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Review article

Dietary phytochemicals alleviate the premature skin aging: A comprehensive review

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ABSTRACT

Skin aging, often called as premature skin aging, is the hastened deterioration of the skin resulting from multiple factors, including UV radiation, environmental contaminants, inadequate nutrition, stress, *etc.* Dietary phytochemicals, present in fruits, vegetables, and other plant-derived meals, have gained interest due to their efficiency to eradicate free radicals and lowering the release of inflammatory mediators which accounts for premature skin aging. Several dietary phytochemicals, *i.e.*, carotenoids, polyphenols, flavonoids, terpenes, alkaloids, phytosterols, *etc.*, exhibited potential anti-oxidant, anti-inflammatory, suppression of UV damage, and promote collagen synthesis. In addition, dietary phytochemicals include sulfur, present in various foods safeguard the skin against oxidative stress and inflammation. Thus, this article delves into the comprehension of various dietary phytochemicals investigated to alleviate the premature skin aging. The article further highlights specific phytochemicals and their sources, bioavailability, mechanisms, *etc.*, in the context of safeguarding the skin against oxidative stress and inflammation. The present manuscript is a systematic comprehension of the available literature on dietary phytochemicals and skin aging in various database, *i.e.*, PubMed, ScienceDirect, Google Scholar using the keywords, *i.e.*, "dietary phytochemicals", "nutraceuticals", "skin aging" *etc.*, *via* Boolean operator, *i.e.*, "AND". The dietary guidelines presented in the manuscript is a unique summarization for a broad reader to understand the inclusion of various functional foods, nutrients, supplements, *etc.*, to prevent premature skin aging. Thus, the utilization of dietary phytochemicals has shown a promising avenue in preventing skin aging, however, the future perspectives and challenges of such phytochemicals should be comprehended *via* clinical investigations.

1. Introduction

Skin aging, also known as premature skin aging, expedite the senescence of the skin that occurs prior to the skin's normal aging process (Ganceviciene et al., 2012a). This is characterized by the early onset of wrinkles, fine lines on skin, dermatologic marks, and uneven skin tone (Papaccio et al., 2022). External factors that increase the chances of premature skin aging include exposure to direct and indirect

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Ultraviolet (UV) radiation, environmental pollutants, poor nutrition, smoking and excessive alcohol consumption. (Ittycheri et al., 2023). Internal factors responsible for premature skin aging includes hormonal changes and chronic stress *etc.* The UV radiation from exposure to direct sunlight can degrade the collagen and elastin fibres of skin therefore reducing the ability of the skin to regenerate and regain its elasticity and firmness (Amaro-Ortiz et al., 2014). Environmental pollutants like cigarette smoke and air pollutants can also cause skin damage by generating free radicals that damage the healthy cells which also degrade collagen and elastin (Amaro-Ortiz et al., 2014). Excessive alcohol consumption, can also contribute to premature skin aging from depriving the skin of essential nutrients and increasing systemic inflammation on skin surface. Chronic stress also accounts for premature skin aging by elevating cortisol levels. Cortisol is one of the biogenic hormones that degrades the collagen and elastin from skin cells (Chen and Lyga, 2014).

Recently dietary phytochemicals have gained considerable popularity owing to their potential benefits towards premature skin aging (Forni et al., 2019a). The dietary phytochemicals act by scavenging free radicals and therefore results in reduced inflammation. Carotenoids, flavonoids and polyphenols are dietary phytochemicals that can scavenge the free radicals and prevent their damaging effects on skin. Carotenoids such as β-carotene and lycopene, boost the health of the skin by decreasing the effect of sunburn and prevents premature skin aging. These dietary phytochemicals can act as UV filters which acts by, absorbing UV radiations to protect the skin from damage (Petruk et al., 2018; Singh et al., 2025). The carotenoids and similar type of dietary phytochemicals improve skin elasticity by stimulating collagen production. Flavonoids *e.g.* Quercetin and kaempferol are important have been found to lower the risk of premature skin aging (Septembre-Malaterre et al., 2022). The study was conducted on rats and mice models to access anti-inflammatory activity. For *in vitro* analysis, cell line including BHK-21 fibroblasts were employed. The study was extended to *in silico* models to elucidate the interaction of quercetin with viral targets like HBV polymerase. The dose of quercetin (25 mg/kg for 7 days) resulted to an increase in markers of mitochondrial biogenesis in skeletal muscle and brain. Furthermore, it was demonstrated that quercetin at an IC50 of 3.2 μM inhibited human cytomegalovirus (HCMV) on primary human embryonic lung fibroblasts. The mechanism of anti-inflammatory activity was related with down-regulating various signaling pathways and inflammatory mediators. The mechanism in this study revealed that quercetin at a concentration of 10 μM inhibited the expression of inducible nitric oxide synthase (iNOS) and nitric oxide (NO) production, showcasing its anti-inflammatory effects. These findings suggest that quercetin exerts its pharmacological effects at relatively low concentrations, making it a promising candidate for various therapeutic applications. Positive controls were employed to validate the efficacy of the compounds being tested whereas negative controls were used to provide a baseline for comparison and to ensure that any observed effects were indeed due to the treatment with quercetin.

These dietary phytochemicals inhibit the cytokines production *e.g.*, interleukin-12 (IL-12) and tumor necrosis factor-α (TNF-α) which are pro-inflammatory in nature, causes collagen degradation and promotes wrinkle formation. Furthermore, flavonoids are capable of eliminating free radicals and protecting skin against oxidative damage (Michalak, 2022a). Polyphenols, such as resveratrol and catechins, are also known to safeguard the skin from damaging UV radiations, reduce inflammation and improve skin elasticity. The dietary phytochemicals stimulate collagen production, reduce collagen breakdown, and inhibit the production of enzymes that contribute to the premature skin aging (Nichols and Katiyar, 2010). Dietary phytochemicals consist of high amounts of whole grains, vegetables, fruits, nuts and seeds. This type of dietary phytochemicals has multiple health advantages, which include the prevention of premature skin aging. `Dietary phytochemicals protect the skin from damage and support its structure and function at the molecular level (Rice-Evans et al., 1997). While they are not a replacement for sun protection and other preventative measures, they can support the overall health of the skin (Pandey and Rizvi, 2009a).

This review offers a comprehensive examination of the significance of dietary phytochemicals in mitigating the onset of premature skin aging. The present article embarks about the mechanism of action of numerous classes of dietary phytochemicals, as well as their sources, their bioavailability, and practical recommendations for incorporating diet which is rich with such dietary phytochemicals. The present article also summarizes the current understanding and prospects of the relationship between dietary phytochemicals and skin health that can prevent premature skin aging. This paper aims to provide useful information for public health, necessity of additional research in this particular field and future scope in this area.

The primary objective of present review is to present the recent updates on impacts of dietary phytochemicals on premature skin aging. The identification, collection of data, clinical trials done in this area and experimental observational data is presented in systematic manner. Additionally with an objective to present the underlying mechanism involved in exhibiting the anti-aging effect of such phytochemicals, the free radical scavenging effects, anti-inflammatory effect, photo-protective effect and collagen enhancing effect was also reviewed and presented for future researcher. Through this review article, an attempt is also made to showcase the data set for future researchers working in the area of dietary phytochemicals. Present review article also embarks on gaps in the current understanding of dietary phytochemicals and premature skin aging and also suggest avenues for future translational research.

2. Search strategy and databases used

The search strategy involved comprehensive use of search engines, *i.e.*, Google scholar, PubMed, Scopus, and various journal databases including ScienceDirect, Springer, Taylor & Francis, among others. We established strict inclusion criteria focusing on dietary phytochemicals and skin anti-aging, with a specific emphasis on valid preclinical and clinical trials. We excluded studies with non-availability of full-text and those not in English. Data collection was conducted through a standardized questionnaire following a predefined protocol, and the findings from both *in vivo* and *in vitro* studies were meticulously incorporated.

3. Types of dietary phytochemicals and their role in preventing premature skin aging

3.1. Carotenoids

Carotenoids are pigments found naturally in carrots, sweet potatoes, spinach, kale, broccoli tomatoes, mangoes, papayas, cantaloupes, apricots, oranges, grapefruits, watermelons, kiwifruits (Dasgupta and Klein, 2014). It has been proved that these dietary phytochemicals have a number of health benefits, which includes the ability to prevent premature skin aging (Tan and Norhaizan, 2019a).

Carotenoids exert their effects at the molecular level through multiple mechanisms, such as their antioxidant activity, regulation of gene expression, and modulation of cellular signaling pathways (Milani et al., 2017). Carotenoids are powerful antioxidants that can scavenge Reactive Oxygen Species (ROS). Scavenging of ROS can reduce oxidative damage to the membrane of skin cells. ROS are generated in response to stressors from environment, like UV radiations, pollution, and it can result in the degradation of collagen and elastin, resulting in premature skin aging (Darvin et al., 2022a). By donating electrons and stabilizing free radicals, carotenoids *e.g.*, beta-carotene, lycopene and astaxanthin can neutralize ROS. This prevents oxidative damage to the skin and promotes skin health (Genç et al., 2020).

Additionally, carotenoids can regulate and modify the expression of genes associated with premature skin aging (Balić and Mokos, 2019a). Research has substantiated the capacity of beta-carotene to elevate the activation of genes responsible for the synthesis of antioxidant enzymes, including superoxide dismutase (SOD) and catalase. By converting ROS into less dangerous molecules, these enzymes play a vital role in preventing oxidative damage. Furthermore, beta-carotene can inhibit the expression of genes encoding interleukin-6 (IL-6), IL-12 and TNF-α (Popko et al., 2010). These interleukins and TNF-α promote skin inflammation, which can lead to breakdown of collagen and elastin (Kurutas, 2016). Carotenoids can also modulate the cell signaling pathways involved in the premature skin aging (Tan and Norhaizan, 2019b). Activating the nuclear factor erythroid 2-related factor 2 (Nrf2) signaling pathway is one example of premature skin aging. Nrf2 is a transcription factor that controls the expression of antioxidant defense and detoxification-related genes (Ma, 2013). Beta-carotene can enhance the expression of antioxidant enzymes and reduce oxidative damage in the skin by activating the Nrf2 pathway.

Lycopene has been shown to inhibit the activity of the transcription factor nuclear factor-kappa B (NF-kB). The transcription of genes associated with inflammation and immune responses is regulated by NF-kB. By inhibiting NF-kB activity, lycopene can reduce inflammation and prevent premature skin aging by preventing NF-kB activation (Yasmeen et al., 2022) (as summarized in Fig. 1).

At the same time, Carotenoids, whether consumed orally or applied topically, can safeguard the skin from UV-induced damage and premature skin aging, as observed in numerous animal and human studies (Balić and Mokos, 2019b). The *in vivo* models were used to study the effects of carotenoids on the skin, including human subjects and animal models. Carotenoids function as antioxidants and neutralize free radicals, thereby protecting the skin from oxidative stress, which can accelerate premature skin aging by degrading DNA, lipids and proteins (Razzak, 2024). In animal studies, topical application of carotenoids including astaxanthin, lycopene, and beta-carotene reduced the UV-induced skin damage, inflammation, and DNA damage (Catanzaro et al., 2020). The study included *in vitro* models to validate the photoprotective activities of astaxanthin (ASX) and fucoxanthin (FX) on skin photodamage and prevention of UV-mediated carcinogenesis. Another part of study included *in vivo* models of study which confirmed the photoprotective potential of ASX and FX. The Studies were conducted on hairless mice and rats exposed to UV radiation to evaluate the effects of these carotenoids on skin damage, wrinkle formation, and epidermal hypertrophy. The study was extended to *in silico* experiments also with an aim to analyse gene expression and identify pathways modulated by UV irradiation and to evaluate the effects of ASX and FX on these pathways. In the present investigation, ASX was administered to dogs at a dose of 20 mg for 16 weeks and to cats at a dose of 10 mg for 12 weeks. In the mice models, ASX was administered at a dose of 100 μg/kg body weight. Findings revealed the minimal active concentration of ASX as10 nM in an *in vitro* study. *N*-acetylcysteine (NAC) as positive control was used to compare the photoprotective effects of ASX and FX. In the present investigation, chronic UVA exposure was given for 70 days in hairless mice fed with ASXME. UVB irradiation was performed for four weeks in mice treated with ASX or FX. Algal extract enriched in ASX, which was found to have a higher concentration of ASX compared to

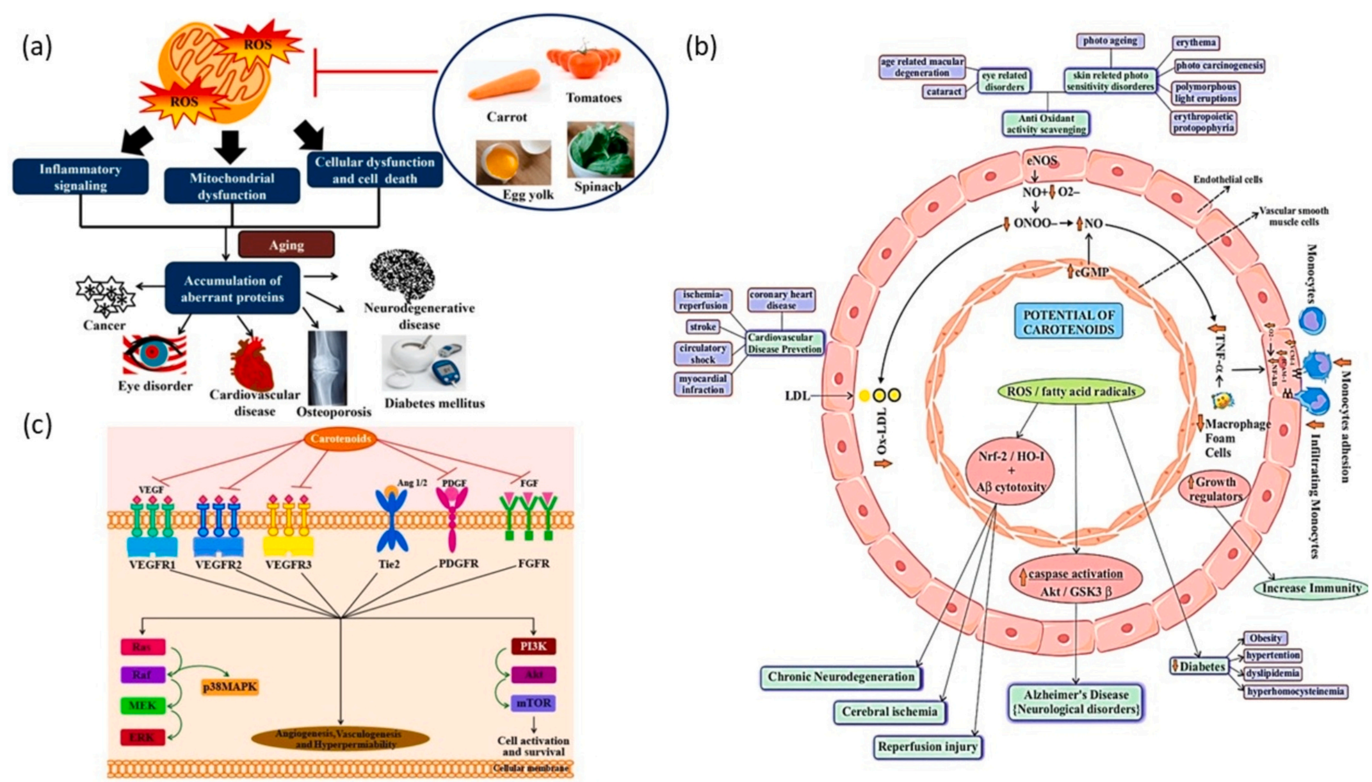


Fig. 1. Carotenoids as antiaging agent. (**a**) the interplay of carotenoids and oxidative stress in connection to Age Related Diseases (ARD). ROS buildup causes inflammation, cell death and malfunction, and mitochondrial dysfunction. Decreased mitochondrial function, the aging body's response to oxidative stress, and the buildup of abnormal proteins may all be factors in ARD. Consuming carotenoids may prevent the development of ROS (Tan and Norhaizan, 2019b). (**b**) Role of carotenoids to prevent diseases and skin related problems, reproduced with permission from Ref. (Bhatt and Patel, 2020), Copyright 2020, Springer. (**c**) Carotenoid's anti-angiogenic effects. Both VEGF-dependent and independent mechanisms are mentioned. FGF stands for fibroblast growth factor, and ERK, extracellular signal-reduced kinase, and FGFR, fibroblast growth factor receptor; mTOR stands for mechanistic target of rapamycin; p38 MAPK stands for p38 mitogen-activated protein kinase; MEK stands for mitogen-activated protein kinase/extracellular signal-reduced kinase kinase; PDGF, PDGFR, and PI3K are acronyms for platelet-derived growth factor, phosphoinositide 3-kinase, and respectively. Tie2 stands for tyrosine kinase with immunoglobulin-like and EGF-like domains 1, RAF stands for rapidly accelerated fibrosarcoma, RAS stands for rat sarcoma, and VEGF and VEGFR stand for vascular endothelial growth factor and receptor, respectively (Sathasivam and Ki, 2018).

synthetic ASX was used as standard. *In vitro* and *in vivo* models were used to study the basic pharmacological activities including the antioxidant properties, anti-inflammatory activity, and immunostimulant effects of ASX and FX.

Studies on humans have shown that increasing carotenoid levels in the skin through oral supplementation with mixed carotenoids enhances radical scavenging activity and protects the skin from stress-induced radical formation (Darvin et al., 2022b). Furthermore, it has been shown that using sunscreen containing carotenoids on a daily basis slows premature skin aging in healthy middle-aged people (Shanbhag et al., 2019). The study was also performed by *in vitro* model to evaluate the release profile of formulations and assessing skin irritation studies. The folic acid loaded nanostructured carriers were used for anti-aging effects. The optimized nanoparticles were evaluated for their *in vitro* release, *ex vivo* skin permeation, and antioxidant properties using marketed tretinoin gel as standard for comparison of *in vivo* skin irritation findings.

Although the specific molecular mechanism by which carotenoids prevent premature skin aging is unknown, it is thought that they protect cellular components such as membranes, proteins, and DNA from deterioration by quenching free radicals and decreasing inflammations (Baswan et al., 2020). Using human models for *in vivo* study, the photoprotective effects of carotenoids was evaluated against UVB-induced erythema edema. The study used a double-blind, placebo-controlled design, with participants randomized to receive either the Nutrilite™ Multi Carotene supplement or a placebo. The placebo group served as the negative control, while the intervention group receiving the carotenoid supplement served as the positive control. These 12 weeks study involved supplementation of Nutrilite™ Multi Carotene supplement to participantsFinally the level of carotenoid levels in skin, UVB-induced minimal erythemal dose (MED), and UVA-induced minimal persistent pigmentation dose (MPPD) were evaluated as important pharmacological aspects.

3.2. Flavonoids

A variety of fruits, vegetables, and herbs contain flavonoids which is considered as class of diverse natural dietary phytochemicals. These flavonoids rich sources serve multiple health advantages, including preventing wrinkles on the skin (Panche et al., 2016a). The complex molecular mechanisms associated with flavonoids in preventing premature skin aging involve multiple pathways. One of the main ways that flavonoids prevent premature skin aging is through their ability to act as antioxidants (Domaszewska-Szostek et al., 2021a). Flavonoids are powerful antioxidants that can neutralize free radicals and ROS produced by UV radiation, pollution, and other environmental stressors. ROS can cause premature skin aging by inducing lipid peroxidation, DNA damage and protein oxidation (Ashique et al., 2024; Tan et al., 2018). The effects of antioxidants on various cellular processes and inflammation were accessed by *in vitro* models. Other than this, the effects of antioxidants on age-related diseases, tumor growth, bone mass, atherosclerosis, and arthritis were done using *in vivo* models also.

Additionally, flavonoids can enhance the activity of antioxidant enzymes like SOD and catalase, which help neutralize ROS and protect the skin. Moreover, flavonoids have anti-inflammatory properties that can prevent premature skin aging (Lobo et al., 2010). Collagen and elastin, two of the skin's most important structural proteins, can be degraded by chronic inflammation (Pfisterer et al., 2021). Flavonoids possess the capability to impede the synthesis of pro-inflammatory mediators including cytokines and enzymes, notably cyclooxygenase (COX) and lipoxygenase (LOX). By reducing inflammation, flavonoids can help preserve the skin integrity and prevent its premature aging. Flavonoids prevent premature skin aging by modulating signaling pathways (Ginwala et al., 2019). For instance, flavonoids can activate the Nrf2 pathway, which controls the expression of antioxidant defense and detoxification genes. Activation of the Nrf2 pathway can increase the resistance of skin to oxidative stress and protect cellular components from damage (Huang et al., 2015). Additionally, flavonoids can activate the sirtuin (SIRT) pathway, which regulates cellular metabolism and stress response. SIRT activation can promote cellular longevity and protect against premature skin aging (Grabowska et al., 2017).

Premature skin aging causes the accumulation of dead cells and it is linked with numerous pathological changes, such as decreased protection from infectious agents (Csekes and Račková, 2021). The anti-senescent mechanisms of natural polyphenols on keratinocytes, melanocytes, and fibroblasts were elucidated using *in vitro* models. Additionally, this model was used to test the senolytic effect of the organic Alpen rose extract on senescent fibroblasts. In case of premature skin aging, a senescence-associated secretory phenotype refers to a particular group of pro-inflammatory mediators which is secreted by senescent cells. It has been demonstrated that flavonoids inhibit the senescence-associated secretory phenotype and prevent the accumulation of senescent cells, thereby exerting anti-senescence effects (Coppé et al., 2010). *In vitro* models were used to study the effects of senescent cells on mammary epithelial cells and the secretion of MMPs and cytokines. In the same study, *in vivo* models were used to observe the effects of senescent cells on tumor development and malignant phenotypes in various tissues, including breast, skin, prostate, pancreas, and oropharyngeal mucosa. Furthermore, flavonoids have been shown to reduce oxidative stress and skin inflammation, with an aim to reduce premature skin aging (Domaszewska-Szostek et al., 2021b).

The present review presents an up-to date information on diverse studies in the area of premature skin aging, incorporating *in vitro* and animal investigations, human trials, and a blend of *in vitro* and human studies. Across this spectrum, all the included studies consistently exhibit the beneficial outcomes of flavonoids and carotenoid-containing plant extracts in mitigating UV-induced skin damage (Anbualakan et al., 2023).

Flavonoids have demonstrated the ability to modulate the release and expression of crucial factors such as Transforming Growth Factor Beta 1 (TGF-β1), Vascular Endothelial Growth Factor (VEGF), Mothers Against Decapentaplegic Homolog 2 (Smad 2), Mothers Against Decapentaplegic Homolog 3 (Smad 3), and Interleukin-10 (IL-10) within macrophages, fibroblasts and endothelial cells. Furthermore, they exhibit a favorable regulatory influence on Matrix Metalloproteinases (MMPs 2, 8, 9, and 13) (Li et al., 2024) along with the Rat Sarcoma protein/Rapidly Accelerated Fibrosarcoma protein/Mitogen-Activated Protein Kinase/Extracellular Signal-Regulated Kinase (Ras/Raf/MEK/ERK), Phosphoinositide 3-Kinase/Protein Kinase B (PI3K-PKB/Akt) and Nitric Oxide (NO) pathways. This modulation contributes to a reduction in the release of inflammatory cytokines, ROS and the M1 phenotype (Anbualakan et al., 2023).

3.3. Polyphenols

Polyphenols which are a diverse class of bioactive dietary phytochemicals found in different kinds of plant-based products, has a variety of health benefits, including the ability to prevent premature skin aging (Zhang et al., 2022) (as shown in Fig. 2). In the present study, use of both *in vivo* and *in vitro* models in the context of pharmacological studies on polyphenols as plant-based nutraceuticals has been covered. These models are crucial for understanding the biological activities and potential health benefits of polyphenolic compounds. Anti-aging effects of polyphenols on the skin have been extensively researched, which revealed their potential to counteract the damaging effects of environmental stressors on premature skin aging (Nobile et al., 2021; Verma et al., 2024). The antioxidant activity of polyphenols is one of the primary mechanisms by which they prevent premature skin aging. Polyphenols also have strong antioxidant properties that can quench free radicals and ROS, which damage skin cells and accelerate premature skin aging (Michalak, 2022b). Polyphenols also possess anti-inflammatory properties, which contribute to their effectiveness in

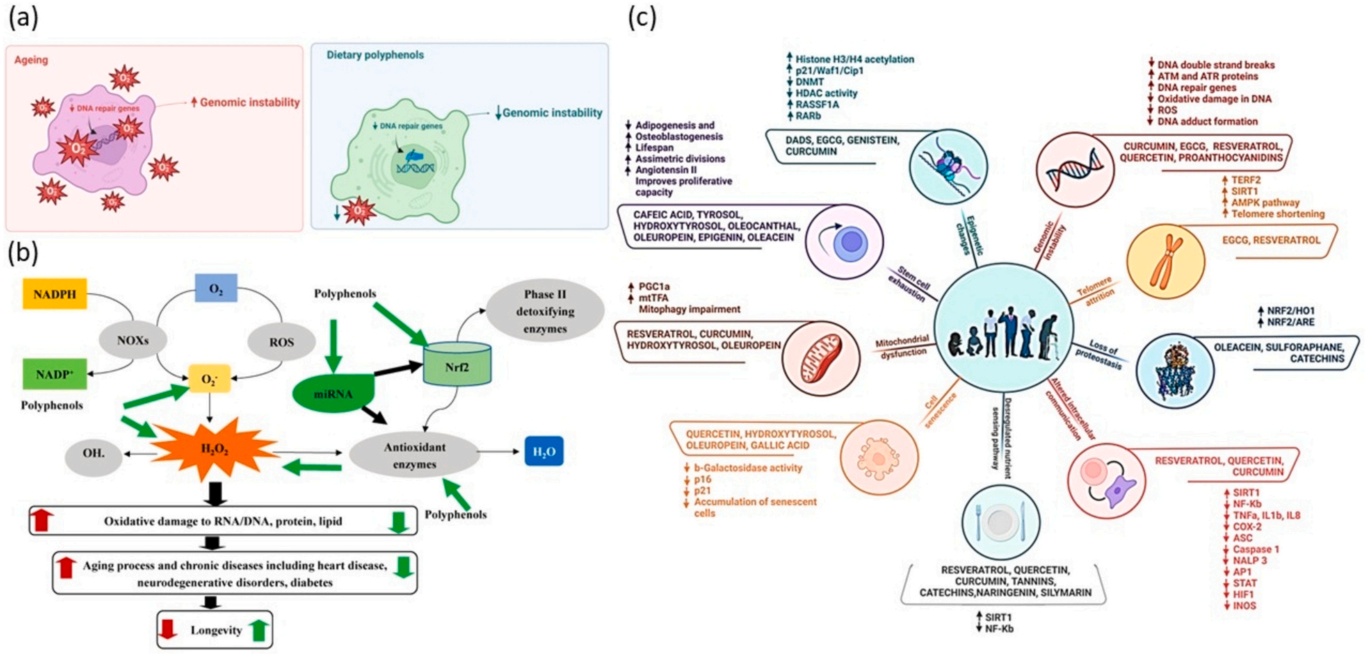


Fig. 2. Polyphenols potential roles in Anti-aging and Reducing ROS. (**a**) Significant indicator of aging is genome instability (left panel). Through the control of ROS levels and a rise in DNA repair activity, dietary polyphenols can reduce the instability of genomic DNA (right panel) (Pereira et al., 2023). (**b**) Illustration showing the antioxidant mechanisms of polyphenols. Nrf2 is the nuclear factor erythroid 2-related factor (Luo et al., 2021). (**c**) An overview of polyphenolic chemicals' major effects on the molecular mechanisms behind age-related signs (Pereira et al., 2023).

preventing premature skin aging. Chronic inflammation has been shown to hasten premature skin aging by promoting the breakdown of collagen and elastin (Cao et al., 2020). The *in vitro* models were employed for elucidation of the molecular mechanisms of skin aging and the effects of different antioxidants on skin aging. Other than this, animals including mice were also used to evaluate the effects of different extracts and compounds on skin aging. The duration of the studies varied, ranging from 24 h to 12 weeks and in the study, collagen peptides, gelatin hydrolysate, fermented fish oil, and olive oil were used for comparison. Polyphenols can help maintain the integrity of collagen and elastin therefore in turn, prevent premature skin aging by reducing inflammation in the skin (Lee et al., 2022).

Polyphenols can stimulate the production of collagen (Michalak et al., 2021). With age, collagen production decreases, resulting in wrinkles and sagging skin. Polyphenols can aid in the maintenance of collagen levels in the skin, thereby reducing the signs of premature skin aging and promoting healthy skin function (Reilly and Lozano, 2021). Like Carotenoids and Flavonoids, Polyphenols can also shield the skin from the UV radiation, which is a leading cause of premature skin aging. UV radiations cause DNA damage, inflammation, and breakdown of collagen and elastin, which accelerate premature skin aging (Michalak, 2022c). Polyphenols have the ability to scavenge ROS produced by UV radiation and reduce inflammation, thereby reducing the harmful effects of UV exposure and promote the normal skin functions (Afaq and Katiyar, 2011). It can be elucidated that, polyphenols can influence gene expression in skin cells, alter the cell signaling pathways that control numerous cellular processes such as inflammation, DNA repair and apoptosis. Polyphenols can help the skin cells to maintain their health and function by regulating gene expression, reducing the signs of premature skin aging, and promoting healthy skin function (DH et al., 2024; Yahfoufi et al., 2018). Using *in vitro* models, the effects of polyphenols on immune cells and cytokine production was screened. Furthermore, animal models were used to investigate the anti-inflammatory and antitumorigenic activities of polyphenols. Studies on both humans and animals' models have shown that polyphenols can reduce the damaging effects of UV radiation on the skin and prevents premature skin (Saric and Sivamani, 2016). *Camellia sinensis*, *Theobroma cacao*, *Romanian propolis*, *Calluna vulgaris*, *Vitis vinifera*, *Cyclopia intermedia*, *Lepidium meyenii* and *Coffea arabica* are sources of polyphenols, including chlorogenic acids, which may prevent premature skin aging by reducing hyperpigmentation of pigmented spots on the skin surface which is an indicator of premature skin aging (Fukushima et al., 2015). To evaluate the effectiveness, mode of action, and possible side effects of various polyphenol types and concentrations, more research is necessary (Rudrapal et al., 2022).

3.4. Sulfur-containing dietary phytochemicals

Sulfur-containing dietary phytochemicals, like sulforaphane, allicin, and lipoic acid, play a vital role in preventing premature skin aging (Lee et al., 2012). Common sources of these dietary phytochemicals include cruciferous vegetables, garlic, and particular dietary supplements (Shang et al., 2019a). The sulfur-containing dietary phytochemical sulforaphane is found in broccoli, brussels sprouts, and other cruciferous vegetables. Sulforaphane is an extremely potent activator of the Nrf2 pathway, which regulates the expression of antioxidant and detoxification enzyme (Houghton et al., 2016). It has been shown that sulforaphane safeguards skin cells from oxidative stress and inflammation. Oxidative stress and inflammations are two of the leading causes of premature skin aging (Santín-Márquez et al., 2019). Additionally, it inhibits the expression of MMP (Li et al., 2024), the skin enzymes that degrade collagen and elastin. By promoting antioxidant defense and inhibiting MMP expression, sulforaphane contributes to the preservation of the structure and function of skin (Bosch et al., 2015). The present study involved mice to study the photoprotective activity of phytochemical derivatives against UVB radiation. Finding of this *in vivo* study concluded that compounds including baicalin, flavangenol, black raspberry extract, and *Photomorphe umbellata* extract, showed photoprotective activity against UVB radiation.

Garlic is one of the important sources of dietary phytochemicals containing sulfur. It has potent antioxidant and anti-inflammatory properties, that may help to protect the skin from UV radiation and other stresses from the environment (Borek, 2001). In order to evaluate the effects of aged garlic extract (AGE) on tumor promotion and skin carcinogenesis, *in vivo* and *in vitro* studies were performed. Allicin inhibits the activation of NF-kB, which regulates the expression of inflammatory cytokines. By inhibiting NF-kB activation, allicin contributes to the reduction of skin inflammation, which can contribute to premature skin aging (Arreola et al., 2015). For this study, researchers involved *in vitro* assay procedures using neutrophil-like cells (HL-60 cell line) to study the effects of garlic oil on chemotactic responsiveness and motility of cells. Other than this, Balb/c mice infected with *Plasmodium yoelii* was used to investigate the immunoregulatory mechanism of allicin in malaria in dose range 3 or 9 mg/kg/day and this study was continued up to 2 days. The type of extract used was garlic oil.

Lipoic acid is a sulfur containing dietary phytochemical that is synthesized naturally by the body and is also present in foods like spinach and red meat (Salehi et al., 2019a). Lipoic acid shields the skin from oxidative damage and is a powerful antioxidant capable of regenerating other antioxidants such as vitamins C and E (Pullar et al., 2017). It has also been demonstrated that lipoic acid stimulates collagen synthesis and inhibits MMP expression, which can help to maintain the skin's structural integrity (Poon et al., 2015).

Animal and human studies have also demonstrated the effectiveness of sulfur-containing dietary phytochemicals in preventing premature skin aging. Sulfur is a vital element for the whole biological kingdom because of its incorporation into amino acids, proteins, and other biomolecules (Atmaca, 2004). Sulfur containing dietary phytochemicals are found in all body cells and are indispensable for life. A variety of sulfur-containing natural products derived from fungi, plants, bacteria, and animals have been studied for their therapeutic value. They have provided evidence for antioxidant, antibacterial, antimicrobial, antifungal, and anticancer properties (Jacob, 2006) Research has demonstrated that certain sulfur-containing antioxidant phytochemicals present in *Allium* species, including garlic, leeks, onions and shallots, can inhibit premature skin aging (Higuchi et al., 2003). Furthermore, Indonesian gingers such as Gajah, Red and Emprit ginger are thought to contain dietary phytochemicals that combat premature skin aging (Asoka et al., 2022). Seaweeds, such as *Sargassum spp.*, have also been found to have multiple functions in preventing premature skin aging. Moreover, a study evaluated the efficacy of amla in preventing premature skin aging (Chaikul et al., 2021). It can be concluded that sulfur containing dietary phytochemicals are effective in preventing premature skin aging (Mi ekus et al., 2020).

3.5. Other dietary phytochemicals

Several other dietary phytochemicals have been reported to prevent premature skin aging in addition to the well-known carotenoids, flavonoids, polyphenols, and dietary phytochemicals containing sulfur (Forni et al., 2019b). Terpenes, which are found in many plants and known for their antioxidant and anti-inflammatory effects, are one such class of dietary phytochemicals being used against premature skin aging (Masyita et al., 2022). Terpenes prevent the synthesis of ROS and pro-inflammatory cytokines on skin to prevent premature skin aging (Proshkina et al., 2020). Terpenes have also been demonstrated to promote collagen synthesis (Binic et al., 2013). Alkaloids, which are dietary phytochemicals with a nitrogen content that are present in numerous plant species, are another class of bioactive metabolites that have been shown to prevent premature skin aging (Dey et al., 2020). Another secondary metabolite naming Alkaloids work by preventing the activity of the enzymes that break down collagen and elastin, these proteins are considered as essential skin-structuring proteins that gradually deteriorate with age (McKleroy et al., 2013). Alkaloids have also been demonstrated to improve skin hydration and to decrease hyperpigmentation, which results in more youthful and radiant appearance (Davis and Callender, 2010).

Another class of dietary phytochemicals that has been discovered to have advantageous effects on skin health is phytosterols. These phytosterols have structural similarities with cholesterol and this can serve as a natural substitute for skincare products that contain synthetic cholesterol (Upadhyay and Dixit, 2015). Wound healing and angiogenesis were evaluated by *in vivo* models however, effects of phytochemicals on inflammatory mediators and gene expression were screened by *in vitro* methods.

Phytosterols are known to enhance the protective barrier of skin, which can aid in reducing moisture loss and avoiding skin dryness and irritation (Lin et al., 2018). Furthermore, phytosterols have been shown to increase collagen production while lowering the activity of MMP, enzymes that accelerate the premature skin aging process by breaking down collagen and elastin (Pittayapruek et al., 2016). Coumarins, a class of dietary phytochemicals, have also been found to possess antioxidant as well as anti-inflammatory properties. By neutralizing free radicals and reducing the production of pro-inflammatory cytokines, coumarins delay the onset of premature skin aging and prevent skin damage (Mucha et al., 2021). Table 1 depicts the examples of numerous dietary phytochemicals that prevents the premature skin aging.

4. Sources of dietary phytochemicals and their bioavailability

4.1. Carotenoids

Carotenoids are a class of dietary phytochemicals found in fruits, vegetables, and certain animal products (Lohr, 2009). These dietary phytochemicals are responsible for the red, orange, and yellow hues of foods and have been linked to a variety of health benefits. The benefits include prevention of premature skin aging as discussed earlier using *in vitro* and *in vivo* models in addition to that it can help in reducing the risk of chronic diseases like cancer, cardiovascular disease, and age-related macular degeneration (Zhang et al., 2015b). In the present investigation, aged rats were used to evaluate the effects of phytochemicals for antioxidant activity. Quercetin and resveratrol were used as standard marker compound for evaluation of inhibition of inhibition of acetylcholinesterase and butyrylcholinesterase using *in vitro* models. Ascorbic acid was used as positive control and placebo was used for negative controls.

Carrots, sweet potatoes, tomatoes, spinach, kale, broccoli, egg yolk and salmon are common food sources of carotenoids (Abdel-Aal et al., 2013). Numerous factors can influence the bioavailability of carotenoids. The food matrix, which is a complex web of nutrients can have an impact on the solubility and absorption of carotenoids (Van Het Hof et al., 2000). Carotenoids in raw fruits and vegetables, for instance, are frequently encapsulated in cell walls, which can hinder their absorption. The bioavailability of carotenoids can be increased by cooking and processing techniques such as heating, grinding, and blending, which break down cell walls and increase bioavailability (Ryan et al., 2008). Carotenoids are fat-soluble, so the presence of fat in the diet is also essential for their absorption. Consuming carotenoid rich foods with a source of dietary fat, such as avocado, nuts, or olive oil, can therefore increase their absorption (Elvira-Torales et al., 2019). The microbiota of the gut can also influence the bioavailability of carotenoids. Some strains of gut bacteria can convert carotenoids into more bioavailable form, while others can degrade these carotenoids. The makeup of the gut microbiota, which can vary depending on factors like diet, use of antibiotics, and age, can affect the bioavailability of carotenoids. Several strategies can be implemented to increase the bioavailability of carotenoids (Eroglu, 2023). Consuming carotenoids with a source of dietary fat can enhance their absorption. In addition, consuming carotenoids as supplements or fortified foods can enhance their bioavailability (Mashurabad et al., 2017). Combining carotenoids with other nutrients or substances, such as vitamin C, can increase their absorption (Kultys and Kurek, 2022).

Table 1
Examples of dietary phytochemicals in preventing premature skin aging.

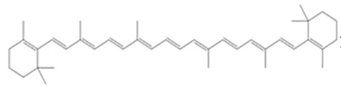
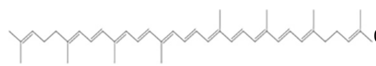
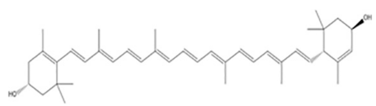
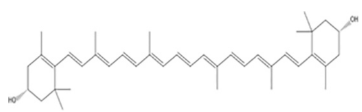
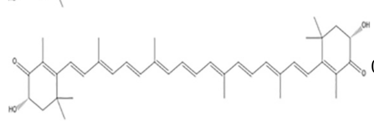
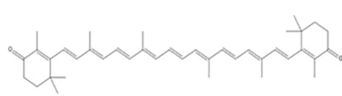
Category	Common Name of Dietary Phytochemical	Chemical Structure	Mechanism in preventing premature skin aging	References
Carotenoids	Beta-carotene	 1,1′-[(1E,3E,5E,7E,9E,11E,13E,15E,17E)-3,7,12,16-Tetramethyloctadeca-1,3,5,7,9,11,13,15,17-nonaene-1,18-diyl]bis(2,6,6-trimethylcyclohex-1-ene)	β-carotene regulates lipid peroxidase, which protects blood vessels, skin, and the neurological system. It also has anti-tumor effects and enhances immunity. The therapy of inflammation may benefit from β-carotene's ability to increase cell viability, suppress the percentage content of ROS, lower the release of inflammatory proteins, and decrease the expression of the NF-kB p65 protein. In order to reduce LPS-induced inflammation, β-carotene can dramatically reduce the production of IL-1β, IL-6, and TNF-α as well as down-regulate mRNA expression. It can also suppress the NF-κB, JAK2/STAT3, and JNK/p38MAPK signal pathways in macrophages.	(Das et al., 2024; Heinrich et al., 2003; Wu et al., 2023)
	Lycopene	 (6E,8E,10E,12E,14E,16E,18E,20E,22E,24E,26E)-2,6,10,14,19,23,27,31-octamethyldotriaconta-2,6,8,10,12,14,16,18,20,22,24,26,30-tridecaene	Reduces oxidative stress and skin inflammation and protects against UV-induced damage. It can also prevent TNF-α from being released and promoting the generation of IL-10, hence mitigating inflammation.	(Hazewindus et al., 2012; Imran et al., 2020)
	Lutein	(1*R*)-4-[(1E,3E,5E,7E,9E,11E,13E,15E,17E)-18-[(1*R*,4*R*)-4-hydroxy-2,6,6-trimethylcyclohex-2-en-1-yl]-3,7,12,16-tetramethyloctadeca-1,3,5,7,9,11,13,15,17-nonaenyl]-3,5,5- trimethylcyclohex-3-en-1-ol 	Improves skin hydration by moisturizing the skin and elasticity, by inducing collagen synthesis in the body. It also protects against oxidative stress and inflammation.	(Buscemi et al., 2018)
	Zeaxanthin	(1*R*)-4-[(1E,3E,5E,7E,9E,11E,13E,15E,17E)-18-[(4*R*)-4-hydroxy-2,6,6-trimethylcyclohexen-1-yl]-3,7,12,16-tetramethyloctadeca-1,3,5,7,9,11,13,15,17-nonaenyl]-3,5,5-trimethylcyclohex-3-en-1-ol 	Reduces the formation of age spots and improves skin hydration and elasticity. It has also shown photoprotective activity against UV rays in human.	(González et al., 2003)
	Astaxanthin	 (6*S*)-6-hydroxy-3-[(1E,3E,5E,7E,9E,11E,13E,15E,17E)-18-[(4*S*)-4-hydroxy-2,6,6-trimethyl-3-oxocyclohexen-1-yl]-3,7,12,16-tetramethyloctadeca-1,3,5,7,9,11,13,15,17-nonaenyl]-2,4,4-trimethylcyclohex-2-en-1-one	Protects against UV-induced damage, reduces inflammation, and improves skin elasticity and hydration. Prevents NF-κB from entering the nucleus, leading to inhibition of MCP-1 which further contributed to low levels of VEGF receptor expression, VEGF expression and IL-6 expression. It also decreased the levels of IL-1β and CXCL2 in mice model.	(Yuan et al., 2011)
	Canthaxanthin	 2,4,4-trimethyl-3-[(1E,3E,5E,7E,9E,11E,13E,15E,17E)-3,7,12,16-tetramethyl-18-(2,6,6-trimethyl-3-oxocyclohexen-1-yl) octadeca-1,3,5,7,9,11,13,15,17-nonaenyl]cyclohex-2-en-1-one	Improves skin hydration and reduces the visible signs of wrinkles by improving the elasticity of the skin. It does possess anti-inflammatory activity as well, which prevent breakdown of collagen. Also, absorbs UV-A radiation and help in protection from the harmful UV rays.	(Naz et al., 2021)

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Table 1 (*continued*)

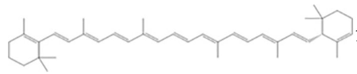
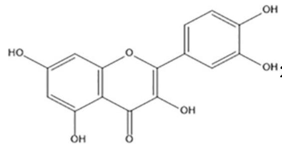
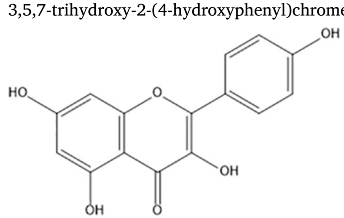
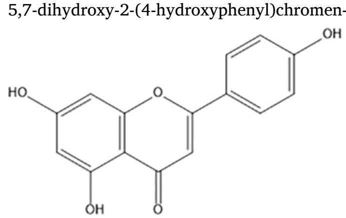
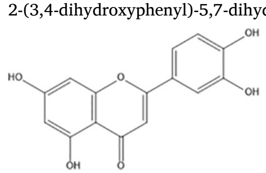
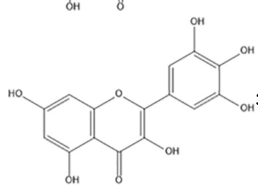
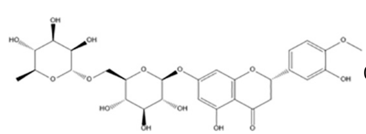
Category	Common Name of Dietary Phytochemical	Chemical Structure	Mechanism in preventing premature skin aging	References
	Alpha-carotene	 1,3,3-trimethyl-2-[(1E,3E,5E,7E,9E,11E,13E,15E,17E)-3,7,12,16-tetramethyl-18-[(1*R*)-2,6,6-trimethylcyclohex-2-en-1-yl]octadeca-1,3,5,7,9,11,13,15,17-nonaenyl]cyclohexene	Protects against UV-induced damage and reduces inflammation in the skin. Acts as a free radical scavenger lowering the oxidative stress levels of the cells.	(Stahl et al., 2006; Ucci et al., 2019)
Flavonoids	Quercetin	 2-(3,4-dihydroxyphenyl)-3,5,7-trihydroxychromen-4-one	Inhibition of NF-κB pathway, matrix metalloproteinases2 and 9 showing anti-metastatic behavior. It also works as an antioxidant and ROS scavenger.	(Anand David et al., 2016a)
	Kaempferol	3,5,7-trihydroxy-2-(4-hydroxyphenyl)chromen-4-one 	Antioxidant and anti-inflammatory effects. It has shown to inhibit synthesis of nitric oxide and reduced the secretion TNF-α and IL-1B.	(Alam et al., 2020)
	Apigenin	5,7-dihydroxy-2-(4-hydroxyphenyl)chromen-4-one 	Protection against UV-A induced damage. It has also demonstrated to induce dermal collagen synthesis *via* smad2/3 signaling, which might improve the elasticity of the skin.	(Zhang et al., 2015a)
	Luteolin	2-(3,4-dihydroxyphenyl)-5,7-dihydroxychromen-4-one 	Photoprotection against UV-B, *via* modulation of SIRT3/ROS/MAPK pathways. It has also shown anti-inflammatory activity.	(Mu et al., 2021)
	Myricetin	 3,5,7-trihydroxy-2-(3,4,5-trihydroxyphenyl)chromen-4-one	Collagen synthesis stimulation. Suppresses UVA and UVB induced MEK and ERK phosphorylation as well as Raf kinase activity.	(Jung et al., 2010)
	Hesperidin	 (2*S*)-5-hydroxy-2-(3-hydroxy-4-methoxyphenyl)-7-[(2*S*,3*R*,4*S*,5*S*,6*R*)-3,4,5-trihydroxy-6-[[(2*R*,3*R*,4*R*,5*R*,6*S*)-3,4,5-trihydroxy-6-methyloxan-2-yl]oxymethyl]oxan-2-yl]oxy-2,3-dihydrochromen-4-one	Reducing the levels of MMP-1 and 2 (collagenase and gelatinase A respectively). It also has anti-oxidant properties.	(Novotná et al., 2023)

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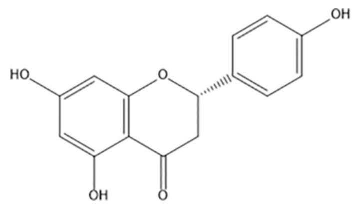
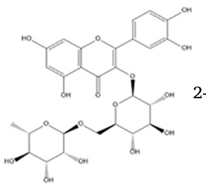
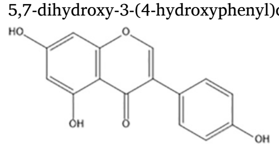
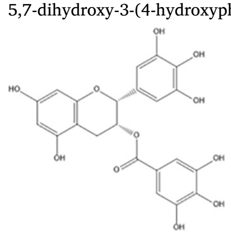
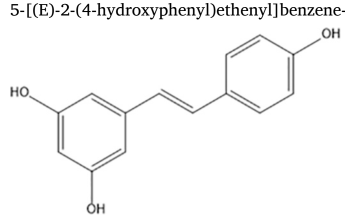
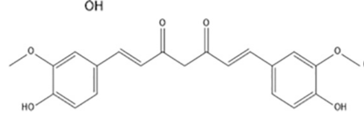
Table 1 (*continued*)

Category	Common Name of Dietary Phytochemical	Chemical Structure	Mechanism in preventing premature skin aging	References
	Naringenin	(2*S*)-5,7-dihydroxy-2-(4-hydroxyphenyl)-2,3-dihydrochromen-4-one 	Protection against UV-B induced damage, proinflammatory cytokine production, myeloperoxidase activity, also inhibiting MM-9 activity.	(Şahin et al., 2023)
	Rutin	 2-(3,4-dihydroxyphenyl)-5,7-dihydroxy-3-[(2*S*,3*R*,4*S*,5*S*,6*R*)-3,4,5-trihydroxy-6-[[(2*R*,3*R*,4*R*,5*R*,6*S*)-3,4,5-trihydroxy-6-methyloxan-2-yl]oxymethyl]oxan-2-yl]oxychromen-4-one	A potent senomorphic agent which provides protection against collagen degradation. It can reduce the levels of NF-κB, TNF-α, IL-1β, COX-2 as well as block MAPK activation.	(Ganeshpurkar and Saluja, 2017; Muvhulawa et al., 2022)
	Genistein	5,7-dihydroxy-3-(4-hydroxyphenyl)chromen-4-one 	Protection against UV-B damage to the keratinocytes. Lower the proinflammatory cytokines CXCL1, IL-1, and MIF.	(Tang et al., 2022)
Polyphenols	Epigallocatechin gallate	5,7-dihydroxy-3-(4-hydroxyphenyl)chromen-4-one 	Protects skin from sun damage by acting as an antioxidant and anti-inflammatory. Also controls gene expression of TNF-α and IL-1β which further led to control of iNOS and COX-2 genes involved in inflammation. Pro-inflammatory NO production is also inhibited in mice model.	(Lee et al., 2016; Zhong et al., 2012)
	Resveratrol	5-[(E)-2-(4-hydroxyphenyl)ethenyl]benzene-1,3-diol 	Exhibits antioxidant and anti-inflammatory activity, promotes collagen synthesis, and regulates gene expression. It activates Sirt-1 which blocks TLR-4/NF-κB/STAT pathway aiding in anti-inflammatory activity. It can also lower the levels of cellular MMP-1 MMP-3 MMP-13 and iNO expression.	(Das and Das, 2007; Meng et al., 2021)
	Curcumin	 (1E,6E)-1,7-bis(4-hydroxy-3-methoxyphenyl)hepta-1,6-diene-3,5-dione	Exhibits antioxidant and anti-inflammatory activity. It reduces free radicals in the body and protect the mitochondria. It can down-regulate NF-κB by binding to Peroxisome proliferator-activated receptor gamma (PPARγ). iT is also known to inhibit the activation of NLP3 inflammosome pathway. It also inhibits COX-2 and iNOS.	(Menon and Sudheer, 2007; Merrell et al., 2009)

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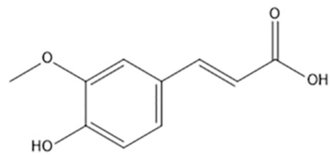
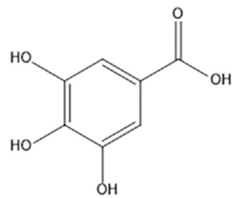
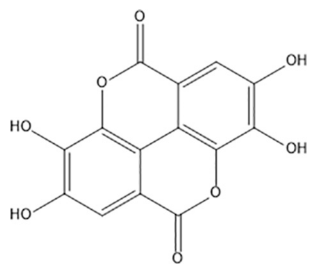
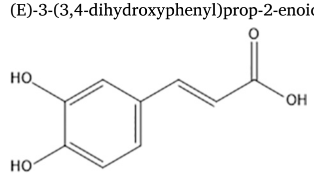
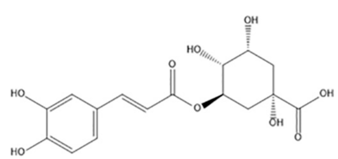
Category	Common Name of Dietary Phytochemical	Chemical Structure	Mechanism in preventing premature skin aging	References
	Ferulic acid	(E)-3-(4-hydroxy-3-methoxyphenyl)prop-2-enoic acid 	Exhibits antioxidant property aiding to free radical scavenging and anti-inflammatory activity.	(Zduńska et al., 2018)
	Gallic acid	3,4,5-trihydroxybenzoic acid 	Exhibits antioxidant and anti-inflammatory activity, stimulates collagen synthesis, and prevent UV-induced skin damage.	(Gao et al., 2019)
	Ellagic acid	6,7,13,14-tetrahydroxy-2,9-dioxatetracyclo[6.6.2.04,16.011,15]hexadeca-1(15),4,6,8(16),11,13-hexaene-3,10-dione 	Acts as an antioxidant by inducing NRF2 expression. It also enhances expression of SIRT1(protective factor in aging) pathway.	(Naghibi et al., 2023)
	Caffeic acid	(E)-3-(3,4-dihydroxyphenyl)prop-2-enoic acid 	Exhibits antioxidant and anti-inflammatory activity, promotes collagen synthesis, and protects the skin from UV damage.	(Cos et al., 2002)
	Chlorogenic acid	(1*S*,3*R*,4*R*,5*R*)-3-[(E)-3-(3,4-dihydroxyphenyl)prop-2-enoyl]oxy-1,4,5-trihydroxycyclohexane-1-carboxylic acid 	Exhibits antioxidant and anti-inflammatory activity, promotes collagen synthesis, and prevent UV-induced skin damage.	(Kitagawa et al., 2011)

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Table 1 (*continued*)

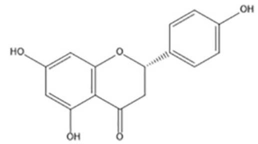
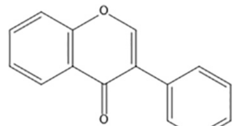
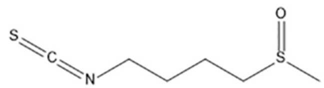
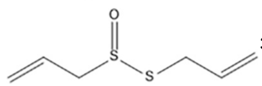
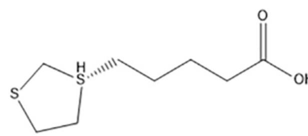
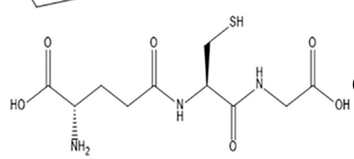
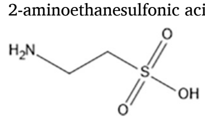
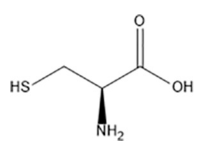
Category	Common Name of Dietary Phytochemical	Chemical Structure	Mechanism in preventing premature skin aging	References
	Naringenin	(2*S*)-5,7-dihydroxy-2-(4-hydroxyphenyl)-2,3-dihydrochromen-4-one 	Show antioxidant and anti-inflammatory activity, promotes collagen synthesis, and protects the skin from UV damage.	(Salehi et al., 2019b)
	Isoflavone	3-phenylchromen-4-one 	Exhibits antioxidant activity, stimulate collagen synthesis, and prevent UV-induced skin damage.	(Křížová et al., 2019)
Sulfur-containing dietary phytochemicals	Sulforaphane	1-isothiocyanato-4-methylsulfinylbutane 	Activates the Nrf2 pathway, promotes antioxidant defense, and inhibits MMP expression.	(Zhou et al., 2019)
	Allicin	 3-prop-2-enylsulfinylsulfanylprop-1-ene	Possesses potent antioxidant and anti-inflammatory properties, inhibits NF-κB activation, and reduces inflammation in the skin.	(Zhang et al., 2017)
	Lipoic acid	 5-[(3*R*)-dithiolan-3-yl]pentanoic acid	Regenerates other antioxidants, protects the skin from oxidative damage, stimulates collagen synthesis, and inhibits MMP expression.	(Packer et al., 1995)
	Glutathione	 (2*S*)-2-amino-5-[[(2*R*)-1-(carboxymethylamino)-1-oxo-3-sulfanylpropan-2-yl]amino]-5-oxopentanoic acid	Acts as an essential antioxidant in the body, safeguards the skin from damage caused by oxidative stress, and controls the proliferation and death of cells. It is a potent free radical scavenger.	(Lv et al., 2019)
	Taurine	2-aminoethanesulfonic acid 	Acts as an antioxidant, helps regulate skin inflammation and immune response.	(Marcinkiewicz and Kontny, 2014)
	Cysteine	(2*R*)-2-amino-3-sulfanylpropanoic acid 	Enhances the production of glutathione and other antioxidants, aids in preventing skin damage caused by oxidative stress, and supports collagen synthesis.	(Paul et al., 2018)

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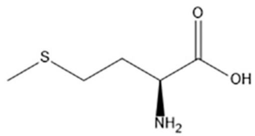
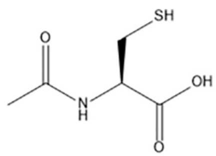
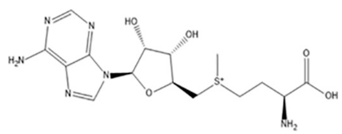
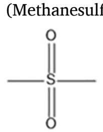
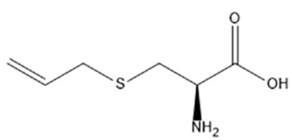
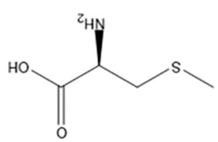
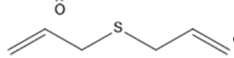
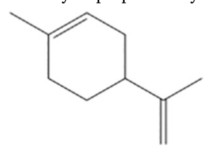
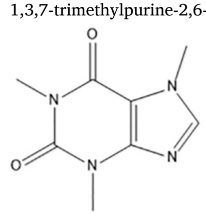
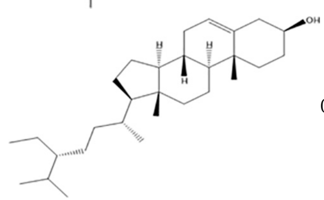
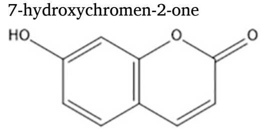
Table 1 (*continued*)

Category	Common Name of Dietary Phytochemical	Chemical Structure	Mechanism in preventing premature skin aging	References
	Methionine	(2*S*)-2-amino-4-methylsulfanylbutanoic acid 	Supports the production of glutathione and other antioxidants, aids in preventing skin damage caused by oxidative stress, and supports collagen synthesis.	(Martínez et al., 2017)
	N-acetylcysteine	(2*R*)-2-acetamido-3-sulfanylpropanoic acid 	Enhances the production of glutathione and other antioxidants, reduces oxidative stress and inflammation in the skin.	(Hardwick and Sefton, 1995)
	S-adenosylmethionine	[(3*S*)-3-amino-3-carboxypropyl]-[[(2*S*,3*S*,4*R*,5*R*)-5-(6-aminopurin-9-yl)-3,4-dihydroxyoxolan-2-yl]methyl]-methylsulfanium 	Supports the production of glutathione and other antioxidants, helps to safeguard the skin against oxidative stress, inflammation, and supports collagen synthesis.	(Aversa et al., 2016)
	Methylsulfonylmethane	(Methanesulfonyl)methane 	Acts as a potent antioxidant, reduces inflammation in the skin, and supports collagen synthesis.	(Bahado-Singh et al., 2017)
	S-allyl cysteine	(2*R*)-2-amino-3-prop-2-enylsulfanylpropanoic acid 	Possesses potent antioxidant and anti-inflammatory properties, helps safeguard the skin against oxidative stress, inflammation, and supports collagen synthesis.	(Nyoman et al., 2018)
	S-methyl cysteine	(2*R*)-2-amino-3-methylsulfanylpropanoic acid 	Shields the skin from oxidative stress and inflammation by acting as a potent antioxidant and anti-inflammatory agent.	(Kumari et al., 1995)
	Diallyl sulfide	 di-2-propenyl sulfide	Acts as a potent antioxidant and anti-inflammatory agent, helps safeguard the skin against oxidative stress, inflammation, and supports collagen synthesis.	(Shang et al., 2019b)

(*continued on next page*)

Table 1 (*continued*)

Category	Common Name of Dietary Phytochemical	Chemical Structure	Mechanism in preventing premature skin aging	References
Terpenes	Limonene	1-methyl-4-prop-1-en-2-ylcyclohexene 	Exhibit antioxidant properties and prevent UV-induced skin damage.	(Hagvall et al., 2007)
Alkaloids	Caffeine	1,3,7-trimethylpurine-2,6-dione 	Enhance the flow of blood to the skin, providing necessary nutrients and oxygen to maintain healthy skin.	(Li et al., 2018)
Phytosterols	Beta-sitosterol	 (3*S*,8*S*,9*S*,10*R*,13*R*,14*S*,17*R*)-17-[(2*R*,5*R*)-5-ethyl-6-methylheptan-2-yl]-10,13-dimethyl-2,3,4,7,8,9,11,12,14,15,16,17-dodecahydro-1H-cyclopenta[*a*]phenanthren-3-ol	Exhibit anti-inflammatory properties and may help prevent collagen breakdown, which contributes to skin pre-aging.	(Yuan et al., 2019)
Coumarins	Umbelliferone	7-hydroxychromen-2-one 	Safeguard the skin from UV damage and may also have anti-inflammatory effects.	(Molnar et al., 2017)

4.2. Flavonoids

Flavonoids are a group of polyphenolic dietary phytochemicals obtained from a wide range of plant-based foods, including fruits, herbs, vegetables as well as spices. Flavonoids are responsible for the bright colours of fruits and vegetables and have been linked to health benefits, including premature skin aging. Additionally, they also aid in lowering reducing the risk of chronic diseases such as cancer, cardiovascular ailments and neurodegenerative diseases (Panche et al., 2016b). Common food sources of flavonoids include berries, citrus fruits, apples, onions, parsley, and tea *etc.* Various food sources contain varying quantity of flavonoids, and their abundance is subject to fluctuations influenced by factors such as soil quality, climate conditions, and agricultural methodologies (Janabi et al., 2020).

The bioavailability of flavonoids can be affected by several factors. The food matrix, or the complex network of nutrients and other dietary phytochemicals present in a food, can impact the solubility and absorption of flavonoids (Kamiloglu et al., 2021). For example, flavonoids in whole fruits and vegetables are often encapsulated in cell walls, which can limit their absorption. Processing methods such as heating, grinding, or blending can break down the cell walls and increase the bioavailability of flavonoids also (Kumar and Pandey, 2013). The presence of dietary fat can also influence the absorption of flavonoids, as they are often poorly soluble in water. Therefore, consuming flavonoid-rich foods with a source of dietary fat, such as nuts, seeds, or olive oil, can increase their absorption (Kawabata et al., 2019; Panche et al., 2016).

To increase the bioavailability of flavonoids, several strategies can be employed. Consuming flavonoids with a source of dietary fat can enhance their absorption. Additionally, consuming flavonoids in the form of supplements or fortified foods can increase its bioavailability. Certain processing techniques, such as fermentation can also improve the bioavailability of flavonoids by breaking down complex structures and enhancing their release from the food matrix (Thilakarathna and Vasantha Rupasinghe, 2013).

4.3. Polyphenols

Polyphenols are a class of naturally occurring dietary phytochemicals that exist in vegetables, fruits, nuts, seeds, whole grains, and beverages such as tea, coffee, and red wine (Pandey and Rizvi, 2009b). They are well known for being rich in antioxidants and have been linked to several favorable health benefits like preventing premature skin aging. Additionally, polyphenols help to reduce the risk of long-term illnesses like cancer, neurological diseases, and cardiovascular disease. Apples, berries, grapes, orange fruits, pomegranates, cherries, plums, kale, spinach, broccoli, onions, garlic, chocolate, tea, coffee, and red wine are the foods that are considered as source of polyphenols (Zehiroglu and Ozturk Sarikaya, 2019). This study involved number of *in vivo* and *in vitro* models to evaluate the antioxidant effect of these dietary phytochemicals.

The polyphenol content present in food can vary greatly based on numerous factors, including the type of plant, soil quality, climate, and farming practices. Several factors can influence the bioavailability of polyphenols, including the type of polyphenol, the food matrix, the gut microbiota, and individual differences (Manach et al., 2004). Different structures and molecular weights of various polyphenols can affect their absorption and bioavailability. Polyphenols can be bound to other dietary phytochemicals in the food matrix, thereby decreasing their bioavailability (D'Archivio et al., 2010). In a similar manner, gut microbiota can metabolize polyphenols into different forms, which can influence their bioavailability. Age, genetics, and health status are the factors that can also have an impact on polyphenol absorption and metabolism. Several strategies are implemented to increase the bioavailability of polyphenols (Filosa et al., 2018). Consuming polyphenols with a source of dietary fat can increase their bioavailability. Consuming polyphenols in the form of supplements or fortified foods can also increase their bioavailability. Cooking techniques, such as steaming and boiling, can also increase the bioavailability of polyphenols by breaking down their complex structures and facilitating their release from the food matrix (Aloo et al., 2023). Consuming polyphenols in combination with other bioactive dietary phytochemicals is an additional method for enhancing their bioavailability. Consuming polyphenols with fiber, for instance, can slow their absorption and lengthen the time of stays in the gut, give the gut bacteria more time to metabolize into more bioavailable forms (Plamada and Vodnar, 2022).

4.4. Sulfur containing dietary phytochemicals

Numerous health benefits have been associated with sulfur-containing dietary phytochemicals. The sulfur-containing dietary phytochemicals are accountable for the pungent odor and flavor of certain vegetables, *e.g.* onions, garlic, and cruciferous vegetables (Marcinkowska and Jeleń, 2022a). Garlic, onions, shallots, leeks, chives, cruciferous vegetables such as broccoli, cauliflower, and kale, asparagus, mushrooms, and legumes are common food sources of sulfur-containing dietary phytochemicals (Kim et al., 2012).

Sulfur rich dietary phytochemicals are widely consumed and are recognized for their distinctive tastes and aromas. Several factors can influence the bioavailability of dietary phytochemicals containing sulfur (Marcinkowska and Jeleń, 2022b). For instance, the methods of preparation and cooking can affect the bioavailability of these dietary phytochemicals. These dietary phytochemicals get degraded by cooking which exposes for high temperatures and lengthy cooking times, which reduces its bioavailability. In contrast, gentle cooking methods such as steaming can help to maintain the integrity of these dietary phytochemicals, thereby enhancing their bioavailability. The presence of other food metabolites can also affect the bioavailability of sulfur-containing dietary phytochemicals (Yuan et al., 2009). For instance, dietary fiber can bind to these dietary phytochemicals and restrict their absorption in the gastrointestinal tract, thereby reducing the bioavailability. The research findings indicates that consuming sulfur-containing dietary phytochemicals with a source of dietary fat can improve their absorption (Palafox-Carlos et al., 2011a). Increasing the bioavailability of sulfur-containing dietary phytochemicals can be accomplished by consuming these materials, as well as in conjunction with dietary fat. In addition, the bioavailability of sulfur-containing dietary phytochemicals can be increased by consuming them along with other bioactive dietary phytochemicals (Toohey, 2014). Consuming garlic with foods rich in vitamin C, such as bell peppers and citrus fruits, can increase the absorption of sulfur-containing dietary phytochemicals (Batiha et al., 2020).

4.5. Other dietary phytochemicals

Terpenes, alkaloids, phytosterols, and coumarins are considered as additional phytochemicals found in numerous plant-based foods and linked with several health benefits. Terpenes are present in citrus fruits, mint, and herbs like rosemary and thyme (Lourenço et al., 2019). Tea, coffee, cocoa, and certain spices like black pepper and paprika contain alkaloids. Phytosterols are present in plant oils, nuts, seeds and whole grains. Coumarins are present in foods such as cinnamon, parsley and celery (Plaskova and Mlcek, 2023).

Depending on the particular class of dietary phytochemical, the factors influencing the bioavailability of these can vary. Cooking methods and food processing can have an impact on the bioavailability of terpenes also (Elizalde-Romero et al., 2021). Heating can reduce the bioavailability of terpenes by causing their decomposition. Alternatively, certain food processing methods, such as juicing, can increase the bioavailability of terpenes. The bioavailability of alkaloids can be affected by the presence of other food metabolites, individual differences, and gut microbiota (Vaou et al., 2021). Furthermore, the antimicrobial activity of mentioned plant extracts was evaluated by *in vitro*

Table 2
Summarizes the various sources of dietary phytochemicals and their classes.

Class of dietary phytochemicals	Dietary phytochemicals	Food sources	References
Carotenoids	Beta-carotene	Carrots, sweet potatoes, pumpkin, spinach, kale, cantaloupe, mangoes.	(Tanumihardjo et al., 2009a)
	Lycopene	Tomatoes, watermelon, pink grapefruit, papaya.	(Story et al., 2010)
	Lutein	Spinach, kale, collard greens, turnip greens, broccoli, peas.	(Eriksen et al., 2017)
	Zeaxanthin	Corn, egg yolks, spinach, kale, collard greens, turnip greens.	(Sommerburg et al., 1998)
	Astaxanthin	Salmon, trout, krill, shrimp, crayfish, microalgae.	(Honda et al., 2022)
	Canthaxanthin	Salmon, trout, crustaceans, mushrooms.	(Manikandan et al., 2020)
	Alpha-carotene	Carrots, sweet potatoes, pumpkin, spinach, kale, broccoli.	(Tanumihardjo et al., 2009b)
Flavonoids	Quercetin	Onions, apples, berries (*e.g.*, blueberries, cranberries), grapes, citrus fruits (*e.g.* grapefruits), capers, broccoli, tea, red wine, leafy greens	(Riva et al., 2019)
	Kaempferol	Broccoli, kale, spinach, green beans, tea, berries (*e.g.*, strawberries, cranberries), grapes, tomatoes	(Calderón-Montaño et al., 2011)
	Apigenin	Parsley, celery, chamomile tea, oranges, grapefruits, onions, broccoli and leafy greens	(GUVEN et al., 2019)
	Luteolin	Parsley, thyme, celery, broccoli, peppers, chamomile tea, carrots, olive oil	(Wang et al., 2021)
	Myricetin	Berries (*e.g.*, cranberries, bilberries), grapes, nuts, tea, onions, kale	(Kang et al., 2011)
	Hesperidin	Citrus fruits (*e.g.*, oranges, lemons), apricots, cherries, grapes, plums, berries (*e.g.*, blueberries, raspberries)	(Mas-Capdevila et al., 2020)
	Naringenin	Grapefruit, oranges, tomatoes, cherries, tea	(Chen et al., 2019)
	Rutin	Buckwheat, asparagus, tea, apples, citrus fruits (*e.g.*, oranges, grapefruits), berries (*e.g.*, cranberries)	(Chattopadhyay et al., 2017)
	Genistein	Soybeans, tofu, tempeh, legumes (*e.g.*, lentils, chickpeas), peanuts, flaxseeds	(Tuli et al., 2019)
Polyphenols	Epigallocatechin gallate	Green tea, black tea	(Chen et al., 2009)
	Resveratrol	Grapes, red wine, peanuts	(Sanders et al., 2000)
	Quercetin	Onions, apples, berries	(Anand David et al., 2016b)
	Curcumin	Turmeric, curry powder	(Tayyem et al., 2006)
	Genistein	Soybeans, soy products	(Fukutake et al., 1996)
	Luteolin	Celery, parsley, thyme	(Alizadeh and Daneghian, 2022)
	Apigenin	Parsley, celery, chamomile tea	(Shankar et al., 2017)
	Ferulic acid	Whole grains, nuts, seeds	(Kumar and Pruthi, 2014)
	Gallic acid	Blueberries, black tea, red wine	(Seeram et al., 2008)
	Ellagic acid	Berries, pomegranates	(Usta et al., 2013)
	Caffeic acid	Coffee, apples, pears	(Olthof et al., 2001a)
	Rutin	Buckwheat, citrus fruits	(Kreft et al., 2006)
	Chlorogenic acid	Coffee, blueberries, apples	(Olthof et al., 2001b)
	Naringenin	Grapefruits, tomatoes	(Amin et al., 2020)
	Kaempferol	Broccoli, kale, green tea	(Dabeek and Marra, 2019)
	Isoflavones	Soybeans, soy products	(WANG et al., 2013)
	Oleuropein	Olive oil, olives	(Omar, 2010)
	Piperine	Black pepper	(Derosa et al., 2016)
Sulfur-containing dietary phytochemicals	Sulforaphane	Broccoli, cauliflower, kale, brussels sprouts, cabbage	(Augustin et al., 2019)
	Allicin	Garlic, onions, shallots, leeks	(Nicastro et al., 2015)
	Lipoic acid	Broccoli, spinach, potatoes, tomatoes, carrots, beets	(Incerti et al., 2009)
	Glutathione	Avocado, asparagus, spinach, okra, broccoli, garlic, tomatoes	(Ortiz-Avila, 2017)
	Taurine	Seaweed, soybeans, lentils, nuts, seeds, beans, whole grains	(Plotnikoff et al., 2023)
	Cysteine	Garlic, onions, broccoli, Brussels sprouts, oats, wheat	(Yudhistira et al., 2022)
	Methionine	Brazil nuts, sesame seeds, oats, wheat, beans, lentils	(Nuru et al., 2018)
	N-acetylcysteine	Garlic, onions, broccoli, red pepper, oats	(Shih et al., 2018)
	S-adenosylmethionine	Soybeans, lentils, nuts, seeds, beans, whole grains	(Tien Lea et al., 2016)
	S-allyl cysteine	Garlic, onions	(Colín-González and Santamaría, 2017)
	S-methyl cysteine	Garlic, onions	(Wiseman, 2005)
	Diallyl sulfide	Garlic, onions, leeks, chives	(Fitzpatrick and Woldemariam, 2017)

models.

The absorption and bioavailability of phytosterols can be influenced by factors such as the quantity consumed, the presence of dietary fat, and the gut microbiome. The bioavailability of coumarins can be affected by cooking methods and the presence of other food metabolites, such as vitamin K (Li et al., 2022). To increase the bioavailability of such dietary phytochemicals, it is possible to consume them raw or with minimal processing, as well as with a source of dietary fat. In addition, consuming them with other bioactive metabolites such as fiber, vitamins, and minerals increases their absorption and bioavailability (Palafox-Carlos et al., 2011b). Table 2 and Fig. 3 further summarized the various dietary sources of phytochemicals.

5. Current scenario and future perspectives of dietary phytochemicals in skin health

Due to their potential to prevent premature skin aging, dietary phytochemicals are gaining popularity in the cosmetics industry, which is experiencing an increase in demand for natural and organic products (Ribeiro et al., 2015). In scientific studies, dietary phytochemicals such as turmeric and ferulic acid have been shown to have powerful antioxidant and anti-inflammatory properties. Dietary Phytochemicals have been the subject of research as potential additives in skincare products with the aim of mitigating premature skin aging, owing to their advantageous characteristics. It has been discovered that plants such as *Juglans regia* L. and *Spilanthes* contain high concentrations of phenolic metabolites as bioactive metabolites, both of which have the potential to slow the appearance of premature skin aging (Michalak, 2022d). Several

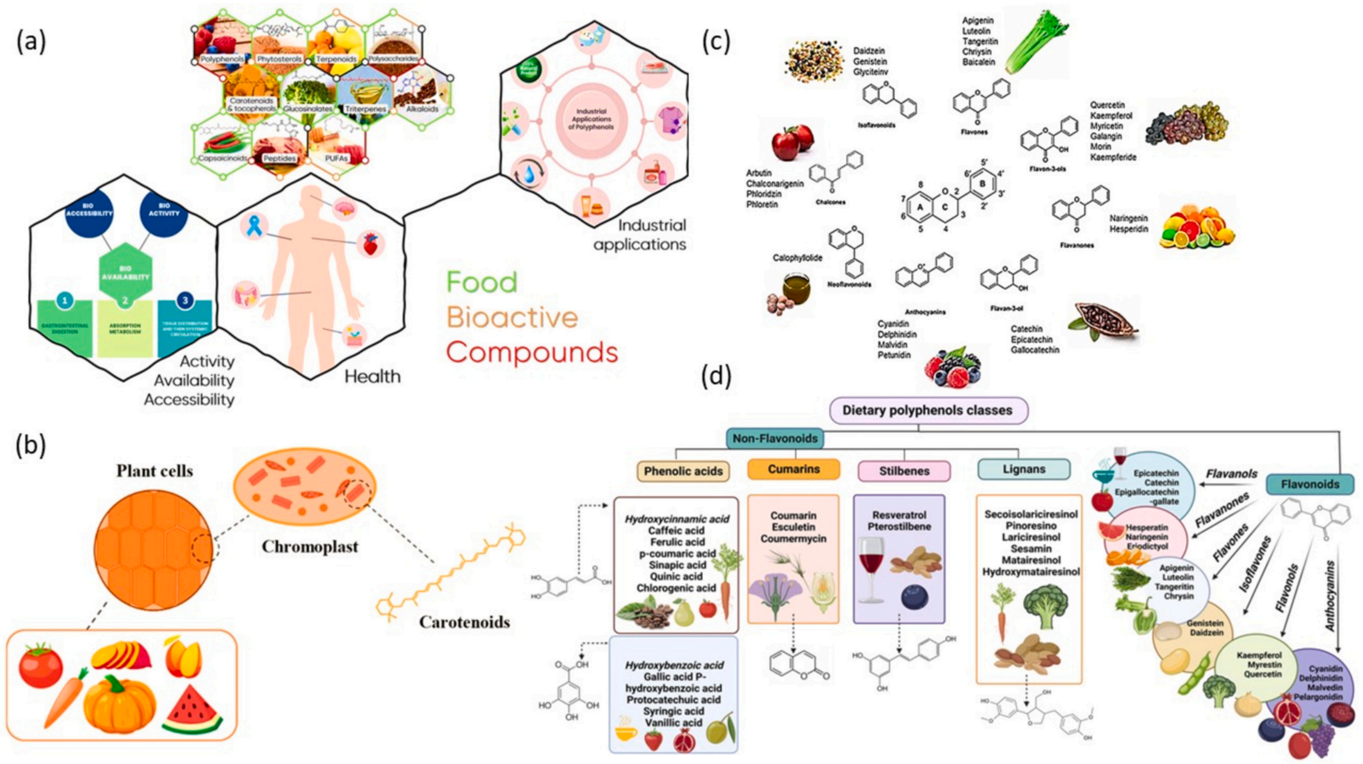


Fig. 3. Dietary sources of phytochemicals. (**a**) Major sources and classification of food bioactive metabolites (FBMs). For each class, a representative source and metabolites are listed, such as polyphenols (chlorogenic acids in blueberry and raspberry fruits), phytosterols (stigmasterol in soybean), terpenoids (limonene in citrus fruits), polysaccharides (cellulose in flax seeds), carotenoids & tocopherols (-carotene/vitamin A), glucosinolates (sulforaphane in broccoli), triterpene (Câmara et al., 2020). (**b)** Carotenoids' primary sources and chromoplast structures are shown schematically (Lombardelli et al., 2022). (**c**) Dietary sources of Flavonoids (Khan et al., 2021). (**d)** Summarized the classification of dietary polyphenols and their sources (Pop et al., 2023).

studies have demonstrated that dietary phytochemicals may prevent the onset of premature skin aging. Some plant extracts and dietary phytochemicals have been discovered to inhibit melanin production, which can lead to abnormal pigmentation and skin diseases, and thus improve the appearance of the skin (Feng et al., 2022). A meta-analysis of eleven studies was done by some researchers which found that astaxanthin, a xanthophyll carotenoid derived from microalgae, when ingested or applied topically, can reduce premature skin aging by increasing moisture content and elasticity while decreasing (Zhou et al., 2021). HR-1 hairless mice served as animal models to study the effects of Astaxanthin on skin aging. In order to induce the atopic dermatitis, phthalic anhydride (PA) was used.

The consumption of total polyphenols (TPs), primarily in coffee and green tea, was negatively correlated with UV pigmented spot scores in a cross-sectional study of healthy Japanese women aged 30 to 60. Several polyphenols, including anthocyanins, ellagitannins, epigallocatechin gallate, oleuropein dihydroxy phenyl, punicalagin, quercetin, resveratrol, and theaflavin, reportedly have chemo-preventive effects against skin cancer metastasis (Sajadimajd et al., 2020). Recently, an epidemiological investigation revealed that the exposome influences premature skin aging, with age, smoking, sunscreen use, and cosmetics use identified as predictors of premature skin aging (Buendía-Eisman et al., 2020). Furthermore, the inclusion of bioactive dietary phytochemicals in food supplements with appetite/hunger-suppressing and/or satiety/fullness-increasing properties can facilitate weight loss and improve patients' adherence to minimizing food and caloric intake, potentially leading to weight loss and improved skin health (Stuby et al., 2019). (Jenkins et al., 2014) found that a combination of soy isoflavones, lycopene, vitamin C, vitamin E, and fish oil reduced facial wrinkle depth and increased the deposition of new collagen fibres in the dermis. In a double-blind, placebo-controlled clinical trial with healthy volunteers, (Meinke et al., 2013) discovered that a supplement containing dietary carotenoids increased radical scavenging activity and provided significant protection against stress-induced radical formation. In addition, a longitudinal study was conducted by a team of researchers in Queensland, Australia, discovered that moderate consumption of oily fish and wine lowered the risk of developing actinic keratoses, a precursor to skin cancer (Hughes et al., 2009). A two-year, double-blind, randomized, placebo-controlled trial of oral green tea polyphenols found that long-term supplementation with GTPs was not superior to placebo after 24 m of use (Janjua et al., 2009). However, a study involving women with moderate skin aging found no significant clinical improvements with the use of a combination regimen of topical and oral green tea supplementation, except for a histologic improvement in elastic tissue content (Chiu et al., 2005). Present *in vivo* study of 8 weeks involved placebo cream as negative control whereas topical 10 % green tea cream was applied as treatment regimen in dose of 300 mg twice-daily. The green tea polyphenols were used as sample extract which contained epicatechin, epigallocatechin, and catechin. The histology suggested positive improvement in the elastic tissue content of treated specimens, which elucidates the potential protective effects of green tea polyphenols on photoaging.

The topical and oral administration of antioxidant metabolites including ascorbic acid, tocopherol, α-lipoic acid, melatonin, and emblica reduced oxidative stress and lipid peroxidation in the blood serum and skin of elderly volunteers with dry skin and photo-aging (Morganti et al., 2002). These studies provide evidence that certain dietary phytochemicals in the diet may be effective in preventing premature skin aging and associated skin diseases. Numerous studies have focused on a specific dietary phytochemical or plant extract, and it is unknown how these dietary phytochemicals may interact with other dietary or environmental factors to affect skin health. To overcome these

Table 3
Dietary guidelines for optimal skin health, suggestions for incorporating phytochemical-rich foods, supplements, and functional foods for skin health.

Recommendations of dietary phytochemicals for good skin health	Suggestions for Incorporating Phytochemical-Rich Foods	Supplements and Functional Foods for Skin Health	References
Eat a diet rich in antioxidants	Include berries, leafy greens, nuts, seeds, and colorful fruits and vegetables in the diet to protect skin cells from free radicals and prevents premature skin aging.	Vitamin C supplements, green tea extract, resveratrol supplements, and astaxanthin supplements can help to support skin health and reduce the risk of premature skin aging.	(Schagen et al., 2012)
Include healthy fats	To keep skin hydrated, reduce inflammation, and shield from sun damage, eat foods high in omega-3 fatty acids, like fatty fish, flaxseeds, chia seeds and walnuts.	Fish oil and krill oil, two common sources of omega-3 fatty acids, have been shown to improve skin health and reduce inflammation.	(Gerling et al., 2019)
Limit refined carbohydrates and sugar	Avoid foods that can cause inflammation in the body and contribute to premature skin aging, like refined carbohydrates and sugar. Option for complex carbohydrates and natural sweeteners instead.	Probiotic supplements, fermented foods like kimchi and kefir, and fibe supplements can help to support gut health, which is important for maintaining healthy skin.	(Kirjavainen et al., 1999)
Stay hydrated	Drink at least 8 cups of water per day and consume hydrating foods like watermelon and cucumber to prevent dehydration, which can cause dry, dull and wrinkled skin.	Supplements containing hyaluronic acid can help maintain skin hydration and diminish the signs of fine lines and wrinkles.	(Papakonstantinou et al., 2012)
Consume collagen-rich foods	Include bone broth, chicken, and fish in the diet to support prevent premature skin aging and reduce the signs of wrinkles.	Collagen supplements can aid in maintaining skin elasticity and diminishing the signs of fine lines and wrinkles.	(Al-Atif, 2022)
Incorporate phytochemical-rich foods	Add colorful fruits and vegetables like blueberries, blackberries, raspberries, spinach, kale, and broccoli to the meals to boost antioxidant levels and support healthy skin aging. Also, consider using herbs and spices like turmeric, ginger, and garlic to add flavor and antioxidants to the dishes.	Green superfood powders, such as spirulina or chlorella, can help to boost antioxidant levels and prevents premature skin aging.	(Minich, 2019)

limitations, research is being done to examine the effects of dietary phytochemical combinations and their interactions with other dietary and environmental factors. This is done in order to better comprehend their potential mechanisms of action (Hoang et al., 2021). Future research is also required to consider the use of advanced imaging techniques, such as high-resolution ultrasound or optical coherence tomography, to provide more objective and accurate measurements of premature skin aging and associated skin diseases. In general, there is bright future to determine the optimal doses, combinations, and duration of phytochemical supplementation or topical application for optimal skin health benefits (Babalola et al., 2014).

6. Practical recommendations of dietary interventions to prevent premature skin aging

Premature skin aging is a major concern to preserve healthy appearance. In addition to genetic and environmental factors, dietary interventions can have an effect on the health of skin (Table 3) (Ganceviciene et al., 2012b). Dietary interventions are required to prevent premature skin aging. A diet rich in antioxidants is an effective dietary intervention for preventing premature skin aging. Antioxidants protect the cells from free radical damage, which can speed up the aging process of the skin. Antioxidant-rich foods including berries, leafy greens, nuts, seeds, and brightly colored fruits and vegetables are high in demand due to this reason. These foods can support healthy skin aging when incorporated into the diet (Michalak, 2022e). Some beneficial fatty acids, omega-3 fatty acids are crucial for skin hydration, reduction of inflammation, and protection from sun damage. Flaxseeds, chia seeds, and walnuts, are excellent sources of omega-3 fatty acids. Sugar and refined carbohydrates contribute to inflammation in the body, which can accelerate premature skin aging (Manson et al., 2019). Consequently, limiting consumption of these foods can promote healthy skin aging. Apart from rich dietary intake hydration is necessary for maintaining healthy skin. This suggests that dehydration can cause skin to become dry, dull, and more susceptible and ultimately results in the development of wrinkles. In addition to consuming hydrating foods *e.g.* watermelon and cucumber and consuming at least 8 cups of water per day can prevent premature skin aging (Popkin et al., 2010).

7. Limitations and future prospectives

Although phytochemicals have shown promising results in preventing premature skin aging, many dietary phytochemicals have poor bioavailability; for instance, curcumin, found in turmeric, has shown poor bioavailability due to its poor absorption and high excretion rate (Anand et al., 2007). Resveratrol, found in grapes (wine) is another polyphenol has demonstrated problems with bioavailability owing to rapid metabolism and excretion from the body (Bohara et al., 2022). Epigallocatechin gallate found in green tea, is a potent antioxidant which suffers from poor bioavailability just like the above-mentioned examples (Bansal et al., 2018). Querceptin, Genistein, Capsaican, Lycopene and many other dietary phytochemicals have demonstrated this issue of poor bioavailability (Islam et al., 2020), and hence research needs to be focused on their delivery and which metabolites may be administered in conjunction with these phytochemicals in order improve their bioavailability in human body. The effects of these dietary phytochemicals are dependent upon plethora of factors such as life style, genetics, diet *etc.* hence it is difficult to standardize a dose or therapeutic approach for a large population. It is important to make a standardized formulation which is beneficial for a significant amount of people. Moreover, skin aging itself is a polygenic trait and epigenetically controlled (Orioli and Dellambra, 2018). Hence, dietary phytochemicals may show increased efficacy against certain factors responsible for premature skin aging, but it is difficult to find out a formulation of phytochemicals which can address all the factors which lead to premature skin aging. Whether phytochemicals can become a mainstay in skin therapeutics or be a complementary approach alongside skin care products is yet to be understood and subject to further research findings.

8. Conclusion

The potential of dietary phytochemicals in mitigating premature aging of skin has been underscored in this article. Through research findings it has been confirmed that Carotenoids, flavonoids, polyphenols, sulfur, terpenes, alkaloids, phytosterols, coumarins and other phytochemicals have shown promising outcomes in mitigating certain factors which lead to premature skin aging such as free-radicals and inflammatory processes. Hence, addition of dietary phytochemicals in regular diet of a person may have positive impact on his/her skin health by delayed cellular senescence. However, it is important to note that although these phytochemicals have shown a promising avenue in preventing certain factors affecting skin aging it is still a matter of rigorous research to comprehensively elucidate the efficacy of these phytochemicals. Further research will provide valuable insights into the ways to optimize the delivery as well as efficiency of these phytochemicals.

CRediT authorship contribution statement

Harpreet Singh: Writing – original draft, Supervision, Conceptualization. **Y.T. Kamal:** Supervision, Conceptualization. **Jessica Pandohee:** Supervision, Conceptualization. **Arun Kumar Mishra:** Writing – review & editing, Visualization, Supervision. **Aritra Biswas:** Writing – original draft, Supervision. **Sourav Mohanto:** Writing – review & editing, Supervision. **Arvind Kumar:** Writing – review & editing, Supervision. **Sagnik Nag:** Writing – original draft, Supervision. **Amrita Mishra:** Visualization, Supervision. **Mhaveer Singh:** Visualization, Supervision. **Himanshu Gupta:** Visualization, Supervision. **Hitesh Chopra:** Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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