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NANOTECHNOLOGY IN COSMETICS AND COSMECEUTICALS: PROGRESS AND PERSPECTIVES

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ABSTRACT

Nanotechnology is transforming the cosmetics and cosmeceutical industry by enabling the development of products that are more efficient, stable, and consumer-friendly. Nanoparticles, which range between 1 and 100 nanometers in size, exhibit unique properties such as a large surface area, improved solubility, transparency, and the ability to deliver active ingredients in a slow, controlled, and targeted manner. These qualities make them highly suitable for transporting bioactive compounds like vitamins, antioxidants, UV filters, and peptides into deeper layers of the skin, offering longer-lasting and more noticeable results compared to conventional formulations. Based on their composition, nanoparticles are broadly classified into two groups: inorganic and organic. Inorganic nanoparticles such as gold, silver, titanium dioxide, zinc oxide, and aluminum oxide are well recognized for their roles in UV protection, antimicrobial activity, and anti-aging formulations. On the other hand, organic nanoparticles—including liposomes, solid lipid nanoparticles, nanoemulsions, cubosomes, dendrimers, and chitosan systems—are widely used to deliver both hydrophilic and lipophilic actives. These carriers are applied in a wide range of cosmetic and personal care products, including sunscreens, moisturizers, anti-aging creams, whitening agents, acne treatments, perfumes, and hair care solutions. To prepare nanoparticles with the desired size and stability, methods such as solvent evaporation, Nano precipitation, Ultrasonication, high-pressure homogenization, and spray drying are employed, while safety and quality are assessed using techniques like light scattering, zeta

potential analysis, spectroscopy, and microscopy. Although nanotechnology-based cosmetics provide enhanced absorption, controlled release, greater stability, and improved product feel, concerns remain regarding deep tissue penetration, oxidative stress, bioaccumulation, environmental impact, and the absence of strict safety regulations**.** In conclusion, nanotechnology holds tremendous promise for advancing cosmetic science by combining effectiveness with innovation, but long-term studies on safety, sustainability, and regulation are essential to ensure its responsible application and to build consumer trust.

KEYWORDS: Nanotechnology, Cosmetics, Controlled release, Cosmetic science.

INTRODUCTION

The design, characterization, manufacturing, and use of structures, devices, and systems by altering size and shape at the nanometer scale—which covers the size range of 1 nanometer to 100 nanometers (nm), where 1 nanometer is one billionth of a meter—are all included in the cutting-edge science of nanotechnology. Applications of nanotechnology have been found in a variety of scientific fields, including electronics, medicine, and cosmetics, where it is now known as nanocosmetics. Due to the improved characteristics that nanoparticles achieve, such as color, transparency, and solubility, nanotechnology has a significant impact on the cosmetics industry. Solid lipid nanoparticles, liposomes, fullerenes, and nanosomes are among the several kinds of nanomaterials used in cosmetics.[1]

One of the first industries to use nanotechnological concepts in product creation was the cosmetics sector. In 2009, over 13% of the more than a thousand registered nanotechnology-based products available on the global market were categorized as cosmetics.[2] By providing creative ideas and boosting product efficacy, nanotechnology demonstrates advancements in the field of research and development. The use of nanotechnology in cosmeceuticals is growing in order to address some of the shortcomings of conventional products.[3] Nanotechnology has been used in a variety of scientific disciplines, including engineering, physics, chemistry, biology, and more. It has been used in cosmetics, health goods, and skin preparations for almost 40 years.

Cosmetics that use biologically active ingredients with therapeutic effects on their surface are known as cosmetics. Since they are supposed to improve appearance, they are used as cosmetics. Cosmetic goods have proven therapeutic value on the skin, while pharmaceutical formulations and drugs have spread from the skin to the body and hair. Numerous disorders,

such as wrinkles, photoaging, dry skin, dark spots, uneven complexion, hyperpigmentation, and hair damage, are treated with them.[3] The application of nanotechnology has generated advances in cosmetic research, which has raised global consumer demand.[4] Presently, nanoparticles are getting interest in this sector, since they offer significant advantages over commonly utilized cosmetic items. Furthermore, the global growth in the market share of cosmetics and medicines has been significantly aided by the combination of nanomaterials. The global nanomaterials market was valued at USD 8.5 billion in 2019 and is projected to grow at a compound yearly growth rate of up to 13.1% between 2020 and 2027. Despite the fact that the idea of nanomaterials—gold and silver nanoparticles—has been utilized in cosmetics for a number of years, the range of applications has increased recently.[5]

The market for skincare items is expanding significantly, and cosmetics are thought to be the segment of the personal care business with the quickest rate of growth. Several topical cosmeceutical treatments have gained popularity for problems like wrinkles, hair damage, photoaging, and hyperpigmentation. The benefits of nanotechnology-based cosmeceuticals include product variety, enhanced bioavailability of active ingredients, and improved appearance of cosmeceutical products with long-lasting effects. However, the growing application of nanotechnology in cosmetics has sparked worries about potential health risks and the ability for nanoparticles to pass through the skin.[6] The use of nanotechnology in cosmeceuticals aims to prolong the wear of perfumes, sunscreens, antiaging creams, and moisturizers so that the skin stays hydrated. Because the cosmeceuticals market is so diverse and products come from both large and small manufacturers as well as local businesses worldwide, the cosmeceutical industry is growing daily. As a result, nanotechnology-based cosmeceutical products have to be created and marketed with the environment and consumer health in mind.[7]

NANOPARTICLES

The word nano derived from the Latin word nanus means tiny or dwarf. Nanoparticles are the particles with sizes in nm range.[8] Particulate dispersions or solid particles with a size between 1 and 100 nm are referred to as nanoparticles. The medication is encapsulated, dissolved, trapped, or bonded to a matrix of nanoparticles. Nanoparticles, nanospheres, or nanocapsules can be produced based on the preparation technique.[9] for thousands of years, various businesses and humanity have utilized particles in these size ranges; but, because to the ability to synthesis and manipulate such materials, there has been a recent comeback.[10]

The inclusion of nanotechnology has resulted in improvements in cosmetic science, increasing consumer demand around the world. Since they provide more benefits than conventional cosmetics, nanomaterials are currently garnering interest in this field. Additionally, the combination of nanomaterials has significantly boosted the market share of cosmetics and pharmaceuticals worldwide.[5]

Nanoparticles used in cosmetic products

Materials with at least one dimension in the nano range and notably different physicochemical characteristics are called nanomaterials. For many years, the cosmetics industry has made extensive use of these materials. When compared to micro scale cosmetics, cosmetics containing nanoparticles exhibit greater benefits. These particles' effective transportation, absorption, bioavailability, transparency, and long-lasting effects are all due to their large surface area. To avoid the related toxicity, nevertheless, the concentration should be taken into account.[11]

The nanoparticles are composed of different layers such as

- Core layer
- Shell layer
- Surface layer.[12]

Nanoparticles are of different shapes like Spherical, cylindrical, conical, and tubular, rod shape or irregular. Nanomaterials can be made by two different methods either by breaking down complex into simple or by combining small particles to form Nanoparticle. Nanoparticles are used in different fields such as fertilizers in Agriculture, as medical devices in medicine, also used in electronics.[13]

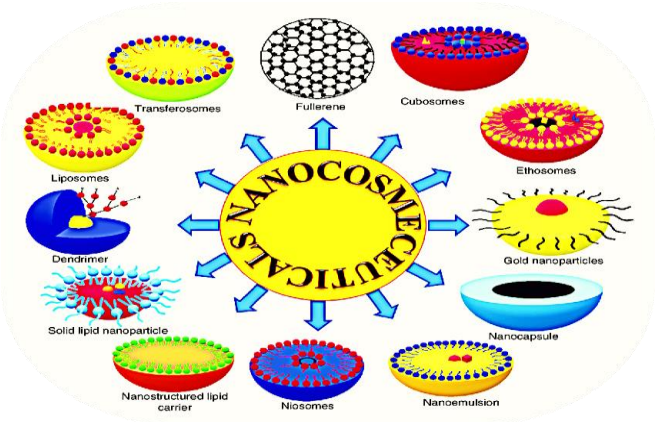

Fig. 1: Different drug delivery systems in cosmetics.

CLASSIFICATION OF NANOMATERIAL

Nanomaterials are classified into different types

1. Based on their dimensionalities

a) Zero-dimensional nanomaterial

b) One-dimensional nanomaterial

c) Two- dimensional nanomaterial

d) Three-dimensional nanomaterial

Zero-dimensional nanomaterial:- These have all three dimensions in nanoscale.

→ Example: Quantum dots, fullerenes.

One-dimensional nanomaterial:-These have only one dimension outside the nanoscale.

→ Example: nanotubes, nanofibers, nanowires.

Two-dimensional nanomaterial:-These have two dimensions outside the nanoscale.

→ Example: nanolayers, nanofilms, nanosheets.

Three-dimensional nanomaterial:-These materials are free from dimension.

→ Example: bulk powders, arrays of nanotubes, dispersion of nano particles.

2. Based on their composition

- Inorganic nanoparticle
- Organic nanoparticle
- Carbon based nanoparticle.[14]

1). INORGANIC NANOPARTICLES

Inorganic nanoparticles are the particles that are not made up of carbon. It comprises inorganic materials like ceramics, metal oxides and metals. These are widely used due too small size and unique structural properties in the fields like drug delivery, catalysis, imaging and environmental remediation.[15] Compared to natural nanoparticles, these are safer, more hydrophilic, biocompatible, and remarkably more stable particles. Since these nanoparticles are made from inorganic materials (Ag, Au, Ti, etc.) and the natural ones are made from polymers, they can be very different.[16]

1.1). METAL BASED NANOPARTICLES

Metal based nanoparticles can be obtained from metals such as silver, aluminium, gold, iron, copper, zinc, cobalt, cadmium, etc. these have wide range of applications.[15]

Characteristics of metal nano particles

- High energy surface
- Their surface area to volume ratio is larger than that of bulk.
- Quantum confinement
- Plasmon excitation
- Increased number of kinks.[17]

a). Silver nanoparticles

One of the most common ingredients in cosmetics is silver nanoparticles (AgNPs). Approximately 12% of all nanoparticles used in cosmetics are silver nanoparticles.[18] Because AgNPs have antibacterial qualities, it has been suggested that silver encourages the disruption of the bacterial cell wall. Furthermore, Kim and colleagues (2008) showed that AgNPs inhibit dermatophyte growth. AgNPs therefore have antibacterial and antimicrobial qualities and function as anti-infective agents.[19] AgNPs have anti-inflammatory properties that help wounds and burns heal more quickly, which is why the cosmetics industry uses them. The amount of silver in a nanosilver skin gel is thirty times lower than that of silver sulfadiazine, a common chemical in this field. Patients with burned skin benefit from this. AgNPs thereby restore and mend skin tissues.[20]

b).Gold nanoparticles

Gold nanoparticles are the tiny particles ranging from 5 to 400 nm in size and come in various shapes such as Nano rods nanospheres and nanotubes. These particles are inert, non-toxic, biocompatible and stable. These can improve blood circulation, enhance skin firmness and provide anti-ageing and anti-inflammatory benefits. They are known for being safe non-toxic and gentle on skin which makes them perfect for wound healing, reducing inflammation and improving skin structure. They are also used in lipsticks, deodorants, sprays, tooth paste and even mouth fresheners because of their anti-microbial properties. Over all, gold nano particles are a power full ingredient's that blends beauty with science.[21]

c).Aluminium nanoparticles

Aluminium nanoparticles have unique physical, chemical and optical properties. These nano particles are used primarily as coating agents in Titanium dioxide and Zinc oxide formulations. It is used in cosmetics for tooth remineralisation and polishing. These are also used to control fizzy hair.[22]

d). Platinum nanoparticles

Despite being excellent therapeutic agents for the treatment of cancer cells, platinum nanoparticles appear to have unfavorable side effects.[23]

In one study conducted in vitro, they investigated the cytotoxic impact of platinum nanoparticles on human ovarian teratocarcinoma, lung adenocarcinoma, By causing ovarian teratocarcinoma cells to undergo apoptosis, the anticancer potential of pancreatic cancer cells and healthy peripheral blood mononucleocyte cells was assessed. They discovered that whereas normal cells had no cytotoxic effect at the greatest dose, platinum nanoparticles had a cytotoxic effect on cancer cell types. The findings demonstrated that via inducing apoptosis and cell cycle arrest, platinum nanoparticles exhibited strong anticancer effects against an ovarian teratocarcinoma cell line.[24]

When exposed to platinum nanoparticles at low levels, many stress reactions, proinflammatory cytokine release, and modification of signal transduction that is dependent on insulin-like growth factor-1.[25] Compared to larger nanoparticles, smaller ones showed greater activation of caspases and a more detrimental effect on DNA stability.[26]

1.2).METAL OXIDE NANOPARTICLES

Because of their special physical and chemical characteristics, like heat transfer and thermal conductivity, metal oxide nanoparticles are regarded as one of the most promising nanomaterials in various fields. Numerous metal oxide nanoparticles have been employed in the oil and gas sector for nearly every facet of hydrocarbon E&P, including as a catalyst, wettability agent, enhanced oil recovery, reservoir imaging, filler or additive in drilling/completion fluid, and for trapping and fine particle mobility control.[27] Fe_2O_3, SiO_2, Al_2O_3, MgO, CeO_2, TiO_2, and ZnO are among the most widely employed types of metal oxide nanoparticles. In general, there are two types of metal oxide nanoparticle fabrication: liquid-solid and gas-solid, depending on the type of phase transformation. Because it can

readily manipulate morphological traits like size and shape, the former is thought to be the most straightforward and prevalent of the two.[28]

a). zinc oxide nanoparticles

Zinc oxide nanoparticles are inorganic chemical compound which is used in daily life and the physiochemical properties depend on the method of preparation. Zinc oxide nanoparticles are used in the form of creams and ointments in wound healing, also used in temporary dental fillings. It exhibits greater stability, better crystallinity. So, they are used in degradation of various organic impurities. It is a white powder that is in soluble in water.[29]

b). Iron oxide nanoparticles

Drug administration, magnetic resonance imaging, thermal ablation therapy, in vivo cell tracking, and other biomedical applications have made extensive use of iron oxide nanoparticles. magnetic separation of molecules or cells because of their super paramagnetic characteristics. Furthermore, nanoscale zero-valent iron particles are used in environmental cleanup due to their large specific surface area and strong reactivity.CO_2 absorption from the water was greatly enhanced as an environmental remediation technique employing Nano fluid made from iron (II, III) oxide. The mechanism of CO_2 absorption was described using the hydrodynamic effect and grazing. The absorption of gas molecules using the surfaces of the nanoparticles at the bubble interface and the subsequent removal of the adsorbed gas components from the surface of the nanoparticles into the fluid are related to the grazing action.[30]

c). Titanium dioxide nanoparticles

TiO_2 is utilized in toothpaste, paints, coatings, plastics, papers, inks, medications, pharmaceuticals, food items, and cosmetics. Even skim milk can be whitened by using it as a pigment. Sunscreens also contain TiO_2 NPs. Furthermore, TiO_2 has been a part of articulating prosthetic implants for a long time, particularly for the knee and hip. Occasionally, a prolonged inflammatory reaction to the implant material or material degradation cause these implants to fail.[31]

d). Aluminum oxide nanoparticles

Aluminum oxide nanoparticles (Al_2O_3 NPs) have garnered a lot of interest from a variety of scientific and industrial domains because of their distinct bio-/physicochemical characteristics, which include large surface area, high hardness, electrical insulation, thermal stability, biocompatibility, and surface functionalization.[32]

In comparison to its bulk form 4, Al_2O_3 shows improved functional performance, increased surface area, and surface reactivity when produced as nanoparticles.

Usually found in the 1–100 nm range, these nanoparticles exhibit quantum confinement effects, which add to their distinctive nature.[33] To create Al_2O_3 nanoparticles with regulated size, shape, and phase composition, a variety of synthesis methods have been devised.

These consist of mechanical milling, hydrothermal synthesis, combustion procedures, sol-gel methods, and green synthesis employing microbes or plant extracts.[34]

Inorganic nanoparticles, such as gold(Au), silver(Ag), silica(SiO_2) and aluminum oxide(Al_2O_3), exhibit excellent structural stability, high surface area, tunable optical/electronic properties, and thermal resilience. These characteristics make them particularly effective in fields such as biosensing, catalysis, and cancer theranostics. Moreover, they are easily functionalized with biomolecules for targeted delivery, despite their non-biodegradable nature.

2).ORGANIC NANOPARTICLES

In cosmetics, organic nanoparticles such as liposomes, solid lipid nanoparticles, and nanoemulsions are nanoscale (1–100 nm) delivery systems composed of biodegradable substances like lipids, proteins, or natural polymers that provide controlled active ingredient delivery and improved skin compatibility.[35] Without the use of harsh chemical enhancers, they improve penetration, allow controlled release, safeguard delicate bioactives from deterioration, and increase skin retention.[36]

TYPES OF ORGANIC NANOPARTICLES[37]

1. Solid Lipid Nanoparticles. (SLN)
2. Chitosan nanoparticles.
3. Polymeric Nanoparticles.
4. Cubosomes.
5. Nanoemulsions.
6. Dendrimers.
7. Liposomes.
8. Niosomes.

1). Solid Lipid Nanoparticles (SLN)

Solid lipids (such as triglycerides, fatty acids, and waxes) that stay solid at room temperature and body temperature are the building blocks of solid lipid nanoparticles (SLNs), which are submicron-sized particles (50–1000 nm). Surfactants like sodium cholate, lecithin, or polysorbate 80 stabilize them. They are made up of solid lipids that, at body and room temperature, do not change their solid state.[38]

They were created to address issues with previous delivery methods such liposomes, polymeric nanoparticles, and nanoemulsions.[39] Concerns regarding possible toxicity from synthetic polymers were frequently raised by polymeric nanoparticles.[40] The crystalline solid lipid matrix that SLNs offer shields the active chemicals from oxidation, photodegradation, and hydrolysis.[41] This makes them ideal for sensitive actives like vitamins and retinoids, which are frequently employed in dermatological and cosmetic applications.[42] Nowadays, SLNs are frequently found in a wide range of cosmetic formulations, such as sunscreens, moisturizers, anti-aging creams, and acne remedies.[43] Their usefulness is further expanded by their capacity to encapsulate both lipophilic and somewhat hydrophilic compounds.[44]

2). Chitosan nanoparticles

The natural polymer chitosan, which is produced by deacetylating the chitin present in crustacean shells, is the source of chitosan nanoparticles (CSNPs), which are organic, biodegradable, and biocompatible nanocarriers.[45] Chitosan has polycationic qualities in acidic conditions because it is made up of N-acetyl-D-glucosamine and β-(1→4)-linked D-glucosamine units.[46] Chitosan's positively charged amino groups enable it to interact strongly with biological membranes that are negatively charged.[47] This enhances the mucoadhesive and permeation-enhancing properties of chitosan nanoparticles for topical and transdermal delivery.[48] This improves the chitosan nanoparticles' mucoadhesive and permeation-enhancing qualities for topical and transdermal administration.[49] Usually, ionic gelation, emulsion-based techniques, or polyelectrolyte complexation are used to create chitosan nanoparticles.[50] Chitosan nanoparticles are frequently used in cosmetics to deliver active substances including vitamins, antioxidants, and anti-aging chemicals in a controlled manner.[51] Additionally, they function as film-forming agents, which increase skin hydration and decrease trans epidermal water loss by covering the skin with a protective layer.[52] Because of their antibacterial and antifungal properties, CSNPs are used in acne treatment and dandruff-control haircare products.[53] All things considered, chitosan nanoparticles are

becoming more and more adaptable and sustainable nanocarriers for formulations of the next generation of cosmetics.[54]

3). Polymeric nanoparticles

Submicron carriers (10–1000 nm) made of biodegradable or biocompatible polymers including PLA, PCL, and PLGA are known as polymeric nanoparticles. Both lipophilic and hydrophilic cosmetic actives can be encapsulated by these particles, increasing their stability and bioavailability. Because of their microscopic size, they can penetrate the skin more deeply, improving the delivery of antioxidants and anti-aging substances like retinol, resveratrol, and vitamin C. Additionally, polymeric nanoparticles prolong the shelf life and effectiveness of active substances by protecting them from environmental deterioration such as oxidation or photodegradation. They are therefore perfect for sunscreens, skin-lightening products, and anti-aging lotions.[55] By providing a sustained and regulated release of active ingredients, these nanoparticles lower the daily treatment requirements and improve patient compliance. They avoid discomfort brought on by abrupt increases in active concentration by gradually preserving medication concentration within therapeutic ranges. For instance, encapsulated glycolic acid or salicylic acid, which are used to treat acne, are kinder to the skin than their free counterparts. Furthermore, their regulated release profile improves the functionality of therapeutic substances and lessens negative effects. Additionally, they enhance the targeting of chemicals to particular layers of the skin, maximizing potency with a low dosage. Because of their adjustable characteristics, polymeric nanoparticles are perfect for cosmetics. Charge, rate of breakdown, and hydrophobicity can all be altered in the polymer matrix. Their use in a variety of cosmetic forms, including gels, emulsions, sprays, and serums, is made possible by this modification. They improve the way that sunscreens distribute UV filters, whitening agents, and antioxidants. By creating a protective layer on the skin, these nanosystems guarantee sustained active ingredient contact and stop transepidermal water loss. Furthermore, the use of naturally occurring polymers such as chitosan and alginate is consistent with the cosmetics industry's growing trend toward sustainable and eco-friendly formulations.[56]

4). Cubosomes

Because of its small particle size (~100–300 nm) and structural resemblance to biological membranes, cubosomes improve skin penetration. Through the slow diffusion of active substances through the layers of the skin, their cubic phase enables continuous release. By

momentarily upsetting the lipid layers of the stratum corneum, they can enhance medication diffusion and retention without irritating the skin. For the delivery of active ingredients like niacinamide, kojic acid, and vitamin E in brightening and anti-aging formulas, this feature is quite beneficial. They are appropriate for a variety of skin types and climates due to their ability to stay stable under changing pH and temperature conditions.[57]

Even in the absence of refrigeration, cubosomes have superior colloidal and thermodynamic stability in contrast to conventional emulsions or liposomes. They are ideal for skincare products with a long shelf life because of their interior structure, which resists aggregation, phase separation, and deterioration over time. Cubosomes can also be reconstituted and freeze-dried without losing their functioning, giving producers more formulation options. This guarantees that lotions, gels, and creams stay effective from the point of packaging until the point of use. Because of their durability, they are perfect for adding delicate or volatile substances like UV filters, herbal extracts, and essential oils.[58]

5). Nanoemulsions

Nanoemulsions are colloidal dispersions of water and oil that are thermodynamically kinetically stable and stabilized by surfactants or surfactant–cosurfactant combinations. They produce transparent or translucent formulations with droplet sizes ranging from 20 to 200 nm. Their large surface area enhances skin penetration and absorption by improving the solubilization of hydrophobic cosmetic actives (such as vitamin E and plant oils). These technologies extend shelf life and shield delicate substances from deterioration. In skincare, nanoemulsions provide hydration while enhancing the transport of peptides and botanical extracts. They also allow for the efficacy of UV-protective, anti-aging, and brightening solutions with less irritation.[59]

Depending on the sensitivity of the ingredients, nanoemulsions are made utilizing both low-energy (phase inversion temperature/composition) and high-energy (high-pressure homogenization, ultrasonication) approaches. Consistent delivery and penetration into deeper skin layers and hair follicles are made possible by their homogenous droplet size. They improve the transport of antioxidants or collagenase-inhibiting agents and increase hydration by producing a lipid film that decreases transepidermal water loss. When plant-based nanoemulsions, such Passiflora quadrangularis oil, were clinically evaluated on volunteers, they significantly reduced wrinkles and hydrated their skin without causing any irritation.[60]

Because of their mild surfactant systems and regulated release, nanoemulsions are known for their exceptional skin tolerability and low irritancy. By reducing irritation, they can consistently enhance the effectiveness of strong actives like peptides or AHAs. Nanoemulsions with botanical or peptide actives showed anti-sebum benefits and improved skin texture in cosmeceutical tests, particularly in those with oily or acne-prone skin. An important benefit of these carriers in commercial skincare products is their long-term colloidal stability, which prevents phase separation, creaming, and coalescence during storage.[61]

6). Dendrimers

Dendrimers are artificial, monodisperse, highly branched macromolecules with a central core, repeating branching units, and surface functional groups. They are usually less than 15 nm in length. They are adaptable for delivering vitamins, peptides, and botanical extracts in cosmetic compositions since they can contain both hydrophilic and hydrophobic actives. Their variable surface charge and multivalency (amine-terminated PAMAM, for example) promote bio adhesion and skin penetration. Their penetration through epidermal layers is influenced by variables such generation size, surface charge, and hydrophobic modifications (like oleic acid conjugation). Controlled release is still difficult, despite its effectiveness. For safer, more accurate cosmetic administration, research is still being done on ligand-targeted or stimuli-responsive systems.[62]

7). Liposomes

Liposomes are spherical phospholipid vesicles that range in size from around 50 to 300 nm. They can contain both hydrophilic and hydrophobic active ingredients, including sunscreens, vitamins, peptides, and plant extracts. Because of their structural resemblance to skin cell membranes, the encapsulated chemicals can penetrate more easily and release gradually. Liposomal compositions reduce irritation and oxidative degradation of sensitive chemicals while enhancing skin hydration and barrier restoration. To further enhance cutaneous delivery, advanced vesicle forms such as ethosomes, transfersomes, and invasomes have been developed. Because liposomes may localize active ingredients in particular skin layers, they can also be utilized to treat pigmentation issues, acne, and hair follicles.[63]

8). Niosomes

Similar to liposomes but more stable and less expensive, niosomes are self-assembled vesicles made of cholesterol and non-ionic surfactants. Both hydrophilic and lipophilic

cosmetic actives can be encapsulated by them, improving controlled release and skin penetration. Niosomes enhance solubilization, shield delicate substances (such as peptides or antioxidants) from deterioration, and offer prolonged delivery in topical applications. They are perfect for formulations containing botanical extracts, sunscreens, and anti-aging creams because they are easier to sterilize and more physically stable than liposomes.[64]

Table 1: Nanoparticles with advantages disadvantages and applications.

Type of Nanoparticle	Advantages	Disadvantages	Applications in Cosmetics
Titanium dioxide (TiO_2)	Transparent UV protection, stable, no whitening	May penetrate damaged skin, inhalation hazard	Sunscreens, UV creams
Zinc oxide (ZnO)	Broad UV protection, antibacterial	Possible ROS generation, penetration concerns	Sunscreens, antibacterial creams
Gold (AuNPs)	Anti-aging, anti-inflammatory, skin brightening	Possible irritation, unclear long-term safety	Anti-aging creams, facial masks
Silver (AgNPs)	Strong antimicrobial, extends shelf life	Possible toxicity, environmental impact	Deodorants, antibacterial creams
Silica (SiO_2)	Improves texture, low cost	Inhalation hazard, long-term safety unclear	Lipsticks, foundations
Carbon black	Deep black pigment	Cytotoxicity, irritation risk	Mascaras, eyeliners
Liposomes	Better delivery of actives, moisturizes	Stability issues, limited loading	Moisturizers, serums
Solid lipid nanoparticles (SLN/NLC)	Protect actives, enhance hydration	General safety concerns	Sunscreens, moisturizers
Nano-hydroxyapatite	Remineralizes teeth, safe for oral use	Limited to oral care	Toothpaste, mouthwash

PREPARATION OF NANOPARTICLES

Preparation methods[65]

1. Solvent Evaporation Method.
2. Ion exchange method.
3. Emulsion Diffusion Method.
4. Nano precipitation (Solvent Displacement Method).
5. High-Pressure Homogenization.
6. Ultra sonication.
7. Spray Drying.
8. Supercritical Fluid Technology.
9. Sol-gel method.
10. Vacuum Deposition Method.

1). Solvent Evaporation Method

The solvent evaporation method is a widely adopted technique for fabricating polymeric nanoparticles, especially for drug delivery applications. This method involves dissolving a biodegradable polymer—such as PLGA—along with the target drug in a volatile organic solvent like dichloromethane or ethyl acetate, forming the organic phase. This solution is then emulsified into an aqueous phase containing a stabilizer such as polyvinyl alcohol (PVA), using high-speed homogenization or ultra-sonication to form an oil-in-water (O/W) emulsion. The organic solvent is subsequently removed by continuous stirring at room or slightly elevated temperatures, or under reduced pressure, causing the polymer to precipitate and harden around the drug molecules. This process results in the formation of solid nanoparticles. These are typically collected by centrifugation, washed to remove residual surfactants and solvents, and then dried, often via freeze-drying. The technique is known for its simplicity, scalability, and effectiveness in encapsulating hydrophobic drugs. However, precise control over parameters like solvent type, polymer concentration, emulsifier content, and processing conditions is essential to achieve uniform particle size, high drug loading, and reproducibility. Recent studies have continued to refine this method to improve encapsulation efficiency and optimize drug release profiles, making it a reliable and adaptable approach in pharmaceutical research.[66]

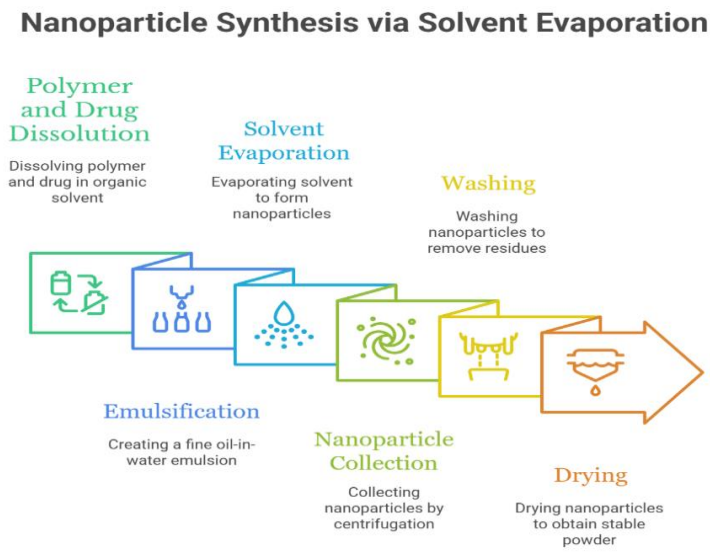

Fig. 2: Solvent Evaporation Method.

2). Ion exchange method

The ion exchange method is a versatile and widely used technique for synthesizing drug-loaded nanoparticles and controlled release formulations. It works on the principle of

exchanging ions between a solution and an ion exchange resin or material. In pharmaceutical applications, drugs are often loaded onto ion exchange resins through electrostatic interactions, where the drug ions replace counter-ions initially present on the resin. This technique allows for a controlled and sustained release of drugs, as the exchange process is gradual and can be influenced by the surrounding pH, ionic strength, or the presence of competing ions. The method is especially useful for improving the stability of sensitive drugs and reducing their dosing frequency. It's also considered safe and efficient since it often avoids the use of harmful solvents or high temperatures. Researchers value the ion exchange method for its simplicity, scalability, and ability to fine-tune drug release profiles for specific therapeutic needs.[67]

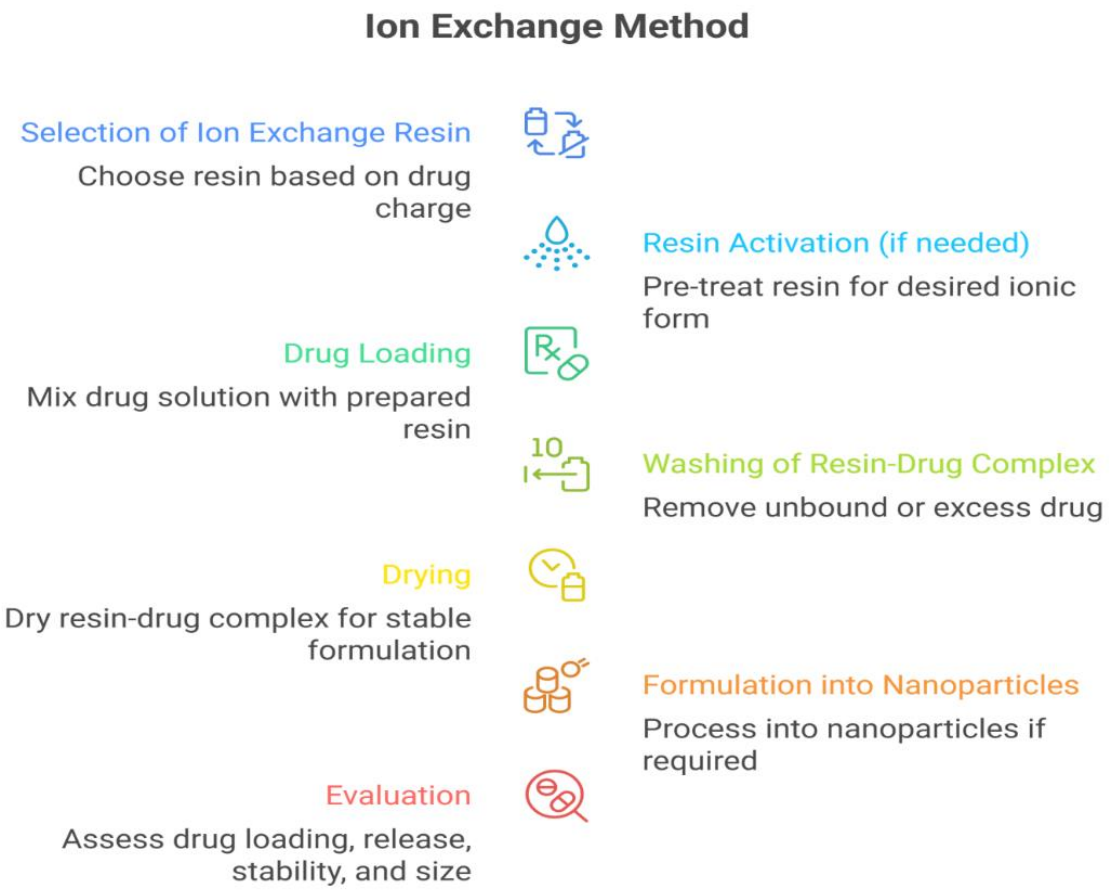

Fig. 3: Ion Exchange Method.

3). Emulsion Diffusion Method

The emulsion diffusion method is a widely used technique for preparing polymeric nanoparticles, particularly for drug delivery applications. This method starts by dissolving a polymer and the drug in a partially water-miscible organic solvent such as ethyl acetate. This solution is then emulsified into an aqueous phase containing a stabilizer (like polyvinyl

alcohol), forming an oil-in-water (O/W) emulsion. Once the emulsion is formed, water is added to the system to promote solvent diffusion from the organic droplets into the external aqueous phase. As the solvent diffuses out, the polymer precipitates and forms solid nanoparticles encapsulating the drug. The final product is typically collected by centrifugation or filtration. This method offers good control over particle size and drug encapsulation efficiency, and it's especially valuable for loading hydrophobic drugs. Since it avoids high temperatures and harsh conditions, it's suitable for encapsulating sensitive compounds like peptides or vaccines.[68]

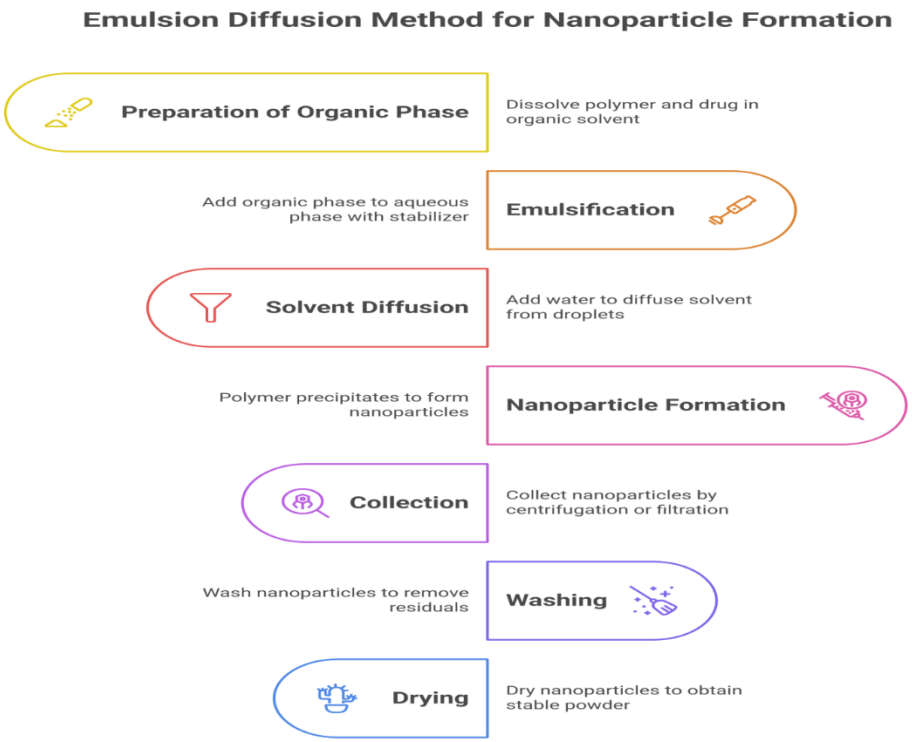

Fig. 4: Emulsion diffusion method.

4). Nano precipitation Method

The Nano precipitation method, also known as the solvent displacement technique, is a widely used and straightforward approach for preparing polymeric nanoparticles. In this method, a polymer and drug are first dissolved in a water-miscible organic solvent like acetone or ethanol. This organic solution is then slowly added to an aqueous phase containing a stabilizer, such as polyvinyl alcohol (PVA), under gentle stirring. Once mixed, the rapid diffusion of the organic solvent into the water causes the polymer to precipitate and form nanoparticles, with the drug often encapsulated inside. No high-energy equipment is required,

making this method especially useful for heat-sensitive drugs. The nanoparticles are then separated, typically by centrifugation, and washed to remove any excess solvent or surfactant. This method is appreciated for its simplicity, reproducibility, and ability to produce small-sized nanoparticles with narrow size distribution. It is especially suitable for encapsulating lipophilic drugs and is commonly used in pharmaceutical formulations.[69]

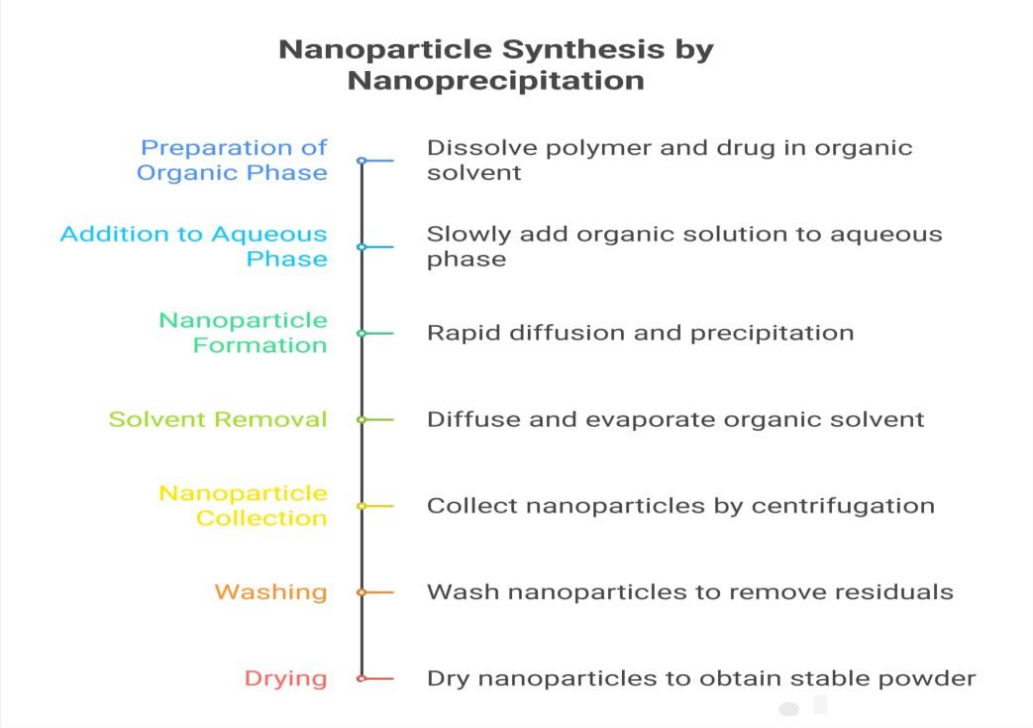

Fig. 5: Nano Precipitation Method.

5). High pressure homogenization

High-pressure homogenization (HPH) is a robust and scalable technique used to produce nanoparticles, especially lipid-based systems like solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs). In this method, a lipid phase (which may contain the drug) is first melted and mixed with an aqueous surfactant solution to form a coarse pre-emulsion. This mixture is then forced through a narrow homogenization gap at very high pressures, often ranging from 100 to 1500 bar. The intense shear forces, turbulence, and cavitation break down the droplets into nanometer-sized particles. The process can be done using hot HPH (above the lipid's melting point) or cold HPH (for temperature-sensitive drugs). The resulting nanoparticles typically have uniform size distribution and good physical stability. HPH is widely used in the pharmaceutical industry due to its reproducibility, lack of harmful solvents, and suitability for large-scale production.[70]

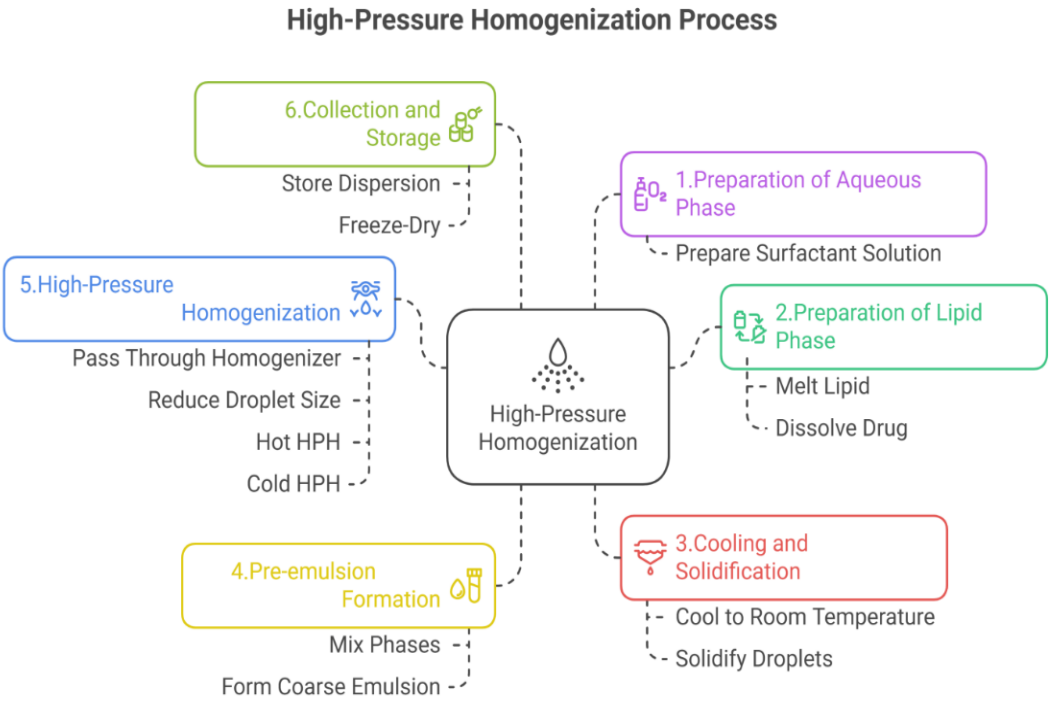

Fig. 6: High Pressure Homogenization Method.

6). Ultrasonication

The ultra-sonication method uses high-frequency sound waves to gently yet effectively convert larger droplets or particles into nanoscale forms. In practice, a drug is mixed with a polymer or lipid in an appropriate solvent and emulsified into an aqueous medium. The emulsion is then treated with ultrasonic energy—typically via a probe sonicator—to generate tiny vapor-filled cavities (cavitation bubbles). As they collapse, intense micro‑jets and shear forces fragment the droplets down to nanometer size, often producing uniform nanoparticles in the 20–200 nm range. This method avoids harsh heating and harsh chemicals, making it ideal for temperature-sensitive drugs. By adjusting sonication time, amplitude, and setup (bath vs. probe), we can fine-tune particle size and distribution. After processing, the nanoparticles are recovered by centrifugation and washed to remove excess surfactant or solvent. Ultrasonication is popular for making nano‑emulsions, lipid nanoparticles, and polymeric nanocarriers because it's scalable, controllable, and relatively easy to set up in the lab or pilot plants.[71]

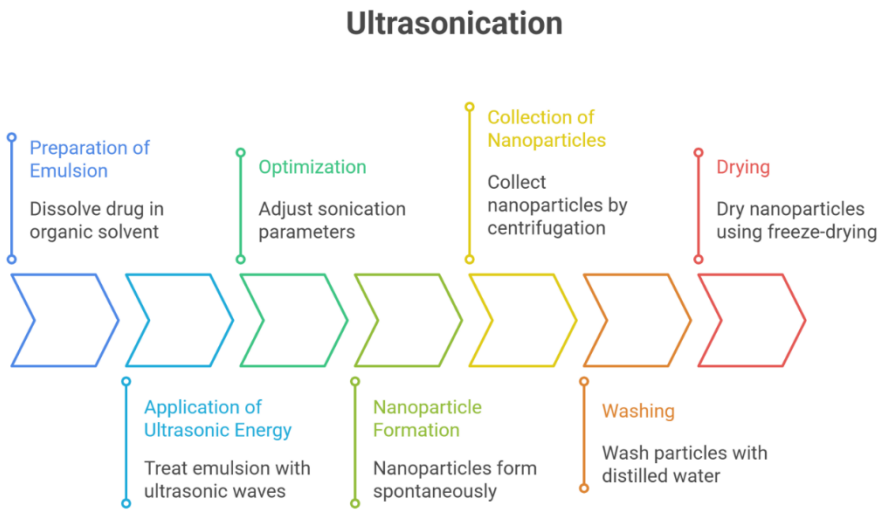

Fig. 7: Ultrasonication Method.

7). Spray drying

Spray drying transforms liquid formulations into dry powders by atomizing a solution or suspension into a heated chamber. When adapted for nanoparticle production—sometimes called nano spray drying—it enables the gentle formation of particles in the sub‑micron range. First, your drug or nanoparticle suspension is infused with excipients or polymers and fed via a fine nozzle into a stream of controlled hot drying gas. The droplets instantly lose solvent and become solid particles. Key advancements in nano spray drying include vibrating mesh nozzles that produce uniform droplets, laminar dryer airflow to avoid particle damage, and electrostatic collectors that capture ultrafine particles—often down to ~300 nm—with high efficiency. Because the process is fast and scalable, it's ideal for formulating inhalable powders or stabilizing sensitive biological molecules. By tweaking parameters such as inlet temperature, feed concentration, spray mesh size, and excipient choice, you can carefully control particle morphology, size distribution, drug loading, and release behavior. This method is widely used to develop dry powders for inhalation, oral delivery, and other routes where nanostructured particles offer advantages in bioavailability and stability.[72]

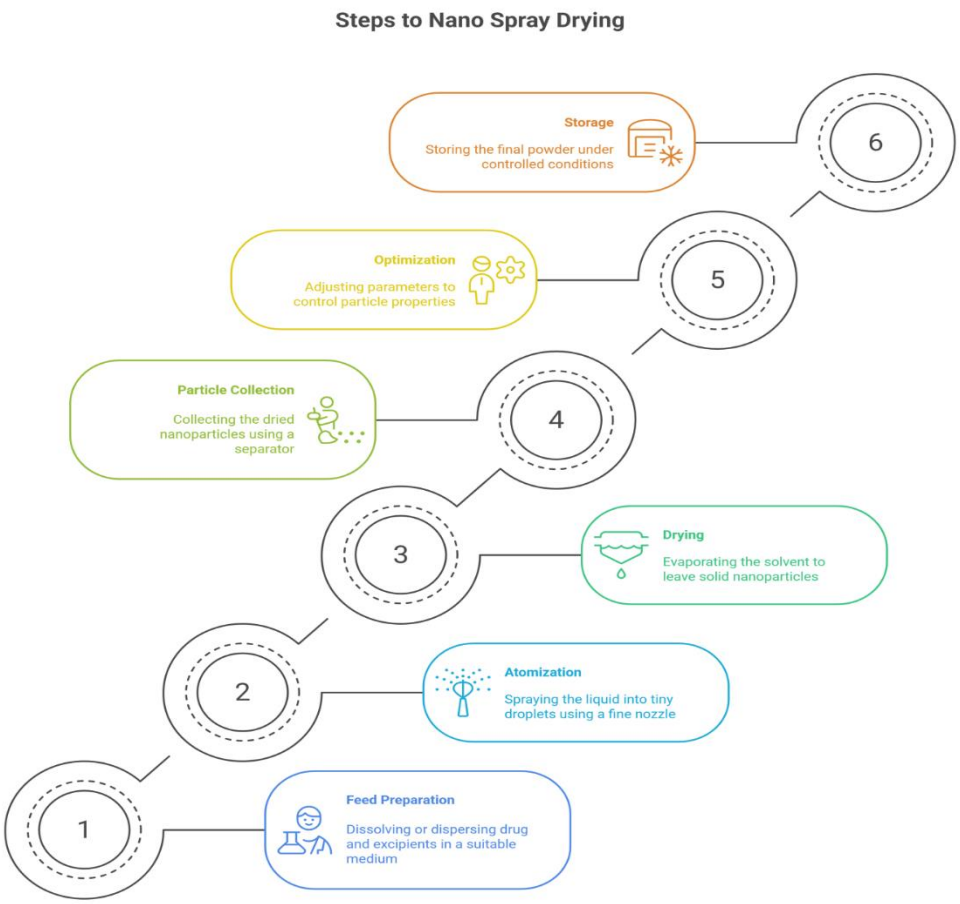

Fig. 8: Spray Drying Method.

8). Supercritical Fluid Technology

Supercritical Fluid Technology follows a carefully controlled process that takes advantage of the unique properties of certain fluids—most often carbon dioxide (CO_2)—when they are brought above their critical temperature and pressure. At this supercritical state, CO_2 behaves like both a gas and a liquid, giving it the ability to deeply penetrate materials and dissolve specific compounds. The process typically starts by placing the raw material, such as a plant extract or drug substance, into a specially designed extraction chamber. Carbon dioxide is then pressurized and heated beyond 31.1°C and 73.8 bar to reach its supercritical form. Once it becomes supercritical, it flows through the extraction vessel, selectively pulling out the desired components due to its unique solvent properties.

After the extraction is complete, the CO_2 carrying the dissolved compounds is transferred to a separator unit. In this next stage, the pressure and temperature are carefully lowered, causing the extracted substances to drop out of the CO_2 stream as it loses its ability to hold them in solution. These precipitated compounds are collected, and the CO_2—now back to its gaseous

form—is either vented or reused in the system. In cases where SCFT is used for particle formation, such as in pharmaceutical formulations, methods like RESS (Rapid Expansion of Supercritical Solution) or SAS (Supercritical Anti-Solvent) are employed. These help in producing ultra-fine drug particles with controlled size and enhanced solubility. Overall, the procedure is clean, efficient, and particularly suited for heat-sensitive compounds, making it highly valuable in pharmaceutical, food, and cosmetic applications.[73]

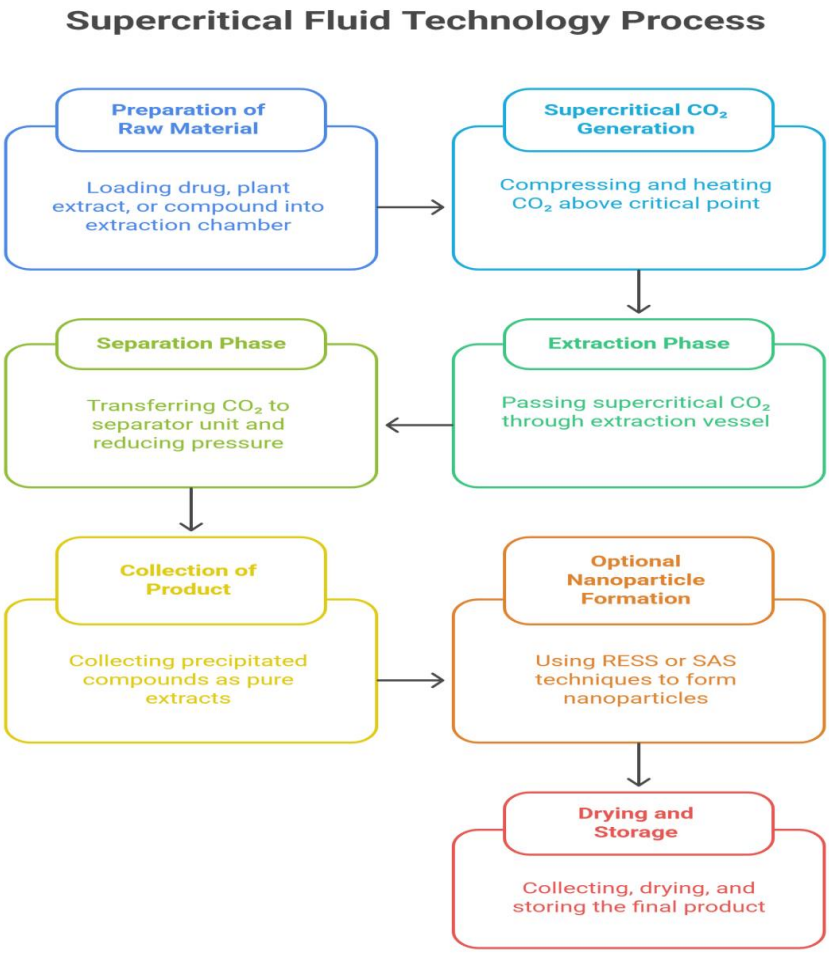

Fig. 9: Super Critical Fluid Technology.

9). Sol gel method

The sol–gel method is a versatile and low-temperature technique widely used for synthesizing nanoparticles, especially metal oxides like TiO_2, ZnO, and SiO_2. The process begins by dissolving a metal precursor—usually a metal alkoxide or salt—into an alcohol-based solvent. Upon the addition of water under acidic or basic conditions, hydrolysis and polycondensation reactions initiate, gradually transforming the clear solution (sol) into a wet

three-dimensional gel. This gel is then aged, dried, and thermally treated to remove organic content and crystallize the final nanoparticles. By adjusting parameters such as pH, temperature, precursor concentration, and aging time, scientists can precisely control particle size, porosity, and surface area. The method is especially valuable for applications in catalysis, drug delivery, and biosensors, thanks to its ability to produce high-purity, homogeneous, and stable nanostructures. Its eco-friendly nature and scalability make sol–gel synthesis an ideal option for both lab and industrial nanoparticle production.[74]

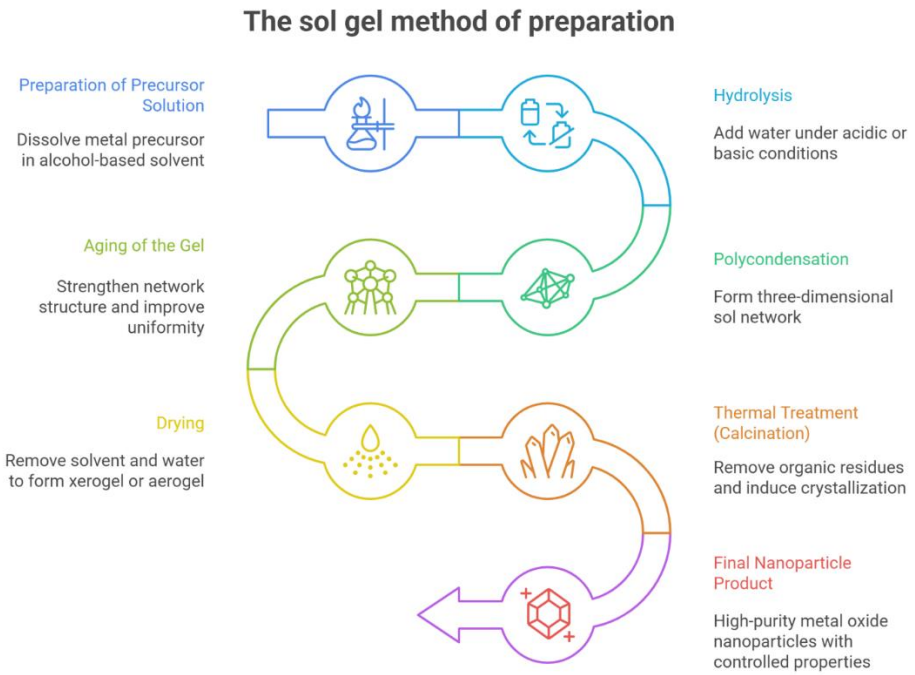

Fig. 10: Sol Gel Method.

10). Vacuum Deposition Method

The vacuum deposition method is a widely adopted technique in the fabrication of nanoscale coatings and thin films, especially in the fields of electronics, optics, and drug delivery. This method involves the deposition of a material onto a substrate in a vacuum environment, which helps prevent contamination and ensures a high-purity, uniform film.

There are two main types: physical vapor deposition (PVD) and chemical vapor deposition (CVD)**.** In PVD, the material to be deposited is first vaporized using thermal energy, electron beam, or sputtering, and then condensed onto the target surface. In contrast, CVD involves the use of chemical reactions in the gas phase that result in the formation of a solid film on

the substrate. The high vacuum environment not only supports better film adhesion but also improves control over film thickness and morphology, making the process suitable for precision applications, such as microelectronics and biomedical implants. This method is particularly useful in drug delivery systems for preparing biocompatible and functional coatings on nanoparticles, which enhance their stability, targeting efficiency, and release profiles.[75]

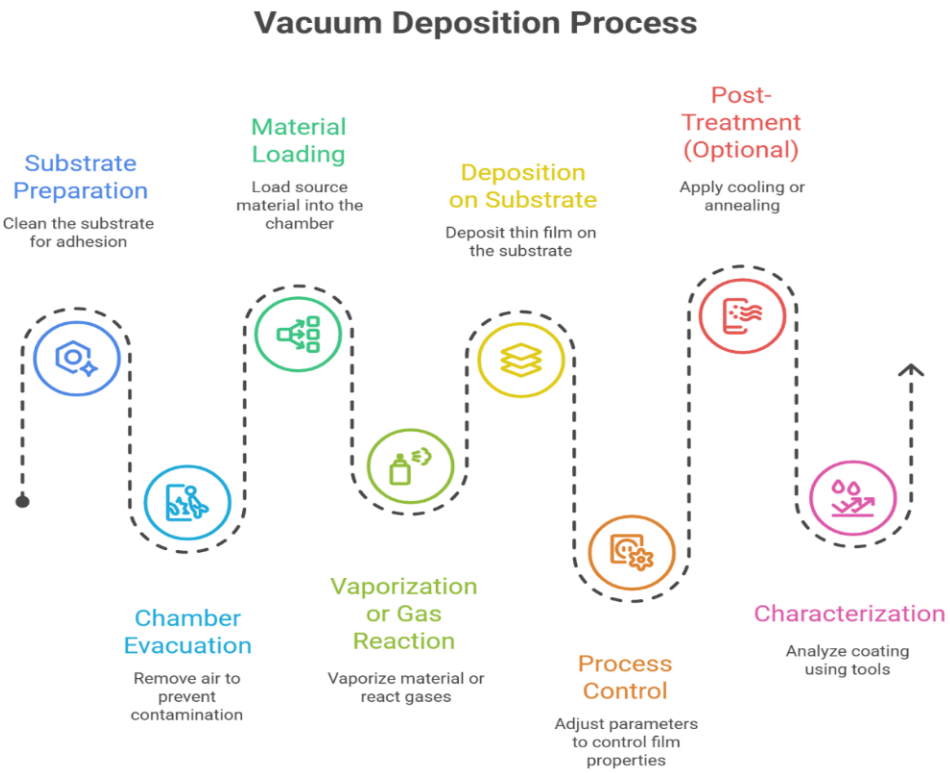

Fig. 11: Vacuum Deposition Method.

CHARACTERIZATION OF NANOPARTICLES

For ensuring safety, stability, and efficacy in cosmetic and cosmeceutical formulations, nanoparticle characterization is crucial. Important factors include morphology, which impacts how the product spreads on the skin; zeta potential, which indicates colloidal stability; and particle size, which affects skin penetration. The structural integrity and chemical compatibility of the active substances within nanoparticles are confirmed by further crucial investigations such as FTIR, DSC, and TEM/SEM. Together; these tests verify that the formulation will function as planned over time without causing irritation or deterioration. Additionally, accurate characterization increases consumer confidence in skincare products based on nanotechnology and conforms to regulatory criteria.[76]

Particle size

One of the most important factors in creating cosmetic formulas based on nanoparticles is particle size. It influences a product's stability, look, and texture in addition to determining how well it penetrates the skin. Smaller particles (less than 200 nm) can more readily penetrate the skin's deeper layers, increasing the effectiveness of active substances like vitamin C or retinol. Dynamic Light Scattering (DLS), which employs laser light to quantify how quickly particles move in a solution, is the most widely used technique for measuring particle size. This aids in figuring out the nanoparticles' average size and dispersion within a composition. Consistency in particle size in cosmetics prevents clumping or rough textures and guarantees even application. Therefore, keeping a product at its ideal size improves user experience and product performance.[77]

Zeta potential

Nanoparticles' colloidal stability is mostly determined by their zeta potential, which is a measurement of the electrical charge on their surface. Put more simply, it indicates whether particles will cluster together (which could destroy the formulation) or repel one another (which is excellent). The particles are more likely to remain evenly distributed without settling or aggregating if the zeta potential is large, whether it is positive or negative. This is particularly significant in cosmetics where physical stability is essential, such as in lotions, gels, or nanoemulsions. Electrophoretic light scattering, which is frequently incorporated into DLS devices, is the most widely used technique for detecting zeta potential. Zeta potential is a crucial component for targeted distribution since it also affects how nanoparticles interact with the skin.[78]

Fourier Transform Infrared Spectroscopy (FTIR) and Differential Scanning Calorimetry (DSC)

Fourier Transform Infrared Spectroscopy (FTIR) and Differential Scanning Calorimetry (DSC) are analytical methods for determining the chemical integrity and compatibility of constituents in nanoformulations. Functional groups and interactions between actives (such as retinol or niacinamide) and carriers (such as lipids or polymers) are detected by FTIR. It attests to the successful encapsulation of the active ingredient and ensures that it is neither broken down or chemically changed. DSC, on the other hand, examines thermal characteristics including crystallinity and melting points. It contributes to the stability of the nanoparticle system throughout manufacturing and storage. When creating long-lasting

cosmetics, where the active ingredients need to maintain their potency over time, these methods are especially helpful.[79]

Morphological analysis

Morphological analysis allows scientists to better understand the form and surface structure of nanoparticles, which determines how they distribute on the skin and how stable they are in a product. For instance, spherical particles typically provide better skin compatibility and a smoother application. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) are the most often used instruments for this investigation. While TEM uses extremely high magnification to reveal inside structures, SEM offers detailed surface images. To verify the homogeneity of nanoparticles such as liposomes or solid lipid nanoparticles utilized in anti-aging serums and sunscreens, these instruments are crucial in cosmetic research. Consistent function and appearance are guaranteed by an even and predictable morphology, which is essential for customer satisfaction.[80]

Thermal stability

For cosmetics that are shipped or stored in several climates, thermal stability is essential. The product may break down, separate, or lose its efficacy if the nanoparticles lose their structure at high temperatures. To examine how nanoparticles react to heat, methods such as Differential Scanning Calorimetry (DSC) and Thermo gravimetric Analysis (TGA) are employed. Weight loss as temperature rises is measured by TGA, which shows component evaporation or breakdown. To detect variations in melting or crystallization, DSC monitors heat flow. These techniques aid in ensuring that nanoformulations, like moisturizer gels or sunscreens, are stable without oxidizing, separating, or prematurely releasing active ingredients. This guarantees that the product will function well for the duration of its shelf life.[81]

ADVANTAGES OF NANOPARTICLES IN COSMETICS AND COSMECEUTICLES

- **Enhanced Skin Penetration & Improved Absorption**

Nanoparticles (1–100 nm) can penetrate skin layers more effectively, improving delivery of actives like vitamins and antioxidants.

- **Controlled and Targeted Delivery**

Nanocarriers enable sustained release and targeting.[82]

- **Greater Stability & Shelf Life**

Nanoparticles enhance formulation stability and shelf life.[83]

- **Improved Texture, Appearance & Feel**

Nanocosmetics provide smoother texture and improved finish.[84]

- **Transparent UV Protection (No White Cast)**

TiO_2 and ZnO NPs act as transparent UV filters.

- **High Surface-Area Enhances Reactivity**

Increased surface-to-volume ratio improves reactivity and interaction.

- **Better Suspension & Stability**

Nanoemulsions resist settling and improve stability.[85]

- **Hydration & Moisturizing Benefits**

Nanoemulsions improve occlusion and skin hydration.

- **Strong Anti-aging Potential**

Gold NPs, for example, offer anti-inflammatory and anti-aging benefits.[86]

DISADVANTAGES OF NANOPARTICLES IN COSMETICS AND COSMECEUTICLES

- **Oxidative stress & DNA damage** – High surface reactivity can generate reactive oxygen species (ROS), causing cellular damage and inflammation.
- **Deep tissue penetration** – Nanoparticles can cross the skin barrier, reach systemic circulation, and accumulate in vital organs.
- **Inhalation hazards** – Spray-based products may allow nanoparticles to enter the lungs, leading to irritation or increased carcinogenic risk.
- **Environmental impact** – Wastewater release can harm aquatic life, disrupt ecosystems, and cause bioaccumulation in the food chain.
- **Toxicological concerns** – Evidence from laboratory studies indicates potential genotoxic, neurotoxic, and reproductive effects.
- **Regulatory gaps** – Limited specific regulations and insufficient long-term safety data increase uncertainty about chronic exposure.

- **Occupational risks** – Workers in manufacturing and handling processes face potential health hazards from prolonged exposure.[1]

APPLICATIONS OF NANOPARTCLES IN COSMETICS AND COSMECEUTICALS

In cosmetic and cosmeceutical formulations, nanoparticles are frequently employed to improve the effectiveness and distribution of active chemicals. They provide better moisturization, anti-aging, and photoprotection because of their nanoscale size, which allows them to reach deeper layers of the skin. Common nanoparticle systems that offer stable and regulated release of delicate substances, such vitamins and UV filters, include liposomes, nanoemulsions, and solid lipid nanoparticles. Their use decreases the frequency of application and improves skin absorption. To evaluate their long-term safety and any toxicological effects, more research is necessary.[87]

List of Applications of Nanoparticles in Cosmetic and Cosmeceutical Preparations

1. Sunscreens.
2. Moisturizers.
3. Skin Whitening Products.
4. Hair Care Products (Shampoos, Conditioners, Serums).
5. Perfumes & Fragrance Gels.
6. Face Masks and Serums.
7. Anti-Aging Creams.
8. Acne Treatment Gels/Creams.
9. Makeup Products (Foundations, Creams).
10. Eye Creams & Serums.

1. Sunscreens

Titanium dioxide and zinc oxide nanoparticles in sunscreens provide invisible, broad-spectrum UV protection. Their nanoscale size ensures even skin coverage without leaving a white cast, while offering long-lasting stability under sunlight.[88]

2. Moisturizers

In moisturizers, lipid-based nanoparticles enhance hydration by forming an occlusive layer that reduces water loss while delivering vitamins and antioxidants deep into the skin. This improves skin smoothness, elasticity, and long-lasting moisturization without greasiness.[89]

3. Whitening products

Nano encapsulated arbutin in whitening creams ensures controlled release, deeper penetration, and prolonged brightening effects, reducing hyperpigmentation effectively without skin irritation.[90]

4. Hair care products

Hair Serum:-Silica nanoparticles in hair serums improve shine, reduce frizz, and protect hair from heat damage by forming a smooth, invisible coating on each strand, enhancing hair texture.[7]

Anti-dandruff Shampoo:-Zinc oxide nanoparticles in anti-dandruff shampoos enhance antifungal action against Malassezia, providing longer-lasting scalp protection while improving hair feel and cleanliness.[91]

5. Perfumes & Fragrance Gels

Polymer-based nanoparticles encapsulate aromatic molecules, protecting them from oxidation and enabling controlled, sustained release. This technology prolongs fragrance longevity, reduces volatility, and ensures a consistent scent profile throughout wear.[92]

6. Face Masks and Serums

In face masks and serums, nanoparticles act like tiny delivery agents, carrying vitamins, antioxidants, and hydrating ingredients deep into the skin. They boost absorption, enhance glow, and provide longer-lasting hydration, leaving skin refreshed, smooth, and revitalized after each use.[93]

7. Anti-Aging Creams

In anti-aging creams, nanoparticles deliver peptides, antioxidants, and retinoids deep into the skin, where they can boost collagen, smooth wrinkles, and improve elasticity. Their tiny size ensures better absorption, giving skin a firmer, more youthful appearance over time without feeling heavy.[93]

8. Acne Treatment Gels/Creams

In acne treatment gels and creams, nanoparticles—especially silver or zinc oxide—act like tiny warriors, targeting acne-causing bacteria deep within pores. They help calm inflammation, speed up healing, and reduce redness, all while being gentle on the skin and preventing further breakouts.[91]

9. Makeup Products (Foundations, Creams)

In foundations and creams, ultra-fine nanoparticles work like a beauty filter for your skin. They scatter light to blur pores and fine lines, making your complexion look smooth and even. Some also double up as sun protectors, giving you a radiant, lightweight finish that lasts.[7]

10. Eye Creams & Serums

In eye creams and serums, tiny lipid or polymer-based nanoparticles act like microscopic carriers, delivering antioxidants, vitamins, and peptides right where they're needed. They gently target the delicate under-eye skin, helping to smooth fine lines, fade dark circles, and reduce puffiness—without causing irritation.[93]

CONCLUSION

Nanotechnology is bringing big changes to cosmetics and skincare by making products more effective and enjoyable to use. Tiny nano-sized carriers help important ingredients reach deeper layers of the skin, leading to better hydration, stronger sun protection, anti-aging benefits, and improved acne care. They also give creams and lotions a smoother texture and lighter feel, which people appreciate. At the same time, there are concerns about safety, since nanoparticles can sometimes go too deep into the body, build up over time, or affect the environment. This is why proper safety checks and clear rules are so important. In the future, scientists are focusing on creating safe, eco-friendly materials so that nanotechnology can be trusted and used responsibly in beauty products.

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