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Nanoencapsulation in Cosmetics: Modern Strategies for Enhanced Delivery of Skincare Actives

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Abstract: Nanoencapsulation is as an effective method for active ingredients delivery within cosmetic science. The delivery of bioactive compounds (such as vitamins and peptides) via nanoscale carriers, increases the stability of the compound, protects one from environmental degradation, and enhances bio-availability (the usability of the active ingredient by a living organism). More importantly, nanoencapsulation allows for controlled and sustained release of active ingredients; thus, improving both the performance and efficacy of the cosmetic formulation - primarily by enhancing both skin penetration of the active ingredient and allowing for the targeting of the active ingredient to specific areas of the skin. This article reviews the major types of nanoencapsulation systems that have been used in the field of cosmetics (i.e., liposomes, niosomes, solid lipid nanoparticles, and nanostructured lipid carriers), along with information on newly emerging green nano-technological methods that can be used to develop sustainable formulations. Each type of nanoencapsulation system is critically reviewed with respect to structural characteristics, composition, preparation methods and the intended use within cosmetics. Ultimately, the article establishes that nanoencapsulation represents an exciting and innovative approach that will have a tremendous impact on developing new advanced cosmeceuticals.

Keywords: *Nano Carriers, Liposome, Noisome, SLN, NLC.*

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I. INTRODUCTION

Cosmetic innovation has seen an increasing demand for products characterized by safety, the environment and stability while utilizing advanced actives. Active ingredients, be they synthetic or plant-derived, play an important role in improving both the overall performance and attractiveness of cosmetic formulations. However, there are many challenges that formulators face when utilizing active ingredients such as vitamins, peptides, antioxidants, and fragrances; they are all sensitive to many factors including temperature, light, and exposure to oxygen and humidity. If active ingredient instability occurs, it will lead to degradation of those active ingredients resulting in decreased efficacy and shortened shelf life for finished products. In order to minimize these issues, a great deal of attention has been given to encapsulation technology and more particularly, nanoencapsulation. This form of encapsulation is accomplished by encapsulating an active(s) within a nanoscale protective carrier made up of polymers, lipids, proteins, or inorganic materials that protect the actives from the effects of external factors thereby providing resilience, stability and functionality to the actives. The two main forms of encapsulation are microencapsulation and nanoencapsulation; however, there are advantages associated with nanoencapsulation as compared to microencapsulation with respect to increased stability, controlled release and improved delivery efficiency for cosmetic applications.

Nanoencapsulation is an approach that involves encapsulating active compounds in extremely small delivery systems (nanometer-sized). Delivery systems that have a size range from 1 nm to 1000 nm, and are made from materials such as lipids, polymers or proteins, can enhance the functional characteristics of the active compound; these include increasing the efficiency with which the product can be dispersed (in formulations), improving the compounds' resistance to degradation and enhancing their absorption. Further, because these systems are at the nanoscale, they can provide controlled release or site-specific release of the active compound; this should increase the overall efficacy of the active ingredient.

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II. DIFFERENT MATERIALS USED FOR NANOCARRIERS

Different materials are used in the formation of nano-carriers, which can be categorised as follows-

- Lipid-based nanocarriers: Fatty acid nano-carriers are commonly studied methods for the delivery of products due to their compatibility with human biology, which helps them closely resemble natural membranes found in our bodies. They can also carry many classes of active compounds because of their malleability, providing stability and solubility to the various types of active compounds that can be incorporated. Lipid-based nano-carrier systems have the potential to help with the directed delivery of active ingredients into specific tissues or cells in the body. Lipid-based nano-carriers include liposomes, solid lipid nanoparticles (SLNPs), nanostructured lipid carriers (NLCs), and hybrid lipid/polymer systems.

- Polymer-based nanocarriers- Nanocarriers made from polymer represent a highly customizable class of delivery systems out of either synthetic or natural sources of polymers for delivery purposes. The adjustable structure allows control over multiple characteristics such as size, surface properties, and degradation, which in turn gives control over the release kinetics of the encapsulated bioactive. The nanocarrier systems have advantages such as: ease of chemical modification, high loading capacity, and potential for environmentally controlled-release (pH, temperature, enzymatic activity).

- Hybrid nanocarriers- Novel hybrid nanocarriers are a new type of delivery system that combines the structural and functional benefits of both lipid- and polymer-based systems. Hybrid systems are intended to address the limitations of single-component carriers, such as instability in lipid-based systems or limited biocompatibility in some polymers. For example, hybrid nanocarriers often can provide improved physical stability, loading capacity, and control of release compared to lipid or polymer systems. Due to these features, hybrid nanocarriers present advantages for a wide range of biomedical and cosmetic applications where effective, stable, controlled release of active agents is desired.

III. RELEASE MECHANISM

The nano-encapsulation mechanism describes the techniques by which active ingredients are incorporated, entrapped, or adsorbed within nanoscale carriers. Depending on the physical and chemical properties of both the carrier and the bioactive, different encapsulation techniques can be applied, each having distinct structural and release properties. These varied mechanisms not only impact the loading efficiency and protection of the bioactive, but are also a key determinant of the release behaviour, targeting potential and overall performance of the nanocarrier system.

Methods of preparation include physical methods such as high-pressure homogenization, chemical methods such as polymerisation, self-assembly, etc.

A. Types of Nanocarriers Used in Cosmetics-

➢ *Liposomal Systems:*

Liposomes are small-scale vesicular systems composed of one or more phospholipid bilayers that can hold both water-soluble and oil-soluble actives in their aqueous core or lipid membrane, respectively. This duality in structure makes them very appealing for enhancing the delivery efficiency and bioavailability of cosmetic materials. liposomes can be considered multifunctional and/or multipurpose delivery systems for use in cosmetics and pharmaceutical products.

➢ *Composition of Liposomes-*

The lipid composition of a liposome plays an important role and affects the rigidity, particle size and the stability of a liposomal system. Some of the commonly used lipids for the formation of liposomes are listed below-

- Natural lipids
- Synthetic lipids
- Steroid
- Surfactant

B. Classification of Liposomes-

➢ *Classification Based on Size and Number of Bilayers-*

Multilamellar vesicles (MLV) which have 2 or more bilayers, yield a 40% encapsulation efficiency. Large unilamellar vesicles (LUV), which have a large single bilayer and Small unilamellar vesicles (SUV) which have a single bilayer but are smaller in size Liposomes can also be classified based on their composition and application into Conventional liposomes, Charged liposomes, Stealth stabilised liposomes, Stimuli-responsive liposomes, etc.

➢ *Methods of Preparation of Liposomes-*

Thin film hydration method (Bangham method) is the most common method for preparation of liposomes. To create liposomes using the thin film hydration, lipids and hydrophobic materials are dissolved in organic solvents and then evaporated by reducing the pressure. This leaves a thin film of lipid on the bottom of the container. When this dry film comes in contact with water at temperatures above the lipid transition temperature, it will absorb water and swell until it separates from the surface of the container and forms vesicles. The efficiency of encapsulating an active ingredient into the vesicle via the thin film hydration method will depend on several variables, such as the rate of hydration and temperature, with slower rates of hydration usually resulting in better encapsulation of active ingredients.

C. Application of Liposomes in Cosmetics

- Solubility challenges- Due to the bifunctional structure of liposomes, they efficiently eliminate the solubility issue of active cosmetic ingredients, and they can entrap hydrophilic, lipophilic, and amphiphilic molecules based on solubility. Hydrophilic entities reside in the aqueous

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core of the liposome, and lipophilic or amphiphilic molecules reside in the lipid bilayer. This property improves stabilisation and reduces the loss of material during storage. Liposomes allow for the incorporation of hydrophobic materials in aqueous-based cosmetic products. Therefore, lipid-based liposomes are excellent vehicles for fat-soluble vitamins (A, D, E, and K). Vitamin E: Researchers have noted several benefits of vitamin E for skin, including anti-ageing, skin moisturization, and protective effects, which include skin protection against UV radiation.

- Improve penetration- For a molecule to readily penetrate the stratum corneum, it must have certain physicochemical properties, including an intermediate distribution coefficient, be low molecular weight, aqueous and oily soluble, and have a low melting point. Compared to traditional dosage forms, liposomes facilitate penetration into the stratum corneum more easily due to their small size and structural similarity to skin in their lipid composition.

- Reduced toxicity- A toxin can be defined as a substance that enters the body in excess of the body's requirement. We mitigate this with liposomes at the minimal effective dose. Furthermore, the controlled release of active ingredients from liposomes will keep the amount below a level that could be considered toxic. By leveraging liposomes, we lower the required dose and the potential overdose of the product, which could cause intoxication. A liposome can offer high efficacy and targeted delivery of ingredients.

- Improving penetration-To efficiently cross the stratum corneum, a molecule is required to possess specific physicochemical properties: intermediate distribution coefficient, weight, water-soluble and oil-soluble (generally). Also, fairly low melting point. Liposomes ease penetration into the stratum corneum layer compared to other traditional dosage forms, based on lipid composition and their size, nothing vastly different from skin itself.

IV. NIOSOMES

Niosomes are vesicles created primarily by non-ionic surfactants; these vesicles are usually stabilised by the addition of an additive such as cholesterol. Niosomes have the ability to form bilayer cell-like structures and can encapsulate both hydrophilic (water-soluble) and lipophilic (fat/lipid-soluble) materials. Due to the properties of niosomes (chemical stability, low toxicity, and low cost), they are a practical substitute for the use of liposomes in a variety of cosmetic and pharmaceutical delivery methods.

A. Composition of Niosomes-

There are 4 important components used in the formation of nisosmes. These are as follows-

- *Non-Ionic Surfactants:*

Non-ionic surfactants are the main component in the formation of niosomes. They are stable, compatible and less toxic when compared with other surfactant groups and have a high interfacial activity. The efficiency of entrapment depends heavily on the length of the surfactant's hydrophobic carbon chain and the size of its hydrophilic head group. Surfactants in the Tween series, which are composed of long alkyl tails and large hydrophilic moieties, will yield improved drug encapsulation of water-soluble compounds when used in a 1:1 molar ratio with cholesterol.

- *Cholesterol:*

It is a waxy steroid material that helps in decreasing the leakiness of the cell membrane by stabilising the membrane when incorporated into the bilayer. It increases the entrapment efficiency of the niosomes. Admission of cholesterol into the non-ionic surfactants gives hardness and proper adjustment to the bilayer, which is formed.

- *Hydration Medium:*

The hydration medium that is most commonly used for niosomes is a phosphate buffer of various pHs. The actual pH of the hydration medium will be determined by the solubility of the drug being encapsulated.

- *Classification of Niososmes*

Multilamellar vesicles (MLV): these vesicles are suitable for lipophilic compounds and have a size range of 0.5-10 µm diameter, Large unilamellar vesicles (LUV) which have a high ratio of aqueous phase to non-aqueous components, Small unilamellar vesicles (SUV) which are mostly prepared by sonication of multilamellar vesicles and have a size range of 10-100 nm.

B. Methods of Preparation of Niosomes-

- Hand shaking method (Thin film hydration technique): In this method, a round-bottom flask is used and the non-ionic surfactant and cholesterol are dissolved in a volatile organic solvent (like diethyl ether, chloroform, or methanol). The organic solvent is removed under room temperature (20°C) via rotary evaporator; after which, there will be a thin layer of solid mixture adhered to the flask wall. The dried surfactant film is hydrated by the aqueous phase with the drug at 50-60°C, and the multilamellar niosomes are created by this stage of the process.

- Ether injection method: In the ether injection technique, niosomes are created by injecting a surfactant solution solubilised in diethyl ether (volatile organic solvent) into warm water kept at a temperature of 60 °C. The surfactant blend in ether is introduced into an aqueous phase of the component using a 14-gauge needle. Single-layered vesicles are created by evaporation of ether (volatile organic solvent).

Other methods include Micro fluidisation, Reverse Phase Evaporation (REV), the Bubble method, etc.

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C. Application of Niosomes in Cosmetics

- Delivery of skin-care actives- Niosomes, which are vesicles made with non-ionic surfactant, have great promise for enhancing delivery, stability, and efficacy with natural bioactive compounds in cosmetics and pharmaceuticals. Niosomes enhance the penetration through the skin, as well as controlled release and antioxidant capacity with numerous compounds, due to the property of being able to encapsulate both lipophilic and hydrophilic materials. For example, niosomes enhanced skin permeation of ellagic acid (EA) vs. a solution of EA, and curcuminoid-loaded niosomes improved antioxidant effects, benefits related to skin tone, while achieving 83% encapsulation in manufacturing. Additionally, formulations based upon niosomes that contained resveratrol and curcumin improved skin protection. Importantly, a niosome containing blackberry extract achieved and maintained stability and antioxidant capacity due to polyphenols.

- Application in haircare- Nanotechnology, particularly niosomal delivery systems, has been utilised more and more in hair care cosmeceuticals to assist hair health, shine, and growth. Niosomes are considered novel non-greasy carriers that can deliver active ingredients into the strands and deep into hair follicle margins to help repair damage, bring back natural tone, and improve hair's overall appearance. Multilamellar niosomes made from cholesterol, poloxamer 407, and glyceryl monooleate were shown to effectively deliver hydrophobic agents into the deeply situated hair follicles and were shown to be useful for conditions of hair follicle and dermal disorders. Other niosome delivery systems, for example, pumpkin seed oil niosomes, which were prepared with cholesterol and tween 20 by the ether injection method, improved the penetration into hair roots, and in the process showed anti-inflammatory activity (IL-6 suppression) and inhibition of 5α-reductase; both are key mechanisms to help combat hair loss.

D. Solid Lipid Nano particle [SLN]:

Solid lipid nanoparticles (SLNs), which are colloidal drug delivery systems with a size range of 10-1000 nm, represent suitable alternatives to other colloidal systems, such as liposomes, emulsions, and polymeric nanoparticles. SLNs are referred to as safe carriers because they are made from biodegradable lipids (e.g. triglycerides, partial glycerides, waxes, steroids, and fatty acids) and other materials generally recognised as nontoxic. Their ability to encapsulate hydrophilic and lipophilic drugs with better properties than liposomes, to enable controlled drug release, and to be functionalized with appropriate ligands to specifically target tissue makes SLNs applicable through several routes of administration.

- *Composition of Solid Lipid Nanoparticle:*

SLNs (Solid Lipid Nanoparticles) are small particles made of lipids that stay solid at room temperature and body temperature. They offer a new way to deliver materials into the body compared to conventional delivery systems, as they can be made from materials that are biocompatible (can be used in the body without causing harm), and because they protect sensitive active ingredients (for example, some types of vitamins) from degradation.

SLNs can incorporate both hydrophilic (water-soluble) and lipophilic (fat-soluble) materials into them. The sustained release capability of these materials, as well as the improved stability of formulations containing these materials, is an advantage of SLNs.

- *Classification of SLN-*

- Type 1 consists of the drug dispersed in the lipid core in the homogeneous matrix of solid solutions.
- Type 2- consists of a drug-free lipid core and an external solid shell made up of lipid and drug - drug-enriched shell, and the lipid core is made using no drug.
- Type 3- is made when the solid-like lipid matrix takes up the drug at a concentration near its saturation solubility in the lipid, where it precipitates and takes up some of the limitations from making coverage with extended lipid layers.

E. Method of preparation-

High-pressure homogeniser is the most common technique used to prepare SLN's. HPH drives the liquid through a narrow space (a few microns) and at high pressures (100–2,000 bar). The fluid travels with high velocity over a short distance. Even the homogenization of a high-concentration lipid could be converted into a nanodispersion. Both hot and cold homogenization techniques are used in the preparation of SLN. The key difference is that hot homogenization uses molten lipid, which gives finer and more uniform SLNs, and cold homogenization uses solidified lipid, which gives less uniform SLNs.

Other preparation methods include sonification, supercritical fluid, spray drying, microemulsion, etc.

F. Application of SLNs in Cosmetics-

- Sun protection-Solid Lipid Nanoparticles (SLNs) have an inherent function as physical UV blockers, making them excellent carriers for sunscreen formulations and minimising side effects. Wissing and Müller developed SLNs loaded with tocopherol acetate (vitamin E) for superior sunscreen functionality and prevention of chemical degradation. The SLN-based gels that were created exhibited good stability, small particle size, and a strong ability to block UV, nearly double the ability to block UV as an emulsion created with the same amount of lipid.

- Enhanced moisturization- Solid Lipid Nanoparticles (SLNs) establish a shielding, occlusive layer on the skin surface, preventing water loss, increasing skin moisture, and enhancing skin quality—terms often used interchangeably—or quality, which is especially advantageous for dermatitis and/or eczema. Due to their minuscule size relative to particles in macroemulsions and the same lipid concentration in Nanostructured Lipid

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Carriers (NLCs), SLNs accomplish superior occlusion in comparison.

- Anti-tyrosenase activity- The inclusion of chemically stable active ingredients into the SLN matrix can protect against decomposition. Dingler and colleagues prepared vitamin E-loaded SLNs (vitamin E-SLN) by high-pressure homogenization. These SLNs retain their physical stability in aqueous dispersions and can also be stabilised in a topical cream, confirmed through photon correlation spectroscopy and differential scanning calorimetry. The ultrafine particles created an adhesive film on the skin, leading to an occlusive effect. This occlusion facilitates deeper penetration of the active ingredients, including vitamin E, into the skin, confirmed by stripping tests. SLNs also exhibited a pigment effect, covering up undesirable colours that enhanced overall aesthetic acceptance by consumers. Thus, making SLNs is a versatile carrier for improving skin care formulations.

G. Nanostructured Lipid Carriers [NLC]:

Nanostructured lipid carriers (NLCs) are an innovative lipid-based delivery system designed to remedy the drawbacks associated with solid lipid nanoparticles (SLNs). NLCs are made by mixing solid and liquid lipids, leading to poor internal structure and therefore providing more room for active drug substances. Due to their ability to create a bigger space for active ingredients, the loading capacity of NLCs is enhanced, which leads to a reduced likelihood of drug loss during storage compared with SLNs. Consequently, NLCs have improved stability and greater flexibility in formulation.

H. Composition of Nanostructured Lipid Carriers-

Nanostructured lipid carriers (NLC) are made of a mixture of solid and liquid lipids, with the amount of liquid lipid adjusted so that the overall solid system remains solid both at room and body temperatures. The addition of liquid lipids to the solid lipid framework creates structural imperfections but allows for retention of the overall solid state of the carrier.

To maintain stability of the nanosystem, either one or a combination of surfactants will typically be used at a concentration of between 1.5 and 5% (w/v). Upon contact with the surface of the NLC core, the surfactant will adsorb to the surface of the core and form a protective interfacial layer to minimise particle aggregation. In conjunction with the lipids, the surfactants used in the formulation are important in determining the particle size, degree of crystallinity and other physicochemical properties of the formulation. Additionally, surfactant characteristics (type and number) significantly impact system stability, with combinations of surfactants generally providing smaller particle size, lower crystallinity and improved stability compared with formulations containing an isolated surfactant.

I. Types of NLC-

- Disordered / Imperfect type- Nanostructured lipid carriers' first structural type is known as the imperfect or disordered matrix structure, which is created by blending both solid and liquid lipids. In this type of system, when liquid lipids are blended with solid lipids, the orderly crystalline structure of the solid lipids is disrupted, which creates structural irregularities (i.e., imperfections) in the matrix. To create additional matrix imperfections and maximise the loading capacity of drugs, small quantities of liquid lipids (i.e., oils) that are chemically different from the solid lipids are used to form an imperfectly disordered matrix.

- Amorphous/ non-crystalline matrix type- The second type of structure for nanostructured lipid carriers is through the use of an amorphous (non-crystalline) lipid matrix. This allows for the creation of an amorphous (non-crystalline), solid matrix that does not display any long-range ordering associated with conventional crystalline materials. Because there is no defined crystalline structure, the potential for drug expulsion due to lipid recrystallisation during both cooling and storage is greatly minimised. This can include a combination of selected oils, such as medium-chain triglycerides, e.g. Miglyol® 812, isopropyl myristate or hydroxy-octacosanylhydroxystearate, with solid lipids to give rise to an amorphous, but solid, matrix.

- Multiple type- The use of a higher liquid lipid ratio than with other NLCs defines this type of structure. Many lipophilic drugs have higher solubility in liquid fats versus solid fats, and therefore, more liquid fat means more drug can be accommodated in the matrix. However, during the cooling phase after homogenization and subsequent crystallisation, the solubility of the drug in the lipid phase can decrease because the drug will exceed its solubility limit in the recrystallising lipid matrix. When this occurs, continued decreases in solubility will lead to the drug being expelled from the nanoparticles. To overcome this limitation, increasing the amount of liquid lipid within a formulation creates oily nanocompartments within the solid matrix. The liquid regions provide areas for high drug solubility, while the solid matrix provides structural integrity and prevents leakage from the nanocompartments.

V. METHODS OF PREPARATION

Hot high-pressure homogenization- High-pressure homogenization generates nanostructured lipid carriers through top-down processing by applying high mechanical pressure to allow for droplet size reduction of coarse microemulsion droplets to the nanometer (10^-9 m) range. To start, solid lipid is melted; then, liquid lipid is added to achieve a homogeneous heated lipid phase. The surfactant, with or without a cosurfactant, is dissolved in water to create the aqueous phase. The lipids and surfactant/aqueous phase are mixed while maintaining both phases at the same temperature, resulting in a hot microemulsion. The hot microemulsion is then reduced in droplet size/number via

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high-pressure homogenization. The number of homogenization cycles can be based on the targeted size and size distribution of the final product. When the nanoemulsion is cooled to room temperature, NLCs are formed by the recrystallisation of the lipid. NLCs with average particle sizes < 100 nm can be produced with the use of intermediate pressure (~ 1000 bar) for an extended time period. However, this method may not be suitable for thermolabile drugs or materials that are heat sensitive.

Other methods of preparation include cold high-pressure homogenization technique, high-speed/shear homogenization technique, Microemulsion, etc.

➢ *Application of NLC's in cosmetics-*

- Skin Hydration/Electricity- Solid lipid nanoparticles (lidocane) in their different formulations (solid lipid nanoparticles and nanostructured lipid carriers) have been shown to help with skin hydration by reducing transepidermal water loss (TEWL) by having occlusion properties, which helps create a barrier to reduce water loss from the skin surface and improves the amount of moisture retained and the overall function of the skin barrier. Using an in vivo (human test) study on an oil-in-water (o/w) cream containing solid lipid nanoparticle formulations, researchers found that there was a significant difference in the level of hydration (measured over 28 days) between this formulation and a standard (non- lidocane) o/w cream. Likewise, researchers found that using a cream containing nanostructured lipid carriers (NLCs) produced a statistically significant difference in skin hydration (moisture) level when compared to a standard (non-lidocane) cream over the same 28-day study. Thus, these types of lipid nanoparticle systems have been shown to provide enhanced occlusion and moisturization for topical applications.
- Protection from UV Radiation- Lipid nanoparticles, through their ability to attenuate and reflect UV radiation, can be used as a physical blocker of UV light. When combined with organic UV filters (e.g., 2-hydroxy-4-methoxybenzophenone) (benzophenone derivative), lipid nanoparticles increase the overall photoprotective activity of the formulation. This has the effect of decreasing the required concentration of organic UV absorbers, and still providing the same level of sun protection as if the same level of organic UV absorbers had been used. Research indicates that the use of lipid nanoparticles in a formulation can reduce the amount of organic UV-absorbing agents required by as much as 50% while providing equivalent sun protection to the standard use of emulsions. Additionally, the addition of inorganic UV filters (e.g., titanium dioxide) into nanostructured lipid carriers (NLCs) has been shown to significantly increase the SPF, with increases of up to approximately 50%. The enhanced UV-blocking capability of lipid nanoparticle-based sunscreens is contributed to by the improved dispersion, uniform film formation, and improved adherence of the sunscreen to the skin.

Table 1: Comparative Overview of Lipid-Based Nanocarriers Used in Cosmetics

Parameter	Liposomes	Niosomes	SLNs	NLCs
Size Range	10 nm – 5 µm	10 – 1000 nm	50 – 1000 nm	50 – 500 nm
Primary Components	Phospholipids, cholesterol	Non-ionic surfactants, cholestero	Solid lipids (waxes, triglycerides)	Solid + liquid lipids
Encapsulation Type	Hydrophilic, lipophilic, amphiphilic	Hydrophilic & lipophilic	Hydrophilic & lipophilic	Hydrophilic & lipophilic
Drug Loading Capacity	Moderate	Moderate	Low–Moderate	High
Physical Stability	Low–Moderate	Moderate–High	High	High
Skin Penetration	Good	Good	Moderate	Good–Excellent
Controlled Release	Yes	Yes	Yes	Yes (improved over SLNs)
Occlusive Effect	Low	Low	High	High
Preparation Complexity	Moderate	Moderate	Moderate–High	Moderate–High
Cost of Raw Materials	Moderate–High	Low–Moderate	Low–Moderate	Low–Moderate
Biocompatibility	Excellent	Good	Good	Good
Key Cosmetic Applications	Anti-ageing, vitamins, skin hydration	Skin actives, hair care	Sunscreen, moisturization, pigmentation	UV protection, hydration, anti-ageing

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- *Green Synthesis Approaches in Nanoencapsulation for Cosmetic Applications:*

Green synthesis is becoming an exciting and more sustainable way to create nanoencapsulation systems for cosmetic formulations. Instead of relying on harsh chemicals and energy-intensive processes, this approach uses plant-derived compounds that naturally act as reducing, stabilising, and capping agents. These include phytochemicals like polyphenols, flavonoids, terpenoids, and alkaloids, which help form nanoparticles in a controlled way while keeping the process environmentally friendly.

Building on this, recent research highlights the growing role of greener nanobiopolymers—materials derived from renewable sources like plants, microorganisms, and even agricultural waste. These biopolymers, such as cellulose, chitosan, and starch, are not only biodegradable and biocompatible but also highly adaptable at the nanoscale. Their large surface area, functional groups, and ability to form nanocomposites make them ideal candidates for nanoencapsulation systems. In many ways, they act like nature-designed scaffolds, supporting and enhancing the performance of nanoparticles while reducing environmental impact.

One of the most interesting cosmetic applications is in sunscreens. Nanoparticles like zinc oxide (ZnO) and titanium dioxide (TiO_2), when synthesised using plant extracts, can effectively protect against UV radiation while remaining transparent on the skin. This means you get the protection without the white cast. On top of that, the plant-derived coatings often add antioxidant benefits, giving an extra layer of skin defence.

Beyond UV filters, these green-synthesised nanoparticles are also being explored as delivery systems for active ingredients. They can improve how well compounds like curcumin, quercetin, and essential oils penetrate the skin, release over time, and remain stable in formulations. Biopolymer-based nanocarriers, especially those using materials like chitosan or nanocellulose, further enhance this by providing structural stability, controlled release, and better interaction with biological systems.

What makes these systems particularly powerful is the chemistry at their surface. Functional groups like hydroxyl, carboxyl, and amine groups from both phytochemicals and biopolymers interact with nanoparticles, preventing aggregation and adding biological activity. This creates multifunctional systems that are not just carriers, but active contributors to skin health.

However, there are still challenges to solve. One major issue is consistency. Plant extracts and natural biopolymers can vary depending on their source, environmental conditions, and processing methods, making it difficult to achieve reproducible results. In addition, some biopolymers may have limitations like lower mechanical strength or stability, which need to be improved for large-scale applications.

To address this, researchers are increasingly using advanced analytical tools like LC-MS/MS, FTIR, and NMR to better understand and standardise these materials. At the same time, AI-based approaches such as machine learning are helping predict how synthesis conditions influence nanoparticle properties, making the process more reliable and scalable.

Overall, the combination of green synthesis and nano biopolymers brings together sustainability, functionality, and innovation. With continued refinement, it offers a promising pathway toward cosmetic formulations that are not only effective but also environmentally responsible.

VI. CONCLUSION

Nanoencapsulation is a powerful and effective method to guarantee that sensitive active ingredients find their way into cosmetic formulations. In addition to providing significant advantages in terms of stability or increased penetration of active material, nanotechnology has also facilitated the development of control release formulations. The selection of an appropriate encapsulation method for the actives can be determined by both the physics/chemical nature of the active and its desired release profile (time to reach peak concentration) and where you would like the active material delivered (bath, shower, floor, etc.). Nanostructured lipid carriers and liposomes have demonstrated great potential as they demonstrate superior compatibility with living organisms; they accommodate both hydrophilic and lipophylic actives; and, they have demonstrated great penetration capability into human skin.

Although significant improvements have been made, many major deficiencies still exist. There are still minimal standardized in-vivo testing procedures for cosmetic actives that are encapsulated; therefore, the majority of efficacy studies that have been undertaken have been done through in-vitro studies, which do not always reflect the complex nature of skin conditions as they occur in real life. In addition, scaling-up of encapsulated cosmetic product systems from the laboratory to commercial production presents additional challenges as most of the encapsulation techniques developed at the laboratory scale require highly controlled conditions during the encapsulation process when subsequently implemented at an industrial scale, leading to potential loss of encapsulation efficiency and/or consistency in the product.

Using plant-based, eco-friendly materials as components or synthesis agents for building walls is a new way to address sustainability issues related to traditional encapsulation methods. Future studies should continue to design environmentally friendly and scalable encapsulation systems, while developing solid and compatible testing and regulatory methods.

In summary, nanoencapsulation has tremendous potential as a vehicle for delivery in the field of cosmetics. Its ability to provide targeted and controlled release, to increase transdermal penetration, and to stabilize unstable active ingredients makes it one of the most useful tools for today's

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cosmetic formulators. Research and regulation must be linked closer together to fully exploit its scientific and commercial potential.

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