Kanlayavattanakul *et al.*
Food Production, Processing and Nutrition (2024) 6:86
https://doi.org/10.1186/s43014-024-00262-4

Food Production, Processing and Nutrition

RESEARCH

Open Access

Food hydroxycinnamic acids alleviate ageing in dermal cells

Mayuree Kanlayavattanakul[1,2*], Mattaka Khongkow[3], Tawin Iempridee[3] and Nattaya Lourith[1,2]

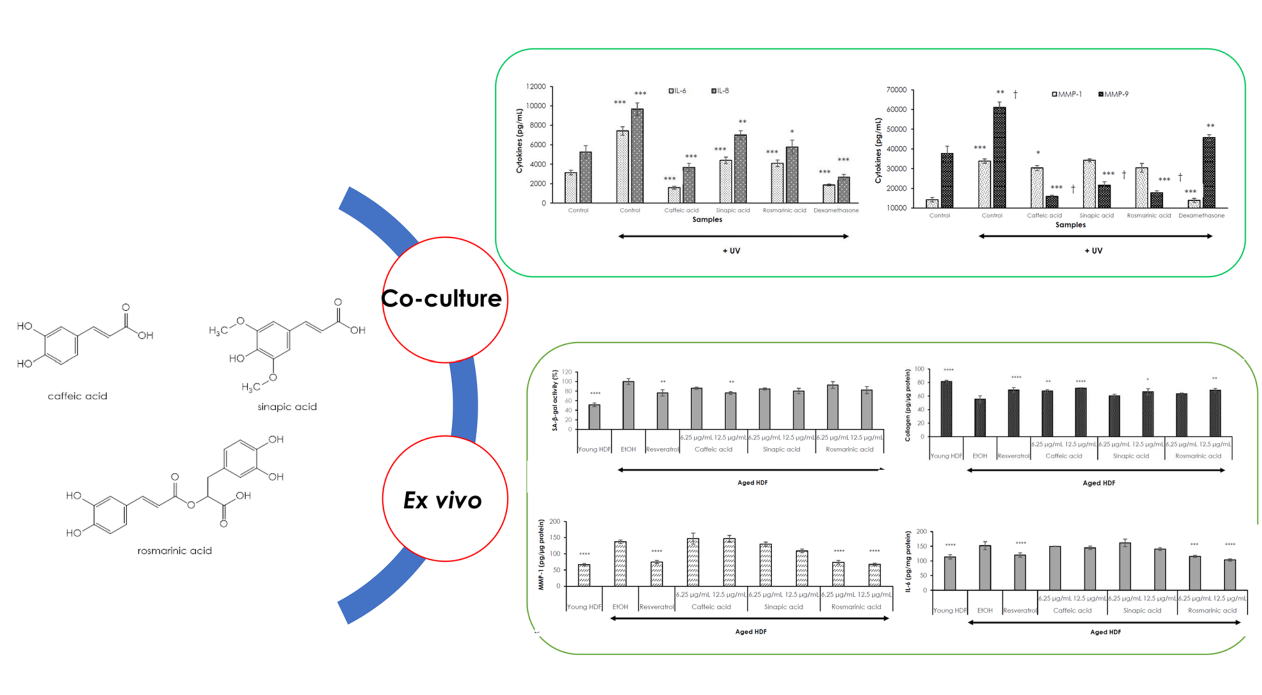
Abstract

Dermal damage is inducible by several factors including UV exposure, oxidative stress and inflammation exacerbating skin senescence and degradation of the skin elastic fibers accumulated in ageing accordingly. Which, phenolics of food hydroxycinnamates with a myriad of health benefits are potentially applicable for ageing treatment. Particularly those of food hydroxycinnamic acids, i.e., caffeic, sinapic and rosmarinic acids, that would be efficient against skin ageing. Effectiveness of caffeic, sinapic and rosmarinic acids alleviating ageing was indicated in human dermal fibroblasts (HDF) and co-culture of human keratinocytes (HaCaT) and HDF. Caffeic acid was exhibited as the strongest ($p < 0.01$) anti-senescent phenolic examined. The studied food hydroxycinnamic acids were shown to induce collagen synthesis in aged HDF with the noted activities inhibiting MMP-1 and IL-6. Their photoaging protections were proved in the co-culture model with significant ($p < 0.001$) inhibitions against IL-6, IL-8, MMP-1 and MMP-9 (collagen and elastin degrading enzymes). Which, caffeic acid was demonstrated as the most potent photoaging agent among its counterparts. Caffeic, sinapic and rosmarinic acids were proved to be the efficient nutrients for ageing treatment. These functional food hydroxycinnamates are proven on their anti-senescent and photoprotection activities, and capable to maintain homeostasis of dermal cells. Food-derived hydroxycinnamic acids are therefore recommended for innovative product alleviates skin ageing.

Keywords Food phenolics, Functional food, Anti-inflammatory, Photoaging

*Correspondence:
Mayuree Kanlayavattanakul
mayuree@mfu.ac.th
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

Phenolics that are commonly found in food have been regarded as the significant functional ingredients with pharmacological effects (Gendrisch et al., 2021; Khan et al., 2020). Their therapeutic effects were demonstrated including the protective role against degenerative diseases. Interestingly, their bioavailability especially the hydroxycinnamic acids fascinated their functional applications (Khan et al., 2020; Kumar & Goel, 2019; Zhao & Moghadasian, 2010). Hydroxycinnamic acids (C6-C3) are secondary metabolites commonly found in cereals, legumes, oilseeds, fruits and vegetables (Khan et al., 2020) that are regarded as the nutritional crops promising for plant-based pharmaceuticals. Accordingly, the natural derived hydroxycinnamic acids with a myriad of health benefits are emerging as attractive molecules (Shahidi & Chandrasekara, 2013) especially for premium food products (Brewer, 2011; Chandrasekara & Shahidi, 2018; Zeb, 2020) servable for health managements (Alam et al., 2016; Chandrasekara & Shahidi, 2011). These phenolics are worthily to be explored on their precise working mechanisms beneficial for skin health (Fam et al., 2022) in addition to their known physiological positive effects. Which, the commonly known hydroxycinnamic acids are *p*-coumaric, caffeic, ferulic and sinapic acids and their esterified/etherified conjugates such as chlorogenic and rosmarinic acids (Shahidi & Chandrasekara, 2010). They are of health importance with cutaneous benefits and suitable for the innovative product development (Gunia-Krzyżak et al., 2018). *p*-Coumaric and ferulic acids are the most studied hydroxycinnamic acids for personal care product applications (Taofiq et al., 2017). Surprisingly, the rest of hydroxycinnamic acid derivatives are remained unexplored.

Studies on *p*-coumaric and ferulic acids for dermatological utilization are prominence on melanogenesis (Choi et al., 2007; Lee et al., 2020). Skin dullness resulted from hyperpigmentation is an importance sign associated in skin ageing and will be exacerbated in photoageing (Kanlayavattanakul & Lourith, 2015, 2018) in the same time with several oxidation events (Kammeyer & Luiten, 2015). However, anti-inflammatory assessment of hydroxycinnamic acids relating with ageing and photoaging of skin (Chung et al., 2006; Salminen et al., 2022) is sparely available as well as their proficiency against senescent ageing.

Caffeic, sinapic and rosmarinic acids (Fig. 1) are the emerging hydroxycinnamic acids feature for anti-ageing products (Magnani et al., 2014; Nguyen et al., 2021; Noor et al., 2022). Nonetheless, the mechanism for skin application is not clearly demonstrated yet. In this present study, caffeic, sinapic and rosmarinic acids were therefore investigated for their effectiveness against cutaneous ageing in cell culture models, i.e., human dermal fibroblasts

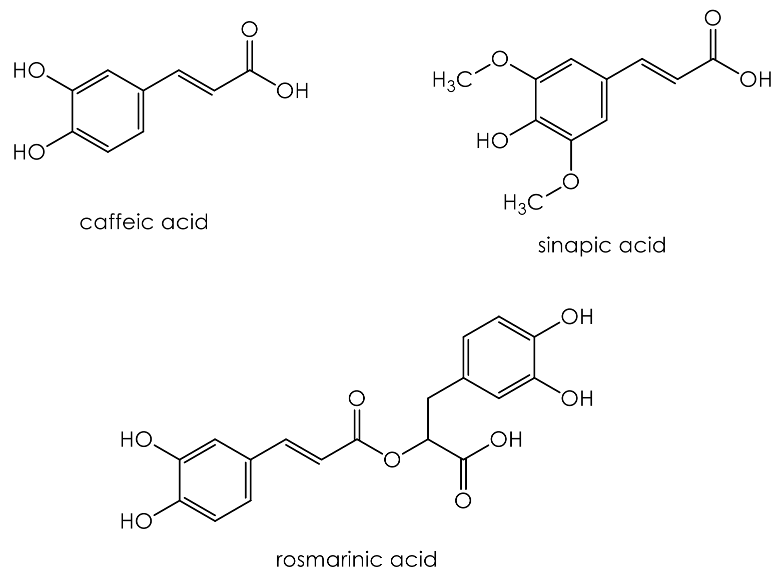


Fig. 1 Hydroxycinnamic acid derivatives examined in this study

(HDF) and co-cultures of human keratinocytes (HaCaT) and HDF. Their activities on anti-senescence ageing, matrix metalloproteinases (MMP) and interleukins (IL) were presented including photoprotection activity. These food-derived hydroxycinnamic acids were demonstrated as the efficient functional ingredients alleviate ageing abided with the indicated mechanisms.

Materials and methods

The experiments were conducted at Mae Fah Luang University and NANOTEC. All of the chemicals and reagents used were of analytical grade. The examined hydroxycinnamic acids (≥ 95% purity) were purchased from Sigma-Aldrich (USA). Mediums for cellular assessments were from Gibco (USA), including the supplements.

Safety and biological activity assessments in HDF

Adult primary HDF (PCS-201–012; ATCC, USA) were examined. The cells were seeded in 96-well plates, grown in Dulbecco's modified (DMEM) with 10% fetal bovine serum (FBS) and 1% penicillin–streptomycin solution. The cells underwent fewer than 7 passages with slight or negative senescence-associated β-galactosidase (SA-β-gal) staining were counted as young HDF. Whist, those that underwent more than 10 passages and positive SA-β-gal stained were regarded as late-passage or aged HDF. Safety of the samples (in DMSO) in term of cell viability was investigated with CellTiter-Flour™ Cell Viability Assay in triplicate during two independent experiments (Klinngam et al., 2022).

HDF (young and aged), seeded in 96-well black plates (Corning, USA), were senescence-induced, treated with vehicle control and the samples for 75 h, and assessed onto SA-β-gal activity using the Cellular Senescence Plate Assay Kit—SPiDER-β-Gal (Dojindo Molecular Technologies, USA). The collected mediums were quantified on the secreted proteins using interleukin (IL)-6 (IL-6, AL223c; PerkinElmer, USA), matrix metalloproteinase-1 (MMP-1, ab215083; Abcam, UK), and procollagen type I C-peptide (PIP, AL353HVc; PerkinElmer) assay kits. IL-6 and MMP-1 that are senescence-associated secretory phenotype (SASP) in HDF and procollagen content were examined as previously described (Klinngam et al., 2022; Shin et al., 2020). Assays were performed in triplicate.

Safety and biological activity assessments in HaCaT and HDF co-culture

Safety and biological activity study in a co-culture model was conducted as previously described (Bassino et al., 2019; Kanlayavattanakul et al., 2023). Briefly, HDF were seeded in 48-well plate for 3 days. Thereafter, HaCaT (Cell Lines Service, Germany, Cat. No. 300493) that were cultured in DMEM supplemented with 10% FBS and 1% penicillin–streptomycin solution were additionally seeded onto the HDF for further 24 h. Thereafter, the co-cultures were treated with the extracts or the standards, incubated for 24 h, exposed with UVA (1040 mJ/cm^2) and UVB (27 mJ/cm^2), incubated for 24 h. Cell viability (%) was monitored with CellTiter-Glo luminance cell viability assay kit (Promega, USA).

Cellular activities of the phenolics in the co-cultures were examined in terms of IL-6, IL-8 (AL328c; PerkinElmer), MMP-1 and MMP-9 (ab100610, Abcam) contents. Which, the supernatants were collected and measured by the relevant enzyme-linked immunosorbent assay kits according to manufacturing protocols in a comparison with the control groups, i.e., vehicle control and non-UV exposure.

Statistical analysis

Data were presented as the means ± SD and a one-way ANOVA test was used to evaluate the difference between groups using the program SPSS version 16.0. The level of significance was at $p < 0.05$.

Results

Anti-senescence activity in HDF

Anti-senescence activity of caffeic, sinapic and rosmarinic acids was determined. The safety doses of the studied phenolics were in the range of 6.25–12.5 μg/mL as evidenced from two independent experiments (Fig. 2) with a cell viability of greater than 80%. All of the studied phenolics suppressed SA-β-gal activity. Anti-senescent activity was pronounced at the higher test concentration (Fig. 3A) with collagen stimulating synthesis in aged HDF (Fig. 3B), and inhibitory effects against MMP-1 (Fig. 3C) and IL-6 (Fig. 3D).

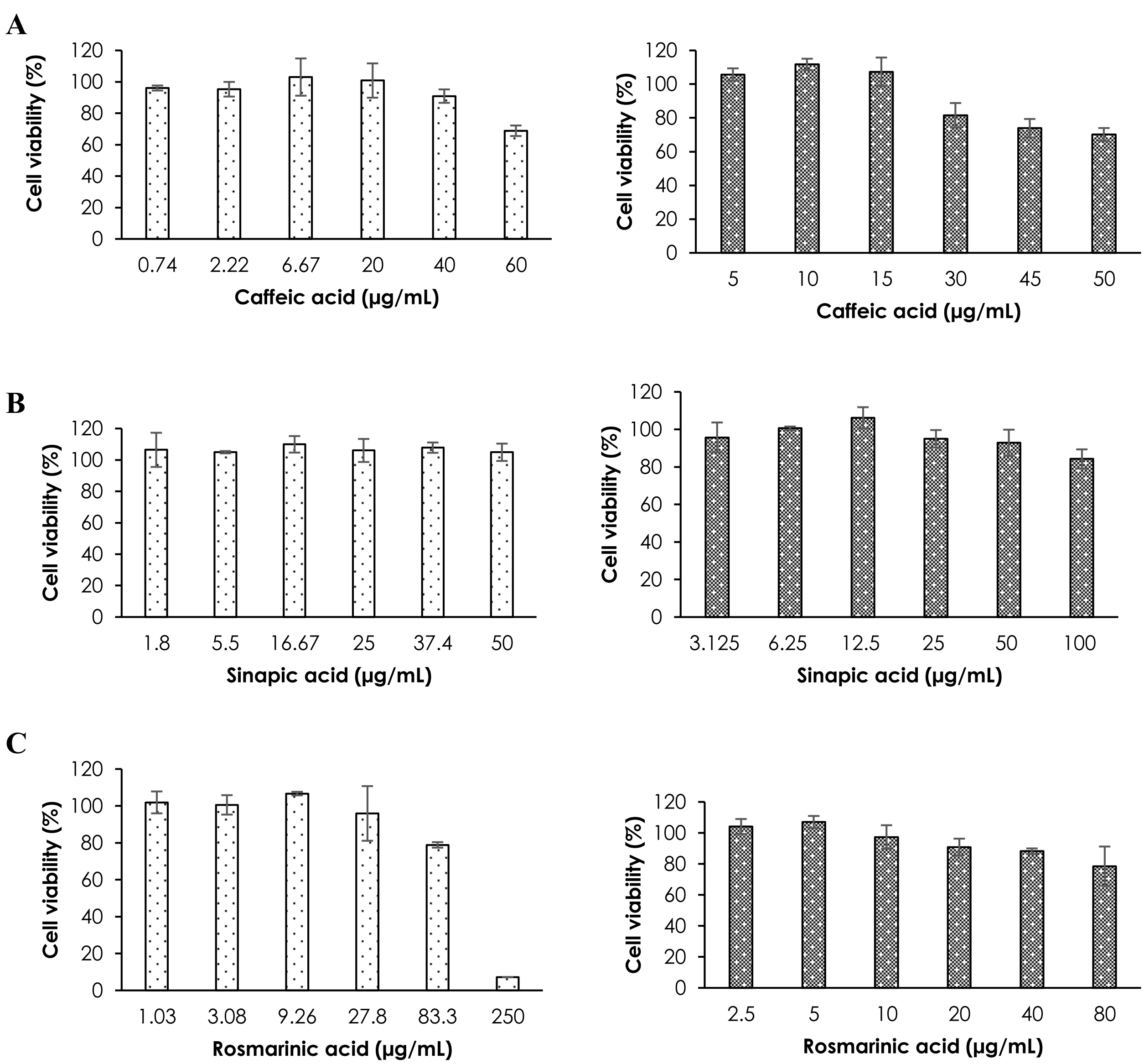


Fig. 2 Safety assessment of caffeic acid (**A**), sinapic acid (**B**) and rosmarnic acid (**C**) in HDF from two independent experiments

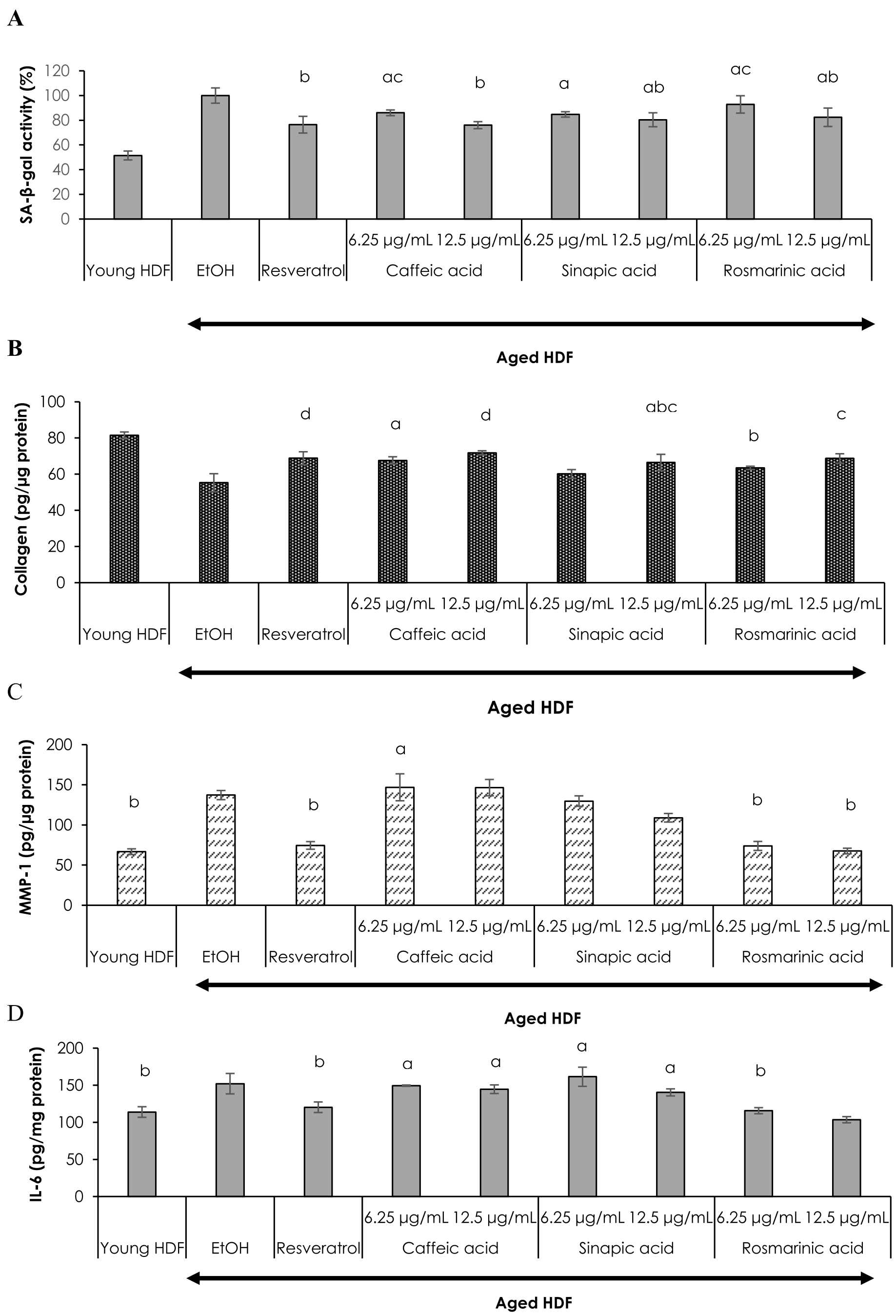


Fig. 3 Activities on SA-β-gal (**A**), collagen (**B**), MMP-1 (**C**) and IL-6 (**D**) of the samples in HDF. The values marked with the same letters represent the insignificant difference ($p > 0.05$)

Biological activities in HaCaT and HDF co-culture

Cytotoxicity of the phenolics was preliminary examined in HaCaT and HDF, separately (Fig. 4A). The phenolics were shown to be safe towards the cells at the concentration ranged from 0–200 µg/mL with cell viability of more than 80%. Thereafter, safety assessment in co-culture model was trialed. Cytotoxicity of the co-culture was initiated by UV radiation. Cell viability was compared with the control groups, medium-treated and non-UV exposure. Of which, the phenolics (150 µg/mL) were proved onto their photoaging protection against UVA and UVB (Fig. 4B).

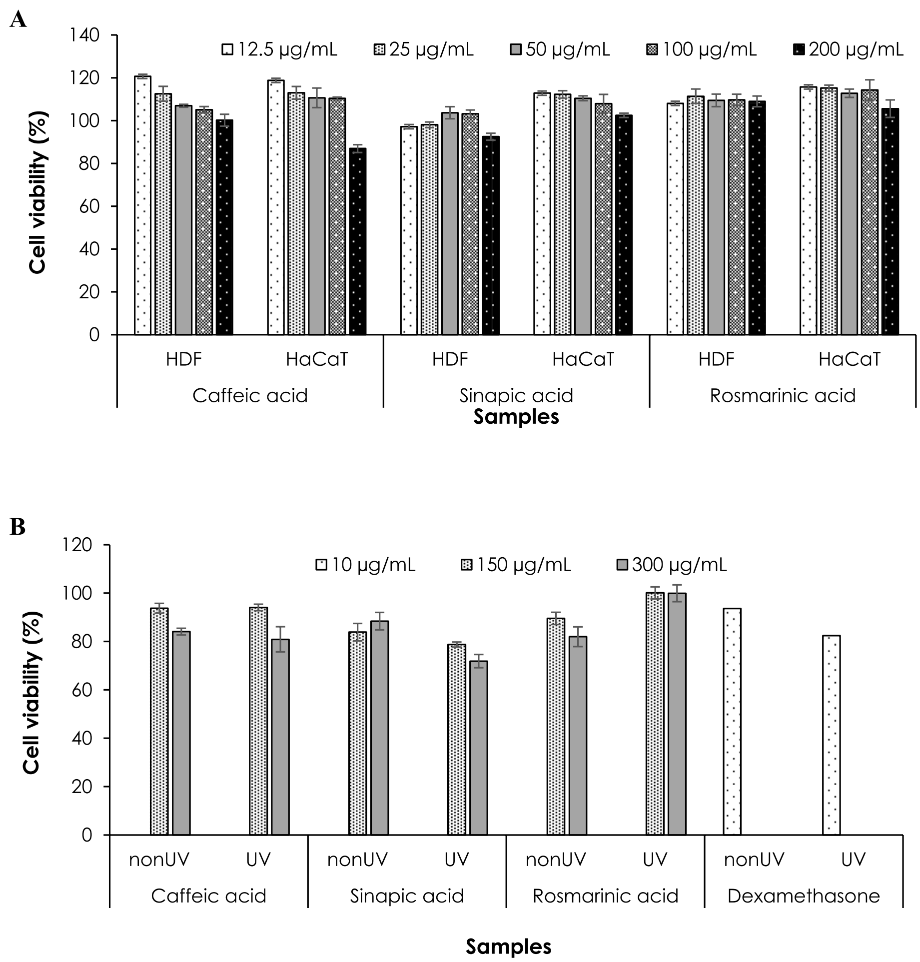


Fig. 4 Safety assessments in HaCaT and HDF (**A**) and co-culture of HaCaT and HDF (**B**) of the samples

Anti-inflammatory activity of caffeic, sinapic and rosmarinic acids was monitored in the co-culture that photodamaged (Fig. 5A). Caffeic acid was the most potent anti-inflammatory phenolic against IL-6 followed by rosmarinic and sinapic acids, respectively. In addition, the activity profile against IL-8 was in the same trend with those of IL-6.

An inhibitory effect against MMPs degrading collagen (MMP-1) and elastin (MMP-9) was studied. Caffeic acid was the best enzymes inhibitor amidst the studied phenolics (Fig. 5B).

Discussion

Cutaneous ageing is caused by several factors. UV exposure in addition to oxidative stress elevate inflammation causing degradation of the extracellular matrix, which are regarded as the major cause of skin wrinkles, one of the signs of ageing. Dermal damage is inducible by UV exposure at the shorter wavelengths (UVB) which are absorbed by the epidermis prior to irradiation of keratinocytes. On the mean time that longer wavelengths (UVA) penetrate the skin and interact with epidermal and dermal cells that majorly composing with fibroblasts. MMPs are propagated resulting in degradation of extracellular matrix (ECM), i.e., collagen and elastin fibers. These events are accelerated with age, UV exposure and radicals including inflammation and accumulated/exacerbated senescent ageing (Chung et al., 2006; Kanlayavattanakul & Lourith, 2015; Salminen et al., 2022).

Phenolics especially the hydroxycinnamic acid derivatives are regarded as safe and efficient natural derived biologically active molecule proficiently for ageing treatment including photoaging (Kammeyer & Luiten, 2015; Kanlayavattanakul & Lourith, 2018). Of which, *p*-coumaric and ferulic acids are those of widely studied in accordance with their abundances (Gunia-Krzyżak et al., 2018) and bioavailability (Shahidi & Chandrasekara, 2010). In contrary with the rest of their counterpart hydroxycinnamates, i.e., caffeic, sinapic and rosmarinic acids, which are gaining high

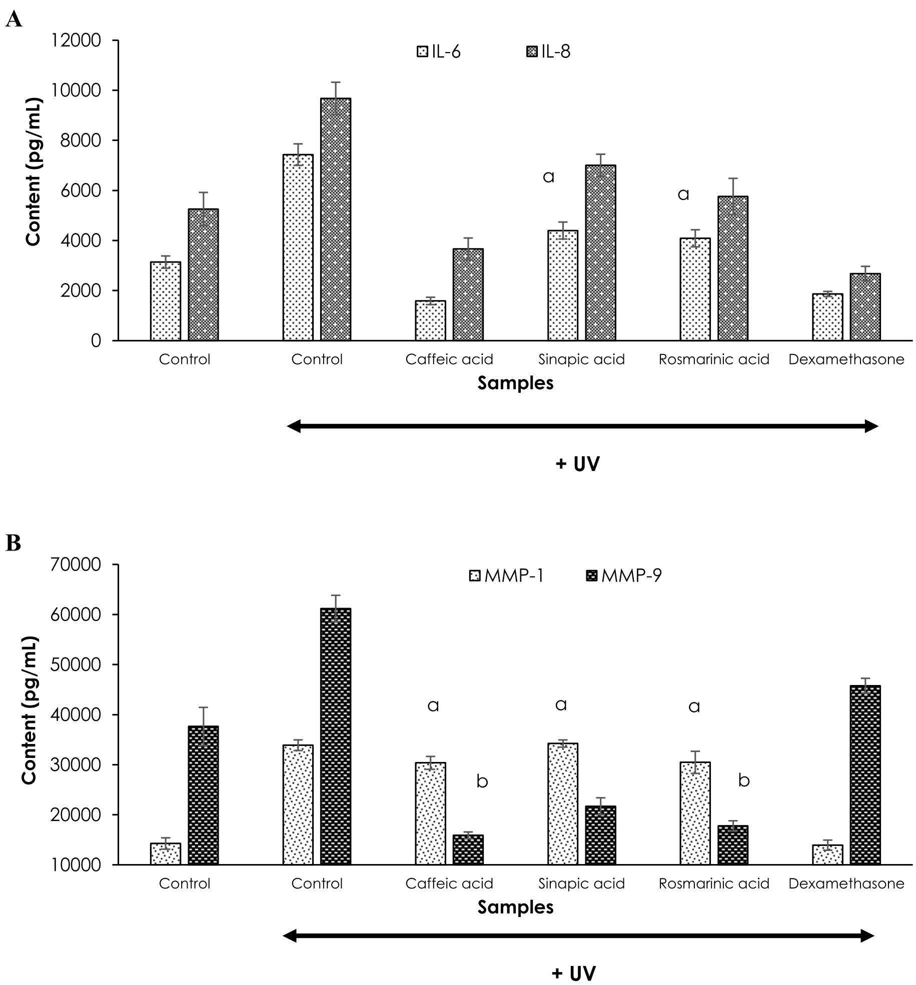


Fig. 5 IL-6 and IL-8 (**A**) and MMP-1 and MMP-9 (**B**) contents in the cells treated with the samples. The values marked with the same letters represent the insignificant difference ($p > 0.05$)

interests on their anti-ageing application (Magnani et al. 2014; Nguyen et al., 2021; Noor et al., 2022). In line with the recent concept on food application for skin health (Fam et al., 2022). Effectiveness of caffeic, sinapic and rosmarinic acids, the food phenolics, against skin ageing are worthily to be revealed, and specified on the working mechanism.

Tissue culture-based study is crucial for cosmetic claim substantiation in terms of safety and efficacy (Antignac et al., 2011; Ramata-Stunda et al., 2013). Fibroblasts and keratinocytes are obvious the types of skin cells for the assessment. Which, the cell culture test model can be the monocultures of these cells. In addition, the co-cultures are appointed for simultaneous stimulation of several cell types for safety and efficacy assessments together with an evaluation upon the changes in their interactions. Of which, keratinocyte-fibroblast co-culture is of physiological importance interplaying a significant role in skin tissue homeostasis and regeneration (Borg et al., 2013). Thus, these tissue culture models were undertaken in this study.

Anti-senescence activity in HDF

Cutaneous ageing is exacerbated with several factors included senescence, which downregulates skin cells' activities. Senescent ageing is worsened by the cellular oxidation events, inflammations and UV exposure as well. Accordingly, an observation of SA-β-gal activity is the key strategy monitoring skin senescence (Klinngam et al., 2022; Salminen et al., 2022). Because an accumulation of senescent cells is a common hallmark of the skin ageing process (Salminen et al., 2022). Which, senescent cells upregulate secretions of cytokines, chemokines and MMPs, and accelerate skin ageing consequently.

Caffeic acid was exhibited as the strongest anti-senescent phenolic and comparable with the benchmark resveratrol (Fig. 3A) at its maximum dose in similar with sinapic and rosmarinic acid. In addition, their proficiencies against senescent ageing were indicated to be stronger than the herbal-derived verbascoside that previously reported at the same concentration (Kanlayavattanakul et al., 2023). Thus, the anti-senescent activity would be more flavor on the smaller phenolics. These antioxidative hydroxycinnamic acids (Chandrasekara & Shahidi, 2011) that were previously indicated onto their health beneficials (Chandrasekara & Shahidi, 2018; Shahidi & Chandrasekara, 2013), were proved to protect the cells from senescent ageing. Whether these attractive molecules capable to promote dermal matrix chiefly responsible for skin elasticity, i.e., collagen, and how they work were next questioned. Consequently, the anti-ageing mechanism was observed in the aged HDF. Collagen content in the aged HDF was indicated to be achieved following treatments with hydroxycinnamic acids. The most potent anti-senescent ageing caffeic acid was found to be best stimulating cellular collagen production and comparable with resveratrol. It should be noted that although the hydroxycinnamic acids were capable to promote collagen production in the aged HDF, but the contents were lower than those of the young HDF. An expression of MMP-1, collagen degradable enzyme, is activated with IL-6. In regards with the demonstrated proficiencies of the phenolics recovering aged HDF, we further questioned on their activities on MMP-1 (collagenase) and IL-6, the markers of collagen breakdown and inflammation associated in ageing. The hydroxycinnamic acids suppressed MMP-1 in the senescent-induced aged HDF and their anti-MMP-1 were obviously promoted with concentration. Interestingly, rosmarinic acid was indicated as the most potent anti-MMP-1, followed by sinapic and caffeic acids, respectively. Rosmarinic acid significantly ($p < 0.0001$) suppressed MMP-1 secretion in aged HDF in similar with resveratrol, with the comparable MMP-1 content as the young HDF (Fig. 3C). Which in harmony with the anti-inflammatory activity against IL-6 (Fig. 3D). Taken into account, these food-derived phenolics that tremendously constituted in cereals including millet (Shahidi & Chandrasekara, 2013) ameliorate senescent ageing on the basis of their inhibitory effects against MMP-1 and IL-6, while promoting collagen in turn. In addition, the proficiencies were in a dose-dependent behavior.

Senescent ageing is accumulated and exacerbated with UV exposure. UV-induced oxidative stress worsens dermal damaged upregulating MMPs especially MMP-1 and MMP-9 (gelatinase), the extracellular matrices degradable enzymes (Kohl et al., 2011; Lourith & Kanlayavattanakul, 2016). We therefore proposed that these hydroxycinnamic acids would alleviate inflammatory mediators and MMPs activities, which are activated by UV exposure in keratinocytes and fibroblasts. Accordingly, biological activities of these phenolics were further challenged in a coculture model.

Biological activities in HaCaT and HDF co-culture

Effectiveness of caffeic, sinapic and rosmarinic acids against senescent-ageing was demonstrated in HDF. In which, their positive effects on collagen production, and negatively against MMP-1 and IL-6 were indicated. We hypothesized that they may exert some degree of prevention or protection against photoaging. Photoaging is becoming a serious event deteriorating ageing. Which, the agent with an identifiable activity combating photoaging is of significant for the new generation of anti-ageing agents (Huang & Chien, 2020). The performance of caffeic, sinapic and rosmarinic acids against senescent-ageing was observed in HaCaT and HDF co-cultures.

Cellular oxidative damage was induced by UV exposure impairing skin homeostasis implicates inflammation, cellular senescence, and further degenerate dermal tissues promoting ageing consequently. In addition, UV-induced inflammation accumulates in tumors that may severely progress into photo-carcinogen. Thus, anti-photoaging agent is parity applicable for skin health in addition to its aesthetic condition.

Caffeic, sinapic and rosmarinic acids exhibited photoaging protection against UVA and UVB (Fig. 4B). Of which, rosmarinic acid was more potent than caffeic and sinapic acids, respectively (4, 2 and 1 aromatic hydroxyl groups) as indicated with a greater cell viability. Their protections against cellular photodamage are contributed by the hydroxyl moieties (Shahidi & Chandrasekara, 2010). They are therefore able to maintain skin homeostasis following UV-induced oxidative stress.

Taken into account upon the oxidation events and inflammation. Their anti-inflammatory activity was monitored (Fig. 5). UV-radiation specifically elevates IL-6 and IL-8 secretions. These skin senescent factors further escalate MMPs particularly MMP-1 (collagenase) and MMP-9 (gelatinase), respectively, accumulating skin photoaging (Fitsiou et al., 2021). MMP-1 cleavages fibrillar collagen in the dermis, which the resulting denatured collagen is then further degraded by MMP-9. UV-induced cellular collagen degradation is therefore sequentially started by MMP-1 and fully with MMP-9.

The cytokine (IL-6) and chemokine (IL-8) were dramatically increased following UV exposure (Fig. 5A).

The phenolics were noted on their potent activities suppressing the inflammatory mediators' secretions. The anti-inflammatory activity of the phenolics was more selectively against IL-6, which caffeic acid was noted on its potent activity. Although the activity was noted to be modulated by the hydroxyl moieties (Shahidi & Chandrasekara, 2010), the side chain of rosmarinic acid molecule may hinder its activity to a lesser degree than caffeic acid, the counterpart phenolic with half of hydroxyl moieties. Furthermore, it should be noted that caffeic acid significantly ($p < 0.01$) suppressed IL-6 better than the positive control, dexamethasone (Fig. 5A). In addition, the activity against IL-8 of the studied phenolics was in the same trend against IL-6. Caffeic acid was obviously ($p < 0.01$) noted onto its IL-8 suppression activity over the counterpart phenolics. Thus, caffeic, sinapic and rosmarinic acids are proven on their anti-inflammatory involving in photoaging of skin (Borg et al., 2013; Salminen et al., 2022), with the prominence activity onto IL-6.

Furthermore, an inhibitory effect against collagen and elastin, the major extracellular matrix (ECM) responsible for skin elasticity (Lourith & Kanlayavattanakul, 2016) degradation enzymes, i.e., MMP-1 and MMP-9, was studied. Collagenase and gelatinase are attributable to inflammations induced by UV-dermal damage, i.e., photoaging. A secretion of the enzymes was clearly upregulated following UV exposure (Fig. 5B), particularly MMP-9, which is specifically upregulated by IL-8 (Li et al., 2003). Which, MMPs contents were sharply reduced in the co-cultures treated with the phenolics. Interestingly, inhibitory effects against MMP-9 of caffeic, rosmarinic and sinapic acids were superior ($p < 0.001$) over dexamethasone. Caffeic acid was the best MMP-1 inhibitor, but weaker than the positive control dexamethasone (Fig. 5B). Inflammatory of skin induces MMP production that cause skin ageing by an irreversibly epidermal damaged (Borg et al., 2013). Thus, these studying hydroxycinnamic acids are proved onto their protecting activities against photoaging with anti-inflammatory and anti-MMP actions.

Caffeic, sinapic and rosmarinic acids are proved onto their effectiveness against photoaging. This study revealed the photoprotective effects of these hydroxycinnamic acids for the first time, in addition to their known application as antioxidants (Kumar & Goel, 2019). The revealed properties identify them as the new generation of anti-ageing agents (Huang & Chien, 2020) with integrated functions as primary and secondary photo-protecting agents. Which, the primary agents provide skin-protective effects on the basis of UV filtering action in regards with the structures of the phenolics. The latter type confers to those that prevent or protect the cells from relevant events to DNA damage/repair, UV-induced inflammatory adverse effects on ECM degradations. Herbs and spices are regarded as the main sources of caffeic and rosmarinic acids especially rosemary, oregano, sage, thyme, marjoram, parsley, lemon and mint (Brewer, 2011; Rubió et al., 2013), while cereals are the promising sources of sinapic acid (Nićiforović & Abramovič, 2014). Accordingly, food rich in these functional phenolics are known metabolomic sources for pharmaceutical applications (Fam et al., 2022; Gunia-Krzyżak et al., 2018), and applicable for innovative anti-ageing product.

Conclusions

Caffeic, sinapic and rosmarinic acids are proven for their effectiveness against senescent ageing and photoaging. This study revealed the anti-ageing properties of food hydroxycinnamic acids with the demonstrated mechanisms in dermal cells, in addition to their known application as antioxidants (Kumar & Goel, 2019). These food hydroxycinnamates are proven on their anti-senescent and photoprotection activities, and capable to maintain homeostasis of dermal cells. Food derived hydroxycinnamic acids are therefore recommended for innovative products for ageing treatment/prevention in terms of nutraceuticals and cosmeceuticals for example beverages (Chandrasekara & Shahidi, 2018) that are highly in demand towards bio-based or natural-derived compounds. Furthermore, fruits, vegetables, cereals, herbs and spices that are abundant in these phenolics are recommended as the functional foods.

Acknowledgements

Mae Fah Luang University and NANOTEC are acknowledged for facility supports. The reviewers are acknowledged on their valuable suggestions that make the article more comprehensive.

Authors' contributions

Mayuree Kanlayavattanakul: Conceptualization, Methodology, Project administration, Investigation, Writing-Reviewing and Editing. Mattaka Khongkow: Investigation, Formal analysis, Data curation. Tawin Iempridee: Investigation, Formal analysis, Data curation. Nattaya Lourith: Investigation, Writing—Original Draft.

Funding

This work was supported by Mae Fah Luang University.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests
The authors declared that there is none of conflict of interest.

Author details
[1]School of Cosmetic Science, Mae Fah Luang University, Chiang Rai 57100, Thailand. [2]Phytocosmetics and Cosmeceuticals Research Group, Mae Fah Luang University, Chiang Rai 57100, Thailand. [3]National Nanotechnology Center (NANOTEC), National Science and Technology Development Agency, Pathum Thani, 12120, Thailand.

Received: 13 October 2023 Accepted: 7 May 2024
Published online: 07 October 2024

References

Alam, M. A., Subhan, N., Hossain, H., Hossain, M., Reza, H. M., Rahman, M. M., & Ullah, M. O. (2016). Hydroxycinnamic acid derivatives: a potential class of natural compounds for the management of lipid metabolism and obesity. *Nutrition & Metabolism,13*, 27. https://doi.org/10.1186/s12986-016-0080-3

Antignac, E., Nohynek, G. J., Re, T., Clouzeau, J., & Toutain, H. (2011). Safety of botanical ingredients in personal care products/cosmetics. *Food and Chemical Toxicology,49*, 324–341. https://doi.org/10.1016/j.fct.2010.11.022

Bassino, E., Gasparri, F., & Munaron, L. (2019). Natural dietary antioxidants containing flavonoids modulate keratinocytes physiology: *in vitro* tri-culture models. *Journal of Ethnopharmacology,238*, 111844. https://doi.org/10.1016/j.jep.2019.111844

Borg, M., Brincat, S., Camilleri, G., Schembri-Wismayer, P., Brincat, M., & Calleja-Agius, J. (2013). The role of cytokines in skin aging. *Climacteric,16*, 1–8. https://doi.org/10.3109/13697137.2013.802303

Brewer, M. S. (2011). Natural antioxidants: sources, compounds, mechanism of action, and potential applications. *Comprehensive Reviews in Food Science and Food Safety,10*, 221–247. https://doi.org/10.1111/j.1541-4337.2011.00156.x

Chandrasekara, A., & Shahidi, F. (2011). Antiproliferative potential and DNA scission inhibitory activity of phenolics from whole millet grains. *Journal of Functional Foods,3*, 159–170. https://doi.org/10.1016/j.jff.2011.03.008

Chandrasekara, A., & Shahidi, F. (2018). Herbal beverages: bioactive compounds and their role in disease risk reduction – a review. *Journal of Traditional and Complementary Medicine,8*, 451–458. https://doi.org/10.1016/j.jtcme.2017.08.006

Choi, S., Lee, S. K., Kim, E. O., Oh, J. H., Yoon, K. S., Parris, N., Hicks, K. B., & Moreau, R. A. (2007). Antioxidant and antimelanogenic activities of polyamine conjugates from corn bran and related hydroxycinnamic acids. *Journal of Agricultural and Food Chemistry,55*, 3920–3925. https://doi.org/10.1021/jf0635154

Chung, H. Y., Sung, B. Y., Jung, K. J., Zou, Y., & Yu, B. P. (2006). The molecular inflammatory process in aging. *Antioxidants & Redox Signaling,8*, 572–581. https://doi.org/10.1089/ars.2006.8.572

Fam, V. W., Charoenwoodhipong, P., Sivamani, R. K., Holt, R. R., Keen, C. L., & Hackman, R. M. (2022). Plant-based foods for skin health: a narrative review. *Journal of the Academy of Nutrition and Dietetics,122*, 614–629. https://doi.org/10.1016/j.jand.2021.10.024

Fitsiou, E., Pulido, T., Campisi, J., Alimirah, F., & Demaria, M. (2021). Cellular senescence and the senescence-associated secretory phenotype as drivers of skin photoaging. *Journal of Investigative Dermatology,141*, 1119–1126. https://doi.org/10.1016/j.jid.2020.09.031

Gendrisch, F., Esser, P. R., Schempp, C. M., & Wölfle, U. (2021). Luteolin as a modulator of skin aging and inflammation. *BioFactors,47*, 170–180. https://doi.org/10.1002/biof.1699

Gunia-Krzyżak, A., Słoczyńska, K., Popiół, J., Koczurkiewicz, P., Marona, H., & Pękala, E. (2018). Cinnamic acid derivatives in cosmetics: current use and future prospects. *International Journal of Cosmetic Science,40*, 356–366. https://doi.org/10.1111/ics.12471

Huang, A. H., & Chien, A. L. (2020). Photoaging: a review of current literature. *Current Dermatology Reports,9*, 22–29. https://doi.org/10.1007/s13671-020-00288-0

Kammeyer, A., & Luiten, R. M. (2015). Oxidation events and skin aging. *Ageing Research Reviews,21*, 16–29. https://doi.org/10.1016/j.arr.2015.01.001

Kanlayavattanakul, M., Chaikul, P., Kongkow, M., Iempridee, T., & Lourith, N. (2023). Anti-aging of phenolic-rich Acanthus ebracteatus Vahl. extracts. *Chemical and Biological Technologies in Agriculture,10*, 32. https://doi.org/10.1186/s40538-023-00403-w

Kanlayavattanakul, M., & Lourith, N. (2015). An update on cutaneous aging treatment using herbs. *Journal of Cosmetic and Laser Therapy,17*, 343–352. https://doi.org/10.3109/14764172.2015.1039036

Kanlayavattanakul, M., & Lourith, N. (2018). Plants and natural products for the treatment of skin hyperpigmentation - a review. *Planta Medica,84*, 988–1006. https://doi.org/10.1055/a-0583-0410

Khan, M., Liu, H., Wang, J., & Sun, B. (2020). Inhibitory effect of phenolic compounds and plant extracts on the formation of advance glycation end products: a comprehensive review. *Food Research International,130*, 108933. https://doi.org/10.1016/j.foodres.2019.108933

Klinngam, W., Rungkamoltip, P., Thongin, S., Joothamongkhon, J., Khumkhrong, P., Khongkow, M., Namdee, K., Tepaamorndech, S., Chaikul, P., Kanlayavattanakul, M., Lourith, N., Piboonprai, K., Ruktanonchai, U., Asawapirom, U., & Iempridee, T. (2022). Polymethoxyflavones from Kaempferia parviflora ameliorate skin aging in primary human dermal fibroblasts and ex vivo human skin. *Biomedicine & Pharmacotherapy,145*, 112461. https://doi.org/10.1016/j.biopha.2021.112461

Kohl, E., Steinbauer, J., Landthaler, M., & Szeimies, R.-M. (2011). Skin ageing. *Journal of the European Academy of Dermatology and Venereology,25*, 873–834. https://doi.org/10.1111/j.1468-3083.2010.03963.x

Kumar, N., & Goel, N. (2019). Phenolic acids: natural versatile molecules with promising therapeutic applications. *Biotechnology Reports,24*, e00370. https://doi.org/10.1016/j.btre.2019.e00370

Lee, M., Park, H. Y., Jung, K. H., Kim, D. H., Rho, H. S., & Cho, K. (2020). Anti-melanogenic effects of kojic acid and hydroxycinnamic acid derivatives. *Biotechnology and Bioprocess Engineering,25*, 190–196. https://doi.org/10.1007/s12257-019-0421-y

Li, A., Dubey, S., Varney, M. L., Dave, B. J., & Singh, R. K. (2003). IL-8 directly enhanced endothelial cell survival, proliferation, and matrix metalloproteinases production and regulated angiogenesis. *Journal of Immunology,170*, 3369–3376. https://doi.org/10.4049/jimmunol.170.6.3369

Lourith, N., & Kanlayavattanakul, M. (2016). Biopolymeric agents for skin wrinkle treatment. *Journal of Cosmetic and Laser Therapy,18*, 301–310. https://doi.org/10.3109/14764172.2016.1157369

Magnani, C., Isaac, V. L. B., Correa, M. A., & Salgado, H. R. N. (2014). Caffeic acid: a review of its potential use in medications and cosmetics. *Analytical Methods,6*, 3203–3210. https://doi.org/10.1039/C3AY41807C

Nguyen, V. P. T., Stewart, J. D., Ioannou, I., & Allais, F. (2021). Sinapic acid and sinapate esters in Brassica: innate accumulation, biosynthesis, accessibility via chemical synthesis or recovery from biomass, and biological activities. *Frontiers in Chemistry,9*, 664602. https://doi.org/10.3389/fchem.2021.664602

Nićiforović, N., & Abramovič, H. (2014). Sinapic acid and its derivatives: natural sources and bioactivity. *Comprehensive Reviews in Food Science and Food Safety,13*, 34–51. https://doi.org/10.1111/1541-4337.12041

Noor, S., Mohammad, T., Rub, M. A., Raza, A., Azum, N., Yadav, D. K., Hassan, M. I., & Asiri, A. M. (2022). Biomedical features and therapeutic potential of rosmarinic acid. *Archives of Pharmacal Research,45*, 205–228. https://doi.org/10.1007/s12272-022-01378-2

Ramata-Stunda, A., Boroduskis, M., Vorobjeva, V., & Ancans, J. (2013). Cell and tissue culture-based *in vitro* test systems for evaluation of natural skin care product ingredients. *Environmental and Experimental Biology,11*, 159–177.

Rubió, L., Motilva, M.-J., & Romeo, M.-P. (2013). Recent advances in biologically active compounds in herbs and spices: a review of the most effective antioxidant and anti-inflammatory active principles. *Critical Reviews in Food Science and Nutrition,53*, 913–953. https://doi.org/10.1080/10408398.2011.574802

Salminen, A., Kaarniranta, K., & Kauppinen, A. (2022). Photoaging: UV radiation-induced inflammation and immunosuppression accelerate the aging process in the skin. *Inflammation Research,71*, 817–831. https://doi.org/10.1007/s00011-022-01598-8

Shahidi, F., & Chandrasekara, A. (2010). Hydroxycinnamates and their *in vitro* and *in vivo* antioxidant activities. *Phytochemistry Reviews,9*, 147–170. https://doi.org/10.1007/s11101-009-9142-8

Shahidi, F., & Chandrasekara, A. (2013). Millet grain phenolics and their role in disease risk reduction and health promotion: a review. *Journal of Functional Foods,5*, 570–581. https://doi.org/10.1016/j.jff.2013.02.004
Shin, S., Cho, S. H. C., Park, D., & Jung, E. (2020). . Anti-skin aging properties of protocatechuic acid *in vitro* and *in vivo*. *Journal of Cosmetic Dermatology,19*, 977–984. https://doi.org/10.1111/jocd.13086
Taofiq, O., Gonzalez-Paramás, A. M., Barreiro, M. F., & Ferreira, I. C. F. R. (2017). Hydroxycinnamic acids and their derivatives: cosmeceutical significance, challenges and future perspective, a review. *Molecules,22*, 281. https://doi.org/10.3390/molecules22020281
Zeb, A. (2020). Concepts, mechanism, and applications of phenolic antioxidants in foods. *Journal of Food Biochemistry,44*, e13394. https://doi.org/10.1111/jfbc.13394
Zhao, Z., & Moghadasian, M. H. (2010). Bioavailability of hydroxycinnamates: a brief review of *in vivo* and *in vitro* studies. *Phytochemistry Reviews,9*, 133–145. https://doi.org/10.1007/s11101-009-9145-5

Publisher's Note