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MOLECULAR AND CLINICAL INSIGHTS INTO THE ROLE OF MATCHA GREEN TEA POLYPHENOLS IN SKIN REGENERATION AND PHOTOPROTECTION

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ABSTRAK

Matcha, bubuk halus yang berasal dari daun Camellia sinensis yang tumbuh di bawah naungan, sangat kaya akan epigallocatechin-3-gallate (EGCG), suatu polifenol dengan aktivitas antioksidan, antiinflamasi, dan fotoprotektif yang ampuh. Bukti dermatologis yang semakin meningkat menunjukkan bahwa katekin yang berasal dari matcha menetralkan spesies oksigen reaktif, menghambat metaloproteinase matriks (MMP), dan menstimulasi biosintesis kolagen, sehingga mempertahankan homeostasis kulit dan memperlambat penuaan ekstrinsik. EGCG memberikan efek antiinflamasi tambahan dengan menurunkan regulasi NF-κB, AP-1, dan sitokin seperti IL-1β dan TNF-α, sekaligus meningkatkan sintesis seramida dan filaggrin untuk memulihkan lapisan kulit. Studi klinis menunjukkan bahwa formulasi teh hijau oral dan topikal meningkatkan hidrasi, elastisitas, dan keseimbangan pigmentasi, mendukung potensi translasi polifenol matcha dalam fotoproteksi dan regenerasi. Tinjauan pustaka ini mensintesis data molekuler dan klinis yang dipublikasikan antara tahun 2020 dan 2025, yang menyoroti jalur biokimia, strategi formulasi, dan implikasi terapeutik matcha dalam dermatologi estetika dan regeneratif. Dengan mengintegrasikan bukti dari biologi molekuler, farmakologi, dan penelitian klinis, artikel ini menyoroti katekin matcha sebagai agen bioaktif yang menjanjikan untuk intervensi anti-penuaan, penyembuhan luka, dan fotoprotektif di masa mendatang..

Kata Kunci: Matcha, Teh Hijau, Epigallocatechin Gallate, Antioksidan, Fotoproteksi, Regenerasi Kulit, Anti-Penuaan, Polifenol, Kolagen.

ABSTRACT

Matcha, a finely milled powder derived from shade-grown Camellia sinensis leaves, is exceptionally rich in epigallocatechin-3-gallate (EGCG), a polyphenol with potent antioxidant, anti-inflammatory, and photoprotective activity. Increasing dermatologic evidence demonstrates that matcha-derived catechins neutralize reactive oxygen species, inhibit matrix metalloproteinases (MMPs), and stimulate collagen biosynthesis, thereby maintaining cutaneous homeostasis and slowing extrinsic aging. EGCG exerts additional anti-inflammatory effects by

down-regulating NF-κB, AP-1, and cytokines such as IL-1β and TNF-α, while enhancing ceramide and filaggrin synthesis to restore the skin barrier. Clinical studies reveal that oral and topical green-tea formulations improve hydration, elasticity, and pigmentation balance, supporting the translational potential of matcha polyphenols in photoprotection and regeneration. This literature review synthesizes molecular and clinical data published between 2020 and 2025, emphasizing the biochemical pathways, formulation strategies, and therapeutic implications of matcha in aesthetic and regenerative dermatology. By integrating evidence from molecular biology, pharmacology, and clinical research, the article highlights matcha catechins as promising bioactive agents for future anti-aging, wound-healing, and photoprotective interventions.

Keywords: *Matcha, Green Tea, Epigallocatechin Gallate, Antioxidants, Photoprotection, Skin Regeneration, Anti-Aging, Polyphenols, Collagen.*

INTRODUCTION

Skin aging is a complex, continuous biological process influenced by intrinsic and extrinsic determinants that progressively alter the structure and physiology of the epidermis and dermis. Intrinsic or chronological aging arises from programmed cellular decline, telomere shortening, and hormonal changes, whereas extrinsic aging primarily reflects environmental aggressors such as ultraviolet (UV) radiation, air pollution, cigarette smoke, and poor nutrition. Both processes converge on common molecular mechanisms of oxidative stress, mitochondrial dysfunction, extracellular-matrix (ECM) degradation, and chronic inflammation and culminating in dryness, wrinkling, and loss of elasticity[1,2].

Reactive oxygen species (ROS) generated by UV exposure trigger lipid peroxidation, DNA damage, and the activation of transcription factors including NF-κB and AP-1, leading to up-regulation of MMP-1, MMP-3, and MMP-9, enzymes that cleave dermal collagen and elastin[1,3]. This oxidative-inflammatory cycle accelerates visible skin aging. Accordingly, antioxidant interventions capable of quenching ROS and modulating redox-sensitive pathways have become central to modern anti-aging dermatology.

Among botanical antioxidants, *Camellia sinensis* (green tea) and its shade-cultivated powder form, matcha, are prominent due to their high concentrations of catechins, most notably EGCG, together with caffeine, theanine, and chlorophyll[1,4,5]. Matcha differs from conventional brewed tea in both cultivation and preparation: the leaves are shaded for several weeks before harvest to increase amino acids and chlorophyll, then stone-ground into an

ultrafine powder consumed whole. This process yields up to threefold higher total catechin and EGCG content compared with steeped infusions[6]. As a result, matcha delivers a concentrated source of antioxidant and anti-inflammatory compounds that may exert superior dermatologic efficacy.

Emerging research demonstrates that EGCG scavenges free radicals, chelates transition metals, and inhibits oxidative signaling cascades, thereby protecting keratinocytes and fibroblasts from photo-oxidative injury[1,2,7]. It also stimulates dermal remodeling by activating the TGF-β/Smad pathway while suppressing MMP-mediated ECM breakdown[3,8]. These properties underpin its growing reputation as a multifunctional agent for both preventive and regenerative skin care. However, while green-tea extracts have been widely studied, direct dermatologic evidence specific to matcha remains limited. Given its unique phytochemical profile, systematic synthesis of molecular and clinical data is needed to clarify its role in skin regeneration and photoprotection.

This review therefore aims to integrate recent findings (2020–2025) concerning the biochemical pathways, clinical outcomes, and formulation advances associated with matcha-derived polyphenols. By bridging experimental and translational perspectives, it provides an updated framework for understanding matcha's potential as a scientifically validated bioactive in aesthetic and regenerative dermatology.

RESEARCH METHODS

A structured literature search was performed between January 2024 and March 2025 to identify peer-reviewed evidence examining the dermatologic implications of matcha and green-tea polyphenols. Databases included PubMed**,** Web of Science**,** and ScienceDirect. The Boolean search strategy combined terms:

("matcha" OR "green tea polyphenols" OR "epigallocatechin gallate") AND ("skin regeneration" OR "photoaging" OR "wound healing" OR "photoprotection" OR "oxidative stress").

Inclusion Criteria

- Publications from 2020 to 2025 in English.
- Experimental, in vivo, or clinical human studies evaluating matcha, green-tea extracts, or isolated catechins (EGCG) on skin physiology, barrier function, photoaging, pigmentation, or wound healing.

- Reviews and meta-analyses focusing on dermatologic or cosmetic applications.

Exclusion Criteria

- Non-dermatologic outcomes (e.g., cardiometabolic, neurologic).
- Editorials, letters, or opinions without experimental data.
- Animal studies lacking human translational context.

After duplicate removal, 82 articles were screened by title and abstract; 31 met eligibility criteria and were included for qualitative analysis. Data were grouped into two domains: (1) molecular mechanisms and (2) clinical and aesthetic applications. Findings were interpreted following PRISMA guidelines for narrative reviews.

A. Molecular Mechanisms

Matcha polyphenols exert broad biological effects relevant to cutaneous physiology, encompassing antioxidant defense, collagen metabolism, inflammation modulation, and photoprotection.

1. Antioxidant and Free-Radical Scavenging

Oxidative stress represents a key driver of both chronologic and environmental skin aging. EGCG, the dominant catechin in matcha, possesses multiple hydroxyl groups that donate electrons to neutralize superoxide and hydroxyl radicals[1,2]. It also chelates Fe^{2+} and Cu^{2+} ions, preventing Fenton-type reactions that generate ROS. In cultured human keratinocytes, EGCG pretreatment reduces UVB-induced ROS and lipid peroxidation markers such as malondialdehyde (MDA)[1].

Beyond direct scavenging, EGCG regulates redox-sensitive signaling by inhibiting MAPK (ERK, JNK, p38) and NF-κB pathways, suppressing transcription of pro-oxidant and inflammatory genes responsible for extracellular-matrix breakdown[1,2,7]. Consequently, fibroblast viability and collagen integrity are preserved, maintaining skin firmness and hydration.

2. Regulation of Collagen Metabolism

Loss of dermal collagen is a hallmark of photoaged skin. Ultraviolet radiation up-regulates MMP-1 and MMP-3, which cleave type I and III collagen, while suppressing TGF-β-driven collagen synthesis. EGCG counteracts these changes by down-regulating AP-1 and

MMP transcription and activating the TGF-β/Smad axis, stimulating procollagen production[1,3,8]. Fibroblast cultures show a 30–40 % reduction in collagen degradation when pre-treated with EGCG before UV exposure[3,9]. These dual actions are preventing breakdown and promoting renewal ofdesignate EGCG as a natural collagen stabilizer.

3. Anti-Inflammatory and Barrier-Repair Effects

"Inflammaging," or persistent low-grade inflammation, accelerates dermal thinning and barrier dysfunction. EGCG and related catechins suppress IL-1β, TNF-α, and IL-6 expression by blocking NF-κB and JAK2/STAT3 signaling[2,9]. They also down-regulate COX-2 and inducible nitric-oxide synthase (iNOS), reducing erythema and edema. In keratinocytes, EGCG up-regulates ceramide synthase and filaggrin gene expression, facilitating lipid barrier recovery after chemical or UV insult[10,11]. Animal models show faster wound closure and enhanced angiogenesis following topical EGCG application[11].

4. Photoprotection and Environmental Stress Resistance

EGCG absorbs UV light in the 270–320 nm range and stimulates DNA repair by up-regulating 8-oxoguanine DNA glycosylase (OGG1) and nucleotide-excision-repair enzymes such as XPA. Keratinocyte cultures treated with EGCG after UVB exposure exhibit ≈50 % fewer cyclobutane pyrimidine dimers[7]. Additionally, catechin-rich Assam-tea extract inhibits particulate-matter-induced activation of AP-1, MAPK, and NF-κB in fibroblasts, limiting MMP-1 expression and cytokine release[12]. Such findings indicate that polyphenols from matcha can protect against both UV and pollution driven photoaging.

5. Formulation and Bioavailability Challenges

Despite compelling mechanistic data, EGCG is chemically unstable and poorly permeable through the stratum corneum. Its hydrophilic structure predisposes it to oxidation and rapid degradation. Recent advances in nanoencapsulation liposomes, solid-lipid nanoparticles, polymeric micelles, and transfersomes, enhance cutaneous delivery[5,10,13]. Such systems protect EGCG from oxidation, improve penetration depth, and extend antioxidant activity on the skin[18]. Encapsulated matcha extracts thus represent a promising platform for cosmeceutical formulation, allowing higher local dermal concentrations and prolonged stability.

B. Clinical And Aesthetic Applications

1) Oral Supplementation and Photoprotection

Clinical evidence demonstrates that oral intake of green-tea catechins improves skin structure and resistance to photodamage. In a randomized double-blind study, Heinrich et al.[4] reported that 12 weeks of daily catechin supplementation (1,402 mg/day) significantly reduced UV-induced erythema by up to 25 % and improved skin density and elasticity. Histologic analysis revealed enhanced collagen deposition and dermal vascularity, suggesting systemic antioxidant effects on skin microcirculation.

Di Sotto et al.[14] corroborated these findings through a systematic review of human trials, concluding that oral green-tea formulations increased hydration, elasticity, and photoprotection with excellent safety profiles. Although most studies use brewed-tea extracts rather than matcha, the latter's higher catechin concentration implies that equivalent or superior efficacy may be achieved with lower dosages.

Additional studies have shown that oral polyphenol supplementation reduces wrinkle formation, pigmentation irregularity, and transepidermal water loss[14,15]. These results collectively support the role of dietary catechins as nutridermatologic agents capable of reinforcing skin defense against UV and oxidative stress.

2) Topical Formulations for Anti-Aging and Pigmentation Control

Topical delivery enables direct interaction of polyphenols with epidermal and dermal targets. A clinical trial by Jagdeo et al.[16] demonstrated that a serum combining vitamins C and E with green-tea polyphenols significantly reduced fine lines and hyperpigmentation after 12 weeks, while increasing hydration and surface smoothness.

In vitro and in vivo studies confirm that topical EGCG reduces UV-induced erythema, suppresses melanogenesis, and accelerates post-laser re-epithelialization[17,18]. EGCG formulations have also been used adjunctively with retinoids to mitigate irritation without compromising anti-wrinkle efficacy[2,8]. Collectively, these results suggest that catechin-enriched serums or emulsions may complement existing aesthetic therapies by enhancing skin tone uniformity and resilience.

3) Clinical Evidence Specific to Matcha

Although most dermatologic studies examine conventional green-tea extracts, Sokary et al.[19] reported that matcha exhibits higher antioxidant capacity and catechin density because the whole leaf is consumed. The shade-grown cultivation increases theanine and chlorophyll levels, potentially amplifying anti-inflammatory synergy. Clinical data directly evaluating topical or oral matcha for skin outcomes remain limited, but biochemical equivalence suggests comparable or greater efficacy. Future controlled human trials are warranted to establish standardized matcha dosages and to quantify its effects on elasticity, pigmentation, and wound healing.

4) Safety and Tolerability

Green-tea polyphenols possess strong safety records in both oral and topical formulations. Adverse effects such as mild gastrointestinal discomfort or transient irritation are rare and dose-dependent[2,14]. EGCG can weakly inhibit cytochrome P450 isoenzymes CYP3A4 and CYP2C9, but this interaction is negligible at dermatologic concentrations[18]. Stability is a key determinant of efficacy; EGCG oxidizes rapidly under light or alkaline conditions. Hence, formulations should maintain pH < 6 and use opaque, airtight packaging[3]. When properly formulated, matcha-based cosmeceuticals demonstrate excellent tolerability and shelf stability.

RESULTS AND DISCUSSION

The accumulated evidence underscores the multifaceted dermatologic potential of matcha polyphenols. EGCG functions as an antioxidant, anti-inflammatory mediator, collagen stabilizer, and UV filter, making it a single compound with multiple skin-protective effects[1-3].

1. Integration of Molecular and Clinical Pathways

Skin aging reflects a network of oxidative and inflammatory signaling events. EGCG inhibits MAPK and NF-κB activation, reducing MMP expression and preserving ECM integrity[1,3,8]. In keratinocytes, it enhances DNA repair enzymes and stimulates ceramide production, contributing to barrier recovery[10,11]. Clinically, these mechanisms translate into measurable improvements in elasticity, hydration, and photoprotection observed in supplementation trials[4,14].

2. Matcha versus Conventional Green Tea

Matcha differs fundamentally from steeped tea in its cultivation and consumption form. Because the entire leaf is ingested, catechins, chlorophyll, and amino acids are delivered at much higher concentrations[19]. Shading prior to harvest increases L-theanine and polyphenol biosynthesis, conferring additional neuroprotective and anti-stress effects that may indirectly enhance skin homeostasis via the gut-skin and brain-skin axes. Quantitatively, matcha may contain up to 137 times more EGCG than some commercial teas[19]. These differences justify the separate evaluation of matcha as a distinct dermatologic intervention.

3. Advances in Formulation Science

EGCG's hydrophilicity and instability have historically limited its clinical translation. Nano-encapsulation and lipid-based delivery systems (liposomes, solid-lipid nanoparticles, transfersomes) have overcome many of these barriers[5,10,13]. Such technologies improve cutaneous penetration, sustain release, and prevent oxidation. Avadhani et al.[10] demonstrated that ultradeformable vesicles containing EGCG and hyaluronic acid enhanced antioxidant activity and anti-aging efficacy in fibroblasts. Similarly, nanoemulsion gels showed stronger photoprotection than free catechins[20]. Integration of these systems with matcha extracts may yield stable, high-performance cosmeceuticals.

4. Translational and Clinical Relevance

Human studies confirm that green-tea catechins can modulate physiological parameters such as microcirculation, collagen deposition, and UV tolerance[4,14]. Topical preparations complement systemic supplementation by targeting local oxidative damage. EGCG's wound-healing potential is especially promising: Xu et al.[11] reported accelerated closure and angiogenesis, while Ning et al.[21] showed improved re-epithelialization in diabetic mice. These results position EGCG as both a preventive and regenerative agent applicable in anti-aging and post-procedure care.

5. Safety, Dose, and Toxicology

Clinical and preclinical data demonstrate that EGCG is safe across a wide range of concentrations[2,14]. Minor side effects are infrequent and reversible. Toxicity typically occurs only at pharmacologic doses exceeding 800 mg/day, far above cosmetic usage. Topical

application is well tolerated and may even reduce irritation associated with retinoids[2,16]. However, formulation optimization remains essential; pH, carrier type, and co-antioxidants (e.g., vitamin C or ferulic acid) significantly influence stability and bioavailability[5,16].

6. Recommended Dosage and Potential Adverse Effects

The optimal dosage of matcha for general health and dermatologic benefit typically ranges from **2 to 4 grams per day**, equivalent to one to two standard servings. This provides an estimated **120–240 mg of EGCG**, sufficient to exert antioxidant and anti-inflammatory effects without exceeding safety thresholds. When consumed within these limits, matcha is well tolerated. However, **excessive intake exceeding 6–8 grams daily** or more than **600 mg of EGCG** may cause **insomnia, irritability, or mild gastrointestinal upset** due to its caffeine and catechin content. At very high doses, catechins can transiently **elevate liver enzymes** and interfere with iron absorption. Individuals with hepatic disorders or sensitivity to caffeine should therefore moderate consumption and ensure adequate hydration. In practice, balanced daily use combined with topical formulations offers the safest and most effective approach for skin regeneration and photoprotection[2,5,16].

7. Broader Implications for Regenerative Dermatology

Matcha polyphenols align with emerging longevity-focused skin care paradigms that target mitochondrial preservation and inflammaging suppression. EGCG activates AMPK and SIRT1, pathways involved in autophagy and metabolic renewal[1,3]. These actions parallel the mechanisms of established anti-aging agents such as resveratrol and retinoic acid. Furthermore, EGCG's melanogenesis inhibition and tyrosinase suppression confer depigmenting effects useful in melasma and post-inflammatory hyperpigmentation[2,8]. Combined with its vascular-enhancing and barrier-restoring properties, matcha represents a holistic approach to cutaneous rejuvenation.

8. Research Gaps and Future Prospects

Despite compelling mechanistic evidence, several gaps persist. Large-scale randomized controlled trials directly assessing matcha are lacking[18]. Future studies should standardize matcha preparations based on catechin concentration, particle size, and chlorophyll content to ensure reproducibility. Pharmacokinetic analyses using LC-MS could clarify absorption and tissue distribution. Incorporating omics-based methodologies (transcriptomics, proteomics,

metabolomics) may reveal new molecular targets and biomarkers of response. Collaborative efforts between dermatologists, pharmacologists, and cosmetic chemists are necessary to develop clinically validated matcha-based therapeutics.

9. Integration into Aesthetic Practice

The synergy between nutritional supplementation and topical application represents an emerging frontier in nutridermatology. Potential clinical applications include:

- **Daily nano-serum formulations** delivering sustained EGCG for continuous antioxidant protection[5,10,13].
- **Oral–topical combination regimens** to provide systemic and local antioxidative support[14].
- **Adjunctive use in procedural dermatology** (laser, microneedling) to reduce erythema and expedite healing[18].
- **Wound-care adjuncts** exploiting EGCG's pro-angiogenic and keratinocyte-activating properties[11,21].

Such strategies bridge molecular insight and clinical innovation, positioning matcha as a sustainable, evidence-based ingredient for next-generation cosmeceuticals.

CONCLUSION

Matcha green-tea polyphenols, particularly epigallocatechin-3-gallate (EGCG), represent one of the most promising natural bioactives for contemporary aesthetic and regenerative dermatology. Acting simultaneously as a potent antioxidant, anti-inflammatory mediator, collagen stabilizer, and UV filter, EGCG targets multiple molecular events underlying intrinsic and extrinsic aging. Experimental and clinical data consistently demonstrate its ability to neutralize reactive oxygen species, suppress MMP-driven collagen degradation, activate the TGF-β/Smad signaling axis, and reinforce barrier function through enhanced ceramide and filaggrin synthesis.

Oral supplementation improves microcirculation, elasticity, and hydration, whereas topical formulations reduce pigmentation, erythema, and wrinkle depth. Nano-encapsulation technologies now overcome EGCG's instability and limited permeability, paving the way for stable, high-efficacy matcha cosmeceuticals.

Although most published studies focus on conventional green-tea extracts, matcha's unique whole-leaf composition yields superior concentrations of catechins, chlorophyll, and theanine—suggesting enhanced dermatologic benefits. Future research should prioritize standardized clinical trials, pharmacokinetic profiling, and multi-omics approaches to validate dosage, delivery, and efficacy across diverse populations.

In summary, the convergence of molecular research, formulation science, and clinical dermatology positions matcha as a scientifically grounded, sustainable agent for photoprotection, wound repair, and anti-aging therapy—offering a green, evidence-based pathway toward healthier and more resilient skin.

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