RESEARCH PAPER

"From Botanical Bioactives to Cosmetic Benefit: A Translational Review of Herbal Interventions for Skin Ageing"

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Abstract
Background: Skin ageing involves oxidative stress, inflammation, changes in the extracellular matrix, cellular senescence, mitochondrial dysfunction, impaired barrier function, and altered pigmentation. Several plant-derived ingredients have shown promising biological activities relevant to these changes. However, findings from laboratory studies do not always translate into visible improvements in human skin.
Objective: This review examines the potential of herbal cosmeceuticals for ageing skin, focusing on their molecular effects, experimental and clinical evidence, formulation approaches, standardisation, and safety.
Methods: Published studies involving botanical ingredients for skin ageing were examined across mechanistic, cellular, ex vivo, animal, formulation, and human clinical research. The evidence was considered in relation to the biological effects reported, the suitability of topical delivery systems, and the extent to which experimental findings were supported by clinical outcomes.
Results: Plant-derived compounds, including polyphenols, flavonoids, phenolic acids, terpenoids, carotenoids, and polysaccharides, have been investigated for their effects on pathways associated with oxidative stress, inflammation, matrix degradation, cellular senescence, mitochondrial function, and pigmentation. Reported findings include changes in inflammatory signalling, collagen-related responses, skin hydration, barrier function, and skin texture. However, differences in plant material, extraction methods, constituent concentrations, formulations, study designs, and outcome measures make the findings difficult to compare. Evidence of biological activity is also more extensive than evidence of consistent clinical benefit.
Conclusion: Herbal cosmeceuticals offer promising approaches to skin ageing, but their value depends on more than the biological activity of individual plant compounds. Reliable assessment requires attention to extract composition, formulation stability, skin delivery, safety, and measurable benefits in human studies. Connecting these aspects during product development may help identify botanical interventions with genuine potential for evidence-based cosmetic use.
KEYWARDS: Herbal cosmeceuticals**,** Skin ageing**,** Botanical extracts**,** Formulation**,** Clinical translation
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Introduction

Skin ageing develops gradually under the influence of biological changes and environmental exposure.[1,2] Its effects are not limited to wrinkles or other visible signs; they also involve epidermal renewal, barrier function, extracellular matrix organisation, pigmentation, and the skin's ability to withstand external stress. These changes have increased interest in cosmetic approaches that aim to support skin function as well as appearance.[1,2,3,4]

Plant-derived ingredients are widely investigated in this area because many botanical extracts and phytochemicals have shown antioxidant, anti-inflammatory, photoprotective, or collagen-related effects in experimental studies.[3-5] These activities have been associated with pathways such as Nrf2–ARE, MAPK/AP-1, NF-κB, TGF-β/Smad, and matrix metalloproteinases (MMPs), as well as cellular senescence and melanogenesis. Such findings provide a scientific basis for exploring herbal ingredients in cosmeceutical formulations.[6,7,8]

The challenge is determining whether these effects lead to noticeable benefits in human skin. Much of the research has been conducted using cultured cells, isolated compounds, animal models, or short-term experiments.[3-5] Clinical studies also vary in their formulations, doses, treatment periods, outcome measures, and methods of botanical standardisation. As a result, evidence of biological activity does not always correspond to evidence of clinical benefit.[6,7]

This review examines herbal cosmeceuticals by connecting the biology of skin ageing with experimental findings, formulation approaches, and clinical outcomes. It also considers the limitations that must be addressed before promising botanical ingredients can be developed into safe, consistent, and useful cosmetic products.

2. SKIN-AGEING BIOLOGY

Skin ageing reflects the combined effects of intrinsic biological changes and environmental exposure. Their relative contributions vary with age, lifestyle, and anatomical site, but together they can alter the skin barrier, extracellular matrix, pigmentation, and capacity for tissue repair.[9-11] The major processes involved in intrinsic and extrinsic ageing, along with their visible effects, are summarised in **Figure 1**.

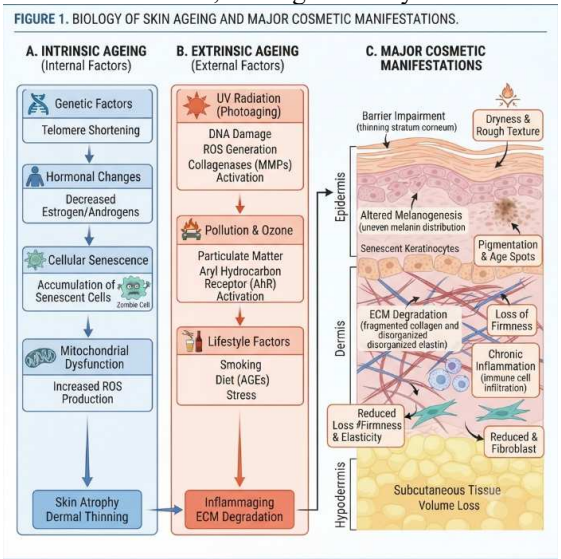


Figure 1. Biology of Skin Ageing and Major Cosmetic Manifestations.

Schematic representation of intrinsic and extrinsic ageing mechanisms, including oxidative stress, chronic inflammation, extracellular matrix degradation, cellular senescence, mitochondrial dysfunction, barrier impairment, and altered melanogenesis, leading to major cosmetic manifestations such as wrinkles, loss of firmness, dryness, and pigmentation.

2.1 Intrinsic Ageing

With intrinsic ageing, epidermal turnover slows and dermal cells become less active. Collagen synthesis declines, while existing collagen fibres gradually become fragmented and disorganised. Changes in epidermal lipids and skin hydration can also weaken barrier performance and contribute to dryness.[12-15] Cellular senescence and age-related mitochondrial dysfunction may further reduce the skin's ability to maintain and repair its tissues.

2.2 Extrinsic Ageing and Photoageing

Environmental factors can accelerate these changes, with chronic ultraviolet (UV) exposure being a major contributor. UV radiation increases reactive oxygen species (ROS) and activates inflammatory and matrix-remodelling pathways.[16] Over time, these responses contribute to collagen breakdown, increased MMP activity, elastotic changes, uneven pigmentation, and reduced elasticity. Air pollution and smoking may add to the cumulative effects of environmental exposure.[17]

2.3 Oxidative Stress and Inflammation

Oxidative stress contributes to skin damage when ROS accumulate beyond the capacity of protective antioxidant systems. These reactive species can damage lipids, proteins, DNA, and extracellular matrix components while activating pathways involved in inflammation and tissue remodelling. Persistent, low-grade inflammation, commonly described as *inflammaging*, may further disturb matrix maintenance and normal repair processes.[18]

2.4 Extracellular Matrix and Collagen Remodelling

The dermal extracellular matrix gives skin much of its firmness and elasticity. As ageing progresses, collagen production declines and matrix-degrading enzymes, including MMP-1, MMP-3, and MMP-9, contribute to the breakdown of existing collagen and other matrix components.[17,18] Fragmented collagen can also disturb interactions between fibroblasts and the surrounding matrix, potentially making tissue renewal less effective.

2.5 Senescence and Mitochondrial Dysfunction

Senescent cells may accumulate in ageing skin and release inflammatory mediators and enzymes that modify the surrounding matrix. At the same time, mitochondrial dysfunction can alter cellular energy production and increase oxidative stress. Together, these changes may contribute to sustained cellular stress and reduced capacity for tissue maintenance.[19-21]

2.6 Barrier Function and Pigmentation

Age-related changes in epidermal renewal, lipid composition, and structural proteins can weaken the skin barrier, increasing dryness and sensitivity to environmental stress. Ageing and repeated UV exposure can also affect melanocyte activity and the distribution of melanin, contributing to uneven skin tone.[20]

These changes influence one another rather than occurring independently. Their combined effects provide a basis for investigating cosmetic approaches that target oxidative stress, inflammation, matrix breakdown, cellular senescence, mitochondrial dysfunction, barrier impairment, and pigmentation. The molecular

pathways associated with these processes are discussed below.[21]

3. MOLECULAR TARGETS RELEVANT TO COSMETIC SKIN AGEING

The visible signs of skin ageing reflect several interacting molecular processes. These pathways are of interest in cosmetic research because changes in their activity may influence wrinkles, elasticity, pigmentation, hydration, and barrier function.[22] However, demonstrating an effect on a molecular target does not necessarily establish a cosmetic benefit. The principal pathways investigated in relation to botanical ingredients are shown in **Figure 2**.

FIGURE 2. MOLECULAR TARGETS OF HERBAL COSMECEUTICALS IN SKIN AGEING.

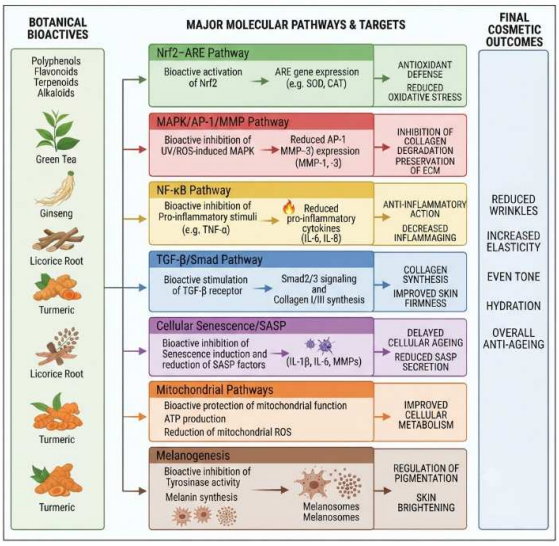


Figure 2. Molecular Targets of Herbal Cosmeceuticals in Skin Ageing.

Major molecular pathways potentially modulated by botanical bioactives, including Nrf2–ARE, MAPK/AP-1/MMP, NF-κB, TGF-β/Smad, cellular senescence/SASP, mitochondrial pathways, and melanogenesis, with their associated biological and cosmetic outcomes.

3.1 ROS/Nrf2–ARE Pathway

Oxidative stress contributes to photoageing and cellular damage when reactive oxygen species (ROS) exceed the skin's protective capacity. Excess ROS can damage cellular components and activate pathways involved in inflammation and matrix breakdown.[23] The Nrf2–ARE pathway helps regulate the expression of antioxidant and cytoprotective genes. Botanical compounds that influence this pathway may help limit oxidative damage, although activity in chemical or cell-based assays alone does not establish anti-ageing efficacy in humans.

3.2 MAPK/AP-1/MMP Pathway

UV radiation and oxidative stress can activate mitogen-activated protein kinase (MAPK) signalling and the downstream transcription factor AP-1. AP-1 regulates several matrix metalloproteinases, including MMP-1, which breaks down collagen. Persistent activation of this pathway may therefore contribute to dermal matrix damage and reduced skin firmness. Botanical compounds that affect MAPK/AP-1 signalling or MMP expression have been investigated for their potential to preserve collagen.[21,23]

3.3 NF-κB and Inflammatory Signalling

NF-κB controls the expression of several inflammatory mediators and can be activated by UV radiation, ROS, and other environmental stresses.[24,25] When this signalling persists, it may contribute to inflammation and changes in extracellular matrix remodelling. Its modulation is therefore relevant to research on inflammation-associated skin damage, although the resulting cosmetic benefits require separate evaluation.

3.4 TGF-β/Smad and Collagen Synthesis

TGF-β/Smad signalling helps regulate extracellular matrix production, including collagen synthesis by dermal fibroblasts. During ageing and photoageing, the balance between collagen formation and degradation becomes disturbed. Changes in this pathway may influence dermal structure and mechanical properties, but its effects depend on the biological context; excessive or inappropriate TGF-β signalling can also have adverse consequences.[26,27]

3.5 Cellular Senescence and SASP

Senescent cells can accumulate in ageing skin and develop a senescence-associated secretory phenotype (SASP). This involves the release of inflammatory mediators and matrix-modifying enzymes that may affect neighbouring cells and tissue structure. Strategies aimed at reducing harmful senescence-associated effects are receiving increasing research attention, although much of the evidence remains preclinical.[28]

3.6 Mitochondrial Dysfunction

Ageing and prolonged environmental stress can impair mitochondrial function, disrupt energy metabolism, and increase ROS production. These changes may affect fibroblast activity, epidermal renewal, and cellular resilience. Botanical compounds that influence mitochondrial antioxidant defence or energy metabolism are being investigated, but their relationship with measurable

improvements in human skin remains insufficiently established.[24,29]

3.7 Melanogenesis

Ageing and repeated UV exposure can alter melanocyte activity and melanin distribution, leading to uneven pigmentation. Tyrosinase and other components of the melanogenic pathway are therefore studied as potential targets for botanical ingredients intended to improve skin tone. Inhibition in enzyme or cell-based assays provides an initial indication of activity, but its relevance to visible pigmentation changes must be established in human studies.[30-32]

Taken together, these pathways help explain how botanical ingredients might influence ageing skin. Their relevance to cosmetic applications becomes more convincing when molecular findings are supported by measurable changes in skin structure or function and consistent results in human studies.[34]

Table 1. Molecular targets associated with skin ageing and their relevance to botanical cosmeceuticals

Molecular target/pathway	Role in skin ageing	Potential botanical action	Relevant cosmetic outcome
ROS/Nrf2–ARE	Oxidative damage and cellular stress	Enhance antioxidant defence	Barrier preservation, skin resilience
MAPK/AP-1/MMP	Collagen degradation	Reduce MMP activity	Wrinkle reduction, firmness
NF-κB	Chronic inflammatory signalling	Modulate inflammatory mediators	Barrier support, reduced inflammation
TGF-β/Smad	Collagen synthesis/remodelling	Support matrix synthesis	Firmness, elasticity
Senescence/SASP	Persistent inflammatory and matrix-altering signals	Modulate senescence-associated responses	Tissue homeostasis
Mitochondrial pathways	Energy dysfunction and ROS generation	Support mitochondrial defence	Cellular resilience
Melanogenesis	Excess/uneven melanin production	Modulate melanogenic pathways	More even skin tone

Footnote: The listed pathways represent interconnected mechanisms rather than independent targets. Evidence from cellular or experimental models does not necessarily demonstrate clinical cosmetic efficacy.

4. HERBAL EVIDENCE ACROSS THE TRANSLATIONAL SPECTRUM

Botanical ingredients have been investigated using methods ranging from biochemical assays to clinical trials.[25,26] Each approach answers a different question, and results from one level cannot automatically be taken as proof of benefit at another.

For example, a compound may affect a molecular target in the laboratory without producing a noticeable improvement in human skin. The following sections examine how evidence develops across mechanistic, cellular, ex vivo, animal, and clinical studies. This progression is illustrated in **Figure 3**.

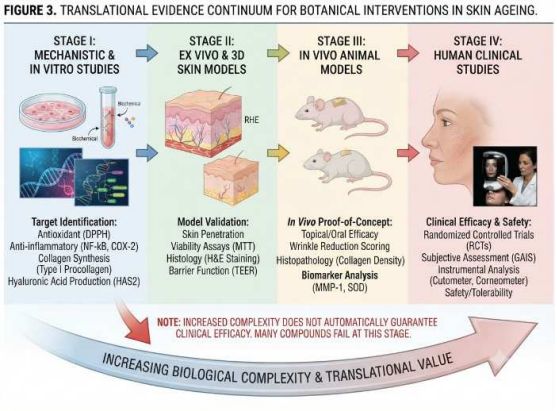


Figure 3. Translational Evidence Continuum for Botanical Interventions in Skin Ageing.

Progression of evidence from mechanistic and cellular studies through ex vivo/reconstructed skin and animal models to human clinical studies. The framework highlights that increasing biological

complexity does not automatically establish clinical efficacy.

4.1 Mechanistic Evidence

Mechanistic studies help identify the biological activities that make certain plant compounds worth investigating.[27,28] Polyphenols, flavonoids, phenolic acids, terpenoids, carotenoids, and other phytochemicals have been studied for their effects on oxidative stress, inflammatory signalling, MMPs, collagen-related pathways, melanogenesis, and cellular stress responses. These findings suggest possible mechanisms of action, but do not by themselves demonstrate a cosmetic benefit.[29]

4.2 Cellular Evidence

Studies using keratinocytes, fibroblasts, melanocytes, and other cell models provide a closer look at how botanical ingredients affect skin-related biological processes. Reported findings include changes in ROS generation, inflammatory mediators, MMP expression, collagen-related responses, and melanin production. The results must be interpreted in light of differences in extract composition, concentration, exposure time, and experimental conditions.[30]

4.3 Ex Vivo and Reconstructed-Skin Evidence

Ex vivo skin and reconstructed-skin models retain some of the tissue organisation missing from conventional cell cultures. They allow researchers to investigate barrier function, hydration, collagen organisation, penetration, tissue responses, and photodamage in a more skin-relevant setting. However, these models cannot fully reproduce prolonged exposure or the biological differences between individuals.[31]

4.4 Animal Evidence

Animal studies can reveal tissue-level effects on photodamage, inflammation, collagen remodelling, and skin morphology, while also providing preliminary safety information. Their findings require caution because skin structure, metabolism, immune responses, and ageing processes differ between species.[32-34] Animal results can support further investigation but cannot replace evidence from human studies.

4.5 Human Clinical Evidence

Human studies provide the most direct assessment of cosmetic outcomes. Botanical interventions have been examined for their effects on wrinkles, elasticity, hydration, skin roughness, pigmentation, barrier function, and responses to UV exposure.[35,36] Comparing these studies is often difficult because they use different plant materials, extract concentrations, formulations, treatment periods, participant groups, comparators, and assessment methods.

Progression from laboratory research to clinical benefit is not guaranteed. Strong mechanistic or cellular findings may fail to produce a measurable improvement in people. Similarly, a botanical preparation may show clinical benefits even when the contribution of each individual constituent remains unclear.[37,38] A convincing assessment therefore considers the identity of the botanical, its biological rationale, its activity in relevant skin models, the suitability of its delivery system, and the consistency of human outcomes.

4.6 Translational Evidence Framework

Evidence for herbal cosmeceuticals can be viewed as a progression from laboratory findings to demonstrated cosmetic benefits:

Molecular target → Mechanistic activity → Cellular response → Tissue-level effect → Animal evidence → Human clinical outcome → Cosmetic relevance

This framework is used to assess the botanical ingredients discussed in the following sections, with attention to how well experimental findings are supported by evidence from human studies.[39]

Table 2. Translational evidence for botanical interventions targeting skin-ageing pathways

Botanical/ active	Molecular target	Model	Study design	Principal endpoint	Main finding	Evidence stage	Key limitation
Multani Mitti and associate d compounds	Hyaluronidase, tyrosinase; antioxidant targets	Biochemical + molecular docking	Enzyme inhibition and docking	Enzyme inhibition activity and docking interactions were investigate	Enzyme-inhibitory ac	Mechanistic	No cellular, animal, ex vivo, or human confirmation

					d for cosmetic anti-ageing relevance		
Nyctanthes arbor-tristis, *Aegle marmelos*, *Musa paradisiaca*	Elastase; oxidative-stress-related targets	Biochemical/cellular	Polyherbal formulation tested for antioxidant and anti-elastase activity	Elastase inhibition; antioxidant activity	Polyherbal formulations demonstrated antioxidant and anti-elastase activity	Cellular / mechanistic	In-vitro evidence; no clinical validation
Woodfordia fruticosa ext	Collagenase	Biochemical enzyme assay	Extracts compared by extracti	Collagenase inhibition	Collagenase inhibitio	Mechanistic	Enzyme assay only; does no
ract			on method; IC_{50} determined		n was quantified and benchmarked across extracts		t establish topical or clinical efficacy
Herbal extracts	NR	Skin-care formulation	Herbal serum development and evaluation	Skin-care/formulation characteristics	Herbal serum formulations were developed and evaluated	Skin-relevant	Anti-ageing molecular or clinical endpoint not established
Ocimum sanctum, *Dauc*	NR	Topical formulation	Herbal cream formulation and	Physicochemical/stability/irritancy parameters	Formulation character	Skin-relevant	Novalidated anti-ageing

uscarota			characterization		istics were evaluated		endpoint
Exotic fats	NR	Topical formulation	Formulation and evaluation	Skin-repair characteristics	Fat-based cosmeceutical formulations were evaluated for skin repair	Skin-relevant	Skin aging-specific evidence not established
Crinum asiaticum extract	NR	Topical lotion	Formulation and evaluation	Moisturisation	Extract-containing lotion was investiga	Skin-relevant	No aging-specific molecular or clinical evide
					ted as a skin moisturiser		nce
Aloe vera, green clay/PVA	NR	Polymeric membrane	Optimisation and formulation evaluation	Membrane/formulation characteristics	Peel-off skin-care membrane was developed and optimised	Skin-relevant	No anti-aging efficacy demonstrated
Herbal sunscreen formulation	NR	Topical formulation	Formulation and evaluation	UV protection	Herbal sunscreen formulation was evaluated	Skin-relevant	Clinical photoprotection not established

					for skin protection from UV radiation		
Polyherbal extracts	NR	Topical cream	Formulation/stability evaluation	Stability/preservation	Natural preservatives were evaluated in polyherbal cream	Skin-relevant	Not an anti-ageing efficacy study
Herbal anti-ageing serum	NR	Topical serum	Formulation and evaluation	Physicochemical/irritancy parameters	Polyherbal anti-ageing serum was	Skin-relevant	Clinical efficacy and molecular mechani

					formulated and evaluated		sm not established
Yellowfin tuna collagen	NR	UV-B-induced Wistar rats	Topical cream intervention	Skin-ageing-related endpoints	Collagen cream was investigated in a UV-B-induced ageing model	Animal	Marine-derived intervention; animal evidence only
Herbal environmental-protection formulation	NR	Topical gel/formulation	Formulation development and evaluation	Protective properties	Herbal formulation was developed aga i	Skin-relevant	Specific anti-ageing mechanism and clinical eff

					nst environmental str		icacy NR
					es sors		

Footnote: Evidence stages are classified as mechanistic, cellular, ex vivo/reconstructed skin, animal, or human clinical. A higher evidence stage does not automatically establish efficacy.

5. CLINICAL EVIDENCE FOR HERBAL COSMECEUTICALS IN SKIN AGEING

Laboratory studies can suggest how a botanical ingredient might work, but human studies are needed to determine whether it produces a noticeable cosmetic benefit. Clinical findings are not always easy to compare, as studies differ in plant material, formulation, dose, treatment duration, participant characteristics, comparator products, and methods of assessment.[40,41] The evidence is therefore considered below according to the main skin-ageing outcomes investigated.

5.1 Wrinkles and Skin Texture

Wrinkles and changes in skin texture are common outcomes in studies of botanical cosmeceuticals. Researchers have examined wrinkle depth, fine lines, surface roughness, and overall skin appearance. Proposed explanations for improvement include reduced oxidative stress, protection of dermal collagen, changes in MMP activity, and effects on extracellular matrix synthesis.[42]

The assessment method matters when interpreting these findings. Instrument-based measurements can provide more objective evidence than visual grading alone. Moisturisation may also make fine lines appear less prominent without necessarily changing the underlying dermal structure. Improvements that persist and are supported by validated measurements therefore provide stronger evidence than short-term changes in appearance.

5.2 Elasticity and Firmness

The decline in skin elasticity with age is associated with changes in collagen and elastin. Botanical preparations have been studied for their effects on elasticity, firmness, and the skin's response to deformation.[43] Any improvement may reflect changes in matrix preservation, collagen breakdown, or hydration. Differences in measurement instruments and study protocols, however, make direct comparisons difficult.

5.3 Hydration and Skin-Barrier Function

Dryness and changes in barrier performance are important features of ageing skin. Botanical formulations containing polyphenols, polysaccharides, lipids, and other constituents have been investigated for their effects on skin hydration and transepidermal water loss (TEWL).[44]

An increase in hydration may result from moisturising ingredients or from improvements in barrier function. Hydration readings should therefore be interpreted alongside TEWL and the properties of the formulation, rather than treated as proof of an anti-ageing effect on their own.[41,43]

5.4 Pigmentation and Skin Tone

Uneven pigmentation can develop or become more noticeable with ageing and cumulative UV exposure. Clinical studies have assessed botanical interventions using measures such as melanin indices, pigmentation intensity, skin brightness, and overall tone. Effects on tyrosinase and related melanogenic pathways provide a possible explanation for some of these findings.[45]

Pigmentation outcomes are also influenced by UV exposure, season, baseline skin characteristics, and other skincare products. Controlled study conditions and validated objective measurements are therefore important when assessing changes in skin tone.

5.5 Photoprotection

Botanical antioxidants and polyphenols have been studied for their potential to limit UV-associated oxidative stress, inflammation, DNA damage, and extracellular matrix degradation.[46] Some human studies have also examined erythema, pigmentation, or responses to controlled UV exposure.

However, evidence of botanical photoprotective activity is not equivalent to demonstrated sunscreen efficacy. Unless a formulation has undergone appropriate validated testing, botanical ingredients should be considered complementary to established sun-protection measures, not replacements for them.[44,45]

5.6 Critical Interpretation of Clinical Evidence

Clinical findings vary because studies differ in extract standardisation, active-constituent content, delivery systems, treatment duration, sample size, comparator products, and outcome measures. Interpreting a result therefore requires more than noting whether an improvement was reported.[47] It is important to consider **what was measured, who participated, which preparation was used, how long treatment lasted, and whether the result was reproduced**.

Ultimately, the value of a botanical intervention depends on the combined evidence for its composition, biological rationale, delivery to the skin, clinical benefit, and safety. This broader assessment helps distinguish promising experimental findings from benefits that have been demonstrated in human studies.[48]

Table 3. Human Clinical Evidence for Botanical Interventions in Skin Ageing

Botanical / active	Formulation / route	Participants (n, characteristics)	Duration	Comparator	Outcomes measured	Main finding
Green tea polyphenols (*Camellia sinensis*)	Topical 10% cream + oral 300 mg twice daily	40 women, moderate photoageing	8 weeks	Placebo cream + oral placebo	Clinical grading, histology (elastic tissue), irritation	Histologic improvement in elastic tissue content; no significant difference in clinical grading of photoageing
Green tea polyphenols	Oral supplementation (dietary)	60 women, 40–65 years	12 weeks	Placebo	Erythema after UV, elasticity, roughness, scaling, wrinkles, TEWL, blood flow	Significant improvement in multiple skin structure and function parameters vs placebo
Centella asiatica extract (standardized triterpenoids)	Oral capsules (200 mg/day)	112 middle-aged women	12 weeks	Placebo	Wrinkle depth/volume, surface roughness, hydration, elasticity, brightness, TEWL	Significant reduction in multiple wrinkle parameters; modest improvements in elasticity, hydration and brightness
Centella asiatica extract	Topical emulsion (3%)	60 women	60 days	Placebo emulsion	Hydration, elasticity, wrinkle depth (eye, cheek), irritation	Significant improvement in hydration, elasticity and wrinkle depth; no erythema/edema reported
French maritime pine bark extract (Pycnoge	Oral capsules (75 mg/day)	20 women, 55–68 years	12 weeks	Placebo	Skin elasticity, hydration, TEWL	Improved skin elasticity (~13% vs 1% placebo) and

nol ®)						hydration; reduced TEWL
Soy isoflavones (soy protein isolate)	Oral supplement (40 mg isoflavone aglycone /day)	Postmenopausal women	3–6 months	Casein protein / placebo food	Fine wrinkles, malar elasticity, skin microrelief	Significant improvement in fine wrinkles and malar elasticity vs control

Footnote: Evidence is presented for botanical interventions evaluated in human studies targeting skin-ageing-related outcomes such as wrinkles, elasticity, hydration, barrier function and pigmentation. Improvements in biophysical or instrumental parameters do not necessarily equate to large visible cosmetic changes, and many studies Proposed translational pathway linking botanical source and chemical characterisation with formulation, stability, skin delivery, molecular response, tissue-level effects, and clinically measurable cosmetic outcomes. The figure highlights key points where evidence gaps may limit clinical translation.

6.1 Conventional Topical Formulations

Creams, gels, lotions, and emulsions are widely used to deliver botanical ingredients to the skin. Their performance depends on factors such as pH, excipient compatibility, extract concentration, and stability throughout storage. The formulation must also keep the relevant constituents sufficiently available for their intended action. In addition, the vehicle itself may improve hydration or barrier function, so its contribution should be distinguished from that of the botanical ingredient.[51]

6.2 Advanced Delivery Systems

Liposomes, nanoemulsions, lipid nanoparticles, polymeric carriers, and other vesicular systems have been explored to improve the solubility, stability, skin deposition, and release of botanical compounds. These systems may help overcome limitations associated with conventional formulations.[52] However, better physicochemical properties or increased skin deposition do not automatically establish improved cosmetic efficacy. Further involve oral supplements rather than topical cosmeceuticals.

6. FROM FORMULATION TO CLINICAL TRANSLATION

A botanical ingredient may show promising biological activity in the laboratory but perform differently once incorporated into a cosmetic product. Limited solubility, chemical instability, oxidation, poor skin penetration, and variation in extract composition can all affect its performance.[49,50] Formulation is therefore an important part of determining whether the activity observed experimentally can be retained in the finished product. This relationship is illustrated in **Figure 4**.

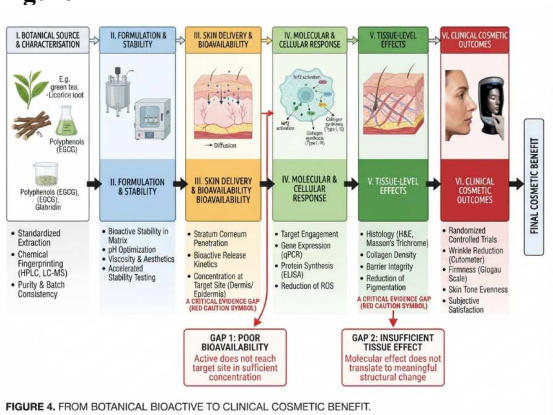


Figure 4. From Botanical Bioactive to Clinical Cosmetic Benefit

biological and clinical evaluation is needed to determine whether these formulation advantages lead to meaningful benefits.

6.3 Standardisation and Reproducibility

The composition of a botanical extract can vary with plant identity, geographical origin, harvesting conditions, extraction procedures, and storage. Such variation may affect both biological activity and product consistency. Botanical authentication, quantitative marker analysis, and clear reporting of extraction methods and constituent concentrations are therefore important. Stability data are also needed to establish whether the formulation retains its relevant characteristics during storage.[53]

6.4 Linking Delivery to Clinical Outcomes

The development pathway can be summarised as follows:

Botanical source → Characterised bioactive → Formulation → Skin delivery → Molecular response → Tissue-level effect → Clinical outcome

For example, reduced MMP-1 activity in a cell-based model supports a possible collagen-preserving mechanism. Evidence of reduced collagen degradation in a skin-relevant model strengthens that interpretation. A reproducible improvement in objectively measured wrinkle parameters in a

controlled human study would provide more direct evidence of cosmetic benefit.[54]

6.5 Translational Evidence Gap

Many botanical studies report promising molecular or cellular findings without establishing whether these effects persist after formulation and topical application. This is a particular concern for skin products, where stability, dose, penetration, exposure time, and vehicle composition can influence the final response.

Formulation should therefore be considered an integral part of development rather than simply the final step. Studies that combine extract characterisation, formulation optimisation, skin-delivery assessment, biological testing, and validated clinical outcomes would provide a clearer basis for judging the potential of botanical cosmeceuticals.[55]

7. CRITICAL GAPS AND TRANSLATIONAL CHALLENGES

Despite the growing research interest in botanical cosmeceuticals, several issues continue to limit the interpretation and application of experimental findings. Addressing these challenges is important for developing products with consistent composition, acceptable safety, and demonstrable cosmetic benefits.

7.1 Botanical Standardisation and Reproducibility

The chemical composition of plant extracts can change with species, geographical origin, harvesting, processing, and extraction methods. Studies should document botanical authentication, extraction procedures, marker compounds, and quantitative composition. Without these details, it becomes difficult to reproduce findings or determine whether two studies have investigated comparable preparations.[53,56]

7.2 Dose and Exposure

A concentration that produces an effect in cultured cells may not be suitable for topical use or reach the same level in human skin. Researchers need to establish dose–response relationships and consider exposure duration and the concentration available at the intended site of action. This is particularly important when results obtained with isolated compounds are applied to complex botanical extracts.

7.3 Stability and Formulation Performance

Light, heat, oxygen, and pH can affect the stability of many phytochemicals. Degradation during manufacture or storage may reduce the amount of active constituent remaining in the product. Stability studies should therefore assess both the physical properties of the formulation and changes in relevant chemical markers over time.

7.4 Skin Penetration and Bioavailability

The effect of a topical ingredient depends partly on whether it reaches the relevant skin layer in a suitable form. Solubility, molecular size, lipophilicity, and chemical stability can influence this process. Although advanced delivery systems may improve skin deposition, evidence of improved delivery should be followed by biological and clinical assessment before stronger efficacy claims are made.

7.5 Safety and Long-Term Use

Being plant-derived does not automatically make an ingredient safe. Irritation, sensitisation, photoreactivity, contamination, interactions with other ingredients, and batch-to-batch variation all require attention. Safety assessment should reflect the intended formulation and pattern of use, with longer-term human data particularly valuable for products designed for repeated application.

7.6 Clinical Endpoints and Study Quality

Differences in sample size, treatment duration, comparator products, assessment methods, and outcome definitions make clinical findings difficult to compare. Well-designed trials should use validated measures of wrinkles, elasticity, hydration, TEWL, pigmentation, and skin structure, alongside relevant participant-reported outcomes. Adequate reporting of study methods and results is also necessary to assess the reliability of the findings.

7.7 The Central Translational Gap

The key challenge is connecting evidence from one stage of development to the next. Ideally, research should establish a defined botanical composition and plausible mechanism, demonstrate activity in relevant skin models, confirm formulation stability and adequate delivery, and then assess the preparation in controlled human studies.[57]

Defined composition → Skin-relevant biological activity → Stable formulation and adequate delivery → Controlled human evaluation → Reproducible cosmetic benefit

Building this connection would make it easier to distinguish botanicals with convincing evidence of practical value from those whose potential is still based mainly on preliminary laboratory findings.

Table 4. Formulation and delivery strategies for botanical cosmeceuticals: opportunities and translational limitations

Delivery system	Primary purpose	Potential advantage	Major limitation	Translational consideration
Cream/emulsion	Topical delivery	Simple, widely applicable	Stability/penetration limitations	Vehicle effects must be considered
Gel	Topical delivery	Light weigh	Limited delivery	Skin deposi

		t applic ation	of poorly soluble actives	tion requir es evalua tion
Nanoe mulsio n	Solubili ty/deliv ery	Impro ved disper sion	Physical/ chemical stability	Clinic al benefi t requir es confir matio n
Liposo mes	Skin deposi tion	Encap sulati on and delive ry	Stability and scale-up	Skin delive ry shoul d be demo nstrat ed
Lipid nanopa rticles	Controll ed	Protec tion of labile	Manufac turing	Long-term safety
	topical delivery	active s	complex ity	requir es evalua tion
Advan ced vesicle s	Targete d delivery	Potent ial enhan ced depos ition	Variable reproduc ibility	Clinic al transl ation remai ns limite d
Plant-derived nanove sicles	Bioactiv e delivery	Emer ging delive ry platfo rm	Characte risation challeng es	Huma n evide nce remai ns limite d

Footnote: Improved encapsulation, stability, or skin penetration should not be interpreted as evidence of superior clinical efficacy unless supported by appropriate human studies.

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