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Review

Recent applications of Traditional Chinese Medicine in cosmetology: a Review

Hanzi Zheng[a], Sicheng Wu[b], Shuhan Wang[c], Benjamin Winkeljann[d, e], Liqiong Liao[b,*], Jian Song[a,*]

[a] *School of Biomedical Engineering, Shenzhen Campus of Sun Yat-sen University, Shenzhen 518107, China*
[b] *Biomaterials Research Center, School of Biomedical Engineering, Southern Medical University, Guangzhou 510515, China*
[c] *Shenzhen Institute for Drug Control, Shenzhen Testing Center of Medical Devices, Shenzhen 518057, China*
[d] *Department of Pharmacy, Ludwig-Maximilians-Universität München, 81377 Munich, Germany*
[e] *Center for NanoScience (CeNS), Ludwig-Maximilians-University München, 80799 Munich, Germany*

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ABSTRACT

Medical cosmetology is a rapidly developing subspecialty of aesthetic medicine that deals with cosmetic issues like pigmentation, skin aging, and adipose deposition. Located between cosmetic surgery and everyday skin and beauty care, the method typically has a high safety profile, few adverse effects, and a quick recovery time. Nevertheless, there are still concerns about the biocompatibility of some of the cosmetic ingredients, as well as the problem of possible safety and the prevalence of allergic reactions. To overcome these limitations, traditional Chinese medicine (TCM) herbs, which are natural plant-based, are considered as safe and biocompatible. The focus of this review is to understand the molecular and biological pathways and therapeutic targets of the most common issues in medical cosmetology. We then review existing literature on TCM herbs and their active constituents that target these conditions. Additionally, recent achievements in the study and practical application of TCM herbs using modern transdermal drug delivery systems (TDDS) are presented. This paper, as a review, offers an innovative approach to the combination of TCM herbs and modern biomedical engineering strategies to be used in medical cosmetology.

1. Introduction

Medical cosmetology is a sub-specialty of medicine, involving the combination of clinical and aesthetic cosmetic solutions to dermatological issues and aesthetic changes, including therapeutic and preventive strategies that are based on evidence-based medicine. It is a multidisciplinary specialty that employs the most innovative regenerative medicine technologies, such as cellular therapies, biocompatible scaffold matrices, and growth factors to repair, regenerate, and improve human appearance and physiologic functioning. This holistic method fills the gap between clinical dermatology and aesthetic medicine, and eventually reaches a harmony between therapeutic efficacy and aesthetic outcomes [1, 2].

Recent scientific and technological developments have transformed the medical cosmetology field as it has been able to treat a wide range of skin problems that act as indicators of mental as well as physical health. Anti-aging [2-4], hair loss prevention [5], skin whitening [6], adipose reduction [7], wrinkle removal [8, 9], and acne treatment [10]are common aesthetic concerns. Such aesthetic expressions are essentially a result of changes in gene expression and protein levels in the human body, which causes observable changes in appearance. To combat this, a range of therapeutic compounds and active ingredients have been used in the medical cosmetology procedures and cosmetic products. Organic agents such as hydroquinone, azelaic acid, and kojic acid, for example, work by inhibiting tyrosinase activity and thereby lowering melanin synthesis to achieve skin brightening and a younger-looking appearance [11]. Nevertheless, these substances are usually associated with cytotoxicity and often lead to localized acute inflammatory responses in the skin, which is manifested in rashes and itching. This has led to growing interest in alternatives that are gentler and more biocompatible yet still therapeutically effective [12].

Traditional Chinese medicine (TCM) herbs are considered potential promising candidates in medical cosmetology due to their natural origin and increased biocompatibility. These herbs possess a range of active constituents, such as polyphenols, saponins, alkaloids, terpenoids, and polysaccharides, that display a variety of physiological functions desirable in cosmetic use [13]. The challenges confronting TCM herbs include poor stability, low efficiency in transdermal delivery, and lack of pharmacological effect which have historically constrained their wider use despite their potential.

To address these shortcomings, scientists have created novel methods that revolve around two key points: altering TCM herbs and their growing environment and the construction of advanced drug delivery systems [13]. Such delivery systems can be categorized based on their carrier mechanisms, including liposomes and nanoparticles (colloidal systems), hydrogels and dendrimers (polymeric systems), and nanotechnology-based solutions. The therapeutic efficacy of these sophisticated delivery systems is increased by better control of pharmacokinetic parameters, augmented stability and solubility profiles, more precise targeting of

* Corresponding author.
E-mail addresses: liqiongliao@hotmail.com (L. Liao); songj67@mail.sysu.edu.cn (J. Song)

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the affected tissues, and minimized off-target toxicity. It is also worth mentioning that the combination of TCM herbs with these sophisticated delivery mechanisms creates a possibility to implement in-hospital grade medical cosmetology care to home-based care plans and that this may serve as an alternative to the traditional cosmetic surgical care.

This review synthetically analyzes the molecular biological basis of the major aesthetic issues, namely, skin aging, hyperpigmentation, and the local accumulation of adipose tissues. It then elaborates the recent studies on TCM herbs and their bioactive compounds targeting these specified molecular pathways in the field of medical cosmetology. The research is based on 10 years of empirical data, which gives clear records of the TCM herbal treatment of the three aesthetic issues. The review also examines advanced delivery systems that have been developed to improve the dermal and subcutaneous absorption of TCM herbs. It is necessary to mention that, due to the limitation of the scope, this study specifically focuses on the three main aesthetic issues, including skin depigmentation, anti-aging effects, and adipose tissue reduction.

2. Molecular mechanisms and TCM approaches in medical cosmetology

This section discusses three core elements of medical cosmetology in which TCM shows potential therapeutic effects, namely skin lightening, anti-aging and localized fat reduction. In each domain, the relevant molecular mechanisms are first delineated to explain these aesthetic concerns, after which the pathway-modulating actions of specific TCM interventions are analyzed. This systematic investigation demonstrates the interactions between different TCM formulations (complex herbal preparations and isolated bioactive compounds) and cellular signaling networks to produce desirable cosmetic effects.

2.1. Skin lightening

2.1.1. Mechanism of pigmentation

The color of the human skin is strongly linked to the level and distribution of the melanin synthesized by melanocytes. Melanocytes are melanosome-producing cells found in the basal layer of the dermal-epidermal junction. Melanin and other skin pigments are produced and accumulated in melanosomes, which are intracellular, lysosome-like organelles found in melanocytes (Fig. 1A) [14]. After being produced, melanin is transported and delivered to adjacent keratinocytes, which gives skin color. Previous studies have proposed four different models explaining the transfer of melanin from melanocytes to keratinocytes, as described in Fig. 1B [15]. The amino acid L-tyrosine acts as the precursor for melanin biosynthesis and produces melanin through various spontaneous enzymatic reactions, also known as the Raper-Mason pathway. Within this pathway, L-tyrosine increases melanosome production, and L-dopachrome enhances tyrosinase activity, both of which exert a major influence on the homeostasis of melanogenic systems [16]. Tyrosinase, a glycoprotein (M_w = 60–70 kDa) containing copper, acts as the rate-limiting enzyme in the melanin biosynthesis pathway and is therefore considered a potential target for several therapeutic agents. Tyrosinase, tyrosinase-related protein-1 (TRP-1), and TRP-2, all involved in melanogenesis, are regulated by the master transcription factor known as microphthalmia-associated transcription factor (MITF). The MITF-mediated melanogenesis process is regulated through four major signaling pathways: the Wnt/glycogen synthase kinase 3 beta (GSK3β) pathway, the alpha-melanocyte-stimulating hormone (α-MSH)/cyclic adenosine monophosphate (cAMP) pathway, the nitric oxide (NO)/cyclic guanosine monophosphate (cGMP) pathway, and the mitogen-activated protein kinase (MAPK) pathway.

2.1.2. TCM for treating skin hyperpigmentation

Tyrosinase inhibitors, represented by hydroquinone, kojic acid, and azelaic acid, have been widely used for the treatment or management of site-specific skin hyperpigmentation and are incorporated into cosmetic formulations such as creams and gels. However, such chemical inhibitors demonstrate non-selective intracellular cytotoxicity and contact dermatitis in previous studies [17, 18]. Natural-source agents, particularly those derived from TCM, encompass a broad range of natural products and generally exhibit fewer adverse effects, thereby representing ideal alternative candidates for cosmetic skin-whitening therapy.

Glycyrrhiza glabra L. (Fabaceae), commonly known as Gancao in TCM, is naturally distributed throughout temperate and subtropical regions of Eurasia, from Central and Western Asia to Europe, China, Mongolia, and the Russian Far East. Within the genus *Glycyrrhiza*, three species (*G. glabra* L., *G. uralensis* Fisch., and *G. inflata* Bat.) are particularly notable for their medicinal value. Their dried roots and rhizomes, officially recognized as Glycyrrhizae Radix et Rhizoma (licorice) in pharmacopoeias, possess significant dermatological properties, including skin lightening, anti-aging, anti-inflammatory, and photoprotective effects, primarily attributed to their potent antioxidant activity [19]. Active ingredients isolated from licorice, including glycyrrhizin, liquiritin, and glabridin, are effective tyrosinase inhibitors and downregulate the expression of melanogenesis-related factors, including MITF, TYR, TRP-1, and TRP-2. It is reported that the extract of *G. glabra* L. inhibits tyrosinase activity by suppressing the oxidation of levodopa (L-DOPA) with an IC_{50} value (the concentration of the inhibitor required to reduce enzyme activity by half) of 53 $\mu g \cdot mL^{-1}$ [20]. Among these, glabridin, a major hydrophobic flavonoid isolated from the root extract of *G. glabra L.*, exhibits the highest tyrosinase inhibition activity among the tested compounds. This bioactive compound effectively decreases tyrosinase activity in cultured melanocytes and inhibits ultraviolet B (UVB)-induced melanogenesis. Molecular docking analysis revealed that glabridin binds to both tyrosinase and MITF through

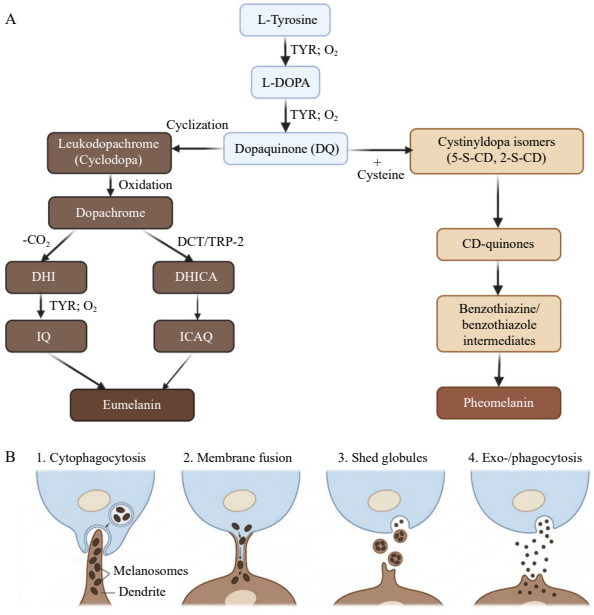

Fig. 1 Melanin biosynthesis and transfer mechanisms. (A) Pathways of melanin biosynthesis (Raper-Mason pathway), in which dopaquinone serves as a key branching intermediate leading to eumelanin and pheomelanin formation. (B) Four proposed models of melanin transfer from melanocytes (dark-colored) to keratinocytes (light-colored): (1) cytophagocytosis of melanocyte dendrite tips containing melanosomes; (2) direct membrane fusion-mediated transfer; (3) shedding of melanosome-containing globules; and (4) exocytosis/phagocytosis of released melanin cores.

hydrogen-bond interactions, thereby reducing melanogenesis by suppressing the PKA/MITF and MAPK/MITF signaling pathways [21].

Panax ginseng C.A.Mey., commonly known as Renshen, has been a cornerstone of traditional medicine in East Asia for millennia, particularly valued in TCM. The aqueous extracts of *P. ginseng* roots contain bioactive phenolic compounds, including protocatechuic acid, vanillic acid, p-coumaric acid, salicylic acid, and caffeic acid, which have demonstrated significant skin-lightening properties. These compounds inhibit melanocyte melanogenesis by reducing the expression of melanogenic enzymes tyrosinase, TRP-1, and TRP-2, as well as their master transcriptional regulator MITF [22]. Vanillic acid, the most abundant phenolic acid in ginseng root extract, inhibits nitric oxide synthase (NOS) activity and decreases NO production, thereby reducing guanylate cyclase (GC) activity, cGMP levels, and protein kinase G (PKG) activity. This cascade ultimately suppresses melanin synthesis by decreasing p-CREB expression and downregulating MITF, TYR, TYRP-1, and TYRP-2 [23]. Salicylic acid, another representative phenolic acid, not only inhibits melanogenesis but also suppresses the expression of transport complex-associated proteins melanophilin and myosin Va, thereby inhibiting melanin transport and keratinocyte phagocytic function, ultimately inducing anti-melanogenic effects [24, 25].

Aloe species (Asphodelaceae), particularly *A. vera* (L.) Burm.f. and *A. arborescens* Mill., have been extensively used in the cosmetic industry as skin whitening agents. The succulent leaves of these species contain tyrosinase inhibitors such as aloesin, aloin, and plicataloside [26, 27]. Aloesin, an aromatic C-glucosylated 5-methyl chromone, has been proven to be a competitive inhibitor of tyrosinase from mushroom, human, and murine sources, modulating melanogenesis through competitive inhibition. Additionally, aloesin inhibits tyrosinase when L-DOPA is used as a substrate and inhibits tyrosine hydroxylase activity when L-tyrosine is the substrate [28]. This unique dual mechanism of action is not observed in other commercial depigmenting agents. Aloin, an anthraquinone glycoside also known as barbaloin, acts as a potent mixed-type inhibitor of mushroom tyrosinase. It induces melanin aggregation in isolated melanophores of tadpoles *via* α-adrenergic receptor (α-AR) stimulation, leading to skin lightening. Plicataloside, a naphthalene derivative isolated from South African *Aloe* species, was first identified as a novel inhibitor of mushroom tyrosinase by Alvaro and co-workers [27]. Molecular docking simulations indicate higher tyrosine docking scores for aloesin than for plicataloside, elucidating its superior tyrosinase inhibition effects.

Other TCM herbs include: (1) *Curcuma longa* L. (Zingiberaceae), commonly known as turmeric, which contains curcumin that inhibits tyrosinase activity by suppressing L-DOPA oxidation [29]; (2) *Camellia sinensis* (L.) Kuntze (Theaceae), commonly known as green tea, which contains (−)-epigallocatechin-3-gallate (EGCG), (−)-epigallocatechin (EGC), and (−)-catechin (C), all of which significantly inhibit melanin synthesis through direct tyrosinase inhibition and downregulation of tyrosinase expression [30]; (3) *Blumea lacera* (Burm.f.) DC. (Asteraceae), which contains various flavonoids and phenolics, such as caffeic acid, rosmarinic acid, and *p*-coumaric acid, that exhibit significant tyrosinase inhibition activity [31]; (4) *Phyllanthus emblica* L. (Euphorbiaceae), which contains gallic acid and vanillic acid that possess strong anti-oxidative activity and inhibit the messenger ribonucleic acid (mRNA) expression of tyrosinase, TRP-1, and TRP-2, demonstrating significant tyrosinase inhibition [32]; (5) *Magnolia officinalis* Rehder & E.H.Wilson (Magnoliaceae), which contains various phenolics whose extract exhibits enhanced anti-tyrosinase and antioxidant activity following *Aspergillus niger* fermentation [33]. Furthermore, additional studies on TCM herbs with potential for skin lightening applications are summarized in Table 1.

2.2. Skin anti-aging

2.2.1. Mechanism of skin aging

Skin aging is a multifactorial biological process macroscopically manifested by reduced structural integrity and loss of physiological functions [34]. The formation of wrinkles and fine lines, collapse of skin tissue, sagging due to loss of elasticity, and dryness are the most common phenotypic changes in aging skin. Current classic theories on the mechanism of skin aging include the free radical and oxidative stress theory, the inflammatory aging theory, and the photoaging theory. These main theories are briefly described below and graphically summarized in Fig. 2.

Free radicals and oxidative stress theory: Free radicals are among the primary causes of diminished bodily function and skin aging. Reactive oxygen species (ROS) are unstable oxygen-containing molecules that readily react with other cellular components. Continuously generated as by-products of mitochondrial aerobic metabolism in the electron transport chain, ROS are considered major contributors to intrinsic aging [35]. The overload of ROS disrupts mitochondria and deoxyribonucleic acid (DNA) structure, leading to cell dysfunction, impaired replication, and depleted collagen in the extracellular matrix (ECM), and thus contributing to aging and wrinkle formation in the skin [36]. As skin ages, the expression of matrix metalloproteinases (MMPs) increases [25]. MMPs facilitate cellular signaling through the degradation of different protein components and the regulation of matrix signaling events within the ECM. An increase in MMP expression and a reduction in tissue inhibitors of metalloproteinases (TIMPs) characterize aging fibroblasts [37].

Inflammation theory: Cellular senescence and skin aging are largely caused by inflammation. Skin aging, a type of organ aging, is often accompanied by inflammatory processes, and the molecular patterns of inflammation stimulate cellular senescence, which, in its turn, increases the inflammation and causes a vicious cycle, called “inflammaging” [38]. The accumulating process of molecular and cellular inflammaging might result in pathological aging of the organs. Senescent fibroblasts and keratinocytes secrete numerous pro-inflammatory cytokines, including interleukins (interleukin (IL)-1α, IL-1β, IL-6), chemokines (e.g., CXCL, CCL), and growth factors (e.g., EGF, FGF2, HGF), collectively termed the senescence-associated secretory phenotype (SASP), which plays a crucial role in driving inflammaging and represents a potential target for anti-aging interventions [39]. This procedure provokes the enhanced production of MMPs, the enzymes that break down collagen, which prompts the dermal structural changes that are manifested by the skin laxity and the formation of wrinkles.

Photoaging theory: Together with intrinsic aging, external factors such as ultraviolet (UV) radiation from sunlight contribute critically to the process of skin aging [35, 40]. UV radiation triggers the generation of ROS and directly inflicts photodamage on DNA, RNA, and proteins, causing molecular damage and impairment of local neuroendocrine axes [41]. It also provokes MMP secretion by the keratinocytes and fibroblasts, destroying dermal ECM components including collagen and accelerating skin aging and cell aging [42, 43].

According to the description of both intrinsic and extrinsic aging factors above, there are at least three main ways to attain skin anti-aging actions: (1) preventing the generation of ROS, thereby suppressing cell oxidative stress; (2) regulating cutaneous and systemic inflammatory responses; and (3)raising collagen concentration and inhibiting MMPs, which diminish protein breakdown in the ECM.

2.2.2. TCM for skin anti-aging

Skin aging is closely associated with the induction of oxidat-

Table 1 Traditional Chinese medicines and their active components that inhibit or promote pigmentation, together with their mechanisms of action.

No.	Source plants	Active ingredient	Experiment materials (Cells/animals)	Mechanism of action	References
			Inhibit pigmentation		
1	*Vaccinium vitis-idaea*	Arbutin	SK-MEL-1	Inhibit TYR activity	117
			melanocytes	Inhibit TYR activity	118
		Aloesin	human skin	Inhibit hyperpigmentation induced by UV radiation	119
2	*Aloe vera*	Aloin	N.A.	Inhibit TYR activity	120
		Plicataloside	N.A.	Inhibit TYR activity	27
		Heated extract	B16F10	Down-regulate TYR	121
3	*Glycyrrhiza uralensis*	Licochalcone A	B16	Activate p-ERK, inhibit MITF, downregulate TYR expression	122
		Glycyrrhiza acid, licochalcone A	HaCaT, melanocytes, B16, C57BL/6	Inhibit melanogenesis and TYR expression	105
		Ginkgolic acid	N.A.	Inhibit mushroom TYR activity	123
4	*Ginkgo biloba*	EtOH extract	B16F10	Decrease MITF, TYR, TRP-1, decreased p-Akt and p-GSK3; inhibit α-MSH-induced melanogenesis	124
		Glycosides	N.A.	Inhibit mushroom TYR activity	125
		EtOH extract	B16F10, HaCaT	Down-regulate MITF expression, inhibit melanogenesis	126
5	*Pueraria thunbergiana*	Calycosin	N.A.	Inhibit mushroom TYR activity	127
		EtOH extract	B16F10	Increase phosphorylation of GSK-3β, down-regulate MITF; Akt/GSK-3β pathway	128
6	*Phyllanthus emblica*	Extract powder	B16F10	Down-regulate MITF, TYR, TRP-1, TRP-2	129, 32
		EtOH extract	B16	Inhibit mRNA expressions of TYR, TRP-1, TRP-2	130
7	*Curcuma longa*	Curcumin Derivative J147	B16F10, HaCaT, melanocytes, zebrafish, and guinea pigs	Degrade EKR-induced MITF, down-regulate TYR, TRP-1, TRP-2, Myosin Va, Rab27a and Cdc42 expression, decrease melanocyte dendricity extension and melanosome transport	131
8	*Vitis vinifera*	Resveratrol	HEMs, B16F10	Inhibit human TYR	132
			Promote pigmentation		
9	*Paeonia lactiflora*	Paeoniflorin	Melanocytes, C57BL/6	Up-regulate MITF, TRP-1; ERK/CREB pathway	133
10	*Sanguisorba officinalis*	Kaempferol	B16F10, Melan-A, SK-MEL-28, normal epidermal tissues, zebrafish	Up-regulate TYR, TRP-1, DCT, MITF, increase dendrite length and cell migration; PI3K/AKT and P38/ERK/MAPK pathway	134
11	*Gynostemma pentaphyllum*	Saponins	B16, B16F10	Up-regulate TYR, MITF, TRP-1, TRP-2, up-regulate p-CREB, β-catenin, p-GSK3β(Ser9) expression; cAMP/PKA and Wnt/β-catenin pathway	135
12	*Glycyrrhiza glabra*	Glycyrrhizin	B16	Increase TYR mRNA, protein and enzyme activity, TRP-2 mRNA	136

ive stress in dermal fibroblasts [36]. Therefore, TCM and its bioactive compounds that mitigate oxidative damage in dermal fibroblasts represent promising candidates for anti-skin-aging agents in cosmetic products.

Astragalus membranaceus (Fisch. ex Link) Bunge (Fabaceae), commonly known as Huangqi in TCM, has been used in TCM for over two millennia to slow skin aging [44]. Chemical analysis of *A. membranaceus* roots has revealed its primary bioactive constituents: astragalosides (cycloartane-type triterpene tetracyclic saponins), astragalans (polysaccharides), and calycosin (the predominant flavonoid). Astragalus polysaccharides (APS) delay aging, scavenge free radicals, and alleviate oxidative stress [45]. Astragaloside IV-treated adipose-derived stem cells (ADSCs) markedly reverse the UVB-induced decrease in type I procollagen (PC-I) secretion and increase in MMP-1 release in fibroblasts by promoting cell proliferation and stimulating robust growth factor secretion from ADSCs [46].

Scutellaria baicalensis Georgi (Lamiaceae, SBG), whose dried roots are known as Huangqin in TCM, has been used for its anti-inflammatory, anti-viral, anti-cancer, antioxidant, and anti-bacterial properties [47, 48]. Research indicates that SBG extracts reduce intracellular ROS and stimulate the Nrf2/HO-1 pathway, which prevents cellular damage caused by oxidative stress and prevents HaCaT cells exposed to oxidative stress-inducing conditions, including DNA damage and apoptosis [49]. Moreover, flavonoids in SBG extract markedly suppress the gene expression of SASP factors by inhibiting IκBζ- and NF-κB-mediated signaling and preventing the expression of C/EBPβ [50, 51]. The topical application of SBG in animal models of skin aging proves to be protective against skin aging in mice as indicated by the reduced wrinkle development, increased superoxide dismutase (SOD) and hydroxyproline (HYP) levels and reduced malondialdehyde (MDA) levels. Moreover, mouse skin treated with SBG has reduced MMP-1 and p53 expression, thinner epidermis, and increased collagen content. Interestingly, the anti-aging effect of SBG can be observed in the regulation of the circadian rhythm factor BMAL1 since it up-regulates the expression of BMAL1, a component of the circadian clock and a well-known anti-aging factor, by antagonizing the expression of REV-ERBα, a recognized BMAL1 inhibitor, which protects against skin aging [52]. These naturally occurring flavonoids regulate SASP production without affecting senescence process itself, providing low toxicity and high safety, mak-

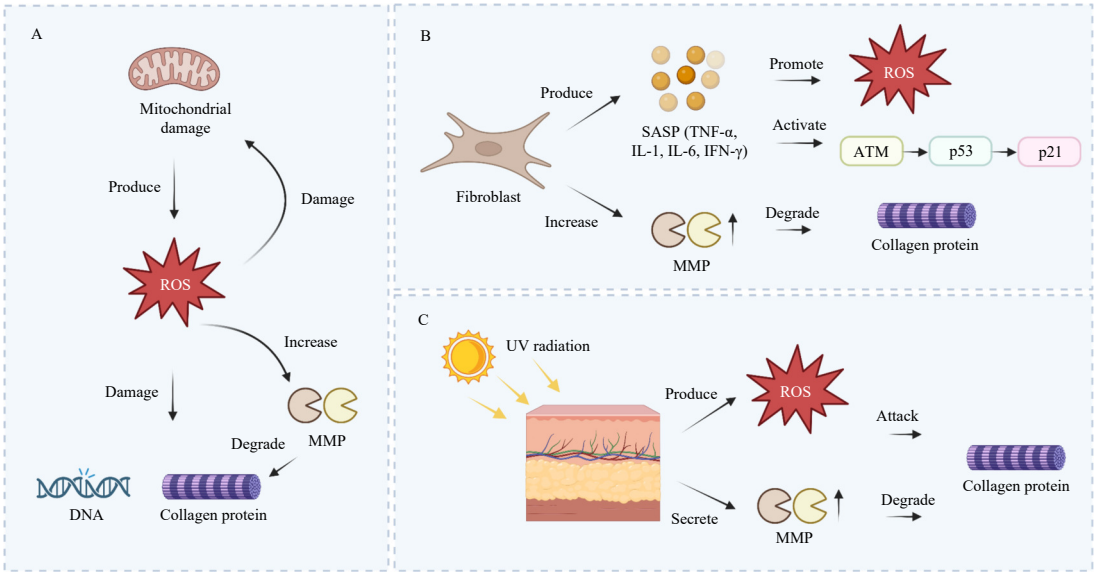

Fig. 2 Mechanisms underlying skin aging. (A) Free radical and oxidative stress theory. Mitochondria produce reactive oxygen species (ROS) through oxidative metabolism. Excessive ROS can damage mitochondrial structures and DNA, leading to decreased collagen levels and increased matrix metalloproteinase (MMP) expression in skin tissue. (B) Inflammation theory. Senescent fibroblasts exhibit a senescence-associated secretory phenotype (SASP), characterized by the secretion of inflammatory factors, including TNF-α, IL-1α/β, IL-6, and IFN-γ. These factors promote ROS production and activate the ATM/p53/p21 signaling pathway, while elevated MMP levels contribute to collagen degradation. (C) Photoaging theory. Ultraviolet irradiation induces ROS production and MMP secretion, which degrade extracellular matrix components of the skin, such as collagen.

ing them attractive as potential inducers of delaying cellular senescence.

Known in TCM as Gotu kola, *Centella asiatica* L. (Apiaceae) is a medicinal herb exhibiting a wide array of pharmacological activities, including antioxidant, anti-inflammatory, wound healing, and neuroprotective properties [53]. Centelloids (asiaticoside, madecassoside, asiatic acid and madecassic acid) are the major bioactive metabolites of *C. asiatica*. *C. asiatica* callus extract (CE) has been demonstrated to trigger the expression of antioxidant enzymes, such as catalase (CAT), glutathione peroxidase 1 (GPx1), and superoxide dismutase 1 (SOD1), which increases the potential of fibroblasts to neutralize detrimental ROS, inhibit oxidative stress, and avoid cell death. Moreover, CE inhibits MMP-9 up-regulation caused by H_2O_2, thus maintaining skin elasticity and integrity and avoiding wrinkle formation and sagging [53]. Phytochemical profiling has shown that *C. asiatica* possesses several bioactive compounds, such as gulonic acid, ferulic acid, kaempferol, chlorogenic acid, and asiatic acid, which together lead to its strong antioxidant activity [54]. In addition, CE has concentration-dependent actions as it profoundly decreases pro-inflammatory cytokines/mediators and oxidative stress. It also successfully lowers high acetylcholinesterase (AChE) activity and inflammation in both *in vitro* and *in vivo* investigations.

Other TCM herbs employed in skin aging include: (1) *Berberis vulgaris* L. (Berberidaceae), often referred to as barberry, which is a source of the active constituent berberine. Research indicates that berberine is a good inhibitor of the TPA-induced ERK activation, leading to reduced AP-1 DNA binding activity and decreased MMP-9 and IL-6 expression in normal human keratinocytes (NHK), thereby preventing skin inflammation and ECM protein degradation [55]; (2) Coptidis Rhizoma (the dried rhizome of *Coptis chinensis* Franch., Ranunculaceae), known as Huang Lian in TCM, which is rich in protoberberine-type alkaloids, including berberine, palmatine, and coptisine, that demonstrate significant antioxidant and anti-inflammatory properties, although their potential toxicity profiles require careful consideration [56]; (3) *Camellia japonica* (Theaceae), which contains kaempferol tri- and tetrasaccharides that inhibit MMP-1 activity in human dermal fibroblasts, indicating its promise as an ingredient in anti-aging skin cosmetics. Moreover, there are TCM herbs that control the activity of other skin components, including elastin degradation and accumulation mediated by elastase [57] and hyaluronic acid turnover mediated by hyaluronidase [58]. Additionally, other studies on TCM herbs that have some possible anti-aging effects on the skin are summarized in Table 2.

2.3. Fat reduction

2.3.1. Mechanism of adipose reduction

Along with obesity, localized fat deposition is another major aesthetic problem. Typical complaints include stubborn fat deposits, such as fatty eyelids [59], submental fat [60], jowls [61], nasolabial fat [62], which are often resistant to reduction and may adversely affect facial and body aesthetics. Therefore, increasing attention has been directed toward therapies aimed at localized fat reduction and body contouring to achieve a slimmer, more aesthetically pleasing, and healthier appearance.

Adipose reduction therapies are based on the breakdown of fats within fat cells, involving a plethora of hormones, peptides, and neurotransmitters that interact with membrane receptors coupled to several GTP-binding proteins to transduce signals [63, 64]. Activation of stimulatory guanine nucleotide-binding proteins (Gs proteins) is the most thoroughly studied mechanism of mediation of lipolysis, and catecholamines, especially adrenaline and noradrenaline, are classical hormonal mediators. Gs proteins are linked to three β-AR subtypes and two α-AR subtypes, with primary expression in white adipose tissue (WAT) and brown adipose tissue (BAT). The Gs/adenylate cyclase/cAMP-dependent protein kinase/hormone-sensitive lipase (Gs/AC/PKA/HSL) pathway is the presentative signaling pathway, which regulates fat breakdown positively through β1-, β2-, and β3-AR activation and negatively through α2-AR. The three β-receptors transmit their activation signals through Gs proteins to AC, leading to enhanced cAMP production. This enhanced cAMP production then activates PKA and results in the phosphorylation and activation of HSL and perilipin A [65, 66]. HSL breaks down triglycerides in adipocytes, producing glycerol and free fatty acids (FFAs). HSL is present as various isoforms with molecular weights of 84-130 kDa and broad substrate specificity and d targets triacylglycerols (TAG), diacylglycerols (DAG), cholesterol esters, and retinyl esters. It is considered the primary enzyme responsible for nearly

Table 2 Traditional Chinese medicines and their active components that exert anti-aging effects through antioxidant activity, MMP inhibition, and promotion of collagen production, along with their mechanisms of action.

No.	Source plants	Active ingredient	Experiment materials (cells/animals)	Mechanism of action	References
1	*Berberis aristata*	Berberine	HDF	Down-regulate MMP-1, type I procollagen	137
2	*Pueraria thunbergiana*	EtOH extract	B16F10, HaCaT	Pro-collagen synthesis, inhibit MMP-1, down-regulate MITF protein	126
		H_2O, EtOH extract	B16F10	Scavenge DPPH, hydroxyl, alkyl radical	128
3	*Astragalus membranaceus*	Polysaccharide	SD rats	Down-regulate MDA, increase SOD activity, and reduce the oxidative damage	45
		H_2O extract	HDF	Inhibit NF-κB P65 and MMP-1 expression and restore procollagen type 1	138
		α-glucan	HaCaT	Scavenge intracellular ROS, mitochondrial membrane potential, alter ATP content	139
4	*Aloe vera*	Extract powder	HaCaT	Prevent photo-oxidation of lipid membranes, protect lysosome membrane, and inhibit lipofuscinogenesis	140
		Sterol	HR-1 mice	Inhibit IL-1β and TNF-α, MMPs (MMP-2, MMP-9, MMP-12, MMP-13)	141
		Polysaccharide	Vero, zebrafish	Scavenge DPPH, hydroxyl, and alkyl radicals and protect against ROS oxidative stress	142
5	*Calendula officinalis*	Extract	HaCaT	Scavenge DPPH and protect against H_2O_2-induced oxidative stress	143
		EtOH extract	L929, HepG2, HRS/J	Scavenge ROS, decrease GSH, MMP-9	144
6	*Camellia japonica*	Oligosaccharide	HSF, Hs68	Inhibit MMP-1 activity	145
7	*Ginkgo biloba*	EtOH extract	N.A.	Scavenge DPPH	146
8	*Ulmus davidiana* var. *japonica*	(−)-Catechin	NHDF	Inhibit MMP-1 activity, suppress TNF-α-induced ROS accumulation and MAPK, Akt, and COX-2 activation	147
9	Rhizoma Coptidis	Berberine	NHEK	Inhibit MMP-9 expression and activity, IL-6 expression, prevent TPA-induced ERK activation and AP-1 DNA binding activity	55
10	*Panax notoginseng*	Metabolites extract	HDF	Scavenge ROS (ABTS, DPPH, FRAP, TPC), up-regulate COLA1, ELN, FEN1 mRNA expression	148
11	*Cordyceps cicadae*	Polysaccharide	*Drosophila*	Up-regulate CAT and GSH-Px activity, inhibit MDA formation, and up-regulate SOD1 and MTH expression	149
12	*Scutellaria baicalensis*	Flavonoid	SD rats	Inhibit IL-6, IL-8, SASP expression; IκBζ and C/EBPβ pathway	51
		EtOH extract	C57BL/6, MDF, NIH3T3, HaCaT, HEKa	Up-regulate SOD, HYP, down-regulate MDA formation, inhibit MMP-1, p53 expression; antagonize REV-ERBα to up-regulate BMAL1	52
13	*Phyllanthus emblica*	EtOH extract	B16, RAW 264.7	Scavenge DPPH	130

all TAG and DAG hydrolase activity and neutral cholesterol ester hydrolase (NCEH) activity in adipocytes [63, 67, 68]. During this process, phosphodiesterase (PDE) hydrolyzes intracellular cAMP generated upon lipolytic stimulation. PDE inhibition elevates intracellular cAMP levels, thus augmenting lipolysis [69]. In general, the lipolysis-stimulating agents are involved in at least three mechanisms of action: β-AR activation, α2-AR inhibition, and PDE/adenosine receptor inhibition.

Another therapeutic target for promoting fat breakdown is the browning of adipose tissue [70] . Mammals contain two major forms of adipose tissue: WAT and BAT. WAT also resides in the visceral and subcutaneous deposits, and its role is to store excess energy as triglycerides, releasing fatty acids into the blood stream when energy is demanded. Overaccumulation of WAT is an obesogenic factor causing metabolic complications that accompany obesity, so it is a primary focus of anti-obesity treatment. In contrast, BAT is specialized at non-shivering thermogenesis and is found predominantly in the interscapular depots of both adults and infants, where it is highly enriched with mitochondria [71]. BAT mitochondria use a unique mechanism involving uncoupling protein 1 (UCP1), unlike typical mitochondria that produce ATP through oxidative phosphorylation. Unlike typical mitochondria that produce ATP *via* oxidative phosphorylation, BAT mitochondria employ a unique mechanism involving uncoupling protein 1 (UCP1). This protein, which is highly expressed in the inner membrane of the mitochondrial structure of BAT, dissociates the process of electron transport with ATP production in the process of respiration. When activated, UCP1 dissipates the proton (H^+) gradient, producing heat and relieving respiratory inhibition by higher ATP/ADP ratios [68, 72]. This thermogenic pathway is activated by the transcriptional co-regulator PRDM16, which forms complexes with proteins like EHMT1. Interestingly, mitochondria-rich adipocytes with UCP1 can also be induced in response to cold exposure or other stimuli within WAT depots; these inducible cells are known as 'beige' or 'brite' (brown-in-white) adipocytes [73]. Beige adipocytes, similar to classical brown adipocytes, have the ability of the transformation of chemical energy into heat. Therefore, measures directed towards the enhancement of WAT browning have attracted immense research interest. Different phytochemicals have been reported to stimulate WAT browning and UCP1-mediated thermogenesis [74-77]. By engaging key mediators such as PRDM16, peroxisome proliferator-activated receptor γ coactivator-1α (PGC-1α), peroxisome proliferator-activated receptor γ (PPAR-γ), SIRT1, adenosine 5'-monophosphate-activated protein kinase (AMPK), and β3-AR, these compounds promote UCP1 transcription, regulate transcription factor activity, and modify enzyme function in metabolic pathways [78]. These two major methods of local fat reduction are shown in Fig. 3.

2.3.2. TCM for localized fat reduction

The aesthetic and therapeutic rationale of localized subcutaneous fat removal has emerged as a more common request in the field of anti-obesity research. Existing systemic weight-loss drugs have focused mainly on energy balance by increasing thermogenesis, increasing metabolic rate, or altering central nervous or digestive systems to decrease appetite, increase satiety, or decrease fat absorption. Conversely, the localized adipose reduction in TCM herbs occurs mainly in the former way, i.e., by facilitating adipose tissue metabolism and thermogenesis, lipid-mobilizing enzymes, and WAT browning [70].

Gynostemma pentaphyllum (Thunb.) Makino (Cucurbitaceae), commonly known as Jiao Gu Lan in TCM, is a perennial creeping

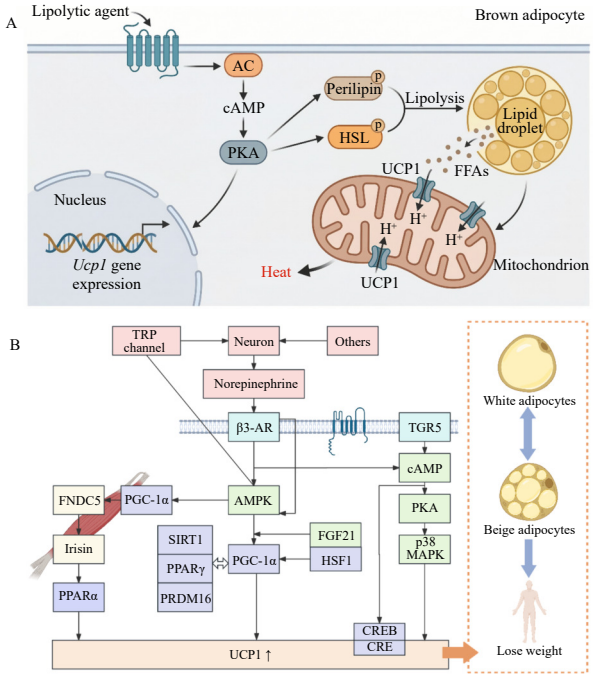

Fig. 3 Mechanisms of fat reduction through G-protein signaling and white adipose tissue browning. (A) Fat reduction therapies act through the Gs/AC/PKA/HSL pathway, in which hormones and neurotransmitters activate membrane receptors, increase intracellular cAMP, regulate α- and β-adrenergic receptors, and stimulate hormone-sensitive lipase to promote triglyceride breakdown in adipocytes. (B) Molecular pathways involved in the browning of white adipose tissue (WAT). UCP1-mediated browning converts energy-storing WAT into metabolically active, heat-generating brown adipose tissue (BAT).

herb of the Cucurbitaceae family. Modern pharmacological studies have identified multiple bioactive properties of *G. pentaphyllum*, including anti-inflammatory, antioxidant, lipid metabolism-regulating, neuroprotective, and anxiolytic effects [79, 80]. Administration of *G. pentaphyllum* extract (GpE) has been reported to stimulate AMPK phosphorylation and SIRT1 expression in high-fat diet (HFD)-induced obese mice, subsequently downregulating PPAR-γ and its downstream targets, such as fatty acid synthase (FAS), adipocyte protein 2 (aP2), HSL, and carnitine palmitoyltransferase 1 (CPT1), ultimately enhancing energy expenditure and promoting fat breakdown [81]. Gypenosides can positively influence glucose and lipid metabolism and increase the activity of the BAT, browning of the WAT, and lipid β-oxidation. Remarkably, they also tune the gut microbiota by decreasing the Firmicutes-to-Bacteroidetes ratio, and enhancing the proportion of Verrucomicrobia [77]. These results suggest that gypenosides stimulate energy expenditure and fat catabolism and have strong anti-obesity capabilities. It is important to note that HFD-induced obese mice are used in most studies as the animal model of adipose reduction. However, given that gypenosides directly promote WAT browning and lipid β-oxidation, targeted delivery to localized adipocytes theoretically holds promise for site-specific fat reduction. Nevertheless, the potential for localized drug toxicity must be carefully evaluated in this context.

Capsicum annuum L. (Solanaceae) has long been used traditionally for the treatment of rheumatism, wound healing, appetite stimulation, and the relief of atonic dyspepsia and flatulence, and it is also known for its antioxidant and immunomodulatory properties [82]. Extracts of *C. annuum* have been shown to inhibit fat accumulation in HFD-fed mice by suppressing adipogenesis and lipogenesis, suggesting anti-obesity potential [83]. The principal bioactive compounds in *C. annuum* include capsaicin, 6,7-dihydrocapsaicin, homodihydrocapsaicin, nordihydrocapsaicin, and homocapsaicin, with capsaicin being the most abundant [84]. Capsaicin induces ATP-dependent thermogenesis through calcium and creatine futile cycles in both 3T3-L1 adipocytes and murine brown and beige adipose tissue, mediated by activation of β3-AR, α1-AR, and TRPV1 [85]. It also up-regulates the expression of brown fat-specific thermogenic markers, including UCP1 and bone morphogenetic protein-8b, in WAT [86].

The *Tripterygium* species (Celastraceae), collectively known as Leigongteng in TCM, have been used to promote weight loss, alleviate insulin resistance, and inhibit polycystic kidney disease [87]. Celastrol, a pentacyclic triterpene isolated from the root bark of *Tripterygium wilfordii* Hook. f., inhibits the differentiation of 3T3-L1 adipocytes and promotes lipolysis through modulation of the PPARγ[2] and C/EBPα signaling pathways [88]. Celastrol also increases energy expenditure, activates BAT, and suppresses *in vivo* gene expression in mitochondria to counteract obesity and metabolic dysfunction *in vivo*. It boosts energy consumption and mitochondrial activities in fat and muscle tissues, thus preventing obesity by pharmacological engagement of heat shock factor 1 (HSF1) and later activation of PGC-1α [89].

Additional TCM herbs that have the potential to act as anti-obesity agents include: (1) *Cinnamomum cassia* (L.) J.Presl (Lauraceae), an active ingredient used traditionally in TCM as a warming agent; the active constituent cinnamaldehyde exhibits anti-adipogenic effects by regulating the PPAR-γ and AMPK signaling pathways [90]; (2) *Foeniculum vulgare* Mill., which contains *trans*-anethole (*trans*-1-methoxy-4-propenyl-benzene) that induces browning of 3T3-L1 adipocytes *via* activation of β3-AR and the AMPK-mediated SIRT1 pathway, which regulates PPARα and PGC-1α [91]; (3) *Pueraria lobata* (Willd.) Ohwi, which contains genistein that reduces adipocyte hypertrophy and inflammation in visceral WAT while increasing energy expenditure through browning of inguinal WAT [92]. Additional TCM herbs with potential for topical fat reduction applications are summarized in Table 3.

3. Strategies for thet enhancement of TCM physicochemical properties

The active ingredients of TCM herbs, such as polyphenols, saponins, alkaloids, terpenoids, and polysaccharides, often suffer from poor stability, low water solubility, limited skin penetration, and inadequate cellular bioavailability. In order to overcome these difficulties, some delivery systems have been designed to improve the physicochemical and pharmacokinetic characteristics of TCM compounds. Colloidal systems, organic and inorganic nanoparticles, as well as dermal and transdermal delivery platforms, are discussed in the following sections (Fig. 4).

3.1. Colloidal carrier system

3.1.1. Microemulsions (MEs) and nanoemulsions (NEs)

Colloidal emulsions can be categorized into water-in-oil (*W/O*), oil-in-water (*O/W*), or bicontinuous structures, depending on the dispersed phase; in both systems, the two phases are not separated into distinct spherical droplets [93]. The size of the particles in these systems is usually between 10 and 100 nm. NEs containing extracts of *Mucuna pruriens* L. are characterized by high encapsulation efficiency and ability to deliver the active ingredients to deep layers of the skin and have antioxidant, anti-aging, and moisturizing effects [94]. NEs can, however, be prone to physical instability over time such as phase separation or droplet coalescence, limiting their shelf life and effectivenes. On the contrary, MEs are thermodynamically stable [95]. A report has come up with a new herbal ME-based UV-shielding cream with lycopene, β-carotene, and curcumin, whose solubility and stability were greatly improved by ME formulation [96]. Despite the relatively low cost and simplicity of manufacturing both MEs and NEs, there are still problems in obtaining homogeneous particle size distribution and optimizing transdermal delivery efficiency [97]. Moreover,

Table 3 Traditional Chinese medicines and their active components that promote adipose breakdown and adipocyte browning, along with their mechanisms of action.

No.	Source plants	Active ingredient	Experiment materials (Cells/animals)	Mechanism of action	References
1	Rhizoma Coptidis	RC and berberine	HFD mice	Promote Fiaf expression, activate AMPK, increase PGC1-α, up-regulate UCP2, CPT1-α, Hadhb mRNA expression	150
2	Green tea	H_2O extract	HFD rats	Activate β-AR, increase energy expenditure	151
		Gallic acid	HFD mice	Activate SIRT1, PGC1-α; SIRT1/PGC-1α pathway	152
3	*Allium hookeri*	H_2O extract	3T3-L1 cells HFD mice	Activate PPAR-γ, up-regulate HSL, LPL, SREBP-1c, SCD-1 and FAS expression	153
4	*Gynostemma pentaphyllum*	H_2O extract	HFD mice	Down-regulate C/EBP-α, PPAR-γ, SREBP-1c, FAS, AP2, SIRT1, up-regulate CPT-1, HSL, activate AMPK	81
		Gypenoside	HFD mice	Up-regulate UCP1, PGC-1α, PRDM16, increase energy expenditure	77
5	*Foeniculum vulgare*	*Trans*-anethole	3T3-L1 cells HFD mice	Up-regulate PGC-1α, PRDM16, UCP1, CD137, Cited1, Tbx1, TMEM26; increase mitochondrial biogenesis	91
6	*Tripterygium wilfordii*	Celastrol	HFD mice	Up-regulate UCP1 and PGC-1α and promote iWAT browning	74
7	*Neopicrorhiza scrophulariiflora*	Vanillic acid	HFD mice	Down-regulate PPAR-γ and C/EBPα, up-regulate AMPKα, and activate the AMPK pathway	76
8	*Sophora japonica*	Quercetin	HFD mice	Up-regulate UCP1, PGC1-α, CIDEA, and TBX1 genes, PRDM16, PPAR-γ, PGC1-α expression, phosphorylation of HSL, promote WAT browning	75
9	*Phyllostachys pubescens*	EtOH extract	3T3-L1 cells	Down-regulate PPAR-γ, C/EBPα, and SREBP-1c and up-regulate UCP1, UCP2, PGC1-α, PRDM16; AMPK pathway	154
10	*Cinnamomum cassia*	EtOH extract	Mice	Up-regulate UCP1, PGC-1α, PPAR-α and PPAR-γ	155

high concentrations of surfactants needed to form MEs can be toxic and limit their application in some formulations.

3.1.2. Liposomes/Phytosomes

Liposomes are phospholipid vesicles that consist of one or more concentric lipid bi-layers within an aqueous core and with a size between 20 and 1000 nm. The amphiphilic structure of them allows to encapsulate both hydrophilic and hydrophobic molecules and as such, they are useful vectors in the delivery of therapeutic agents [98]. For instance, liposomes containing quercetin and rutin through the solvent dispersion technique shield these antioxidants against chemical and physical degradation, promote uptake in cells, and alleviate oxidative stress [99]. However, liposomal drug loading is limited by the solubility of the active compound in either the aqueous or lipid phase, while their practical application is further constrained by physical instability, including vesicle leakage and fusion. Moreover, liposomes usually have a very short shelf life and are quickly cleared by the reticuloendothelial system through intravenous injection.

Unlike liposomes, in which the active ingredient is entrapped within the aqueous lumen or lipid bilayer, phytosomes, phyto-phospholipid complexes, integrate the active molecule into the phospholipid membrane *via* hydrogen bonding between the phytochemical and the polar head group of the phospholipid [100]. A glabridin-loaded liposome was developed to overcome its poor bioavailability, demonstrating lower cytotoxicity and superior melanin-inhibitory efficacy compared to free glabridin, highlighting its potential as a topical agent against UVB-induced skin damage through anti-inflammatory mechanisms [101]. Phytosomes can also be prepared from crude herbal extracts. For example, carotenoid-rich extracts of *Nyctanthes arbor-tristis* and *Tagetes patula* entrapped in phytosomes exhibited enhanced stability after three months of atmospheric exposure and significantly increased dermal and epidermal levels of glutathione (GSH), collagen type I, and elastin, demonstrating potent anti-aging activity [102]. Despite these advantages, phytosomes face limitations such as low drug loading efficiency and challenges in large-scale production [97].

3.1.3. Solid lipid nanoparticles (SLNs)/Nanostructured lipid carriers (NLCs)

SLNs and NLCs have emerged as alternative lipid-based carriers to liposomes, with SLNs composed of solid lipids and NLCs incorporating a blend of solid and liquid lipids. Although SLNs may exhibit limited drug loading capacity and potential drug expulsion during storage, NLCs offer improved drug loading and enhanced physical stability. Both systems demonstrate excellent biocompatibility, making them particularly suitable for dermatological and cosmetic applications [97].

SLNs loaded with EGCG, myricetin, and resveratrol have been formulated to improve storage stability and bioavailability, maintaining effective physicochemical properties for antioxidant applications over 30 days [103]. Glabridin-loaded NLCs prepared *via* ultrasonic emulsification incorporate the compound into a homogeneous lipid matrix, resulting in superior skin retention, enhanced stability against UV irradiation, and prolonged release compared to conventional emulsions.

3.1.4. Micelles

Micelles are self-assembled nanostructures composed of amphiphilic block copolymer in an aqueous solution, with a hydrophobic core allowing lipophilic drug encapsulation and a hydrophilic shell providing aqueous stability. This architecture enhances the solubility and bioavailability of poorly water-soluble compounds, though challenges remain regarding drug loading capacity and stability upon dilution [104].

Glycyrrhizic acid (GA), an amphiphilic triterpenoid saponin extracted from *Glycyrrhiza glabra* L., can self-assemble into micelles with lipophilic drugs, thereby enhancing their solubility, bioavailability, and skin permeability. GA micelles loaded with licochalcone A (LA) efficiently delivered LA to the epidermal layer predominantly *via* hair follicles; following micellar disassembly, LA penetrated deeper skin layers [105]. These micelles enhanced drug penetration through intracellular and intercellular pathways by disrupting the stratum corneum *via* lipid fluidization and keratin denaturation, and demonstrated efficacy in restoring UVB-induced hyperpigmentation by targeting hair follicles.

3.2. Nanoparticles

Nanoparticles represent an advanced class of drug delivery systems with dimensions typically ranging from 1 to 1000 nm, though most biomedical applications utilize particles between 10 and 200 nm [106]. Their unique physicochemical properties, partic-

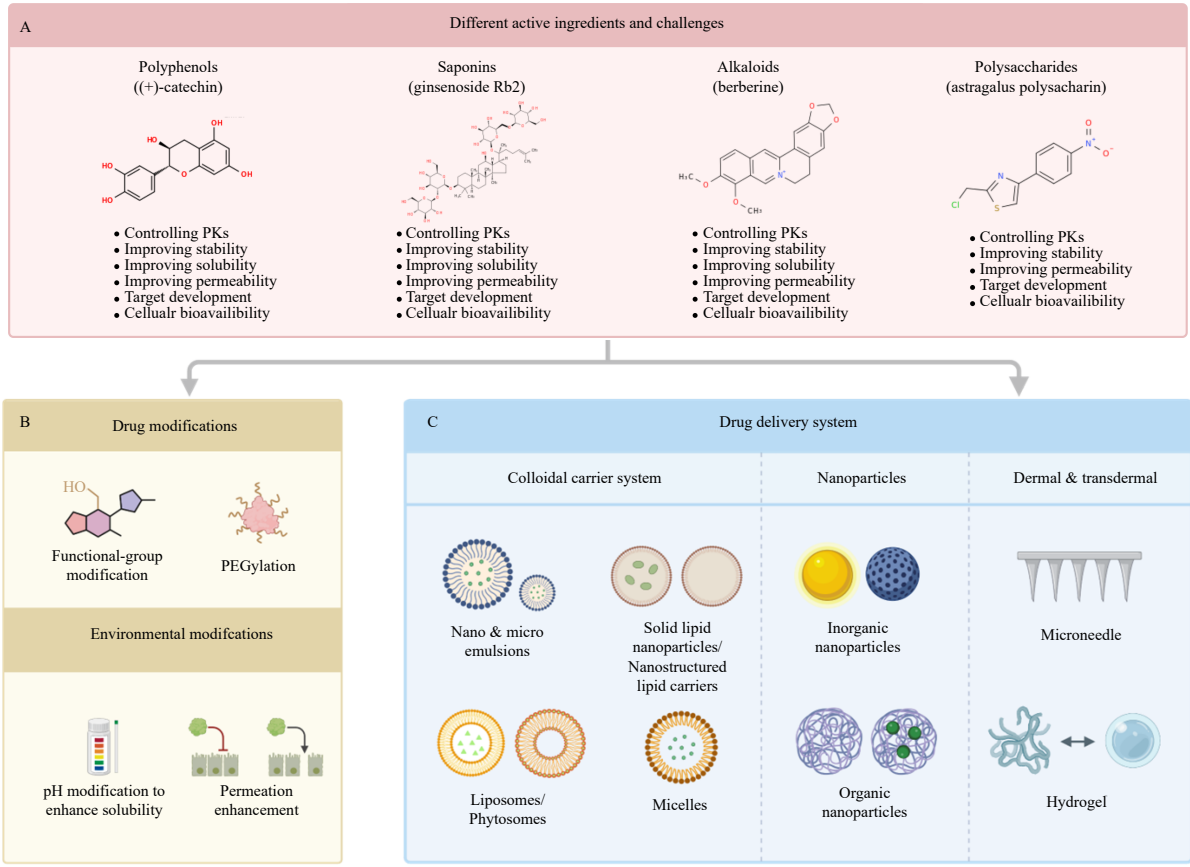

Fig. 4 Delivery challenges and solutions for TCM active ingredients. (A) The four major classes of active ingredients in TCM herbs (polyphenols, saponins, alkaloids and polysaccharides) has their unique delivery challenges in cosmetic applications. These challenges have led to the development of the following delivery paradigms for improved therapeutic function: (B) the modification of the drug or of its environment and (C) the design of drug delivery systems (colloidal carrier, nanoparticle, dermal or transdermal delivery systems).

ularly size-dependent behavior and high surface area-to-volume ratios, facilitate biological barrier penetration, enhanced drug solubility, controlled release kinetics, and targeted delivery. These attributes have enabled the development of both inorganic and organic nanocarrier systems, each offering distinct advantages for specific therapeutic applications.

Mesoporous Silica Nanoparticles (MSNs), representing the inorganic category, enable sophisticated drug delivery design. A notable example is a ROS-responsive MSN-based nanocarrier engineered to deliver glabridin, an active compound that counteracts UVB-induced oxidative damage and hyperpigmentation [107]. These MSNs incorporate a ROS-cleavable boronic acid-catechol ester bond to prevent premature drug release and are further functionalized with a polyarginine (R8) ligand to enhance transdermal delivery, achieving efficient internalization into keratinocytes and melanocytes.

Silk Fibroin Nanoparticles (SFNs), exemplifying organic nanocarriers, highlight the utility of naturally derived materials in drug delivery. In a representative application, SFNs successfully encapsulated *Psidium guajava* L. extract, preserving the antioxidant activity of its phenolic constituents [108]. Synthesized *via* the desolvation method, these nanoparticles exhibited optimal drug delivery characteristics, including particle sizes of 200-700 nm, high entrapment efficiency, thermal stability, and sustained release profiles, underscoring the advantages of protein-based nanocarriers.

3.3. Dermal and transdermal delivery system

Dermal and transdermal delivery systems, particularly microneedles (MNs) and hydrogel-based platforms, represent advanced strategies for delivering therapeutic agents to or through the skin barrier, enabling localized treatment and enhanced efficacy across diverse clinical applications.

MNs are third-generation transdermal delivery systems composed of microscale projections (50-2000 μm) that painlessly penetrate the stratum corneum to create transient microchannels, facilitating efficient delivery of diverse therapeutics while overcoming conventional skin barrier limitations, though challenges related to skin variability and manufacturing complexity persist [2]. A relevant TCM application involves a dissolving MN patch loaded with capsaicin-containing α-lactalbumin nanomicelles, designed to deliver capsaicin to subcutaneous adipocytes, induce WAT browning, and subsequently promote thermogenesis and metabolism for localized fat reduction [109]. Furthermore, MN systems can be integrated with nanotechnology; for instance, hyaluronic acid-based MNs loaded with ginsenoside Rg3-substituted liposomes (in place of cholesterol), combined with berberine and polydopamine, have demonstrated anti-inflammatory and antioxidant effects through minimally invasive administration [110].

Hydrogels consist of three-dimensional, cross-linked polymer networks that can be synthesized from various biopolymers, including collagen, gelatin, hyaluronic acid, and chitosan [111]. A specific application involves a polysaccharide-based hydrogel proposed as a green platform for enhancing transdermal delivery. This hydrogel increases stratum corneum hydration and fluidity, facilitating the penetration of hydrophilic molecules such as arbutin to treat hyperpigmentation [112].

4. Summary and outlook

This article reviews the biological and molecular mechanisms underlying key concerns in medical cosmetology, namely,

pigmentation, skin aging, and adipose accumulation, and summarizes recent advances in the application of TCM herbs to address these conditions. Additionally, modern delivery strategies for administering herbal medicines in cosmetic contexts are discussed. Certain medical cosmetology modalities, such as anti-wrinkle, moisturizing, and acne treatments, were not covered in detail herein. However, these approaches often exhibit synergistic effects with the anti-aging, antioxidant, and pigment-modulating therapies discussed. For example, *Scutellaria baicalensis* extract up-regulates SOD activity, scavenges ROS, and inhibits MMP-1 expression, thereby counteracting skin cell aging, boosting collagen levels, improving skin elasticity, and synergistically reducing wrinkles, demonstrating a comprehensive anti-aging effect [52]. TCM herbs with anti-bacterial, anti-inflammatory, and antioxidant properties also hold promise for acne treatment [113]. Once formulated into medical devices such as hydrogel masks or MN patches, these herbal products may fulfill patient demand for effective home-based therapies and reduce reliance on invasive clinical procedures.

Notably, TCM research continues to face challenges related to standardization, often stemming from methodological inconsistencies and potential bias in existing studies. Therefore, high-quality scientific and clinical investigations are urgently needed to rigorously establish the safety and efficacy of many Chinese herbal products. Moreover, unlike synthetic drugs or biologics, the safety assessment of TCM herbs is complicated by their chemical complexity and the unpredictable interactions among multiple constituents. Active and toxic components in TCM herbs often interact in ways that modulate or counteract each other, and the systemic effects of these multi-component mixtures are highly complex [114]. Additionally, reported cases of TCM herb-related toxicity underscore the need for caution among researchers and clinicians [115, 116]. Consequently, ensuring the safety of TCM-based interventions during treatment remains a significant challenge in drug development, requiring sustained and comprehensive research efforts.

In summary, medical cosmetology represents a promising field at the intersection of scientific innovation and market demand, and low-toxicity, naturally derived TCM herbs are increasingly favored by consumers. The successful integration of TCM into modern medical cosmetology hinges on two critical priorities: elucidating the precise molecular mechanisms of herbal actions and developing advanced drug delivery systems and medical devices capable of effectively harnessing these traditional remedies.

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Declaration of competing interests

These authors have no conflict of interest to declare.

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