicological testing must adhere to Cosmetics Regulation (EC) No. 1223/2009, which forbids the use of animals in cosmetic research and the marketing of cosmetic substances and products that have undergone animal testing. Regarding this, the SCCS considers any toxicological information obtained through other channels, including *in vitro* and *ex vivo* techniques, *in silico* models, grouping and read-across, and modeling based on physiologically based pharmacokinetics or toxicokinetics. Both gene mutations and chromosomal damage (clastogenicity and aneugenicity) should be assessed for *in vitro* genotoxicity evaluation.

5. **Safety Assessment:** The applicant must compile pertinent information and data from many alternative (nonanimal) methodologies and integrate the data to create an overall weight of evidence

**Table 3 | List of nanotechnology-based cosmetics**

S. No.	Nanoparticle Used in Cosmetic	Cosmetic Action	Commercial Name of Cosmetic Product	Company	
1.	Liposomes	Hydration/moisturization	Rehydrating Liposome Day Cream	Kerstin Florian	
		Antiwrinkle and firming	Lumessence Eye Cream	Aubrey Organics	
		Anticellulite	Body Strategist Cream Gel	Comfort Zone	
2.	Ethosomes	Moisturization	Supravir Cream	Trima, Israel	
		Antiaging and skin repair	Decorin Cream	Genome Cosmetics	
3.	Niosomes	Antiaging and skin repair	Yangyang Mayu Niosome Base Cream	Mille Lure	
		Skin Whitening	Deep Action Lightening Cream	Guinot	
4.	SLNs	Moisturization	NanoRepair Q10 cream	Dr. Kurt Richter Laboratories GmbH	
5.	NLCs	Antiaging and skin repair	Cutanova Cream Nano Vital Q10	Dr. Rimpler	
			Phyto NLC Active Cell Repair	SirechEmas	
6.	Nanoemulsions	Body hydration	Bruma De Leite	Natura	
			Skin Caviar	La Prairie	
		Hydration	Nanovital VITANICS Crystal Moisture Cream	Vitacos Cosmetics	
7.	Nanospheres	Moisturization	Nano Emulsion Multipепptide Moisturizer	Hanacure	
		Antiaging	Nanosphere Bio Serum	Dermaswiss	
			Eye Tender	Kara Vita	
		Moisturization	Competence Hydration Ultra- Moisturizing Cream	Coryse Salome Paris	
		Ultra Moisturizing Day Cream	Hydralane Paris		
8.	Nanocapsules	Antiwrinkle	Marine Nano Collagen	AE Naturals	
9.	Nanocrystals	Antiaging	Juvedical Age Decoder Cream	Juvena	
			Cellular Serum Platinum Rare	La Prairie's	
10.	Gold NPs	Moisturization	Skin Brightening Serum	Areoveda	
		Antiaging	Face serum Formulated with Gold Nanoparticles	Savvy Element	
			Nano Gold Antiaging Lifting Serum	Nuvoderm	
11.	Silver NPs	Cleanser and skin purification	Cor Silver Soap	Cor	
				Cosil: Nano Beauty Soap	Natural Korea
				Cleanser Silver	NanoCyclic
			Ag Silver Augmented Face Wash	Elfrou	
		Hydration	The Silver Anytime Moisturizer	Cor	
12.	ZnO and TiO <sub>2</sub>	Sun protection	100% Mineral Sunscreen	Gabit	
				Phytorx UV Defense Sun Block SPF 100	Lotus Professionals
				CLINIQUE SPF 50 UVA/UVB Mineral Sunscreen Fluid for face	Clinique
				Pure Mineral Watery Sunscreen SPF 50+	Orimii Skincare
13.	Silica NPs	Antiaging and skin care	Hyaluronic Hydra Foundation	By Terry	
				Renergie: Lift Makeup/Microlift Eye	Lancome
				Essentials Exfoliante Facial Scrub	MartiDerm La Formula
				Face FWD»Blush Stick	Sugar Cosmetics
14.	Fullerenes	Antiaging and skin repair	Global Antiaging Face Cream	GraceFull Cosmetics	
		Skin Whitening	Pearl Beauty Face Cream	Madamahada Extra	
			Brightening Essence	Juva Skincare	

supporting the safety of the cosmetic ingredient in light of the EU's ban on animal testing of cosmetic ingredients and products. Extrapolation of in vitro to in vivo data will be necessary in cases where safety evaluation is to be predicated mostly or exclusively on in vitro test results. To enable in vitro in vivo extrapolation, kinetic data, which may be obtained from nanomaterial-specific kinetic models, must be added to the in vitro test findings.<sup>61</sup>

#### Scientific Committee on Consumer Safety (SCCS) Opinion on Titanium Dioxide (TiO<sub>2</sub>) Used in Cosmetic Products that Lead to Exposure by Inhalation

According to Regulation (EC) No. 1223/2009, TiO<sub>2</sub> is permitted as a UV filter under entries 27 and 27a (nano

form) of Annex VI as well as a colorant under article 143 of Annex IV. In cosmetics, TiO<sub>2</sub> is also utilized as a filler. In 2000, the Scientific Committee on Cosmetic Products and Non-Food Products intended for consumers (SCCNFP) came to the conclusion that TiO<sub>2</sub>'s toxicological profile "does not give rise to concern in human use since the substance is not absorbed through the skin."

The SCCS issued a new opinion on TiO<sub>2</sub> (nano) in July 2013. The SCCS came to the conclusion in that opinion that using TiO<sub>2</sub> (nano) as a UV filter in sunscreens at concentrations of up to 25% can be regarded as not posing any danger of negative effects on people. Applications such as powders or sprayable items that could expose users to TiO<sub>2</sub> nanoparticles through

inhalation cannot be deemed safe, according to the SCCS. In September 2017, the European Chemicals Agency's (ECHA's) European Risk Assessment Committee (RAC) released an opinion suggesting that TiO<sub>2</sub> be classified as a Carcinogen Category 2 that can only be inhaled. The use of pigmentary TiO<sub>2</sub> in cosmetic items that could expose consumers by inhalation is therefore covered by the conclusions made in this opinion (i.e., aerosol, spray, and powder form products). Because of the composite character of these materials, of which TiO<sub>2</sub> is only a small ingredient, the opinion is therefore not applicable to any pearlescent pigment.

Based on a safety evaluation, the SCCS believes that using pigmentary TiO<sub>2</sub> in a conventional hair styling aerosol spray product at a maximum dosage of 25% is unsafe for both stylists and general customers. According to the safety evaluation, the general public can safely use pigmentary TiO<sub>2</sub> in loose powder up to a maximum concentration of 25% in a standard face makeup application.

According to the SCCS, the maximum concentration of pigmentary TiO<sub>2</sub> in a typical hair styling aerosol spray product is 1.4% for general customers and 1.1% for hairdressers.<sup>62</sup>

#### List of Nanotechnology-Based Cosmetics

Some products prepared by using nanotechnology are summarized in Table 3:

#### Comparative Insights and Regulatory Challenges in Nanocosmetics

Although a variety of nanodelivery vehicles, including liposomes, solid lipid nanoparticles (SLNs), nanoemulsions, and nanostructured lipid carriers (NLCs), provide creative alternatives for cosmetic formulators, little is known about their respective benefits and drawbacks. For example, by adding liquid lipids to their structure, NLCs can obtain greater drug loading and lower ejection during storage compared to SLNs. This creates an amorphous matrix that better maintains active ingredients.<sup>63,64</sup> Nevertheless, it has been demonstrated that formulations containing certain cationic surfactants might cause irritation or inflammatory reactions, highlighting the necessity of careful excipient selection.<sup>65</sup> In terms of safety, nanoscale TiO<sub>2</sub>, which is used in sunscreens, is widely regarded as safe when administered as a coated, rutile-form nanoparticle at concentrations up to 25% under normal circumstances. However, there are still concerns about possible dangers from inhalation in powder sprays.<sup>66,67</sup> This is an example of the larger knowledge gap, the lack of reliable long-term dermal safety data, especially when it comes to interactions with impaired skin barriers and chronic exposure.<sup>68</sup>

Regional differences in regulatory regimes are notable. In addition to requiring premarket notification through the Cosmetic Products Notification Portal and requiring clear labeling of all nanomaterial ingredients (e.g., "zinc oxide (nano)"), the EU also requires products containing new nanomaterials to undergo risk assessment by the SCCS prior to market access.<sup>69</sup> In contrast, the United States has a more lenient stance,

allowing the majority of cosmetic components, including nanomaterials, to be used without prior permission; nonetheless, producers are still accountable for guaranteeing product safety and proper labeling.<sup>70</sup>

To guarantee safe and successful innovation in nanocosmetic technologies, these insights collectively point to important gaps in safety evaluation and emphasize the necessity of more thorough toxicological research, head-to-head comparisons among nanocarrier systems, and the creation of unified regulatory standards.

#### Conclusion

Nowadays, the fields of dermatology, cosmeceuticals, cosmetics, and other biomedical applications are using and appreciating nanotechnology, which is seen as a promising and revolutionary sector. Newer developments and innovative drug delivery methods have raised the market share and popularity of cosmetics and cosmeceuticals. Currently, such cosmetics constitute an integral component of daily consumer use; additionally, the application of nanotechnology to cosmetics has increased their acceptability among consumers worldwide. These days, a variety of cosmetics and cosmeceuticals with improved results are made using unique nanocarriers such as liposomes, ethosomes, nanostructured lipid carriers, solid lipid nanoparticles, nanoemulsions, and niosomes. Through a variety of methods, nanosystems transport and distribute these formulations throughout the skin, providing a number of benefits, such as moisturization, wrinkle reduction, and UV protection. Green nanotechnology has enormous potential for accomplishing sustainability objectives in the cosmetics sector, especially when it comes to packaging materials. We can discover creative ways to design packaging options that are both biodegradable and ecofriendly by investigating the concepts and methods of green nanotechnology. We can help create a more sustainable future for the cosmetics industry and the environment at large by adopting this strategy and putting plans in place to improve sustainability through biodegradable packaging materials. Together, AI and nanotechnology are making it possible to create cosmetics that are more customized, adaptable, and effective. Wearables, digital twins, and more environmentally friendly nanocarriers will enable the next wave of customized nanocosmetics.

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