

Innovative Approaches to Enhancing Formulations and Skin Care Efficacy Through Mesoporous Silica Advancements

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Abstract: Recently, cosmetic products have become an essential part of daily personal care routines. However, conventional cosmetic formulations still face several challenges, including poor stability, limited skin permeability, a higher risk of side effects, and rapid release of active ingredients. Mesoporous silica nanoparticles (MSNs) offer a potential solution to these limitations due to their large surface area, substantial pore volume, and ability to precisely control pore size. MSNs are highly adaptable for cosmetic applications, including enhancing formulation stability, improving skin penetration, and prolonging the release of active ingredients. This review aims to summarize the potential of MSNs as multifunctional carriers in cosmetics, elucidating their mechanism in enhancing the performance of active compounds based on current literature. Various studies show that MSNs consistently improved efficacy, stability, and safety of cosmetics formulations. This review offers insights on the significance of integrating MSNs into cosmetic formulations to improve UV protection, anti-aging effects, antioxidant activity, deodorant action, and protection against dental erosion. Future prospects show favorable potential for cosmetics applications using MSNs.

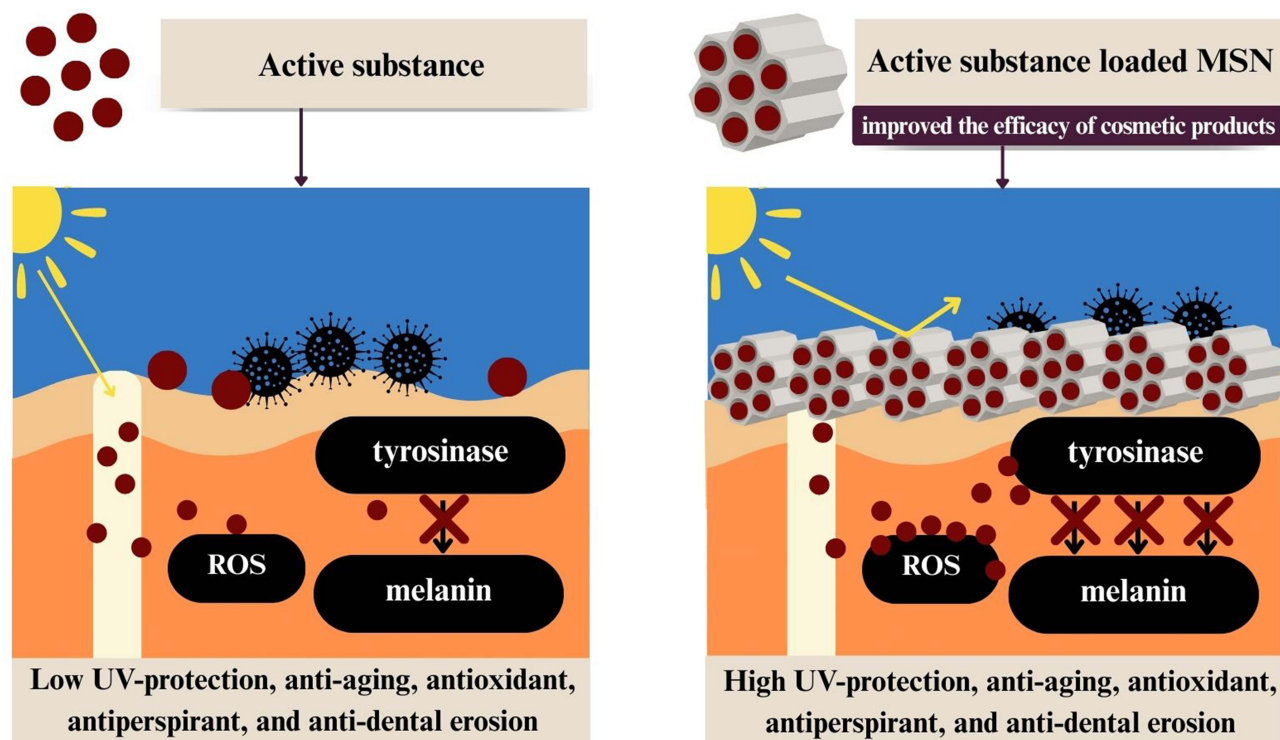
Keywords: cosmetics, mesoporous silica nanoparticles, UV photoprotector, anti-aging, antioxidant

Introduction

Recently, cosmetic products have become an essential part of daily personal care routines. The use of both natural and synthetic active compounds in these products has increased significantly.¹ A wide variety of active ingredients are incorporated into cosmetic formulations to provide functions such as UV protection, anti-aging effects, antioxidant activity, deodorant action, and protection against dental erosion. Consumers are increasingly seeking products that not only enhance appearance but also offer therapeutic benefits with minimal side effects.² The global cosmetic industry is experiencing rapid growth, driven by rising consumer demand for safe, versatile, and sustainable products. However, this growth is accompanied by major challenges, particularly the need for innovative delivery systems that can enhance product stability, improve efficacy, and minimize safety risks.³

In practice, conventional cosmetic formulations still face several challenges, including poor stability, a higher risk of side effects, and rapid release of active ingredients.⁴ From a pharmacological and industrial perspective, these challenges pose significant problems, such as the rapid degradation of sensitive active ingredients, limited bioavailability, and suboptimal skin permeability. These factors often lead to reduced product efficacy and increased production costs.^{5,6} As a result, innovative approaches are needed to improve both the stability and efficacy of cosmetic products. To overcome these formulation challenges, nanoparticles, a type of nanocarrier-based system, have been widely applied in the cosmetic industry for many years. Nanoparticles offer several advantages compared to conventional formulations, including enhanced stability, controlled ingredient release, and improved skin penetration due to their small size and large surface

Graphical Abstract



area.^{5,6} Various types of nanoparticles have been explored in cosmetic applications, including liposomes, polymers,^{1,7} and mesoporous particles.^{8,9}

Among these, MSNs show great promise for enhancing cosmetic efficacy.¹⁰ MSNs can encapsulate and deliver active ingredients to targeted layers of the skin while protecting sensitive compounds from degradation.^{11–13} Their high surface area, uniform pore size, and large pore volume make them effective carriers for both hydrophilic and hydrophobic substances, enabling efficient loading and sustained release.^{14–17} In addition, their physicochemical stability, biocompatibility, and ease of surface functionalization make MSNs are highly adaptable for cosmetic applications, including enhancing formulation stability, improving skin penetration, and prolonging the release of active ingredients.^{18,19}

The versatility of MSNs in modifying the behavior of active compounds has attracted considerable interest in their incorporation into cosmetic formulations. For example, in sunscreens, MSNs can reduce the dermal absorption of UV filters, thereby minimizing the risk of local and systemic side effects. This benefit is achieved by adsorbing the filters within their porous structures and retaining them on the skin surface.^{15,20} Similarly, in anti-aging and anti-pigmentation products, MSNs help enhance the penetration and stability of active compounds, enabling targeted delivery to deeper skin layers or specific cells such as melanocytes.^{8,21}

Although extensive research has explored the use of MSNs for topical applications, comprehensive studies on their mechanisms and overall impact on cosmetic product stability and efficacy remain limited. This review aims to summarize the potential of MSNs as multifunctional carriers in cosmetics, elucidating their mechanism in enhancing the performance of active compounds based on current literature. Additionally, it discusses future research opportunities to support the development of more effective and stable cosmetic products through the application of MSNs.

Methodology

This narrative review employed a comprehensive and systematic approach to collect and elucidate studies investigating the role of MSNs in enhancing the functional performance of active compounds in cosmetic products. Specifically, this review focuses on improvements in UV protection, anti-aging, antioxidant, antiperspirant and deodorant, and anti-dental erosion activities, as outlined in Figure 1. Literature was collected from international databases, primarily Scopus,

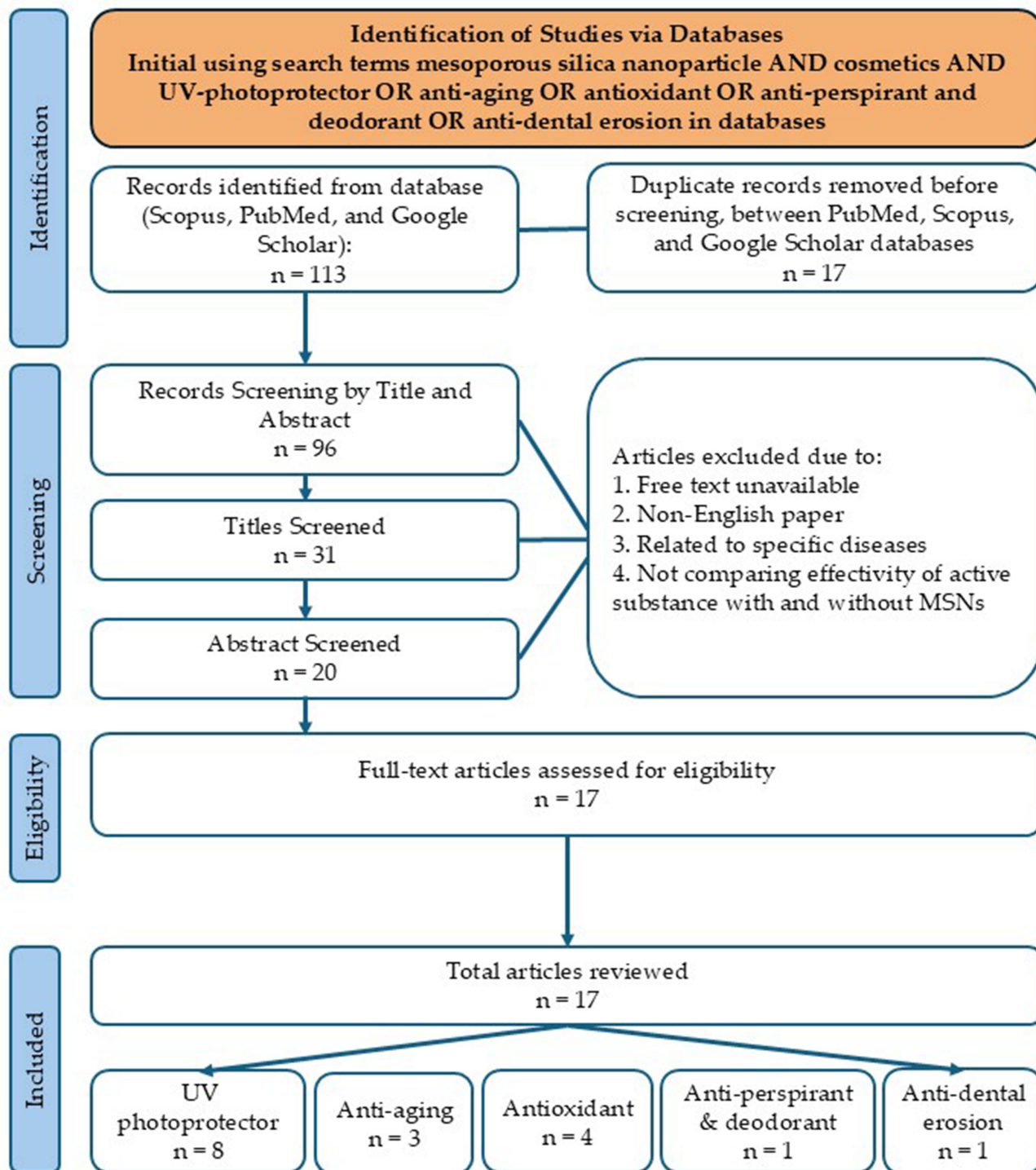


Figure 1 Flowchart of the review methodology.

PubMed, and Google Scholar using targeted keywords such as “mesoporous silica nanoparticles”, “cosmetics”, “UV-photoprotector”, “anti-aging”, “antioxidant”, “antiperspirant”, “deodorant”, “anti-dental erosion”, and “cosmetic.” The search was limited to studies published between 1995 to 2024. Only studies published in English were considered to ensure accessibility and consistency in data interpretation.

Inclusion criteria were defined to focus on peer-reviewed studies and prioritize experimental studies that demonstrated measurable improvements in the functional activities of MSN-loaded cosmetic formulations. Non-experimental or purely theoretical studies were excluded. This selection process ensured that only the most relevant and reliable data were included, providing a solid basis for evaluating the potential of MSNs as multifunctional carriers in cosmetic applications.

Cosmetics

Cosmetics are the mixtures of chemical compounds used to enhance the appearance and odor of the human body.^{22,23} Most cosmetic products are used for topical use²⁴ and can be formulated into various dosage forms, including creams, lotions, ointments, aerosols, gels, suspensions, solutions, powders, pastes, and foams.²⁵ Cosmetics could be applied to the face, hair, and body as sunscreen, makeup, cleanser, hand and hair cream, deodorant, toothpaste, and many more.²⁶ Cosmetics are commonly used as UV photoprotectors, anti-aging agents, antioxidants, antiperspirants, and anti-dental erosion agents.

Mechanism of Cosmetics

UV-Photoprotector

Ultraviolet (UV) radiation contributes to photoaging, sunburn, immunosuppression, and skin cancer by damaging skin cells and suppressing epidermal antigen-presenting cells, thereby increasing cancer risk.^{27,28} UV is classified into UVC, UVB, and UVA, with ozone depletion increasing exposure. UVA penetrates deeply and generates reactive oxygen species (ROS) that indirectly damage DNA and accelerate skin aging.²⁹ In contrast, UVB causes direct DNA damage, such as pyrimidine dimer formation, linked to nonmelanoma skin cancers.^{30,31} To protect the skin, cosmetic products incorporate organic or inorganic UV filters with distinct mechanisms (Figure 2). Organic filters absorb UV radiation and convert it to heat via photophysical and photochemical processes, with their conjugated π -electron systems releasing energy through internal conversion and non-radiative relaxation, preventing DNA damage.^{32–34} Inorganic filters, mainly titanium dioxide (TiO₂) and zinc oxide (ZnO), reflect, scatter, and partially absorb UV radiation.³⁵ Their high refractive index and broad-spectrum coverage block both UVA and UVB. Nanosized TiO₂ and ZnO improve transparency, but concerns about skin penetration and photocatalytic ROS generation have led to surface modifications, such as silica or alumina coatings, enhancing safety and stability. Due to their photostability and minimal systemic absorption, inorganic filters are widely used in combination with organic filters for enhanced sunscreen protection.^{33,36–38}

Anti-Aging

Skin aging occurs via intrinsic and extrinsic processes. Intrinsic aging results from genetic and cellular changes, including free radical accumulation, telomere shortening, and mitochondrial DNA damage, leading to fine wrinkles and reduced elasticity.³⁹ Extrinsic aging, caused by UV radiation, pollution, and lifestyle factors, accelerates oxidative stress, collagen breakdown, and inflammation, leading to premature skin aging.^{40,41} Anti-aging cosmetics target these mechanisms through moisturizing agents, antioxidants, and bioactive compounds (Figure 3). Antioxidants like vitamins C and E, coenzyme Q10, and polyphenols neutralize free radicals,⁴² retinoids and hydroxy acids stimulate collagen synthesis,⁴³ and moisturizers such as hyaluronic acid and glycerol enhance hydration, while UV filters prevent photo-induced damage.⁴⁴ Collectively, these ingredients help slow the aging process, maintaining skin health and appearance.

Antioxidant

Antioxidants play a crucial role in preventing oxidative damage by interrupting radical chain reactions and inhibiting oxidation, making them essential both as active ingredients and stabilizers in cosmetic formulations. Their use in

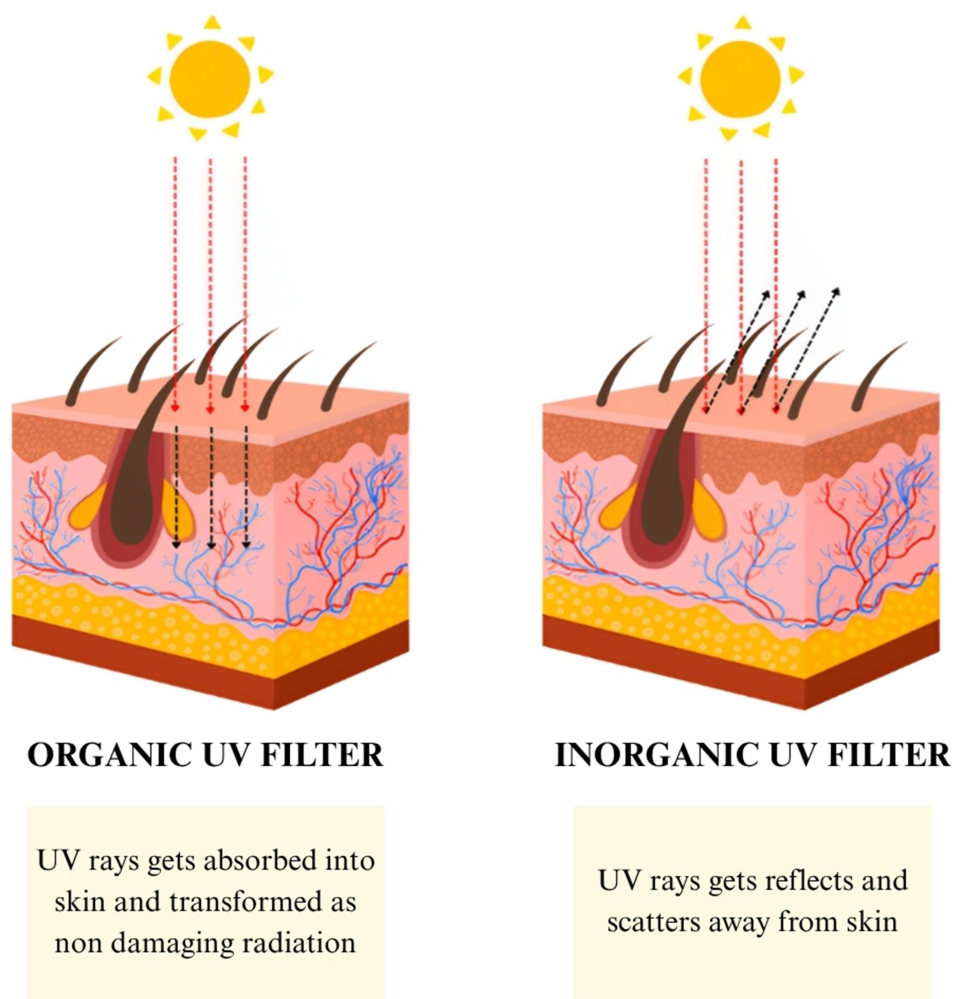


Figure 2 Mechanism of cosmetics as UV-photoprotector. Organic UV filters absorb UV radiation into the skin and convert it into non-harmful energy (left). Inorganic UV filters reflect and scatter UV radiation away from the skin surface (right). Red dotted arrows indicate incoming UV rays, while black dotted arrows represent either absorbed rays (left) or reflected/scattered rays (right), depending on the type of UV filter.⁸⁰

cosmetics has increased significantly; however, achieving optimal efficacy requires careful consideration of several factors. Because reactive oxygen species (ROS) have a short lifespan, antioxidants with high reactivity and capacity are preferred.^{45,46} At the same time, antioxidants must remain stable and avoid degrading into radical forms, such as ascorbyl or tocopheryl radicals, which could promote further oxidation. Stability within formulations is critical, necessitating protection from oxygen and minimal interaction with other ingredients. The selection of antioxidants is often influenced by their hydrophilic or lipophilic properties. However, industry choices sometimes prioritize cost over scientific evaluation, potentially reducing the effectiveness of antioxidants in cosmetic applications.^{2,47}

Anti-Perspirant and Deodorant

Antiperspirants and deodorants offer an effective strategy for reducing body odor, which arises from the breakdown of sweat components by bacteria on the skin's surface.^{48,49} Active compounds commonly used in antiperspirant formulations function by forming a temporary physical barrier at the openings of sweat ducts, thereby minimizing the release of sweat onto the skin surface, as shown in [Figure 4](#). By reducing moisture on the skin, these compounds limit the conditions favorable for bacterial growth and odor production.^{50,51}

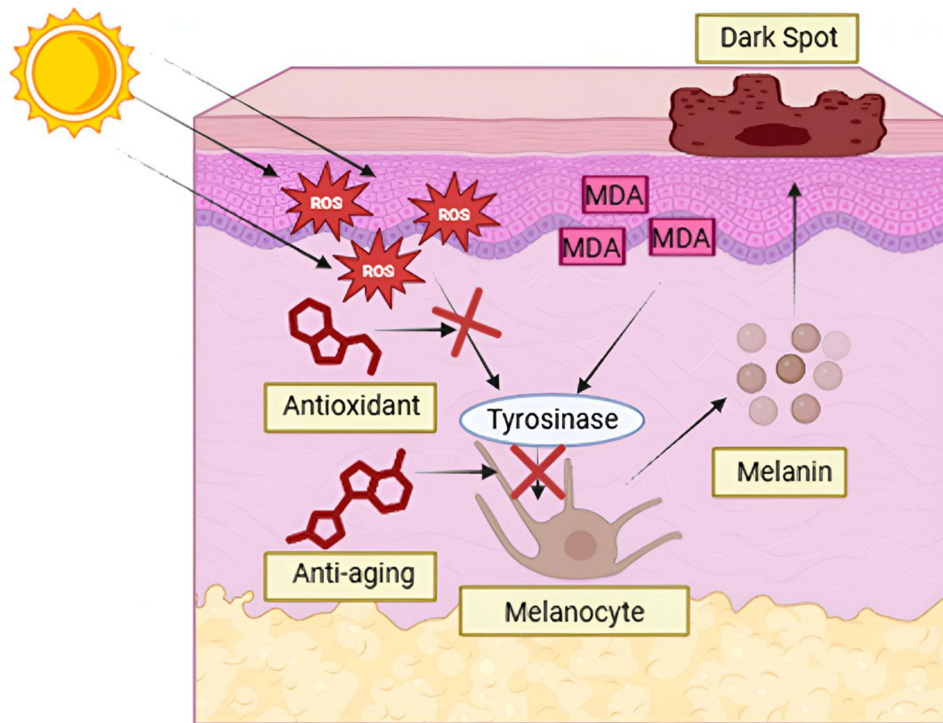


Figure 3 Mechanism of cosmetics as anti-aging and antioxidant. Ultraviolet (UV) exposure generates reactive oxygen species (ROS), triggers lipid peroxidation, and promotes excessive melanin production. Antioxidants neutralize ROS, while anti-aging agents mitigate oxidative stress and inhibit tyrosinase activity, thereby reducing hyperpigmentation. Arrows represent process flow; red crosses indicate inhibition.¹¹⁰

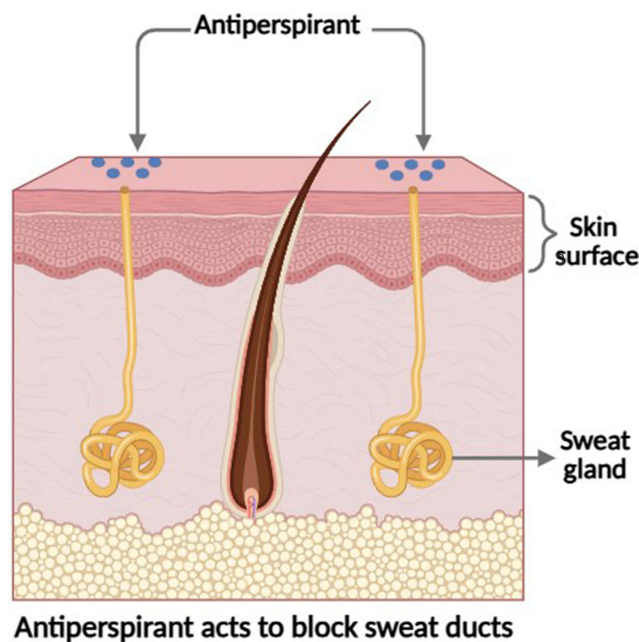


Figure 4 Mechanism of cosmetics as anti-perspirant. Antiperspirant agents (blue dots) form temporary plugs in sweat ducts, preventing sweat from reaching the skin surface. Black arrows indicate the direction of antiperspirant action.⁵²

Anti-Dental Erosion

Protection against dental erosion involves a combination of biological, chemical, and behavioral factors. Saliva plays a key defensive role by diluting and clearing acids, buffering low pH, and supplying calcium and phosphate for remineralization.⁵² Additionally, the acquired enamel pellicle—a salivary protein layer—acts as a diffusion barrier,

though its protective capacity is limited under severe acid exposure. Preventive strategies include the use of fluoride (especially stannous or titanium fluoride), mineral-rich solutions, and agents like CPP-ACP, which reinforce enamel and reduce solubility. Behavioral modifications, such as reducing acidic intake frequency, avoiding nighttime acid exposure, and using straws, further minimize erosion risk.^{53,54} Together, these mechanisms form a multifaceted defense aimed at preserving dental hard tissue integrity in erosive environments.^{55,56}

Limitations of Conventional Cosmetics

Conventional cosmetic formulations face several limitations, including low stability, potential adverse effects, poor skin permeability, and uncontrolled rapid release of active substances.⁴ Among these, stability is a critical factor in cosmetic products because it represents the effectiveness of cosmetic products.⁵⁷ The stability of cosmetic products is low due to the degradation of the active substances. Active substances such as quercetin, which are commonly used in cosmetics, easily degrade after application on the skin.⁵⁸ The degradation occurs due to UV exposure, which converts quercetin into inactive forms, such as 2,3,4-chalcan-trione monoanion, 3,4-dihydroxyphenyl glyoxylate, 2,4,6-trihydroxyphenyl glyoxylate, 3,4-dihydroxybenzoate, and 3-hydroxyphenolate, before reaching the target.^{58,59} Similarly, UV filters such as avobenzene and octinoxate exhibit photoinstability under prolonged exposure to sunlight, resulting in reduced efficacy and the formation of degradation products.^{32–34} These degradation products not only reduce therapeutic effects but can also induce adverse local effects, including dermatitis and allergic reactions.⁶⁰ Moreover, deeper skin penetration of these degradation products may trigger oxidative stress through reactive oxygen species (ROS), leading to DNA damage and dermal inflammation.^{15,31,61} In some cases, degraded compounds have also been detected systemically, raising concerns about systemic side effects.¹⁵ Nevertheless, active substances such as azelaic acid and epigallocatechin-3-gallate have low adverse effects and low permeability due to their physicochemical properties.⁸ The permeability should be enhanced to increase its effectiveness as a cosmetic product. Furthermore, active substances in cosmetic products are released rapidly, which possibly decreases their effectiveness due to low stability and increases their adverse effects.^{62,63} Therefore, a controlled release system is needed to prolong action and reduce the side effects of cosmetic products.^{62,64}

To overcome these challenges, the application of nanocarrier systems offers advanced solutions for enhancing cosmetic efficacy. Nanocarriers could be used due to their ability to improve the stability, safety, and permeability of cosmetic products. Additionally, nanocarriers can control the release of active substances. Therefore, the effectiveness of cosmetic products can greatly improve. One of the promising nanocarriers that have excellent stability, biocompatibility, and coating effects on hazardous active substances in cosmetic products is MSNs.^{65,66}

Mesoporous Silica Nanoparticles (MSNs)

MSNs are advanced nanostructures characterized by a well-organized mesoporous structure with pore and particle sizes depending on the synthesis method.^{67,68} According to previous studies, MSNs can be synthesized from two primary sources, which are organic and inorganic components. Alkoxysilanes, including tetraalkoxysilanes (Si(OR)₄) are organic compounds frequently used as synthetic silica sources.⁶⁹ Other silica sources include inorganic compounds such as silicon tetrachloride, olivine, and sodium silicate solution.⁷⁰ However, sodium silicate is an excellent source for the synthesis of silica-based nanoparticles because it is widely used as a precursor.⁶⁹

The synthesis of MSNs generally involves three fundamental steps: a sol-gel process for silica formation, the use of surfactants as structure-directing agents to create mesoporous materials, and a modified Stöber method under dilute conditions to produce spherical nanoparticles.^{71,72} Initially, the formation of silica nanoparticles starts with the hydrolysis of tetraethyl orthosilicate (TEOS) in the presence of hydroxide ions (OH⁻), which leads to the production of silicic acid. This is followed by a condensation reaction, forming a siloxane (Si-O-Si) matrix that results in a silica nanoparticle structure.⁷³ To initiate the mesoporosity, cationic surfactants such as cetyltrimethylammonium bromide (CTAB) are used to form micelles, which serve as templates for mesoporous structures.⁷⁴ A solution containing silica precursors (TEOS or tetramethoxysilane/TMOS) and surfactants is hydrolyzed and condensed, where the silica frame progressively aggregates around the micelles via siloxane bonds. After the surfactant is removed, well-arranged MSNs with uniform pore sizes are obtained. The use of surfactants as structure-directing agents (SDAs) has an important role in tailoring the porosity and structural properties of MSNs.^{75,76}

MSNs have unique characteristics that make them ideal for encapsulating and delivering bioactive compounds, resulting in promising candidates for controlled release due to their extensive surface area, adjustable pore size, and biocompatibility.¹³ MSNs also protect unstable compounds from degradation, enhance transdermal penetration, and facilitate the prolonged release of active agents.^{18,19} Moreover, the biocompatibility and non-toxicity of MSNs provide safe application in cosmetics.^{77,78} MSNs have been developed as promising carriers for active ingredients in dermocosmetic formulations. Their unique properties, such as a high surface area, uniform pore size, large pore volume, and excellent drug-loading capacity, enable controlled and sustained release, thereby enhancing the efficacy and safety of topical applications.^{18,79}

Several types of MSNs, including MCM-41, MCM-48, SBA-15, core-shell MSNs, and hollow MSNs, have been widely used in cosmetics applications.⁶⁹ A previous study indicated that the encapsulation of OMC to MCM-41 facilitates a broader photoprotection range, improves its photostability, and reduces sunscreen release compared to formulations that contain OMC only.⁸⁰ Another study conducted by Vieira et al explored the application of ZnO-SBA-15 in cosmetics, demonstrating enhanced in vitro SPF, strong antimicrobial properties, and reduced cytotoxicity compared to ZnO. With no measurable toxicity in human skin, these MSNs offer a safer and more effective alternative for cosmetic formulations.⁸¹

Table 1 provides a comparative overview of MSNs with commonly used nanostructures such as liposomes, solid lipid nanoparticles (SLNs), and nanoemulsions.

Table 1 Comparative Overview of Mesoporous Silica Nanoparticles (MSNs) and Other Nanocarriers

Carrier	MSNs	Liposomes	Solid Lipid Nanoparticles (SLNs)	Nanoemulsions (NEs)
Structure	Porous silica structures with tunable pore size and surface modification capability ⁹⁸	Spherical vesicles with phospholipid bilayers and aqueous core ⁹⁸	Nanoparticles with a solid lipid core stabilized by surfactants ⁹⁸	Colloidal dispersions of immiscible oil and water phases stabilized by surfactants ⁹⁸
Synthesis	Sol-gel method, self-assembly, hard and soft templating, aerogel approach, dissolving-reconstruction method ⁹⁹	Mechanical dispersion, solvent dispersion, detergent removal method ⁹⁹	High shear homogenization, hot homogenization, cold homogenization, ultrasonication, solvent emulsification, microemulsion, spray drying ⁹⁹	Miniemulsion polymerization, nanoemulsion-solvent evaporation, spontaneous emulsification, sol-gel processes ¹⁰⁰
Size	1–100 nm ⁹⁹	20–1000 nm ⁹⁸	40–1000 nm ⁹⁸	1–200 nm ⁹⁸
Loading capacity	Very high loading capacity due to large surface area and pore volume; suitable for both hydrophilic and hydrophobic substances ¹⁰¹	Encapsulates both hydrophilic and lipophilic substances, but capacity is often limited ¹⁰²	Provides good loading for lipophilic substances ¹⁰³	Exhibits excellent solubilization of lipophilic compounds, but lacks capacity for controlled adsorption ¹⁰⁴
Skin penetration/retention	Enhances skin retention while reducing systemic absorption; surface can be tailored for desired permeability ¹⁰⁵	Enhances dermal penetration and increases skin permeation ¹⁰²	Improves dermal retention and provides prolonged activity ¹⁰⁶	Increases skin permeation and flux, which may increase the risk of systemic uptake ¹⁰⁴
Release profile	Tunable; enables sustained and stimuli-responsive (pH, redox, enzyme, light) release ¹⁰⁷	Often shows rapid or uncontrolled release; susceptible to leakage ¹⁰²	Provides sustained release, but affected by lipid crystallization ¹⁰⁶	Typically exhibits fast release due to droplet diffusion ¹⁰⁴

(Continued)

Table 1 (Continued).

Carrier	MSNs	Liposomes	Solid Lipid Nanoparticles (SLNs)	Nanoemulsions (NEs)
Stability	Chemically and thermally stable; strong Si–O–Si bonds enhance photostability of sensitive substances ^{101,107}	Limited physical and chemical stability; prone to oxidation and hydrolysis ¹⁰²	Good storage stability; however polymorphic transitions may destabilize the system ¹⁰⁶	Kinetically stable; but sensitive to droplet coalescence and surfactant degradation ¹⁰⁴
Biocompatibility/ Toxicity	Generally biocompatible, safe, and low toxicity ¹⁰⁸	High biocompatibility due to natural phospholipids ¹⁰²	Low toxicity when using GRAS lipids; surfactant type may influence toxicity ¹⁰⁶	Generally safe; however, surfactants may cause irritation if not optimized ¹⁰⁴

Advantages of MSNs in the Cosmetics

Leveraging their unique structural and functional properties, MSNs have been applied across various cosmetic formulations.^{18,79} In sunscreen formulations, repeated application of UV filters over large skin areas may lead to adverse effects due to their absorption in the skin.⁸² Such penetration can result in local reactions (eg, dermatitis, allergic contact) and systemic effects, including mutagenic or estrogenic activity. Loading UV filters into MSNs helps mitigate these issues. The silica matrix and chemical scaffold of MSNs retain UV filters at the skin surface, reducing dermal absorption.^{83,84} Furthermore, MSNs prevent the agglomeration of UV filters made from metal oxides (eg, TiO₂ and ZnO) through their high surface area and pore uniformity, thereby improving UV-blocking performance.⁸¹

Different with the UV filter mechanism, MSN improves anti-aging and anti-pigmentation activity by enhancing the active ingredient's stability, permeability, and resistance to degradation.^{74,85} Functionalizing MSNs with cell-penetrating peptides (CPPs) facilitate deeper skin penetration, while smart delivery systems targeting melanocytes improve selectivity and therapeutic effectiveness.⁸⁶

In dental applications, MSNs serve as carriers in toothpaste formulations, particularly for the treatment of enamel and dentin demineralization.⁸⁷ The incorporation of nanoscale actives within MSNs increases mechanical and thermal stability and enhances resistance to heat and wear. It shows that MSNs are highly effective for oral care products.⁸⁸

MSNs Improve the Activities of Cosmetic Products

The incorporation of cosmetic active substances into MSNs has been reported in several previous studies, as summarized in Table 2.

Table 2 Current Studies of Cosmetic Active Substances Loaded Into MSNs

No	Active Substance	Type of MSN	Preparation Method	Functionalization	In vitro Study	Efficacy	Ref
1.	Avobenzone (AVO)	SBA-15	Solvent evaporation	-	UVA protection of AVO/SBA-15 was 1.50±0.19, while the UVA protection of free AVO was 1.02 ±1.08	AVO/SBA-15 enhanced UVA photoprotection efficacy compared to free AVO.	[109]
2.	Octyl Methoxycinnamate (OMC)	MCM-41	Solvent evaporation	-	After 480 minutes, the amount of OMC released from OMC/MCM-41 was 21%, while the released of free OMC was 60%.	OMC/MCM-41 allowed a broader UV photoprotection range and enhanced photostability compared to free OMC.	[80]

(Continued)

Table 2 (Continued).

No	Active Substance	Type of MSN	Preparation Method	Functionalization	In vitro Study	Efficacy	Ref
3.	Benzophenone-3 (BP-3-E)	MSBP-2	Solvent method	-	SPF and UVA values of BP-3/MSBP-2-E were 17.3% and 17% respectively, higher than free BP-3-E.	BP-3/MSBP-2-E enhanced UV photoprotection efficacy compared to free BP-3 and reduced penetration of BP-3-E.	[110]
4.	Quercetin (QU)	MCM-41	Incipient wetness impregnation	Aminopropyl (NH ₂)	Proliferation inhibition by QU/NH ₂ -MCM-41 on J8 human melanoma cells was 50%, while the inhibition by free QU was 15%.	QU/NH ₂ -MCM-41 enhanced antioxidant efficacy compared to free QU.	[66]
5.	Azelaic acid (AZA)	MSNs with a particle size of 99.15 nm	Incipient wetness impregnation	-	Cumulative drug permeation for AZA/MSN on skin was 85.53%, while the cumulative drug permeation of free AZA was 43.15%.	AZA/MSNs enhanced antiaging efficacy compared to free AZA.	[8]
6.	Glabridin (GB)	Hollow Mesoporous Silica Nanoparticles (HMSN)	Modified flavonoid encapsulation	β-CDs and Polyarginine-R8 (Ada-R8)	GB/HMSN-β-CD/Ada-R8 reduced hyperpigmentation after 2 weeks of topical application without any side effects such as red spots.	GB/HMSN-β-CD/Ada-R8 enhanced photoprotection, antioxidant, and antiaging efficacy.	[93]
7.	Oxybenzone (OXY)	SBA-15	Solvent evaporation	-	OXY/SBA-15 enhanced SPF value approximately 90% from 94.3±5.5 to 179.3±6.5. The transdermal permeation and cutaneous deposition of OXY/SBA-15 was also lower than free OXY.	OXY/SBA-15 enhanced UV photoprotection efficacy and safety compared to free OXY.	[111]
8.	Avobenzene (AVO)	MSN (hexagonal arrangement of tubular mesopores)	One-pot drug loading and synthesis procedure	N-[3-(trimethoxysilyl)propyl] ethylenediamine (DA) and Zn ²⁺ (ZnDA)	AVO/DA-MSN and AVO/ZnDA-MSN increased SPF values which were 5.5±0.1 and 4.3±0.2.	AVO/DA-MSN and AVO/ZnDA-MSN enhanced UV photoprotection efficacy.	[112]
9.	Avobenzene (AVO)	SBA-15	Solvent evaporation	-	AVO/SBA-15 enhanced UVA protection from 0.56 to up to 2.80. AVO/SBA-15 also reduced skin deposition caused by free AVO.	AVO/SBA-15 enhanced UVA photoprotection efficacy and safety compared to free AVO.	[113]
10.	Titanium dioxide (TiO ₂)	MCM-41	Incipient wetness impregnation	-	TiO ₂ /MCM-41 showed lower ROS and cytotoxicity after 6 and 24 hours compared to free TiO ₂ .	TiO ₂ /MCM-41 showed better biocompatibility, biodegradability, stability, and safety compared to free TiO ₂ .	[114]
11.	Quercetin (QU)	MCM-41	Adsorption	-	Radical scavenging activity of QU/MCM-41 increased up to 72±2.0%, while the radical scavenging activity of free QU was 40±5.0%.	QU/MCM-41 enhanced antioxidant efficacy compared to free QU.	[58]
12.	Zinc oxide (ZnO)	SBA-15	-	-	ZnO/SBA increased the SPF value from 3 to 4. ZnO/SBA also decreased cytotoxicity and increased antibacterial efficacy.	ZnO/SBA enhanced UV photoprotection efficacy and safety compared to free ZnO.	[115]
13.	Calcium (CA)	MSNs	-	-	The tooth structure loss value (TSL) of CA/MSN was 12.03, while TSL value of free CA was 20.48.	CA/MSN enhanced anti-dental erosion efficacy compared to free CA.	[116]
14.	Morin flavonoid (MOR)	MSNPs	Adsorption	Aminopropyl-modified silica nanoparticles (AMSNNPs)	Scavenging activity of MOR/AMSNNPs enhanced in 57% compared to free MOR.	MOR/AMSNNPs enhanced antioxidant efficacy compared to free MOR.	[117]

(Continued)

Table 2 (Continued).

No	Active Substance	Type of MSN	Preparation Method	Functionalization	In vitro Study	Efficacy	Ref
15.	Vitamin E (VE)	LMSN	Incipient wetness impregnation	NH ₂ -MSN	After 48 hours, IC50 value of VE/NH ₂ -MSN increased by 22.09 mg/mL, while IC50 of free VE increased by 60.58 mg/mL.	VE/NH ₂ -MSN enhanced antioxidant efficacy and stability compared to free VE.	[83]
16.	Citronellol (CI)	Dendritic Mesoporous Organosilica Nanoparticles (D-MON)	Adsorption	Chitosan (CS)	CI/D-MO/CS reduced unpleasant odors by decreasing hexanal, (E)-2-heptenal, and 2,6-dimethyl-pyrazine, while enhancing the synthesis of novel fragrant esters.	CI/D-MO/CS enhanced anti deodorant efficacy compared to free CI by eliminating malodor-generating microorganisms.	[95]
17.	Epigallocatechin - 3 - Gallate (EGCG)	MSNs	Incipient wetness impregnation	NP-MSN (Nanopeptide-1-MSN)	Melanin content and tyrosinase activity of EGCG/NP-MSN were 0.37% and 19.45% respectively, while the melanin content and tyrosinase activity of free EGCG were 0.55% and 30.57% respectively. EGCG/NP-MSN showed a more efficient inhibition of tyrosinase activity at 19.45% compared to free EGCG at 30.57%.	EGCG/NP-MSN enhanced antiaging efficacy compared to free EGCG.	[62]

MSNs Can Improve UV-Photoprotector Activity

MSNs have been widely used in cosmetic formulations to improve the performance of UV-photoprotective agents. A study by Alalaiwe et al⁸⁹ was conducted on encapsulated AVO in MSNs and formulated into a Carbopol 940 hydrogel. The AVO/MSN formulation achieved a UVA/UVB absorbance ratio of 1.5, compared to 1.02 for free avobenzone. This significant enhancement was attributed to the photostabilizing properties of MSNs, which reduced AVO photodegradation and improved light scattering on the skin surface. In addition to their stabilizing role, MSNs possess inherent optical properties that contribute directly to UV attenuation through reflection and scattering mechanisms. These characteristics of MSN enable a synergistic enhancement of sunscreen efficacy by amplifying the blocking effect of encapsulated UV filters.⁹⁰

AVO skin absorption was also evaluated using a Franz diffusion cell following OECD 428 guidelines. Free AVO hydrogel showed a skin deposition of 0.76 nmol/mg without detectable receptor penetration, indicating strong retention within the skin barrier. Incorporation into MSNs and TiO₂/MSN composites reduced deposition to 0.41 and 0.50 nmol/mg, respectively. These results demonstrate that MSN effectively decreases AVO skin absorption while maintaining its reservoir within the skin, suggesting enhanced safety and controlled topical delivery.⁸⁹

Daneluti et al¹⁵ also incorporated oxybenzone (OXY) into MSNs, resulting in improvements for safety and photoprotective efficacy. After six hours of application, skin retention was reduced by eightfold, and transdermal permeation was reduced up to 30-fold. Moreover, MSNs enhanced the formulation's sun protection factor (SPF) by approximately 90%, increasing from 94.3 ± 5.5 to 179.3 ± 6.5. These improvements were attributed to the ability of MSNs to physically entrap OXY within its pores and chemically stabilize it through hydrogen bonding with surface hydroxyl group.¹⁵ The incorporation of OXY into MSNs also reduced its skin penetration, thereby preserving its UVA filtering efficacy while minimizing the potential risk of toxicity.²⁰

MSN is also used as an ideal support for incorporating metal oxides, such as TiO₂ for photocatalytic applications. The synergy between the high adsorption capacity of the MSN and the photocatalytic activity of TiO₂ significantly enhances pollutant degradation. However, the application of TiO₂ as a photocatalyst has limitations due to its easy aggregation, recombination of charge carriers, and low quantum efficiency. MSN can be a solution for these issues by loading the metal into the mesoporous structure, which helps prevent TiO₂ from aggregating and enhances the specific surface area of TiO₂.⁹¹

MSNs Can Improve Anti-Aging Activity

The inhibition of tyrosinase and the decrease of malondialdehyde (MDA) levels are essential for the anti-aging efficacy of cosmetic products. The inhibition of tyrosinase results in a decrease in melanin content, hence decreasing skin pigmentation.⁹²

This is a crucial function for managing hyperpigmentation, a condition caused by the overproduction and accumulation of melanin. Tyrosinase inhibitors specifically reduce the overproduction of melanin in human skin. Consequently, they have become a major focus in the development of cosmetic formulations.⁹³ The research by Du and Liu (2021)⁹³ shown that the pigmentation-inhibiting properties of glabridin were markedly improved when encapsulated in MSN functionalized with the cell-penetrating peptide Ada-R8 (Glabridin/MSN) in contrast to free glabridin. The topical administration of Glabridin/MSN resulted in a significant reduction in pigmentation within two weeks. This effect was significantly more pronounced than that of free glabridin, which exhibited only a minor decrease in pigmentation. The total melanin concentration in melanocytes treated with Glabridin/MSN was significantly diminished ($P < 0.01$), resulting in a more substantial reduction compared to cells treated with free glabridin ($P < 0.05$). Consequently, the anti-aging efficacy of glabridin-loaded MSN surpasses that of free glabridin. Moreover, anti-aging properties are linked to MDA. MDA serves as a biomarker for lipid peroxidation and oxidative stress, resulting from the interaction of lipids with free radicals.⁹³ It subsequently induces tissue photoaging.⁹⁴ The research by Huang et al (2024)⁶² demonstrated a significant reduction in MDA levels in both nano-peptide-1-conjugated MSN with epigallocatechin-3-gallate (EGCG/MSN) and free epigallocatechin-3-gallate (EGCG) compared to the positive control group. Nonetheless, the MDA content in EGCG/MSN is inferior to that of free EGCG. Moreover, MSN enhances the anti-aging efficacy of cosmetic formulations by augmenting skin penetration. The ex-vivo investigation by Arshad et al (2024)⁸ demonstrated that encapsulating azelaic acid within MSN (AZA/MSN) markedly improves skin permeability relative to free AZA. AZA/MSN also improves the stability of AZA in cosmetic formulations.

MSNs Can Improve Antioxidant Activity

MSNs have significant potential to enhance the antioxidant activity of bioactive compounds through encapsulation and protection mechanisms. Sapino et al (2015)⁶⁶ reported that quercetin—a well known flavonoid—have strong antioxidant properties, exhibited improved stability and bioavailability when loaded into aminopropyl/MSN. The encapsulation not only protected quercetin against UV-induced photodegradation but also promoted its accumulation in the skin layers in ex vivo porcine skin models, demonstrating enhanced dermal delivery without systemic permeation. The other study, Mai et al (2017)⁸³ demonstrated the ability of MSNs to preserve antioxidant capacity of vitamin E acetate (VE) over time, even after exposure to oxidative conditions. MSNs structure provided a confined environment that shielded the sensitive vitamin from degradation, as confirmed by DPPH radical scavenging assays, where VA-loaded MSNs maintained superior antioxidant activity compared to pure VE. Furthermore, the functionalization of MSNs with amino groups not only facilitated efficient loading but also contributed to a controlled and pH-responsive release profile, thereby enhancing the practical applicability of the antioxidant system.

MSNs Can Improve Deodorant Activity

Underarm malodor is generated through the biotransformation of secretions, driven by an increased number of apocrine sweat glands and the activity of microorganisms inhabiting the underarm region. The primary microorganism responsible is *Staphylococcus haemolyticus*, which produces a strong, acrid odor.⁹⁵ Malodor-producing bacteria can be treated using natural fragrances, which possess both antibacterial properties and odor-masking effects. Hu et al (2021)⁹⁵ investigated the use of citronellol (CI) essential oil as an active ingredient with broad-spectrum antibacterial activity. CI was incorporated into mesoporous organosilica nanoparticles functionalized with chitosan (D-MON@CS), resulting in enhanced antibacterial efficacy compared to the free form. This improvement is attributed to the large pore volume of the mesoporous organosilica nanoparticles (MON), which enables efficient encapsulation of CI molecules and provides a high loading capacity. The pH-responsive behavior of the system was also examined, revealing significantly increased antibacterial activity at pH levels below 6.5, leading to near-complete bacterial elimination. Furthermore, D-MON@CS facilitated the sustained release of CI, enhancing antibacterial performance through both pH and redox responsiveness. Thus, the incorporation of citronellol into mesoporous organosilica nanoparticles demonstrated superior deodorizing activity compared to the free form.⁹⁵

MSNs Can Improve Anti Dental Erosion Activity

Exposure of dental tissue to acidic substances, in the absence of microbial involvement, results in an irreversible, localized, chronic, and asymptomatic loss of enamel, known as dental erosion. Dental erosion is commonly treated using

fluoride or calcium-based compounds. A study conducted by Canto et al (2020)⁸⁸ demonstrated that MSNs can enhance the chemical and physical properties of dental erosion treatments by improving their mechanical and thermal stability.

Three-dimensional profilometry was used to evaluate the condition of the samples before and after acid exposure, as well as the effects of various anti-erosive active ingredients. Notably, Ca²⁺ incorporated into MSNs was more effective in preventing enamel loss compared to the control group. This increased efficacy may be attributed to the high surface area-to-volume ratio of the Ca²⁺-loaded MSNs. Overall, the study yielded promising results, with Ca²⁺-MSNs emerging as a novel and highly effective compound in comparison to conventional agents such as TiF₄ and NaF.⁸⁸

Discussion

Cosmetic formulations continue to be improving. However, most conventional cosmetic products still encounter restrictions, including low solubility, poor stability, and a high potential for adverse effects. The limitations could be addressed by incorporating AS into MSN. MSNs have small particle sizes which lower the size of AS and enhance the surface area of the AS.^{5,6} The higher the surface area, the higher the cosmetics effectiveness, such as UV protection, anti-aging effects, antioxidant activity, deodorant action, and protection against dental erosion. Therefore, MSNs have been utilized as advantageous nanocarriers in cosmetics due to their high stability, biocompatibility, capacity to encapsulate and regulate the release of active compounds, and enable the sustained release of active agents.¹³

MSNs are effective nanocarriers that can reduce the absorption of AS due to their small particle size.^{15,89} MSNs also reduce irritation by preventing direct contact between AS and the skin or other sensitive tissues.⁹³ MSNs protect AS from environmental factors such as light, heat, and humidity that can accelerate its degradation. Encapsulating AS with MSNs provides a barrier that keeps AS stable and prevents direct contact with factors that cause degradation.⁹⁰

The first effect to be observed is UV protection as shown in Figure 5a. MSNs could be used as carriers for AS, which has UV-photoprotection activity. AS, which is encapsulated into MSN, has a small particle size compared to AS alone. The small particle size enhanced the surface and contact area of AS/MSN on the skin; thereby, UV-photoprotection activity could be increased. Although the surface and contact area are enhanced, MSNs reduced the penetration of AS,

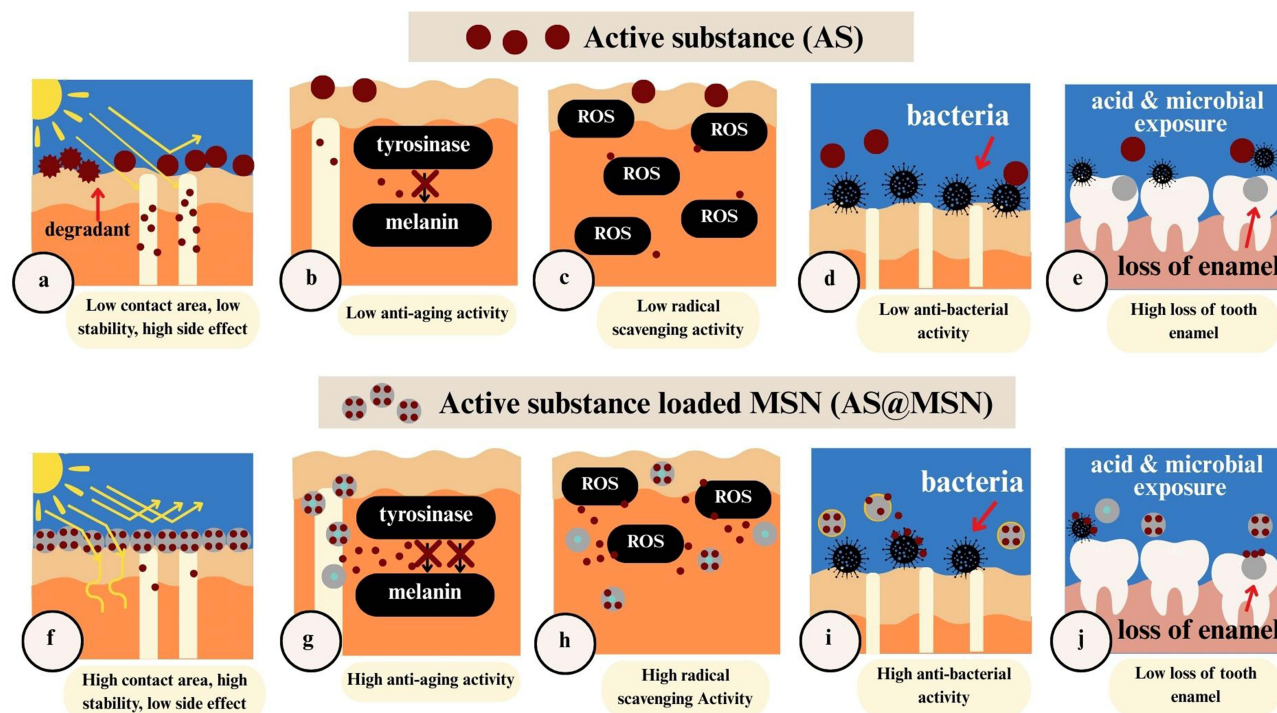


Figure 5 Mechanism of action of AS (panels a–e) compared to AS/MSNs (panels f–j), showing their effects as UV photoprotector (a and f), anti-aging (b and g), antioxidant (c and h), anti-perspirant and deodorant (d and i), anti-dental erosion (e and j). Yellow arrows = UV rays; black arrows = biological pathways; red arrows = microbial/degradative activity; red crosses = inhibition.

which is toxic if absorbed through the skin.^{15,89} Moreover, MSNs themselves can reflect and scatter UV rays on the skin, which protects the AS from degradation.⁹⁰ Without encapsulation of AS into MSN, AS has a larger particle size and more agglomerate on the skin; thereby, the surface and contact area of AS on the skin were reduced, which lowered the effectiveness of AS as a UV photoprotector.

MSNs mechanism on improving anti-aging action, as shown in [Figure 5b](#), is slightly different from their mechanism in UV protection. In anti-aging applications, MSNs were often used with polymer functionalization. The polymer functionalization increased the penetration of AS/MSN into the skin. By encapsulating AS into MSN with polymer functionalization, the particle size of AS was reduced, the surface and contact area of AS were increased, and the penetration of AS into the skin was increased. The higher penetration of AS/MSN into the skin leads to increased tyrosinase inhibition activity, thereby significantly reducing melanin production.⁸ Additionally, oxidative stress markers that trigger melanin production, such as malondialdehyde (MDA), are also reduced.⁶² These oxidative stress markers have also been utilized to trigger the controlled release of AS from functionalized MSNs.⁹³ The reduction of melanin production by inhibiting tyrosinase and decreasing MDA production increased the anti-aging activity of cosmetics.

A similar enhancement is observed in the antioxidant activity of AS when encapsulated in MSNs where the functionalization increases AS penetration into the skin as shown in [Figure 5c](#). In antioxidant applications, MSNs were also often used with polymer functionalization to increase the penetration of AS/MSN. The higher the penetration of the AS/MSN, the more AS interacts optimally with reactive oxygen species (ROS), which are produced during cellular metabolism. Interaction between AS and ROS neutralized the ROS and decreased oxidative stress; thereby, the cells were protected from damage. Consequently, the radical scavenging activity of AS/MSN is higher than free AS.⁹⁶ In addition, MSNs protect AS when applied to the skin, increasing its stability before penetration.⁸³

MSNs improve deodorant properties by prolonging the effectiveness duration of antibacterial agents which work by inhibiting malodor-producing bacteria as shown in [Figure 5d](#). This inhibition depends on pH and redox responsiveness, thereby functionalization using polymer created based on that. As pH decreases, the polymer coating expands, leading to a sustained release of antibacterial agents. In addition, redox responsiveness occurs due to glutathione (GSH) produced by malodor-producing bacteria, which cleaves disulfide bonds within MSNs which then triggers antibacterial agent release.⁹⁵

In dental care, AS-MSNs significantly reduce dental erosion by protecting the active substance from harsh conditions of the mouth such as pH and microbial invasion as shown in [Figure 5e](#). It leads to reducing tooth structure loss (TSL). Additionally, MSNs also have good biocompatibility with calcium and phosphate ions which function as tooth remineralization.⁸⁸

Despite the significant advantages of using MSNs as nanocarriers, their widespread commercial use in cosmetics depends on overcoming several critical limitations. While studies show promising results regarding their efficacy in enhancing UV protection, anti-aging, and other properties, a more critical perspective on their long-term safety profile is essential. The potential for nanoparticle accumulation and unintended cellular interactions due to their size, and the lack of standardized toxicity testing for nanomaterials in cosmetic formulation, present significant safety and regulatory hurdles. Additionally, the high cost and complex processes for synthesizing MSNs with uniform properties make scaling up for mass production a major economic challenge. These factors contribute to a significant barrier for their adoption in the consumer market, as they can lead to higher product costs and a need to address consumer concern regarding the safety of nanotechnology. Future research should focus not only on optimizing the performance of MSNs but also on developing cost-effective and scalable production methods. It is equally crucial to establish robust, long-term safety data that can comply with regulatory standards and build public trust.

Overall, MSNs significantly enhance cosmetic efficacy compared to conventional formulations due to their distinctive characteristics, including the encapsulation and protection of active substances, improved skin transport, and facilitated controlled release. The processes through which MSNs augment efficacy are intricately linked to the particular functionalities of the cosmetic goods. Consequently, additional research is required to investigate the influence of cosmetic formulations and functionalization procedures on the efficacy of MSNs.^{13,66,97}

Future Perspective

The surface functionalization of MSNs offers a promising direction for the advancement of cosmetic formulations. By modifying functional groups such as amino, carboxyl, or cyclodextrin derivatives, the interaction between the nanoparticle matrix and bioactive compounds can be effectively enhanced. This strategy not only improves the protection and delivery efficiency of sensitive molecules but also allows for controlled localization at the skin surface or deeper layers. Immediate-release systems may benefit from high-porosity structures that facilitate rapid diffusion, while sustained-release formulations can employ narrower pores or stronger binding interactions to slow down the release of active compounds.

Future development of MSNs in cosmetics should focus on functionalization strategies that enable personalized skincare. Surface chemistry can be specifically modified to match different skin types, conditions, or even molecular biomarkers, MSNs could enable customized skincare solutions with improved efficacy and safety. Additionally, stimuli-responsive MSN systems offer a opportunity to create truly “smart cosmetics.” These carriers can be designed to release active ingredients in response to endogenous signals such as skin pH shifts, oxidative stress, or bacterial redox activity, as well as exogenous triggers like light or temperature. These responsive mechanisms allows on-demand delivery, thereby enhancing therapeutic outcomes while minimizing side effects. Broadening these approaches across different cosmetic actives could transform conventional formulations into adaptive, intelligent systems that dynamically interact with the skin’s microenvironment. Future studies should explore dual-functional MSNs in cosmetics that not only stabilize and protect sensitive actives from degradation or unwanted skin penetration, but also enable controlled and stimuli-responsive release under specific skin conditions, thereby enhancing efficacy, prolonging activity, and ensuring greater consumer safety. Future studies should prioritize clarifying the distribution and retention of MSNs within different skin layers, as well as their ability to maintain long-term stability of sensitive cosmetic actives in complex formulations, to ensure both efficacy and durability of MSN-based skincare products. Standardized regulatory frameworks specific to nanomaterials in cosmetics, alongside long-term toxicological and environmental assessments, are essential to ensure safe and sustainable application. By addressing these scientific, technological, and regulatory challenges, MSN-based cosmetics have the potential to usher in a new era of personalized, stimuli-responsive, and high-performance skincare solutions.

Conclusion

The application of MSNs in cosmetics significantly enhances the efficacy of conventional formulations. Their ability to encapsulate and protect active compounds, improve skin absorption, and regulate release has been evidenced in several cosmetic applications, including UV protection, anti-aging, antioxidant properties, deodorization, and dental care. MSNs exhibit significant potential to enhance the stability of sensitive chemicals due to their adjustable pore structure, increased surface area, and customizable surface chemistry. Furthermore, functionalized MSNs have facilitated more precise distribution and extended benefits while minimizing discomfort and systemic absorption. Consequently, MSNs demonstrate considerable promise as advanced carriers for the advancement of future cosmetic formulations. Future studies should prioritize addressing safety concerns, long-term stability, large-scale manufacturing, and regulatory approval to ensure the successful translation of MSN-based formulations into commercially viable cosmetic products.

Acknowledgments

We would like to thank the National Research and Innovation Agency (BRIN, RIIM3) and the Indonesia Endowment Funds for Education (LPDP) for supporting this work. We also would like to thank Universitas Padjadjaran for APC.

Funding

This research was funded by the Indonesia Endowment Funds for Education (LPDP) to Arif Budiman (Hibah EQUITY-WCU Kemdiktisaintek) No. 3898/UN6.3.1/PT.00/2025).

Disclosure

The authors declare no conflicts of interest for this review article.

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