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Topical Kombucha as a Natural Antioxidant Against Skin Photoaging: A Literature Review

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ABSTRACT

Skin photoaging refers to degenerative changes in the skin primarily triggered by chronic exposure to ultraviolet (UV) radiation, especially UV-B. This exposure leads to the formation of reactive oxygen species (ROS), stimulates inflammatory responses, and accelerates collagen breakdown through the activation of matrix metalloproteinases (MMPs). This literature review aims to comprehensively analyze the molecular mechanisms of photoaging and evaluate the therapeutic potential of kombucha, particularly when fermented with Hibiscus sabdariffa (rosella), as a natural topical anti-photoaging agent. A systematic literature search was conducted across multiple databases, including PubMed, Scopus, and Web of Science, focusing on studies published between 2019 and 2024, with selective inclusion of landmark studies from earlier years. Search terms included "photoaging," "kombucha," "rosella," "UV-B radiation," "collagen degradation," "TGF-β pathway," and "natural antioxidants." The results demonstrate that kombucha, rich in polyphenols, organic acids, and flavonoids, has shown potential in reducing MMP-1 expression, enhancing TGF-β signaling, and stimulating collagen production. When fermented with Hibiscus sabdariffa (rosella), its antioxidant activity is further enhanced through increased bioavailability of anthocyanins, myricetin, and phenolic acids. Ex vivo studies indicate that kombucha can increase collagen synthesis by up to 40% and reduce MMP-1 expression by approximately 35% in UV-exposed skin models. This review concludes that topical kombucha rosella represents a promising natural therapeutic approach for photoaging prevention and treatment, offering advantages such as minimal side effects, cost-effectiveness, and multi-targeted biological activity.

KEYWORDS *Antioxidant, Collagen, Kombucha, MMP-1, Rosella, Skin Photoaging, TGF-β, UV-B.*

INTRODUCTION

Skin aging represents a complex biological phenomenon influenced by both intrinsic (genetic, hormonal) and extrinsic (environmental) factors, with chronic exposure to ultraviolet (UV) radiation—particularly UV-B (280–315 nm)—recognized as the predominant extrinsic cause of premature skin aging, a condition clinically termed photoaging. Photoaging constitutes a significant global health concern, affecting millions of individuals worldwide, particularly in regions with high UV exposure indices and among populations with increasing outdoor activities. The World Health Organization estimates that over 2–3 million non-melanoma skin cancers and 132,000 melanoma skin cancers occur globally each year, with photoaging serving as a precursor to many of these conditions. Beyond oncological risks, photoaging imposes substantial psychosocial and economic burdens, with the global anti-aging skincare market projected to reach USD 88.3 billion by 2026, reflecting widespread concern about UV-induced skin damage (George et al., 2022; Tanveer et al., 2023). Clinically, photoaging manifests through characteristic features including fine and coarse wrinkles, rough texture, mottled pigmentation, telangiectasias, and loss of skin elasticity, predominantly affecting sun-exposed areas such as the face, neck, forearms, and hands (Kim et al., 2022).

At the molecular level, UV-B exposure triggers a cascade of detrimental processes that fundamentally disrupt skin homeostasis. The formation of reactive oxygen species (ROS) induces oxidative stress that damages cellular proteins, lipids, and DNA, while simultaneously

activating pro-inflammatory signaling pathways, including Mitogen-Activated Protein Kinase (MAPK) and Activator Protein-1 (AP-1) (Pittayapruek et al., 2016). These activated pathways upregulate matrix metalloproteinases (MMPs), particularly MMP-1, which catalyze the degradation of type I and III collagen—the primary structural proteins maintaining dermal integrity. Concurrently, UV-B exposure suppresses the Transforming Growth Factor-beta (TGF-β)/Smad signaling pathway, thereby inhibiting collagen synthesis and disrupting the delicate balance between extracellular matrix (ECM) production and degradation (Feng et al., 2024). This dual mechanism of increased collagen breakdown and decreased collagen synthesis results in progressive dermal atrophy and the clinical manifestations of photoaged skin. Understanding these molecular mechanisms is critical because they represent specific therapeutic targets for photoaging prevention and treatment, with interventions that can neutralize ROS, inhibit MMP activity, and restore TGF-β signaling offering potential to reverse or prevent UV-induced skin damage.

Several therapeutic approaches have been investigated to counteract photoaging, with growing emphasis on natural ingredients due to their favorable safety profiles and multi-targeted biological activities. Choi et al. (2019) demonstrated that green tea polyphenols, particularly epigallocatechin-3-gallate (EGCG), significantly reduced UV-induced MMP-1 expression and increased procollagen synthesis in human dermal fibroblasts through inhibition of AP-1 activation. Similarly, Pullar et al. (2020) showed that topical vitamin C derivatives enhanced collagen production and reduced wrinkle depth in photoaged skin through stimulation of collagen gene expression and inhibition of MMP-1 activity. Resveratrol, a polyphenolic compound found in grapes, has been extensively studied by Ndiaye et al. (2021), who reported its ability to activate SIRT1 signaling pathways that promote cellular repair mechanisms and enhance antioxidant defense systems in UV-exposed skin. More recently, Chuarienthong et al. (2022) investigated Thai herbal extracts rich in flavonoids and demonstrated their capacity to inhibit melanogenesis while simultaneously reducing oxidative stress markers in UV-irradiated keratinocytes. Despite these promising findings, several limitations persist in current photoaging treatments, including (1) stability issues of active compounds under environmental conditions such as light and heat exposure, (2) poor skin penetration due to molecular size and hydrophilicity, (3) limited bioavailability when administered orally, (4) potential irritation or adverse effects at therapeutic concentrations, and (5) high production costs limiting accessibility. These limitations underscore the need for novel therapeutic approaches that combine high antioxidant activity, enhanced skin penetration, minimal side effects, and cost-effectiveness.

The urgency of developing effective photoaging treatments has intensified due to contemporary environmental changes that amplify UV exposure risks. Climate change has led to stratospheric ozone depletion, particularly over mid-latitudes, resulting in increased UV-B radiation reaching the Earth's surface—with some regions experiencing up to 8–10% increases in UV intensity over the past three decades (Watson et al., 2016). Additionally, modern lifestyle patterns involving increased outdoor recreational activities, rising rates of international travel to high-UV regions, and prolonged sun exposure during commuting and work have elevated population-level UV exposure. Furthermore, the aging global population—projected to reach 2.1 billion people aged 60 and over by 2050—faces amplified photoaging concerns, as cumulative UV damage accumulates over decades while endogenous antioxidant defenses

decline with age. The aesthetic medicine and dermatological industry has responded with increasing demand for effective, safe, and natural anti-photoaging interventions. However, existing treatments often involve synthetic retinoids, hydroquinone, or invasive procedures that carry risks of irritation or photosensitivity, or require significant financial investment. This creates an urgent need for accessible, evidence-based natural alternatives that can prevent and reverse photoaging through multiple biological mechanisms while maintaining excellent safety profiles suitable for long-term prophylactic use.

To address these therapeutic gaps, natural ingredients with potent antioxidant and anti-inflammatory properties have gained considerable scientific attention. Kombucha, a fermented beverage produced through symbiotic cultures of bacteria and yeast (SCOBY), contains high concentrations of bioactive compounds including polyphenolic acids (gallic acid, protocatechuic acid), flavonoids (quercetin, myricetin), and organic acids (acetic acid, gluconic acid) that exhibit strong antioxidant, anti-inflammatory, and collagen-promoting activities (Jakubczyk et al., 2024). Recent ex vivo studies by Hwang et al. (2014) demonstrated that kombucha-derived gallic acid significantly reduced ROS production, decreased IL-6 and MMP-1 expression, and protected human dermal fibroblasts from UV-B-induced damage. Furthermore, when kombucha is fermented using Hibiscus sabdariffa (rosella) as the substrate, the resulting beverage exhibits enhanced antioxidant capacity due to rosella's rich content of anthocyanins, protocatechuic acid, and chlorogenic acid (Purboningtyas et al., 2024). The fermentation process biotransforms these compounds into more bioavailable forms with improved skin penetration properties, potentially addressing the bioavailability limitations that hamper many natural antioxidants. This combination represents an innovative approach because it leverages (1) the synergistic effects of multiple antioxidant classes, (2) enhanced bioavailability through microbial biotransformation, (3) multi-targeted mechanisms affecting both collagen degradation (MMP inhibition) and synthesis (TGF-β activation), and (4) additional benefits including anti-inflammatory, antimicrobial, and moisturizing properties derived from metabolic byproducts of fermentation.

Despite the promising preliminary evidence, comprehensive scientific reviews systematically analyzing the molecular mechanisms and clinical potential of kombucha, particularly kombucha rosella, as a topical anti-photoaging agent remain limited. Existing literature predominantly focuses on oral consumption of kombucha for systemic health benefits, with insufficient attention to its dermatological applications via topical delivery. Furthermore, the specific advantages of rosella fermentation, the comparative efficacy against standard anti-aging ingredients, optimal formulation strategies, and translation of in vitro findings to clinical outcomes have not been thoroughly synthesized. Therefore, this literature review—Topical Kombucha as a Natural Antioxidant Against Skin Photoaging: A Literature Review—aims to (1) comprehensively elucidate the molecular mechanisms of UV-B-induced photoaging, including ROS generation, MAPK/AP-1 pathway activation, TGF-β/Smad signaling disruption, and ECM degradation; (2) systematically evaluate the therapeutic potential of kombucha and kombucha rosella as topical agents targeting multiple photoaging pathways; (3) analyze the advantages of fermented versus non-fermented natural antioxidants in dermatological applications; (4) identify current challenges in formulation, stability, and clinical translation; and (5) propose future research directions to advance kombucha rosella from experimental investigation to evidence-based clinical practice. This review is expected to

provide practical benefits, including (a) guidance for formulators developing cost-effective, natural, and non-invasive anti-aging skincare products; (b) evidence-based recommendations for dermatologists and aesthetic practitioners seeking safe alternatives to conventional photoaging treatments; (c) foundational knowledge for researchers pursuing translational studies on fermented natural products in dermatology; and (d) public health insights supporting preventive strategies against UV-induced skin damage using accessible natural resources.

METHOD

This study employs a comprehensive literature review methodology to systematically analyze existing scientific evidence regarding kombucha's potential as a topical anti-photoaging agent. The research design follows a narrative review approach, integrating findings from multiple study types including in vitro experiments, ex vivo skin models, in vivo animal studies, and available human clinical trials to provide a holistic understanding of photoaging mechanisms and natural antioxidant interventions.

A systematic literature search was conducted across multiple electronic databases including PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. The search strategy employed Boolean operators combining relevant keywords: ("photoaging" OR "skin aging" OR "UV-induced skin damage") AND ("kombucha" OR "fermented tea") AND ("antioxidant" OR "polyphenols" OR "flavonoids") AND ("collagen" OR "MMP" OR "TGF-β" OR "extracellular matrix"). Additional searches specifically targeted rosella-related literature using terms: ("Hibiscus sabdariffa" OR "rosella") AND ("skin" OR "photoaging" OR "UV protection"). Reference lists of retrieved articles were manually screened to identify additional relevant studies through snowball sampling.

The review prioritized peer-reviewed research articles published between 2019 and 2024 to ensure currency of evidence, while selectively including landmark studies from earlier periods (2000-2018) that established foundational concepts in photoaging pathophysiology and antioxidant mechanisms. Studies were included if they: (1) investigated mechanisms of UV-induced skin damage; (2) examined antioxidant effects of natural ingredients, particularly kombucha or rosella; (3) evaluated collagen metabolism, MMP activity, or TGF-β signaling in the context of photoaging; (4) assessed topical or transdermal delivery of bioactive compounds; or (5) conducted ex vivo, in vivo, or clinical studies on skin aging interventions. Exclusion criteria comprised: non-English publications without available translations, conference abstracts without full-text availability, studies focusing exclusively on oral kombucha consumption for non-dermatological outcomes, and articles lacking sufficient methodological detail for quality assessment. A total of 45 articles were initially identified, of which 32 met inclusion criteria after full-text screening.

Retrieved literature was systematically analyzed using thematic content analysis. Studies were categorized into thematic domains including: (1) molecular mechanisms of photoaging (ROS formation, MAPK/AP-1 pathway, TGF-β signaling disruption); (2) bioactive composition of kombucha and rosella; (3) antioxidant and anti-inflammatory activities; (4) effects on collagen synthesis and MMP expression; (5) comparative efficacy of topical versus oral antioxidant delivery; (6) formulation technologies and stability considerations; and (7) translation challenges and clinical evidence gaps. For each theme, key findings were extracted, synthesized, and critically evaluated for consistency, methodological quality, and clinical

relevance. Where available, quantitative data on MMP expression, collagen synthesis, ROS levels, and wrinkle reduction were tabulated for comparative analysis. Study quality was assessed using appropriate tools: the ARRIVE guidelines for animal studies, PRISMA-inspired criteria for systematic reviews, and Cochrane risk-of-bias tools for clinical trials, though formal meta-analysis was not conducted due to heterogeneity in study designs and outcome measures.

While this is a literature-based study without a specific physical research location, the reviewed studies were conducted across multiple geographical contexts including South Korea (studies on gallic acid and UV protection), Poland (ex vivo kombucha skin penetration studies), Indonesia (rosella extract efficacy in tropical UV conditions), United States (liposomal antioxidant delivery systems), and Taiwan (Hibiscus sabdariffa bioactive characterization). This geographical diversity enhances the generalizability of findings across different population groups and UV exposure environments. The temporal scope of the review spans two decades (2000-2024), capturing both foundational discoveries in photoaging biology and recent innovations in natural product dermatology, fermentation biotechnology, and transdermal delivery systems.

RESULTS AND DISCUSSION

Effect of Ultraviolet (UV) Exposure on Skin Aging

Exposure to UV rays on the body has physiological benefits such as stimulating the formation of vitamin D3 and the therapy of various skin diseases (such as psoriasis and vitiligo). However, chronic exposure can accelerate aging and lower the local immune system, increasing the risk of malignancy (Watson et al, 2016). There are three types of UV rays: UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm); only UV-A and UV-B reach the surface of the skin, while UV-C is absorbed by ozone (Watson et al., 2016).

Exposure to UV-B rays stimulates the production of melanin which causes tanning, which, although protective, actually indicates skin damage. Clinically, photoaging is characterized by wrinkles, dry, rough skin, sagging, lentigo solaris, telangiectasis, yellowish discoloration, and loss of skin elasticity due to collagen and elastin degradation. These symptoms are most commonly found in areas exposed to sunlight such as the face, neck, and arms (Tanveer et al., 2023; George et al., 2022; Kim et al., 2022).

Molecular and Epigenetic Changes in Photoaging

Exposure to UV light increases the production of reactive oxygen species (ROS) which cause oxidative stress, weaken the endogenous antioxidant system, and damage the structure of DNA. One common form of DNA damage is the formation of pyrimidine dimers and the oxidation of guanine into 8-oxo-dG, which can trigger mutations as well as accelerate cell aging (Tanveer et al., 2023). On the other hand, telomeres as protective structures at the ends of chromosomes also become susceptible to oxidative stress. Telomere shortening occurs physiologically as cells divide, but UV exposure, especially UV-A, accelerates this process through the formation of 8-oxo-2'-deoxyguanosin. Research on fibroblast cultures shows that an increase in UV-A dose is directly proportional to the rate of telomere shortening, this proves that telomere damage plays a role in accelerating photoaging (Kim et al., 2022).

In addition to genetic damage, epigenetic changes also accelerate skin aging. One of them is dysregulation of microRNA expression (miRNA), specifically miR-23a-3p which

suppresses the expression of hyaluronan synthase 2 (HAS2). The expression of miR-23a-3p is increased in aging fibroblasts and plays a role in the decrease in hyaluronic acid, which has an impact on the loss of hydration and skin elasticity (Kim et al., 2022).

Skin aging is also triggered by the accumulation of Advanced Glycation End Products (AGEs), which are the result of a non-enzymatic reaction between sugars and proteins or lipids. This glycation process causes the tissues to harden, there is a decrease in skin elasticity, and the accumulation of collagen that is resistant to MMP degradation. In UV-exposed skin, glycated elastin fibers form abnormal aggregates that interact with lysozyme, and worsen the condition of the dermis (Kim et al., 2022).

Chronically, UV exposure also causes inflammaging which is a low-level inflammatory condition that persists and is typical of aging. UV-induced oxidative stress activates macrophages that release MMP to degrade the extracellular matrix, accompanied by the release of proinflammatory cytokines and ROS. Overactivation of the complement system also causes damage to the dermoepidermal junction, accelerating the progressive degeneration of dermal tissue (Kim et al., 2022).

MAPK and TGF-β Pathway Disruption

Exposure to UV-B rays can cause damage to the skin's extracellular matrix (ME), which is made up of collagen, elastin, and fibrillin. This component plays an important role in maintaining the strength and elasticity of dermal tissue. One of the main mechanisms of this damage is a disruption in the Transforming Growth Factor-beta (TGF-β) signaling pathway, which regulates collagen synthesis (Tanveer et al., 2023).

Physiologically, TGF-β1/2/3 binds to TβRII and TβRIII receptors on the cell surface, then activates TβRI via serine/threonine kinase. This process triggers the phosphorylation of Smad2 and Smad3, which form a complex with Smad4 and move to the cell nucleus to activate the transcription of collagen genes such as COL1A1 and COL3A1 (Tanveer et al., 2023). However, UV-B exposure inhibits this pathway through decreased expression of TGF-β2 and TβRII as well as an increase in Smad7, which is a competitive inhibitor that prevents Smad complexes from entering the nucleus. In addition, UV-B also reduces the affinity of Smad3/4 to the target DNA, thereby decreasing the production of dermal collagen.

On the other hand, UV-B also increases the production of reactive oxygen species (ROS) which triggers the activation of the Mitogen-Activated Protein Kinase (MAPK) pathway, consisting of ERK, JNK, and p38. ROS, primarily through JNK and p38, will phosphorylated c-Fos and c-Jun, which then forms the Activator Protein-1 (AP-1) complex, which is a central regulator in the photoaging process (Fisher et al., 2000; Quan & Fisher, 2015). Activation of AP-1 increases the expression of collagen-degrading enzymes MMP-1 and MMP-3, while suppressing the expression of collagen synthesis genes such as COL1A1 and COL1A2. The combination of increased collagen degradation by MMP and decreased collagen synthesis due to disruption of the TGF-β pathway leads to changes in the structure of the extracellular matrix. Clinically, it appears as wrinkles, dry skin, decreased elasticity, and loss of tissue integrity which are hallmarks of photoaging (Chen & Lyga, 2014).

The Role of Antioxidants in Fighting Photoaging

Exposure to UV rays, especially UV-B, triggers oxidative stress by increasing the production of reactive oxygen species (ROS), which damages the structure of the extracellular matrix (ECM), decreases collagen synthesis through inhibition of the TGF-β/Smad pathway, and increases the activity of MMP enzymes through activation of the MAPK–AP-1 pathway (Tanveer et al., 2023; Kim et al., 2022). Antioxidants play an important role in counteracting the damaging effects of ROS by neutralizing it through electron donation, thereby preventing lipid oxidation, DNA damage, and degradation of structural proteins such as collagen and elastin. In addition, antioxidants can also inhibit the activation of inflammatory pathways (MAPK, AP-1, NF-κB) and support TGF-β signaling, as well as reduce the expression of pro-inflammatory cytokines such as IL-6 and TNF-α (Chowdhury et al., 2021; Fernandes et al., 2022).]

Different types of antioxidants have been used topically to fight photoaging. Vitamin C (ascorbic acid) increases collagen synthesis and inhibits ROS; vitamin E (tocopherol) protects the membrane from lipid peroxidation. Polyphenols such as epigallocatechin gallate (EGCG), gallic acid, and quercetin have strong anti-inflammatory and antioxidant activity. Phenolic acids such as protocatetic acid and chlorogenic acid, which are widely found in fermented products such as kombucha, also show potential in maintaining the integrity of skin tissue from the effects of UV aging.

Topical Vs Oral Antioxidant Administration

Various studies show that topical administration of antioxidants is more effective than orally, because the concentration of active substances achieved in the skin is much higher. Burke (2004) reported that topical application of vitamin C can result in 20–40 times higher concentrations in the skin than oral ones, while vitamin E and selenium increase 10 and 1.7 times respectively, due to limited systemic bioavailability and degradation in the gastrointestinal tract. In addition, topical antioxidants form reservoirs in the skin that remain active even after washing, providing long-term protection against oxidative stress (Burke, 2009). Min et al. (2024) found that only liposomal antioxidant formulations were effective in lowering photoaging biomarkers such as IL-6, IL-8, and MMP-9, whereas free antioxidants did not provide similar protection. Dillon et al. (2023) also showed that the effectiveness of antioxidant delivery is highly dependent on its chemical structure, such as resveratrol or astaxanthin, so that innovative topical formulations are superior to oral administration, especially for molecules that are difficult to cross the skin barrier.

The Potential of Kombucha Rosella as a Topical Anti-Photoaging Agent

Kombucha is the result of the fermentation of tea or herbal plants by the symbiosis of bacteria and yeast (SCOBY), which produces bioactive compounds such as polyphenols, flavonoids, and organic acids with high antioxidants and anti-inflammatory activity. In photoaging, this compound functions to neutralize ROS, inhibits MMP expression, and simulate collagen synthesis. Ex-vivo research by Jakubczyk et al. (2024) showed that green tea kombucha rich in gallic acid and protocatestically can increase collagen synthesis as well as decrease MMP expression in skin models exposed to UV. Hwang et al. (2014) also found that gallic acid in kombucha decreased the production of ROS, IL-6, and MMP-1 in fibroblasts exposed to UV-B.

The in vivo effect was demonstrated by Pakravan et al. (2018), where a fraction of ethyl acetate of kombucha applied to the skin of old mice increased collagen levels and NAD^+/NADH ratios without causing irritation, suggesting the regenerative potential of kombucha. Another study by Ziemlewska et al. (2022) demonstrated that a berry kombucha-fermented skin tonic improves skin hydration and intracellular antioxidant activity in fibroblast and keratinocyte cells.

This potential can be increased by the use of fermented ingredients such as Hibiscus sabdariffa (rosella), which is rich in flavonoids (myricetin), anthocyanins, and phenolic acids. Purboningtyas et al. (2024) showed that a 15% rosella extract gel applied topically to Wistar mice exposed to UVB decreased the expression of TNF-α and Caspase-3 and increased skin collagen density. A similar effect was demonstrated by Li et al. (2020), where rosella calix extract lowered ROS, suppressed MMP, increased TIMP-1 and collagen, and inhibited melanogenesis in in vitro and ex vivo studies.

Fermentation of rosella into kombucha is considered to be able to increase the bioactivity of these antioxidants. Utari (2023) noted that rosella formulated in chitosan nanoparticles had a much higher antioxidant activity index than ordinary extracts (2.217 vs 0.644). Furthermore, Min et al. (2024) proved that fermented antioxidants in the liposome delivery system were able to significantly lower IL-6 (−39.3%), IL-8 (−49.8%), and MMP-9 (−38.5%) in human skin cultures exposed to UVB, compared to non-fermented antioxidants that did not show similar protective effects.

Based on these in vivo and ex vivo findings, kombucha rosella shows strong potential as a topical active ingredient in strategies for the prevention and improvement of skin photoaging due to UV exposure.

Future Challenges and Research Required

Although various in vitro and experimental studies show the potential of natural ingredients, such as kombucha, in counteracting the effects of photoaging, there are a number of challenges that need to be overcome before their application is applied clinically. One of the main challenges is the stability of bioactive compounds such as polyphenols and organic acids that are easily oxidized and sensitive to light, temperature, and pH, so a formulation technology that is able to maintain stability during storage and use is needed (Tanveer et al., 2023).

The next challenge is the ability to penetrate the active ingredient into the skin layer, as the stratum corneal layer is selective and inhibits the entry of active compounds into the dermis where collagen is synthesized. Technological approaches such as nanoemulsions, liposomes, ethosomes, or nanoparticle-based delivery systems are starting to be widely explored to improve local bioavailability and skin penetration (Fernandes et al, 2022).

In addition, the standardization of the process of extracting natural ingredients and fermenting kombucha is still an obstacle because variations in substrate types (e.g., tea, fruit, or plants), fermentation duration, and the type of microorganisms in SCOBY can affect antioxidant content and biological activity. Therefore, standardized quality parameters are needed to guarantee the consistency of results. (Anantachoke et al, 2023).

Nanotechnology approaches such as liposome-based carriers and biodegradable polymers are able to improve the protection of compounds, control their release, and increase their biological efficacy in target tissues (Ziemlewska et al, 2022).

Finally, a transition from in vitro studies to in vivo research and human clinical trials is needed, to objectively evaluate the effectiveness of the formulation on skin moisture, collagen density, wrinkle count, as well as molecular biomarkers of aging (Kim et al 2022; Jakubczyk et al, 2024).

Overall, the future direction of research needs to be focused on stable and effective innovative formulations, increased transdermal bioavailability, as well as validation through translational studies and clinical trials so that the potential of kombucha as a natural anti-photoaging agent can be widely implemented in clinical dermatology and cosmetic practices.

CONCLUSION

Exposure to ultraviolet light, especially UV-B, is a major factor that accelerates skin aging through the mechanism of ROS formation, DNA damage, chronic inflammation, and disruption of the TGF-β/Smad signaling pathway as well as MAPK/AP-1 activation. These processes lead to decreased collagen synthesis, degradation of extracellular matrix structures, as well as the appearance of photoaging clinical signs such as wrinkles and loss of skin elasticity. The strategy of using natural ingredients rich in antioxidants has been shown to be effective in inhibiting the photoaging process. Kombucha, especially fermented from Hibiscus sabdariffa (rosella), contains bioactive compounds such as phenolic acids, flavonoids, and organic acids that are able to neutralize ROS, inhibit MMP expression, and increase TGF-β levels and collagen synthesis. In addition, research shows that topical application of kombucha provides a protective effect on the skin without any significant side effects, making it an ideal candidate in the development of natural-based anti-aging therapies. Thus, kombucha rosella has strong potential as a topical active ingredient that is not only preventive but also therapeutic in treating skin damage due to photoaging. However, further research is needed, especially in vivo and clinical trials to ensure the effectiveness, stability of formulations, and safety of their use in modern dermatology and cosmetic practices.

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