Current State of Knowledge on the Antioxidant Effects and Mechanisms of Action of Polyphenolic Compounds

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Abstract
Quality-of-life improvements have resulted in increasing attention being paid to research on antiaging and antioxidation. Polyphenols are natural antioxidants with excellent biological activities, such as antioxidation and scavenging of free radicals and antiviral activity. Abundant availability and low toxicity of polyphenols have attracted the attention of researchers. In this paper, the antioxidant activities of flavonoids, phenolic acids, stilbenes and lignan polyphenols are analyzed, the corresponding antioxidant mechanisms are investigated, and the antioxidant effects of polyphenols are systematically reviewed. Thus, an effective reference based on the recent literature is compiled for the study of the antioxidant mechanisms of polyphenols that provides a significant theoretical basis for the development of products that are components of polyphenols.

Keywords
polyphenols, flavonoids, phenolic acids, stilbenes, lignans, antioxidation

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Polyphenols have polyphenol structure and are the most common secondary metabolites in plants. Polyphenol compounds are ubiquitous in roots, leaves, fruit pulp and peel across the plant kingdom. More than 8,000 polyphenols, mainly plant polyphenols, have been identified and isolated to date.\textsuperscript{1} Plant polyphenols are secondary metabolites that contain multiple phenolic hydroxyl groups. The ortho phenolic hydroxyl group is most easily oxidized to a quinone.\textsuperscript{2} Reactive oxygen species (ROS), are oxygen-containing substances with strong reactive activity, mainly hydroxyl radical (\(\cdot{\text{OH}}\)), superoxide anion radical (\(\cdot{\text{O}}_2^-\)), singlet oxygen (\(\text{^1}{\text{O}}_2\)), and hydrogen peroxide (\(\text{H}_2\text{O}_2\)). Studies have strongly correlated the presence of ROS with the occurrence and metastasis of tumors. High ROS levels can arrest the cell cycle, inhibit cell proliferation and even cause cell death, whereas low ROS levels can promote angiogenesis and cell proliferation.\textsuperscript{3,4} Cazzola et al. reported that multiple phenolic hydroxyl groups of polyphenols can provide active hydrogen and directly scavenge reactive oxygen free radicals, whereas free radicals formed via self-oxidation have higher stability and less toxic effects \textit{in vivo}.\textsuperscript{5} The long-term use of synthetic antioxidants have toxic and carcinogenic effects on human body, such that the safety of these compounds has been called into question. Therefore, it is particularly important to find safe and efficient antioxidants. Polyphenols are natural antioxidants with high efficacy. The literature on polyphenols is reviewed in this paper, and the antioxidant activity and corresponding mechanism of polyphenols are summarized to provide a reference for the comprehensive development and research of polyphenol-related products.

Classification of Polyphenolic Compounds and an Overview of Their Biological Functions
Since anthocyanins in plants were named in 1835,\textsuperscript{6} more than 100 years of research has been carried out on the definition, source, structure, classification and function of polyphenols. Many important discoveries have been made, especially

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regarding the health effects of polyphenols. Polyphenols comprise a wide variety of complex compounds, which typically include simple phenols, macromolecular polymers and derivatives, or occur in combination with monosaccharides or polysaccharides. Polyphenols can be classified in terms of their plant source into tea polyphenols, apple polyphenols, grape polyphenols and so on. Polyphenols can also be classified in terms of their constituent chemical groups into flavonoids, phenolic acids, stilbenes and lignans. Polyphenolic compounds that be polymerized are categorized as polyphenolic monomers (such as gallic acid, flavonoids, and chlorogenic acid) and tannins (such as gallic tannin).

Recent studies have shown that polyphenols are abundant in phytochemicals consumed by humans, and can improve antimicrobial effects in the human body. Polyphenols can cure cancer by preventing oxidative stress injury and inhibiting the binding of cytokines to cancer cells. In addition, polyphenols enhance antioxidant, antiviral and antitumor effects by lowering blood lipid levels and other actions. Increasing numbers of research studies and reports on the biological functions of polyphenols have caused scholars to extensively investigate the potential application of polyphenols to daily life.

**Antioxidant Effects and Mechanism of Action of Polyphenols**

Numerous studies have shown that free radicals accumulate in animals with age. Excessive accumulation of free radicals accelerates aging of the body and can also easily lead to cancer, tumors and other diseases. Polyphenols, as important active components of most natural plants, are characterized by low toxicity and broad-spectrum pharmacological activity. Thus, polyphenols are good resources for new drug development. Polyphenols contain many hydroxyl groups and can neutralize free radicals in the body and reduce free radicals into stable materials, thereby effectively preventing free radical chain reactions and delaying or inhibiting many diseases. The synergy between polyphenols and other active substances has motivated an increasing number of scholars to study the antioxidant activity of polyphenols.

**Antioxidant Effects of Flavonoids**

Flavonoid compounds, also known as flavonoids, are formed by the connection of two benzene rings (A ring and B ring) through three carbon chains. The polyphenolic hydroxyl groups in flavonoid molecules, release active hydrogen atoms, thus blocking the automatic oxidation of lipids. Flavonoids are found in almost all green plants. Over 4,000 flavonoid species have been isolated so far, mainly flavonols, flavanones, isoflavones, flavones, procyano, anthocyanidins, and anthocyanins. The antioxidant activities of flavonols, proanthocyanidins and anthocyanins are presented in this paper.

**Flavonols.** Flavonols are flavonoids with 2-phenyl chromone as the parent nucleus, among which the most common representatives are quercetin, kaempferol and myricetin derivatives. Studies have shown that quercetin can scavenge free radicals in vitro, inhibit ROS production and alleviate oxidative stress injury in vivo. The main mechanism of action of quercetin occurs via: (1) the direct formation of intramolecular hydrogen bonds by reacting with free radicals; (2) enzyme reaction involving free radicals. Quercetin can also significantly improve oxidative damage of myocardium and inhibit the activation of the NF-κB pathway in vivo and in vitro to protect tissues.

Quercetin has been reported to inhibit the opening of transitional pores for mitochondrial membrane permeability and ROS generation, increase the mitochondrial membrane potential and effectively reduce mitochondrial oxidative damage.

Lin et al. showed that quercetin-3-O-gentiobiose (QG), a novel antioxidant enzyme isolated from the methanol extract of okra, can effectively improve the activity of antioxidant enzymes. For example, glutathione peroxidase (GSH-Px) and superoxide dismutase (SOD) can reduce the oxidative stress damage from high-intensity exercise.

Tian et al. found that using kaempferol to interfere with MS-1 cells treated with fatty acids increase the SOD activity and nonenzymatic antioxidant glutathione (GSH) content. Under specific conditions, kaempferol significantly antagonized the oxidative stress induced by fatty acids.

Ji et al. reported that kaempferol affected the expression of NADPH oxidase and the NF-κB signaling pathway in mice of different age groups, thus achieving antioxidant effect.

Other studies have shown that kaempferol can also reduce the oxidative stress response by inhibiting the decline in the mitochondrial membrane potential during the early stage of H$_2$O$_2$-induced cardiomyocyte apoptosis.

**Proanthocyanidins.** Flavanols are formed by the polymerization of many monomers, such as epicatechin and catechin. The polymers and oligomers of flavanols are called proanthocyanidins. Proanthocyanidins are widely found in fruits, vegetables, and other green plants and particularly concentrated in grape seeds. Proanthocyanidins may be monomeric, oligomeric or have high degrees of polymerization. Proanthocyanidins B2 (PCB2) in proanthocyanidin dimers exhibits strong antioxidant activity.

Kim et al. demonstrated that PCB2 in apples could strongly scavenge free radicals while exhibiting strong reducibility.

The mechanism of action of proanthocyanidin antioxidant activity has been reported as the release of H$^+$ through the body, which competitively combines with free radicals to block free radical chain reactions. The generated semiquinone radicals react by nucleophilic addition to form polymers containing catecholic acid groups that retain strong antioxidant effects.

Proanthocyanidins alleviate oxidative stress by regulating oxidative stress signaling pathways. Kim et al. found that proanthocyanidins inhibit ROS production, oxidative stress injury and apoptosis-related pathways by downregulating the activity of the stress-activated MAPK pathway.

Sun et al. found that grape seed proanthocyanidin (GSP) alleviates...
inflammation and oxidative stress damage in rats by promoting ERK phosphorylation and upregulating the expression of the antioxidant genes Nrf2 and HO-1, thereby inhibiting retinal nerve cell apoptosis and protecting against retinal ischemia-reperfusion injury in rats. He et al. showed that GSP can promote the phosphorylation of PI3K and Akt, and protect PC12 cells from H2O2-induced oxidative damage via the PI3K/Akt signaling pathway. Proanthocyanidins prevent lipid peroxidation. Yu et al. showed that lotus oligomeric proanthocyanidins (L-OPC) can compete with oxidative chain reactions and delay autooxidation by acting as a hydrogen donor to inhibit the action of lipid peroxyl radical (ROO·) and by inhibiting lipoxygenase activity and slowing the enzymatic oxidation of lipids. Other studies have shown that proanthocyanidins in the leaves of red bayberry contain epigallocatechin gallate (EGCG) as structural constituent units. EGCG contains a large quantity of phenolic hydroxy groups that can supply electrons to free radicals, thereby interrupting free radical reactions and delaying the oxidation of oils and fats. Proanthocyanidins classified as polymeric polyphenols for which different degrees of polymerization produce different antioxidant effects.

**Anthocyanins.** Anthocyanins are a class of water-soluble natural pigments within agroup of flavonoids that are abundant in plants. Anthocyanins have good antioxidant activity that depends on the location and quantity of hydroxyl groups, the degree of glycation and electron donors in their structure. Studies have shown that when the planar anthocyanin molecule contains a double bond between the C-2 and C-3 positions that is coupled through the B ring with the A and C rings, saturation of this conjugated double bond and the destruction of coplanarity can inhibit XOD activity. Thus, this structure of anthocyanin hydroxyls results in increased SOD activity of antioxidant enzymes. Therefore, anthocyanins can inhibit the activity of the part of the oxidase that produces ROS to produce an antioxidant effect. Anthocyanins have been shown to enhance the antioxidant activity of ruminants by activating Nrf2 and inhibiting the NF-κB signaling pathway. Anthocyanins can complex with metal ions (Fe2+), thereby reducing the catalytic effect of active metal ions on free radical generation and increasing the antioxidant effect. Anthocyanins can complex with copper to inhibit the oxidation of LDL induced by copper or peroxyl radicals. Anthocyanins have been shown to inhibit the damage of ONOO– to endothelial cells by disrupting the mitochondrial apoptosis pathway and inhibiting Bax nuclear translocation.

**Antioxidant Effects of Phenolic Acids**

Phenolic acids can be categorized into hydroxybenzoic acid derivatives and more common hydroxycinnamic acid derivatives. The main hydroxycinnamic acid derivatives consist of chlorogenic acid, caffeic acid, coumaric acid, ferulic acid, and sinapic acid. Most studies have been performed on chlorogenic acid. The main hydroxybenzoic acid derivatives are gallic acid, protocatechuic acid, and p-hydroxybenzoic acid, among which gallic acid has been most studied. Phenolic acids have been reported to produce antioxidant effects by directly scavenging free radicals, inactivating enzymes related to ROS production and activating the antioxidant enzyme system to remove and repair ROS-induced damage.

**Chlorogenic acid.** Chlorogenic acid is a phenylpropanoid produced by plant cells via the shikimic acid pathway during aerobic respiration. Chlorogenic acid is known as “plant gold” and is widely found in dicots, such as sunflower, honeysuckle, *Eucamnia ulmoides* and coffee, and in ferns. Chlorogenic acid is an ester formed by the condensation of quinic acid and trans-cinnamic acid and occurs as a variety of isomers with a conjugated structure. Chlorogenic acid has many biological functions, such as scavenging free radicals; stimulating the central nervous system; producing hypolipidemic, anti-hypertensive, antiseptic and anti-inflammatory effects and tumor inhibition. Chlorogenic acid is an important dietary antioxidant component. The antioxidant activity of chlorogenic acid mainly derives from its ability to scavenge free radicals but is also related to the lipid peroxidation level in the body. Studies have shown that chlorogenic acid can supply hydrogen atoms to free radicals (DPPH·, ABTS·, ·O2, ·OH, and ONOO–) to suppress the occurrence of oxidative damage and is oxidized to a phenoxy radical and subsequently reaches a steady state by resonance. Chlorogenic acid can also chelate with metal ions to reduce the oxidative damage caused by these ions. Yang et al. showed that chlorogenic acid easily chelates with ferrous ions, blocking ·OH production by the Fenton reaction and protecting cells from oxidative damage. Shibata et al. found that chlorogenic acid can prevent NH4Cl-induced plasmid DNA fragmentation in neutrophils, suggesting that chlorogenic acid can inhibit DNA damage caused by redox reaction byproducts. Li et al. found that chlorogenic acid can reduce the expression of FOXO family genes in bone marrow mesenchymal stem cells by activating the phosphorylation of PI3K/Akt, thereby inhibiting oxidative stress-mediated injury. Recent studies have shown that chlorogenic acid protects the body from oxidative-stress-mediated injury by activating Nrf2 transcription and upregulating the expression of cellular antioxidant enzymes (such as NADPH: quinone oxidoreductase 1).

**Gallic acid.** Gallic acid, also known as 3,4,5-trihydroxybenzoic acid, usually occurs as a hydrate and is ubiquitous in plants such as grapes, tea leaves, flowers of Rhus chinensis, and Caesalpinia spinosa pods. Gallic acid is mainly used in the food, pharmaceutical, and chemical industries. Gallic acid has been reported to reduce the accumulation of active oxygen in tissues by removing ·OH and ·O2 produced by the Fenton reaction, thereby suppressing oxidation mediated by human liver microsome cytochrome P4503A. Another study has shown that gallic acid can inhibit oxidative stress by reducing the accumulation of lipid peroxidation products (MDA and TBARS).
and increasing the activities of antioxidant enzymes (SOD, GSH-Px and CAT). Mohamed et al. found that gallic acid can be used to treat thyroid dysfunction caused by chromium by reducing the expression of proinflammatory cytokines (iNOS, TNF-α, IL-6, COX-2, etc.), reducing lipid peroxidation markers and NO levels and upregulating the mRNA expression levels of SOD and glutathione S-transferases (GST).

Qin et al. found that gallic acid can alleviate oxidative stress by activating the Nrf2/HO-1 pathway. Excellent antioxidant effects make gallic acid a good candidate for use in livestock and poultry production and other related industries. For example, including an appropriate quantity of gallic acid in broiler chicken diets was recently reported to improve the chickens’ plasma antioxidant activity of the chickens. Adding appropriate quantities of gallic acid and oleic acids in a 1:1 molar ratio to the diets of broiler chickens or laying hens was found to increase the chickens’ DPPH· scavenging ability and antioxidant activity in chicken meat and eggs. Other studies have shown that nano-gallic acid is more bioavailable than pure gallic acid and can therefore more effectively alleviate oxidative stress, inflammatory response and mitochondrial dysfunction. The study of nano-gallic acid may become a future research direction.

**Antioxidant Effects of Stilbenes**

Stilbenes are the basic unit of stilbene compounds, which are low in normal plant tissues. Stilbenes can be classified based on their C = C structures into cis and (more stable) trans structures. Resveratrol and its derivatives and analogs in stilbene have attracted considerable attention because of antioxidant, anti-inflammatory and other biological activities. The antioxidant mechanism of resveratrol has been demonstrated as the activation of silent information regulator 1 (SIRT1). Under specific conditions, the proportion of intracellular NAD+/NADH increases, and the expression of SIRT1 in astrocytes is upregulated. SIRT1 deacetylates FOXO4 and then binds to the promoter sites of SOD and CAT, further enhancing the expression of antioxidant enzymes, inhibiting ROS production and alleviating oxidative stress reactions.

Li et al. found three types of natural resveratrol dimers: parthenocissin A (Par), quadrangularin A (Qua) and pallidol (Pal), could quench DPPH· and selectively scavenge ·O2. These resveratrol dimers have almost no effect on ·OH or O2·, but Pal can activate the Nrf2 pathway, induce the expression of antioxidant enzymes and alleviate oxidative stress in the body. Resveratrol can chelate metals to some extent, and novel resveratrol derivatives synthesized using other substances also exhibit good metal chelating properties.

**Antioxidant Effects of Lignans**

Lignans function as metabolites downstream of the biological pathway of shikimic acid in plants and are widely distributed in all plant parts and especially in flaxseed. Lignan compounds can be classified as lignans or neolignans according to the intermolecular linkage of phenylpropyl groups. Antioxidant effects have been confirmed for most lignans.

**Lignans.** Lignans form via the polymerization of two phenylpropyl groups at the β-sites of side chains. Eight types of lignans can be classified according to the carbon chain skeleton, the way oxygen is integrated into the skeleton and the cyclization mode: furan, furofuran, arynaphthalene, aryltetralin, dibenzylbutyrolactol, dibenzylbutyrolactone, dibenzylbutane, and dibenzocyclooctadiene, among which furofuran and dibenzylbutyrolactone exhibit good antioxidant activity. Cao et al. found that furofuran sesamin has an antioxidant effect on fluorine-induced liver oxidative stress by reducing ROS and MDA levels and increasing the antioxidant enzyme activity. Ren et al. found synergistic anti-lipid peroxidation effects for sesamin, VE, EDTA, and citric acid. Sesamin C can chelate Cu2+, thereby inhibiting Cu2+-induced LDL oxidation in human plasma. Other studies have reported antioxidant effects of matairesinol of dibenzylbutyrolactone, although the underlying mechanism has not been elucidated.

**Neolignans.** Neolignans connect via a side chain of a phenyl propy group to a benzene ring of another molecule or by an oxygen atom between two phenyl propyl group molecules. Magnolol is a typical neolignane that has been reported to scavenge free radicals, enhance the activity of antioxidant enzymes and inhibit lipid peroxidation, thus protecting against oxidative damage in the body. Duan et al. found that magnolol can reduce the MDA content and XOD activity of the lung tissue of rats with sepsis and increase the SOD and GSH-Px activities, thus ameliorating acute lung injury in these rats. Ye et al. performed experiments showing that magnolol inhibited the activation of intracellular caspase-3 and ROS production, thereby protecting against PC12 cell injury induced by 6-OHDA. Li et al. showed that magnolol can inhibit lipid peroxidation and thus exert an antioxidant effect.

**Synergistic Antioxidant Effects of Polyphenolic Compounds**

Polyphenolic compounds exhibit their respective antioxidant effects (Table 1), but single phenols cannot be easily isolated, and multiple polyphenols often exert synergistic antioxidant effects. Polyphenolic compounds can interact with other substances to produce antioxidant effects that are frequently more potent than those of the individual substances. The main substances that have been found to produce synergistic effects with polyphenolic compounds are active antioxidants, such as polysaccharides, vitamins C/E and carotenoids, and extracts of natural raw materials, such as kelp extract and sweet potato extract. Complex and varied mechanisms of action have been identified for the synergistic antioxidation by polyphenolic compounds and other substances (Table 2). Six mechanisms are generally accepted: (a) enhanced chelation of phenolic compounds with metal ions can induce oxidation, this process...
Table 1. Antioxidation Mechanisms of Various Polyphenolic Compounds.

| Species          | Representative substance | Sources                                | The basic structure | Antioxidation mechanisms                                                                 | References |
|------------------|--------------------------|----------------------------------------|---------------------|----------------------------------------------------------------------------------------|------------|
| Flavonoids compound | Flavonols                | Citrus fruits, apples fruits, spices, berries etc. | ![Flavonol Structure](image) | a. Forming intramolecular hydrogen bonds by reacting with free radicals  
b. Improving the activity of antioxidant enzymes, such as glutathione peroxidase (GSH-Px) and superoxide dismutase (SOD)  
c. Increasing the mitochondrial membrane potential and decreasing the oxidative damage level of mitochondria | 20-24      |
| Procyanidins     | Wine, cocoa, tea, nuts, heat fruits, etc. | ![Procyanidin Structure](image) |                 | a. As a hydrogen donor, it providing hydrogen atoms to react with free radicals  
b. Chelating with metal ions  
c. Downregulation of stress-activated MAPK pathway activity  
d. Promoting ERK phosphorylation and upregulating the expression of antioxidant genes Nrf2 and HO-1  
e. PC12 cells were protected from H2O2 induced oxidative damage by PI3K/Akt signaling pathway  
f. Inhibits lipid peroxidation activity and slows down the enzymatic oxidation of fat | 31-36      |
| Anthocyanins     | Grapes, wine, berries, black beans, etc. | ![Anthocyanin Structure](image) |                 | a. Regulating oxidase activity (XOD, SOD)  
b. Activating Nrf2 and inhibiting NF-κB signaling pathway  
c. Chelating with metal ions  
d. ONOO−was inhibited by destroying mitochondrial apoptosis pathway and inhibiting Bax nuclear translocation | 39-43,111  |

(Continued)
| Species               | Representative substance | Sources                                                                 | The basic structure | Antioxidation mechanisms                                                                 | References |
|----------------------|--------------------------|-------------------------------------------------------------------------|---------------------|------------------------------------------------------------------------------------------|------------|
| Phenolic acid compounds | Chlorogenic acid         | Higher dicotyledonous plants and ferns such as sunflower, honeysuckle, eucommia, and coffee | ![Chlorogenic Acid](image) | 1. Supplying hydrogen atoms to free radicals  
2. Chelating with metal ions  
3. Preventing \( \text{NH}_2\text{Cl} \)-induced plasmid DNA fragmentation  
4. Reducing the expression of FOXO family genes by activating the phosphorylation of PI3K/Akt  
5. Activating Nrf2 transcription and upregulating the expression of cellular antioxidant enzymes | 46,48-53,56,57 |
| Gallic acid          |                          | Grapes, tea leaves, flowers of *Rhus chinensis*, and Caesalpinia spinosa pods | ![Gallic Acid](image) | 1. Reducing the accumulation of malonaldehyde and NO\(^-\) and enhancing the activities of antioxidant enzymes  
2. Clearing radicals (\( \cdot \text{OH} \) and \( \cdot \text{O}_2^- \)) produced by the Fenton reaction  
c. Activating Nrf2/HO-1 pathway and reducing oxidative stress | 63,64,68 |
| Stilbenes compounds  | Resveratrol               | Grape, knotweed, blackcurrant, peanut, blackberry, blueberry, cranberry | ![Resveratrol](image) | a. FOXO4 was deacetylated and then combined with the promoter sites of SOD and CAT to improve the expression of antioxidant enzymes  
b. Selectively scavenging \( \cdot \text{O}_2^- \)  
c. Activating Nrf2 pathway and inducing the expression of antioxidant enzyme  
d. Chelating with metal ions | 75-81 |
| Lignan compounds     | Lignans                   | Sesame, flaxseed, etc.                                                  | ![Lignans](image)    | a. Reducing ROS and MDA levels, improving antioxidant enzyme activity, and inhibiting liver lipid peroxidation  
b. Chelating with metal ions \( (\text{Cu}^{2+}) \)  
c. Synergistic with VE, EDTA and citric acid | 85-87 |
| Neolignan            | The Japanese ghost light  | Qing, flower tree, pine resin, etc., magnolia officinalis              | ![Neolignan](image) | a. Directly removing \( \cdot \text{OH}, \text{DPPH}^- \) and ABTS\(^-\) and reducing ROS content  
b. Decreasing the content of MDA and XOD, and increasing the activities of SOD and GSH-Px  
c. Inhibiting lipid peroxidation | 89-92 |
It is seen with acidic substances (tartaric acid and citric acid).\textsuperscript{104} (b) acting through chain reactions that inhibits lipid peroxidation by capturing peroxyl radicals; this process is seen with VC.\textsuperscript{105,106} (c) increasing the preservation rate of another oxidative substance; for example, tea polyphenols can increase the preservation rate of β-carotene.\textsuperscript{107} (d) providing and maintaining the level of reducing agent by means of electronic transfer; for example, ascorbic acid provides a hydrogen atom to the α-tocopherol free radical to regenerate α-tocopherol.\textsuperscript{108} (e) coupling oxidation based on redox potential difference. Polyphenolic compounds facilitate the direct reaction of both antioxidants by reducing the corresponding potential difference. The coupled antioxidant oil-water distribution coefficient is complementary to each other, which is reasonably distributed in a certain system and gives full play to the function of each antioxidant.\textsuperscript{109} (f) producing synergistic antioxidant effect of the same antioxidant molecules by the interaction between their structures; for example, a suitable solvent can decrease the enthalpy of dissociation of the hydroxyl O-H bond of ferulic acid glyceryl ester via π-π stacking, thereby reducing the activation energy of the reaction between an antioxidant molecule and DPPH\textsuperscript{·}.\textsuperscript{110}

### Table 2. the Mechanisms of Synergistic Antioxidant Effects of Polyphenolic Compounds.

| Species of synergy                        | Mechanisms of synergistic antioxidant effects                                                                 | References |
|------------------------------------------|-------------------------------------------------------------------------------------------------------------|------------|
| Tea polyphenols-ganoderma lucidum polysaccharide | Mutual synergy, improving the scavenging activity of DPPH\textsuperscript{·} and ·OH of the compounds and their total reducing power | 97         |
| Berry polyphenols-auricularia polysaccharide     | Mutual synergy, improving the scavenging activity of DPPH\textsuperscript{·}, ABTS\textsuperscript{·} and ·OH of the compounds and their total reducing power | 105        |
| Procyanidins-auricularia polysaccharide         | Mutual synergy, improving the scavenging activity of DPPH\textsuperscript{·} and ABTS\textsuperscript{·} of the compounds | 112        |
| Tea polyphenols-phospholipid                  | Improving the lipid solubility of tea polyphenols                                                          | 113        |
| Tea polyphenols-VC                           | a. VC reduces phenoxyethylene radical and promotes regeneration of EGCG
b. VC promotes the redox reaction between tea polyphenols and DPPH\textsuperscript{·}
c. VC plays its acidic role in passivation of metal ions that promote automatic oxidation
d. Tea polyphenols have repair effect on VC and can increase VC content in the body | 98,103,104,109,114-116 |
| Tea polyphenols-VE                           | Tea polyphenols promote regeneration of VE                                                                 | 113        |
| Tea polyphenols-carotenoids                 | Tea polyphenols can increase the preservation rate of β-carotene                                           | 100        |
| Tea polyphenols-kelp extract                | Based on the repair mechanism, the phenolic hydroxyl in tea polyphenols can interact with phenolic substances in kelp to form stable chemical structures of intermolecular complexes | 101        |
| Tea polyphenols,pueraria flavones-sweet potato extract | Increasing the activity of lactate dehydrogenase (LDH), superoxide dismutase (SOD) and inhibiting the production of malondialdehyde (MDA) | 102        |

### Conclusions and Prospects

Polyphenolic compounds have various structures and may be classified in many ways. The antioxidant properties of these substances also vary, and five corresponding mechanisms of action can be categorized (Figure 1): (a) the phenolic hydroxyl groups of polyphenolic compounds act as hydrogen donors to directly react with radicals and reduce the activities of ·O\textsubscript{2}, H\textsubscript{2}O\textsubscript{2}, ·OH, ROO\textsuperscript{·}, O\textsubscript{2}, and other active radicals; (b) polyphenolic compounds reduce the production of radicals by inhibiting the enzyme activities required to produce free radicals; (c) polyphenolic compounds chelate metal ions that induce free radical production, thus reducing the generation of free radicals; (d) polyphenolic compounds inhibit oxidation reactions by increasing the activity of antioxidant enzymes or the expression of antioxidant proteins; and (e) polyphenolic compounds generate synergistic antioxidant effects with other substances. Plant polyphenols are natural antioxidants that exhibit higher antioxidant activity, lower toxicity, and other advantages over traditional synthetic chemical drugs. The antioxidative activities of polyphenolics have been exploited in many fields to date, such as agriculture, food, medicine, nutrition, health care, and...
chemicals used in daily life. In-depth research on the biological functions and action mechanisms of various polyphenolic compounds will make polyphenolic compounds “the seventh major nutrient.”

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Figure 1. Schematic diagram of antioxidant mechanisms of various polyphenols. (A) Antioxidant mechanisms of flavonoids. (B) Antioxidant mechanisms of phenolic acids. (C) Antioxidant mechanisms of stilbenes.
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