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Natural-Based Cosmetics: Trends, Challenges, and Scientific Innovations

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ABSTRACT
The increasing demand for natural-based cosmetics has reshaped the beauty industry, driven by consumers seeking sustainable, eco-friendly, and ethically sourced products. This review explores the current trends, formulation challenges, and scientific innovations in the development of natural-based cosmetics. Key natural ingredients, such as plant extracts, oils, and waxes, are discussed in terms of their benefits, limitations, and formulation complexities. The article also addresses significant hurdles, including stability issues, the need for natural preservation systems, and consumer expectations for product efficacy and sensory experience. Advances in green chemistry, biotechnology, and encapsulation technologies are highlighted as critical drivers for overcoming these challenges. Innovations such as plant stem cells, microbial fermentation, and nanoemulsions have enhanced the performance and stability of natural actives. Looking ahead, the future of natural-based cosmetics lies in further integration of green biotechnologies to create more effective and sustainable bioactive ingredients. By embracing these innovations, the beauty industry is poised to meet consumer demands for high-performance products that are not only natural but also sustainable and ethically transparent.
Key words: natural-based cosmetics, sustainable, formulation, biotechnology

INTRODUCTION
In recent years, there has been a significant shift in consumer preferences towards natural-based products, with the cosmetic industry experiencing an increasing demand for formulations that prioritize natural ingredients[1]. As consumers become more conscious of environmental sustainability, health implications, and ethical considerations, the natural-based cosmetics market has seen rapid growth. This global trend reflects a desire for transparency and trust in the beauty products used in daily routines.

Natural-based cosmetics, which rely on plant-derived ingredients, essential oils, natural preservatives, and other bioactive compounds, are marketed as safer and environmentally friendly alternatives to conventional cosmetics. However, the transition from synthetic to natural formulations poses several challenges, both for formulators and regulatory bodies[2]. Ensuring product stability, maintaining the efficacy of natural actives, and addressing safety concerns such as allergenicity are just a few of the hurdles facing the industry. Moreover, the rapid evolution of green chemistry, biotechnology, and sustainable practices has paved the way for scientific innovations in the development of natural-based cosmetics. These advancements not only aim to improve product performance but also address growing concerns around environmental impact, ethical sourcing, and regulatory compliance. The beauty industry is now exploring cutting-edge techniques, such as biofermentation, plant stem cell technology, and nano-encapsulation, to optimize the use of natural ingredients while minimizing resource depletion. Recent advancements in nanotechnology have opened new avenues in cosmeceutical formulations, offering enhanced stability and delivery of bioactive ingredients. Additionally, the push for sustainable formulation practices has led to a widespread adoption of green chemistry principles in the cosmetics industry. This review explores the current trends driving the demand for natural-based cosmetics, the formulation challenges faced by manufacturers, and the latest scientific innovations in sustainable beauty. By providing a comprehensive overview of the evolving landscape of natural-based cosmetics, this article aims to highlight the opportunities and barriers to further growth in this dynamic sector of the cosmetic industry.

KEY NATURAL INGREDIENTS IN COSMETICS

Natural ingredients have long been valued for their multifunctional benefits in cosmetic formulations. In recent years, their use has grown exponentially as consumers demand more natural and sustainable alternatives to synthetic chemicals. The cosmetic industry has responded by incorporating a wide array of plant-based extracts, oils, and other natural ingredients, each offering unique properties and benefits.

1. Plant Extracts

Plant extracts are among the most commonly used natural ingredients in cosmetics, prized for their bioactive compounds, antioxidants, and anti-inflammatory properties. Ingredients such as aloe vera, green tea, chamomile, and rosehip (Table 1) are often used in skincare formulations for their soothing and rejuvenating effects[3]. Aloe vera, for example, is well-known for its hydration and anti-inflammatory properties, making it a staple in moisturizers, sunscreens, and after-sun products[4]. Similarly, green tea extract is packed with potent catechins like epigallocatechin gallate (EGCG), which provide strong antioxidant and anti-inflammatory effects, making it a popular choice in anti-aging and anti-acne formulations[5]. Chamomile extract, rich in bisabolol and apigenin, has long been used for its anti-irritant, anti-inflammatory, and antioxidant properties, making it ideal for sensitive skin and products aimed at reducing redness [6]. Lastly, rosehip extract, high in vitamins A and C, along with essential fatty acids, is prized for its ability to brighten skin, promote cell regeneration, and reduce the appearance of scars and hyperpigmentation[7].

However, the variability in plant extracts poses significant challenges for formulators. The chemical composition of an extract can fluctuates based on factors such as plant species, harvest time, and extraction methods, leading to inconsistencies in product performance[8]. Plant species is a primary determinant, as different species of the same plant can yield extracts with different levels of bioactive compounds. The geographical location where the plant is grown also plays a critical role, as climate, soil conditions, and altitude affect the concentration of active components in the plant[9]. In addition, the seasonal harvest time can influence the potency and efficacy of plant extracts[10]. For instance, plants harvested during specific growth stages may have higher concentrations of certain beneficial compounds. Moreover, the method used to extract the plant's bioactives also has a substantial impact on the quality of the extract. Traditional methods such as solvent extraction may extract a wide range of compounds, but can also leave behind unwanted residues, while steam distillation is often used for essential oils but may degrade heat-sensitive compounds. Newer techniques like supercritical CO_2 extraction are gaining attention for their ability to extract plant bioactives with high precision and without the use of harmful solvents. Supercritical CO_2 extraction involves using carbon dioxide in a supercritical state to selectively extract compounds from plants, yielding purer and more potent extracts while maintaining the integrity of heat-sensitive phytochemicals[11]. This method also allows for the customization of extract profiles by controlling temperature and pressure, enabling formulators to optimize the desired bioactives for cosmetic applications. Additionally, advancements in fractionation and standardization processes are helping formulators to overcome the variability inherent in plant extracts, ensuring consistency across different batches and improving the reliability of these ingredients in cosmetic formulations.

Despite the technological advancements, safety concerns remain a consideration when using plant extracts. Many plants naturally contain allergens, such as linalool or limonene, which are common sensitizing agents found in essential oils[12]. This can lead to potential skin reactions, especially for individuals with sensitive or compromised skin barriers. Moreover, the potential for contamination with pesticides or heavy metals during cultivation adds another layer of complexity. As a result, formulators must conduct rigorous safety assessments, including allergenicity and irritation testing, to ensure that the plant extracts used are safe and suitable for cosmetic applications.

2. Oils and Butters

Natural oils and butters, such as argan oil, coconut oil, jojoba oil, and shea butter, play a critical role in cosmetics due to their moisturizing and emollient properties. Argan oil, rich in essential fatty acids and vitamin E, is widely used in hair and skincare products for its ability to restore moisture and enhance skin elasticity[13]. Similarly, shea butter is favored for its excellent emollient properties, making it an effective ingredient in products designed to treat dry skin.

The use of natural oils and butters in formulations can pose formulation challenges due to their susceptibility to oxidation, which can lead to product instability and reduced shelf life. Furthermore, the sensory properties of oils, such as their greasy feel, must be carefully managed to meet consumer expectations for lightweight and fast-absorbing products. To overcome these challenges, formulators are increasingly turning to innovative methods like oil encapsulation and the use of natural antioxidants (e.g., vitamin E) to enhance the stability and performance of natural oils in cosmetics[14]. Velmurugan et al. investigated the encapsulation of essential oils in biocompatible nanoparticles, which improves the stability, controlled release, and bioavailability of volatile compounds in oils like lavender[15] and peppermint. Encapsulation is particularly beneficial for maintaining the antimicrobial and anti-inflammatory effects of essential oils in cosmetic formulations[16].

3. Waxes and Emollients

Waxes, such as beeswax and carnauba wax, are essential components in natural cosmetics, providing structure, texture, and water-resistant properties to formulations. These natural waxes are often used in lipsticks, balms, and mascaras to give products their desired consistency and durability. Unlike synthetic waxes, natural waxes are biodegradable, aligning with the sustainability goals of many cosmetic brands.

One of the key challenges with natural waxes is maintaining consistency in product texture across different batches. Variations in the composition of natural waxes can affect their melting points and functionality in formulations. Additionally, the shift toward vegan cosmetics has led formulators to seek plant-based alternatives to traditional animal-derived ingredients like beeswax. Carnauba wax, derived from the leaves of the carnauba palm, has gained popularity as a vegan-friendly alternative, though it can be harder to work with due to its higher melting point[17].

4. Essential Oils

Essential oils, derived from various parts of plants such as leaves, flowers, bark, and roots, have been used for centuries in traditional medicine and cosmetics for their diverse therapeutic benefits. In modern cosmetic formulations, essential oils such as lavender, tea tree, and peppermint are highly prized not only for their natural fragrance but also for their functional properties, including antimicrobial, anti-inflammatory, and antioxidant effects [18]. These oils contain a complex mixture of volatile compounds such as terpenes, aldehydes, and phenols, which contribute to their distinctive aromas and biological activities.

For example, lavender oil, rich in compounds such as linalool and linalyl acetate[19], is commonly used in skincare formulations for its calming and soothing properties. It has been shown to help reduce redness, irritation, and inflammation, making it a popular choice in products aimed at sensitive skin or post-sun care. Tea tree oil, one of the most widely researched essential oils, contains terpinen-4-ol[20], which exhibits strong antibacterial, antifungal, and antiviral activity. Due to these properties, tea tree oil is frequently incorporated into acne treatments[21], scalp care products, and anti-dandruff shampoos[22], where it helps to combat Propionibacterium acnes and other pathogens responsible for skin and scalp issues. Additionally, peppermint oil, with its high menthol content, is valued for its cooling sensation[23], ability to soothe irritation, and potential to stimulate blood circulation[24], making it ideal for use in products designed to refresh the skin, such as body lotions and foot creams.

Despite these notable benefits, the use of essential oils in cosmetic formulations requires careful consideration due to their high concentration of active compounds. Essential oils are highly potent and can cause adverse reactions if not properly diluted. Many essential oils, particularly those with a high concentration of terpenes or phenolic compounds, can be irritating or sensitizing to the skin[25], especially in individuals with sensitive skin or allergies. For instance, improper use of oils like tea tree or cinnamon can lead to contact dermatitis or phototoxic reactions in some users. To minimize the risk of irritation, essential oils are typically diluted in carrier oils [26](e.g., jojoba, argan, or almond oil) or incorporated into cosmetic formulations at concentrations that do not exceed the dermatologically safe thresholds.

Moreover, the growing preference for fragrance-free and hypoallergenic products among consumers has led to increased scrutiny over the use of essential oils in cosmetics. While many consumers appreciate the natural fragrance of essential oils, others are concerned about the potential for fragrance allergens, particularly as certain compounds in essential oils—such as limonene, linalool, and citral—are known to be common sensitizers that can trigger allergic reactions in sensitive individuals. The European Union's Scientific Committee on Consumer Safety (SCCS) has identified several of these compounds as potential allergens, requiring formulators to label them when present at certain concentrations in cosmetic products.

In response to these concerns, formulators face the challenge of balancing the functional benefits of essential oils with the need to mitigate potential skin sensitization and allergenic reactions. This has led to a trend toward low-concentration use of essential oils or even the substitution of essential oils with fragrance-free botanical extracts that provide similar benefits without the same risk of irritation. For example, instead of using high concentrations of peppermint oil for its cooling effect, formulators may opt for menthol derivatives in lower doses to achieve the same sensory benefit with less risk of irritation.

In addition, the purity and quality of essential oils can vary widely depending on factors such as the plant species, growing conditions, and extraction methods. Steam distillation and cold-press extraction are the most common techniques used to obtain essential oils, but these methods must be carefully controlled to prevent degradation of the oil's volatile compounds. Contaminants, adulteration, or improper storage of essential oils can further impact their stability and safety, necessitating rigorous quality control measures in the production process.

5. Natural Preservatives

Preservation is a critical aspect of cosmetic formulation, particularly for products containing water, which are prone to microbial growth. While synthetic preservatives like parabens and formaldehyde donors have been widely used to ensure product safety, consumer concerns over potential health risks have led to a surge in demand for natural preservatives [27]. Tocopherols (vitamin E), grapefruit seed extract, and rosemary extract are examples of natural ingredients with preservative properties.

However, natural preservatives tend to be less effective than their synthetic counterparts, often requiring higher concentrations or a combination of preservatives to achieve the same level of microbial protection. This can create formulation challenges, as higher concentrations of natural preservatives may alter product texture, color, or fragrance. Additionally, the regulatory acceptance of natural preservatives varies by region, complicating global product distribution. Despite these hurdles, ongoing research into novel natural preservation systems continues to show promise for the future of safe and effective natural-based cosmetics.

Table 1. Plants that can be used as basic skincare ingredients based on the skincare category. Reproduced with permission from ref. [3]; copyright 2023. Borneo Press.

Category	Plant	Part	Phytochemical compounds	Experimental outcomes	Ref
Cleanser	Aloe vera (Aloe barbadensis Miller)	Leaf	Saponin glycosides, amino acids (isoleucine, leucine)	0.15 g facial cleansing formula containing 0.5% aloe vera could effectively clean 0.02 g foundation stains	28
	Bitter melon (Momordica charantia)	Leaf	Saponin and oil	Bitter melon ethanol extract provided good effectiveness as a cleanser through mechanisms such as	29

				surface tension reduction, heavy metal absorption, and antibacterial	
	Tea seed oil (Camellia Oleifera Abel)	Seed	Fatty acids (linoleic acids, aplmitic acids, oleic acids, and stearic acids)	The formula of tea seed oil remover provided better cleansing efficacy in cleaning foundation stains and eyeliner compared to benchmark products	[30]
Toner	Green tea (Camellia sinensis)	Leaf	Polyphenols	Anti-sebum efficacy of the 7$ green tea extract toner formula (31.57%) was better than the base (5%) within 28 days)	[8]
	Guava (Psidium guajava L.)	Leaf	Tannins	Anti-sebum efficacy of the 6% guava extract toner formula (forehad 13.10%; nose 21.43%) was better than base within 28 days and more than the	[31]

				requirement (10%)	
	Malaka (Phyllantus emblica L.)	Fruit	Tannins	Anti-sebum efficacy of the 3% Malaka toner formula (23.5%) was better than the base (12%) within 3 hours after application	32
Moisturizer	Aloe vera (Aloe barbadensis Miller)	Leaf	Amino acids, polysaccharides (acemannan, glucomannan)	10% aloe vera cream formula was significant: decreasing trans-epidermal water loss (TEWL), increasing water content of the stratum corneum, as well as increasing elasticity and firmness of the skin	4
	Pegagan (Centella asiatica L. Urban)	Herb	Triteroene saponins (centelloid), sugars (glucose, rhamnose), polyphenols, terpene (Asiatic acid, madecassic acid, astiaticoside)	5% pegagan cream formula was significant: decreasing TEWL, increasing skin hydration	33
	Rose (Rosa chinensis & Rosa rugosa)	Flower	Polysacharides	Rose extract was significant: increasing aquaporine-3	34

				expression = increasing skin hydration	
	Kelor (Moringa oleifera)	Leaf	Ascorbic acids (vitamin C), phenolic acids (gallic, ellagic, chlorogenic,ferulic), flavonoids (quercetin, kaemferol, rutin), amino acids (histidine, serine, arginine, glycine, threonine, alanine), vit A, vit B, beta-carrotene	3% kelor cream formula was significant: decreasing TEWL, increasing skin hydration	[35]
	Prickly pears (Opuntia ficus-indica (L.) Mill)	Cladode	Polysaccharides (rhamnose, galacturonic acid, arabinose, glucose)	1% and 3% opuntia cream formula were significant: decreasing TEWL, increasing skin hydration up to 4 hours after application	[36,37]
	Papaya (Carica papaya)	Fruit	Polysaccharide (papain)	Papaya polysaccharides had significantly stronger moisture absorption and retention capabilities than glycerol and hyaluronic acid	[38]

	Hibiscus (Hibiscus rosa-sinensis L.)	Leaf	Polysaccharides (uronic acid, glucuronic acid, galacturonic acid)	The moisture efficacy of mucilage hibiscus extract 0.2% was better than hyaluronic acid	39
	Dendrobium orchid (dendrobium spp.)	Flower	Uronic acid	Dendrobium extract was significant: increasing skin hydration	40
	Prospis juliflora	Leaf	α-glucan and phenolic compound	Propis julifora granule formula was significat: decreasing TEWL, increasing skin hydration	41
	Argan oil (Argania spinosa L.)	Seeds	Triglyceride	3% argan oil serum formula was significant: increasing moisture content of 19.67% after 15 min application	42
Sun protection	Olive (Olea europaea L.)	Leaf	Phenolic compounds (oleuropin; luteolin-7-O-glucoside; apigenin-7-O-glucoside; verbascoside)	Sun protection factor (SPF) value reached 56 at extract concentration 3-5%	43
	Sambiloto (Andrographis paniculata L. Ness)	Leaf	Flavonoid (quercetin-3-glycosides)	SPF value 15.42-28.41 at extract	44

				concentration 12-20 μg/mL	
	Rambutan (Nephelium lappaceum L.)	Peel	Flavonoids (apigenin, quercetin, anthocyanins, cathechin); tannins (ellagic tannins, corilagin, geraniin)	Base SPF value increases 2.5 times (26.3) at 1% extract addition	45
	Coconut (Cocos nucifera L.)	Husk fiber	Phenolic compounds (quercetin, cathechin, epicathechin, vanillic acid, caffeic acid)	SPF value 15.94 in 20% coconut husk fiber extract cream formula	46
	Guava (Psidium guajava L.)	Fruit	Flavonoids (quercetin, myricetin, catechin) and tannins	SPF value of synthetic photoprotective agent EHM increases 134% (8.1 to 18.9) with the addition of 7.5% guava extract	47
	Green tea (Camellia sinensis L.)	Leaf	Polyphenols	SPF value 14.59 at 10% extract concentration	48

FORMULATION CHALLENGES

The formulation of natural-based cosmetics presents a unique set of challenges that distinguish it from conventional cosmetics, primarily due to the nature of the ingredients, regulatory requirements, and consumer expectations. As consumers increasingly demand products that are both natural and effective, formulators must navigate the complexities of ingredient variability, stability issues, and preservation without compromising on performance or safety. Below are some of the key formulation challenges that the cosmetic industry faces when working with natural-based ingredients.

1. Stability and Shelf Life

One of the most significant challenges in formulating natural-based cosmetics is ensuring product stability. Natural ingredients are often more prone to degradation compared to synthetic counterparts, which can affect the product's appearance, texture, efficacy, and safety over time[49]. For instance, plant oils and extracts, commonly used in natural cosmetics, are susceptible to oxidation, leading to rancidity and loss of functional properties. The absence of synthetic stabilizers often exacerbates this issue.

Formulators must employ various strategies to improve stability, such as using natural antioxidants like tocopherol (vitamin E) or rosemary extract to protect oils from oxidation. Additionally, advanced encapsulation technologies, such as liposomes and nanoemulsions, are being explored to enhance the stability of sensitive natural actives. However, these techniques often increase formulation complexity and cost, making it challenging for small-scale brands to implement them.

2. Preservation Without Synthetic Preservatives

The preservation of cosmetics is crucial to prevent microbial contamination, particularly in water-based formulations where bacteria and fungi can thrive. In conventional cosmetics, synthetic preservatives like parabens, phenoxyethanol, and formaldehyde-releasing agents are highly effective at ensuring long-term microbial safety. However, consumer concerns over the safety of these preservatives have driven demand for natural alternatives.

Natural preservatives, such as grapefruit seed extract, honeysuckle extract, and lactic acid, are often less potent than their synthetic counterparts, requiring higher concentrations or combinations of multiple ingredients to achieve effective preservation[27]. This can pose challenges, as high concentrations of natural preservatives may affect the product's sensory qualities, such as color or scent. Moreover, the preservation efficacy of natural compounds may not be as broad-spectrum, leading to a shorter shelf life. Ensuring consistent and reliable preservation while maintaining a "natural" label remains one of the most significant hurdles in natural-based cosmetic formulation.

3. Texture and Sensory Experience

In cosmetic products, texture and sensory experience are crucial factors that influence consumer satisfaction. Consumers expect natural cosmetics to deliver the same level of performance and pleasant user experience as conventional products. However, many natural ingredients have distinct textures or sensory characteristics that may not align with consumer preferences.

For example, natural oils like coconut oil and shea butter are excellent emollients but can leave a greasy or heavy feel on the skin, which might be undesirable for products aimed at lightweight hydration. Additionally, the removal of synthetic emulsifiers and thickeners can result in formulations with less consistency, stability, or desirable texture. This challenge can be addressed by formulating with natural emulsifiers and thickeners such as xanthan gum[50], sclerotium gum, or lecithin[51], but achieving the right balance for an optimal texture without compromising product stability can be difficult.

4. Efficacy and Bioavailability of Natural Actives

Natural ingredients are often perceived as being gentler and safer than synthetic ones, but their efficacy can vary widely. The active compounds in natural ingredients are typically present in lower concentrations compared to synthetic equivalents, and their bioavailability — or ability to penetrate the skin and deliver results — can be limited.

For instance, plant extracts like green tea or turmeric are rich in antioxidants, but their efficacy in topical applications depends heavily on the concentration of active components, their stability, and their ability to penetrate the skin barrier[49]. Achieving the desired efficacy using only natural actives can require high concentrations, which can lead to formulation challenges in terms of texture, cost, and stability.

Innovative approaches, such as encapsulation and delivery systems, are being developed to improve the bioavailability of natural actives. These technologies allow for controlled release and enhanced penetration of active ingredients, helping to bridge the gap between consumer expectations and the limitations of natural formulations. However, these methods add complexity and cost to the formulation process, presenting challenges for natural beauty brands that aim to remain affordable.

SCIENTIFIC ADVANCES IN NATURAL-BASED COSMETIC FORMULATION

The development of natural-based cosmetics has driven significant scientific innovation over the last decade. As the demand for eco-friendly and sustainable products has surged, researchers and formulators are increasingly exploring advanced technologies to overcome the challenges posed by natural ingredients. These innovations not only address the inherent limitations of natural-based formulations, such as stability and efficacy, but also offer new opportunities for enhancing product performance while maintaining natural integrity. Below are some of the key scientific advances shaping the future of natural-based cosmetic formulations.

1. Green Chemistry and Sustainable Sourcing

One of the most important scientific advances in the natural cosmetics space is the adoption of green chemistry principles. Green chemistry focuses on designing products and processes that minimize the use and generation of hazardous substances, reduce energy consumption, and utilize renewable raw materials[52]. This approach is particularly relevant in the formulation of natural-based cosmetics, where sustainability and environmental impact are critical consumer concerns.

For example, the development of bio-based surfactants derived from renewable plant sources has replaced traditional petrochemical-based surfactants[53]. Surfactants such as coco-glucoside and sodium cocoyl isethionate offer gentle cleansing properties while being biodegradable, making them ideal for eco-conscious formulations[54]. Additionally, sustainable extraction techniques like supercritical CO_2 extraction have become popular for isolating high-purity plant extracts without the use of harmful solvents, preserving the integrity of bioactive compounds[55].

Moreover, advances in sustainable sourcing have improved traceability and ethical procurement of natural ingredients, ensuring that raw materials like argan oil and shea butter are harvested in environmentally responsible ways that support local communities. These innovations are not only addressing environmental concerns but are also reshaping consumer perceptions of ethical beauty.

2. Biotechnology and Natural Ingredient Enhancement

Biotechnology has emerged as a transformative tool in the formulation of natural-based cosmetics, enabling the production of high-quality natural ingredients through sustainable and efficient processes. One major breakthrough is the use of plant stem cells in cosmetic formulations. Plant stem cells, derived from the meristematic tissue of plants, have demonstrated the ability to enhance skin regeneration, protect against oxidative stress, and improve skin hydration[56]. These bioactive compounds can be produced in large quantities in controlled environments, reducing the need for harvesting endangered or rare plants.

Additionally, microbial fermentation has become an innovative approach for producing high-value cosmetic ingredients. Fermentation processes can enhance the bioavailability and potency of natural actives, such as hyaluronic acid, peptides, and ceramides, which are crucial for anti-aging and moisturizing formulations[57]. Fermentation allows for the development of ingredients with enhanced skin compatibility and performance, while reducing the need for synthetic processing.

The ability to bioengineer natural molecules through synthetic biology also holds great potential. For example, squalane, originally derived from shark liver oil, is now being sustainably produced from sugarcane through bioengineering [58]. This innovation has allowed formulators to access high-quality, natural alternatives without relying on animal-derived ingredients, aligning with vegan and cruelty-free standards.

Hermosaningtyas et al. explore the use of plant-derived stem cells in cosmetics, focusing on their regenerative properties[59]. This study highlights how plant stem cells can be produced sustainably, reducing the environmental impact compared to traditional botanical harvesting.

3. Encapsulation and Delivery Systems

A major hurdle in natural-based cosmetics is ensuring the effective delivery of active ingredients to the skin while maintaining product stability. Recent advancements in encapsulation technologies, as can be seen in Figure 1, have provided novel solutions to this problem. Encapsulation techniques, such as liposomes, nanoemulsions, and microspheres, have been developed to protect natural actives from degradation, improve their penetration into the skin, and enable controlled release over time[60].

Figure 1 outlines various approaches to enhance the solubility and bioavailability of hydrophobic drugs. These strategies include complexation with cyclodextrins, solid dispersions, amorphization, mesoporous silica nanoparticles, pH modification, and polymer-lipid hybrid systems. Crystal engineering techniques, such as co-crystals, salt formation, and polymorphs, modify the drug’s crystalline structure to improve solubility. Lipid-based systems, like polymeric micelles, nanoparticles, and self-emulsifying systems, aid in drug delivery by enhancing solubility in lipid carriers. Polymeric systems, including dendrimers and polymeric nanoparticles, offer advanced nanocarriers for efficient drug delivery. Additionally, reducing particle size through micro/nanonization increases surface area and improves dissolution, further enhancing drug bioavailability. These methods collectively aim to make hydrophobic drugs more soluble and effective for therapeutic applications.

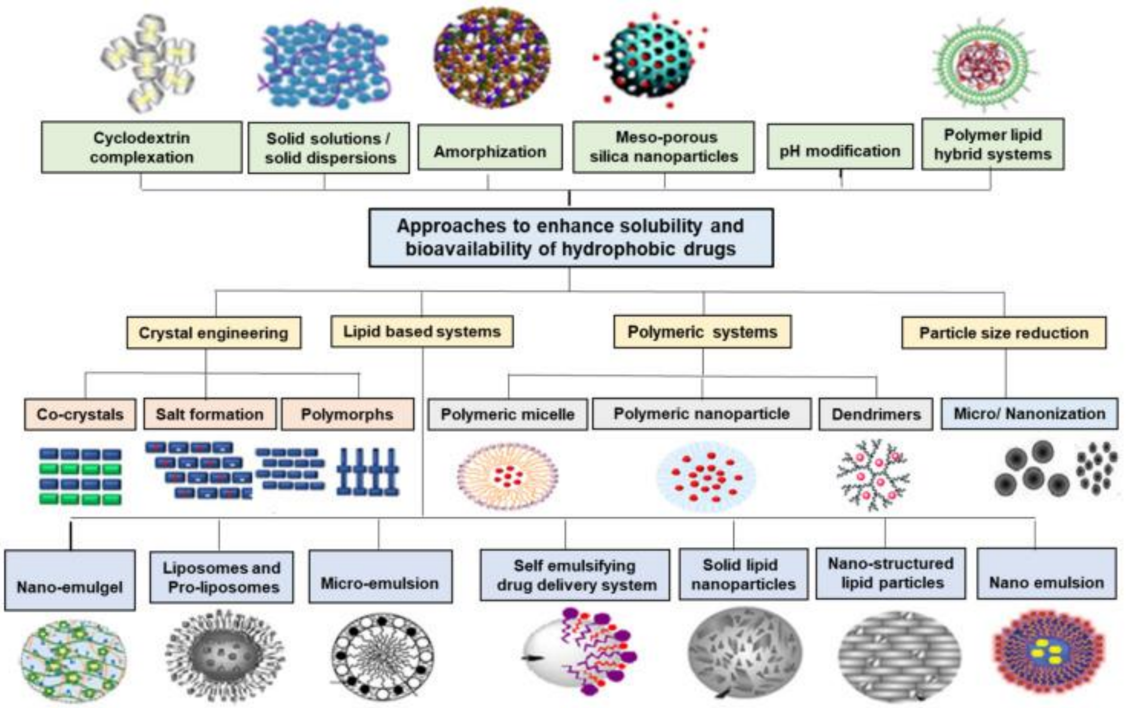

Figure 1. Strategies to improve solubility and bioavailability of lipophilic drugs

Liposomes, for instance, are spherical vesicles composed of phospholipids that can encapsulate both hydrophilic and hydrophobic compounds[61]. These vesicles enhance the penetration of active ingredients such as vitamin C[62], coenzyme Q10[63], and retinol[64] into deeper skin layers, where they can exert their anti-aging and antioxidant effects. Liposome-based systems also improve the stability of sensitive natural ingredients, which are otherwise prone to oxidation and degradation.

Similarly, nanoemulsions have gained attention for their ability to deliver natural oils and extracts more effectively[65]. Nanoemulsions are submicron-sized emulsions that offer increased surface area for absorption, improved texture, and enhanced stability of oil-in-water systems. These technologies enable formulators to incorporate otherwise challenging ingredients, such as essential oils and plant extracts, into lightweight and non-greasy formulations.

Donthi et al. discussed the innovative use of nano-emulgels to enhance the delivery of lipophilic compound[66]. Lipophilic compounds often face challenges such as poor solubility, low bioavailability, and unpredictable absorption, which can limit their efficacy in traditional topical and oral formulations. The nano-emulgel system offers a promising solution by combining the benefits of nanoemulsions and gels, resulting in improved drug stability, controlled release, and enhanced skin penetration. Donthi et al. also highlighted the components of nanoemulgel formulations, such as natural oils (e.g., oleic acid and emu oil) for their biocompatibility and skin-permeation enhancement, and surfactants (e.g., Tween and Span) for their role in stabilizing the emulsion. These ingredients are crucial for optimizing the cosmetic's delivery, stability, and therapeutic effectiveness.

4. Natural Preservative Systems

The challenge of preserving natural-based cosmetics without synthetic preservatives has led to significant advances in the development of natural preservative systems. Conventional preservatives such as parabens and formaldehyde-releasers, though effective, have raised concerns about their potential health risks. In response, formulators are turning to alternative preservation strategies that meet consumer demand for "clean" and "natural" labels while ensuring product safety.

Recent research has focused on the use of antimicrobial peptides[67], organic acids (such as lactic and citric acids), and plant-derived antimicrobials[68] (such as rosemary extract and neem oil) as natural preservatives. Tocopherols (vitamin E)[69] and aspen bark extract[70] are being explored for their antioxidant properties, which help prevent product spoilage by inhibiting oxidation.

One particularly promising innovation is the use of multifunctional ingredients that serve dual purposes, such as providing both preservation and skin benefits. For example, glyceryl caprylate acts as both a preservative and an emollient[71], reducing the need for additional chemical ingredients. Advances in the formulation of natural preservatives are essential to ensuring the safety and shelf-life of natural-based cosmetics without compromising their natural positioning.

FUTURE PERSPECTIVES AND INNOVATIONS

As the demand for natural-based cosmetics continues to rise, the future of the industry will be shaped by several key trends and innovations. Consumers are increasingly seeking products that not only align with their desire for natural and sustainable ingredients but also deliver high performance, customization, and ethical transparency. To meet these demands, cosmetic companies and researchers are focusing on cutting-edge technologies and practices that push the boundaries of natural formulation.

Looking ahead, the development of next-generation bioactive through green biotechnology holds great promise for natural-based cosmetics. Scientists are increasingly turning to biotechnological methods to create more effective and sustainable bioactive ingredients. This includes using genetically engineered microorganisms to produce high-performance natural ingredients that would otherwise be difficult or environmentally harmful to extract from nature.

For example, advancements in microbial fermentation and synthetic biology allow for the production of rare and potent bioactives, such as resveratrol[72], collagen[73], and squalane[74], in a sustainable and scalable way. These bioactives can be produced without depleting natural resources, making them more environmentally friendly and more affordable for large-scale production.

In addition, the exploration of marine biotechnology offers exciting new opportunities for natural-based cosmetics[75]. Ingredients derived from marine sources, such as algae[76], seaweed[77], and marine collagen[78], are gaining attention for their potent antioxidant, anti-inflammatory, and moisturizing properties. The use of algae-derived polysaccharides in cosmetics is also expected to rise due to their moisturizing[79] and anti-aging effects[80], which align with consumer demand for innovative, natural ingredients. Future research may unlock even more potent marine bioactives that offer unique benefits for skin health and anti-aging.

CONCLUSION

The natural-based cosmetics industry is undergoing rapid transformation as consumer preferences shift toward sustainability, ethical sourcing, and high-performance natural ingredients. While the use of plant-based extracts, oils, and other natural ingredients presents unique formulation challenges—such as stability, preservation, and efficacy—scientific innovations are continually expanding the potential of natural-based cosmetics. Advances in green chemistry, biotechnology, and encapsulation techniques are driving significant progress in overcoming these barriers, allowing formulators to develop products that meet both consumer expectations and regulatory standards. By leveraging cutting-edge technologies and aligning with ethical and environmental values, the industry can offer consumers products that not only enhance their beauty routines but also contribute to a more sustainable and responsible beauty future.

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