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Review Article

Research progress on bioactive components and functions of fruits and vegetables

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Abstract: Globally, humans are at risk of increasing incidence of metabolic diseases, the occurrence of which is closely linked to people's daily diet. Fruits and vegetables are among the important daily food types for people. Varieties of plants' secondary metabolites are contained in fruits and vegetables, including phenolic acids, flavonoids, anthraquinones, terpenoids, alkaloids, steroidal saponins, and polysaccharides. These metabolites usually have multiple bioactive functions, such as antioxidant, antitumor, hypoglycemic, hypolipidemic, neuroprotection, anti-inflammatory, antibacterial, and disease prevention, which are of great importance in preventing the occurrence of human metabolic diseases. However, the composition, content, bioactive functions, and mechanisms of action of these metabolites in different types of fruits and vegetables vary greatly. The progress of the research on the main bioactive components of fruits and vegetables and their multi-functions is reviewed in this paper to promote people's understanding and utilization of the functional components of fruits and vegetables.

Keywords: fruits and vegetables; bioactivity; function; secondary metabolism

1. Introduction

The 2022 edition of "The State of Food Security and Nutrition in the World Report", jointly issued by the Food and Agriculture Organization of the United Nations, pointed out that people in developed regions of the world are at risk of being overweight and obese and that the incidence of metabolic diseases, such as hyperlipidemia, hyperglycemia, and atherosclerosis, are rising. The health and nutritional balance of diet has attracted more and more attention from people, and people's demand for healthy and functional foods has become stronger. Fruits and vegetables are an important part of people's healthy diet. They not only provide people with a variety of food types but also provide rich nutrients and important bioactive components for maintaining human health and preventing metabolic diseases. There are a variety of bioactive components in fruits and vegetables, mainly secondary metabolites of fruits and vegetables, including substances such as phenolic acids[1], flavonoids[2] anthraquinones[3], terpenoids[4], alkaloids[5], steroidal saponins[6], etc. The composition and content of the main bioactive components in different fruits and vegetables vary greatly. A large number of studies have shown that some bioactive components in fruits and vegetables generally have functions that include antioxidant, antitumor, hypoglycemic, hypolipidemic, neuroprotective, anti-inflammatory, antibacterial, etc., and some also have antidepressant and sleep-improving functions[7,8]. As people pay more and more attention to the relationship between food's functional ingredients and human health, the functional properties of food-derived bioactive ingredients have been more and more studied. To this end, the research progress of bioactive components and functions of fruits and vegetables was reviewed to provide a basis for exploring the nutrition and functions of fruits and vegetables.

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2. Bioactive components in fruits and vegetables

The bioactive components of fruits and vegetables are complex and diverse, and the main types are shown in **Table 1**.

Table 1. Main bioactive components in fruits and vegetables.

Type	Source	Extraction method	Separation method	Content (mg/kg)	Compound name	Reference
Anthocyanins	Blueberry	1% citric acid-water	HPLC-PDA-MS/MS	1717 ± 7	Cyanidin-3-*O*-glucoside	[9]
		Ultrasound-assisted extraction	Purified by strong cation exchange (SCX) column, separated by HPLC method	1082.3	Delphinidin-3-galactoside, cyanidin-3-galactoside, delphinidin-3-arabinoside	[10]
		Microwave	HPLC-DAD	1.02 μg/mL	Pelargonidin	[11]
	Aronia berry	Ultrasound-assisted extraction	UPLC ESI-MS	5673.2	Cyanidin-3-*O*-xyloside, cyanidin-3-*O*-arabinoside	[12]
Phenolic acids	Ponkan citrus	Ultrasound -assisted extraction	HPLC–PDA	2848.45±76.39	Caffeic acid	[13]
	Apple	2% formic acid,-70% methanol	HPLC/UV	8.3 ± 0.5 38.5 ± 0.9 2.5 ± 0.5 0.4 ± 0.1	Gallic acid Chlorogenic acid Caffeic acid *p*-coumaric acid	[14]
	Grapes	Ethyl acetate	Micro-high-performance liquid chromatography (μ-HPLC)	3.95 ± 0.18	*Trans*-resveratrol	[15]
Flavonoids	Avocado	Solid-liquid extraction	HPLC-DAD-ESI-QTOF-MS	-	Flavanol	[16]
	Apple	2% formic acid,-70% methanol	Detection via p-DMACA	200.2 ± 6.7	Flavanol	[14]
	Citrus	Juice	HPLC，MS and MS–MS	700.08 ± 25.41 mg/L	Lucenin-2 4'-methyl ether scoparin 3-hydroxy-3-methylglutaryl glycosyl quercetin flavanone O-rutinoside hesperidin chrysoeriol 7-*O*-neoesperidoside hesperidin	[17]
	Rubus corchorifolius fruit	Ultrasound-assisted ethanol extraction	Semi-separation RP-HPLC, semi-preparation HPLC	-	L-epicatechin apigenin-7-*O*-*β*-D-glucopyranuronide isorhamnetin-7-*O*-*β*-D-glucopyranuronide quercetagetin-7-*O*-*β*-d-glucopyranoside 7,3',4'-trihydroxyflavone luteolin quercetin apigenin quercetin-3-monomethyl ether naringenin kaempferol kaempferide	[18]
	Durian	Ethanol extraction, cyclohexane chloroform extraction	Silica gel column fractionation, HPLC identification	0.828×10^{-3}	2a-hydroxyursolic acid ursolic acid	[19]
	Pummelo	Acetone extraction	Silica gel column purification, dichloromethane and isopropanol elution	1.138×10^{4}	Limonoid	[20]

Table 1. (*Continued*).

Type	Source	Extraction method	Separation method	Content (mg/kg)	Compound name	Reference
Terpenoids	Carrot	Microwave extraction with a mixed solvent of hexane, acetone and ethanol	Separation by filtration	517.9 ± 21.1 232.6 ± 20.5	Total carotenoids *β*-Carotene	[21]
	Cocoa	Cold acetone extraction	Petroleum ether extraction centrifugation	17.08 ± 2.10 13.74 ± 0.29	*β*-carotene Lycopene	[22]
	Citrus	Ethyl acetate maceration	HPLC	2.51	All-trans-*β*-carotene	[23]
Polysaccharides	*Lycium barbarum*	Water extraction-alcohol precipitation	Fractional precipitation separation, gel permeation chromatography purification	0.05% 0.03% 0.19%	*Lycium barbarum* polysaccharide-I-1 *Lycium barbarum* polysaccharide-I-2 *Lycium barbarum* polysaccharide-I-3	[24]
	Passion fruit	Hot-water extraction, ultrasonic-assisted extraction	GPC analysis	10.21 ± 2.06% 12.37 ± 3.18%	Hot-water extraction Ultrasonic-assisted extraction	[25]
	Hawthorn	Water extraction-alcohol precipitation	Fehling liqueur formed an insoluble complex, washed and purified with ethanol	2.19%	Hawthorn water-soluble polysaccharide	[26]

2.1. Phenolic acids

Phenolic acids generally refer to aromatic carboxylic acid compounds that have multiple phenolic hydroxyl substitutions on a benzene ring. They usually exist in the form of amides, esters, or glycosides in plants, and a small part exists in the free form. It plays an important role in seed development, flowering, fruit development, and ripening[1]. Phenolic acids are produced through the phenylpropanoid metabolic pathway. Under the action of a series of enzymes, phenylalanine is converted into trans-cinnamic acid, which is converted into p-coumaric acid. Further conversion can produce many phenolic acids, such as caffeic acid, chlorogenic acid, sinapic acid, and ferulic acid. Plant cell walls contain esterified phenolic acids, which are released upon acid/alkali hydrolysis. Phenolic acids are widely found in fruits and vegetables and are rich in variety. Phenolic acids in fruits and vegetables are usually extracted with ethanol or other organic solvents and then separated and identified by chromatography or mass spectrometry. Wang et al.[14] used high-performance liquid chromatography (HPLC) to separate and identify phenolic acids in the peels and pulps of five varieties of apples, including caffeic acid, gallic acid, chlorogenic acid, p-coumaric acid substances, etc. Sun et al.[13] extracted a high content of ferulic acid substances from Weizhang Satsuma and Navel orange and also isolated caffeic acid substance, p-coumaric acid, protocatechuic acid, and other phenolic acids substances. Fan et al.[15] extracted resveratrol substances from grapes with ethyl acetate, separated them, and identified trans-resveratrol by micro-high-performance liquid chromatography. Clifford et al.[27] extracted and separated eight kinds of phenolic acids substances from daylily and, through some qualitative analysis and research via liquid chromatography–mass spectrometry, determined them as three different kinds of caffeoylquinic acid substances: 3-*O*-caffeoylquinic acid, 5-*O*-caffeoylquinic acid, and 4-*O*-caffeoylquinic acid. Three kinds of *p*-coumaroylquinic acid substances were also identified, which were 3-*O*-*p*-coumaroylquinic acid, 5-*O*-*p*-coumaroylquinic acid, and 4-*O*-*p*-coumaroylquinic acid. In addition, two kinds of feruloylquinic acids were identified: 3-*O*-feruloylquinic acid and 4-*O*-feruloylquinic acid. The separation and identification technology of phenolic acids is very mature. With the wide application of metabolomics analysis technology, researchers continue to discover and identify new phenolic acid compounds from fruits and vegetables.

2.2. Flavonoids

Flavonoids refer to a general term for a class of compounds derived from 2-phenylchromone as a skeleton, which are important plant secondary metabolites. Flavonoids usually accumulate in the vacuoles of plant cells in the form of glycosides. In chemical structure, flavonoids have three rings (C6-C3-C6) as their basic skeleton. According to structural differences, flavonoids are generally divided into seven subclasses based on the degree of oxidation of the central heterocycle: flavonols, flavones, isoflavones, anthocyanidins, flavanones, flavanols, and chalcones. The biosynthesis of flavonoids starts from p-coumaroyl-CoA ester and malonyl-CoA, and coumaroyl-CoA esters come from phenylpropanoid metabolic pathways, while malonyl-CoA comes from acetyl-CoA. The flavonoid biosynthetic pathway generates different metabolic branches, resulting in different subclasses of compounds[2]. The methyl and hydroxyl sites on the other two rings of flavonoids can be modified, and various types of anthocyanins and flavonols can be synthesized into relatively stable flavonoids through acylation, methylation, and glycosylation and accumulated in pulp tissues, peel, and seeds. Most flavonoids exist in the form of glycosides in combination with sugars, and a few exist in the free form, which endows fruits and vegetables with different colors and various physiological functions.

Generally, organic solvents or water are used to extract flavonoid substances in fruits and vegetables, and then ion exchange columns or chromatographic columns are used for separation and purification. The method for the separation and identification of flavonoid substances and their glycosides is technically difficult, requiring the use of different technologies, such as high-performance liquid chromatography–tandem mass spectrometry (LC-MS/MS), ultra-high-performance liquid chromatography–tandem mass spectrometry (UPLC-MS/MS), etc. Zhang et al.[10] used ultrasound-assisted extraction, strong ion-exchange column purification, and high-performance liquid chromatography to obtain a series of anthocyanin substances in flavonoid compounds from blueberry pomace, including delphinidin-3-galactoside, delphinidin-3-glucoside, cyanidin-3-galactoside, delphinidin-3-arabinoside, cyanidin-3-glucoside,petunidin-3-galactoside, malvidin-3-galactoside, malvidin-3-arabinoside, etc. Ferreira et al.[9] also extracted two different substances, which were delphinidin-3-galactoside and cyanidin-3-glucoside, from blueberries. Benbouguerra et al.[28] extracted flavonoids from grape peels with acetone and separated and identified them via HPLC to obtain flavanols and anthocyanins. Among them, the flavanol content of grape skins in the green stage and close to the veraison period was higher, while the anthocyanin content of grape skins in the veraison and maturity period was higher. Santiago-López et al.[29] isolated flavanols, such as catechin and epicatechin, from avocado pulp, peel, and seeds. Tian et al.[18] extracted flavonoids from *Rubus corchorifolius* with 80% ethanol concentration, and separated and purified them with polyamide (30–60 mesh) of different meshes to obtain 12 kinds of flavonoids, which were L-epicatechin, quercetin-3-monomethyl ether, apigenin-7-O-β-d-glucopyranuronide, luteolin, isorhamnetin-7-O-β-d-glucopyranuronide, quercetagetin-7-O-β-d-glucopyranoside, 7,3’,4’-trihydroxyflavone, quercetin, apigenin, naringenin, kaempferol, and kaempferide.

2.3. Terpenoids

Terpenoids are a general term for a class of natural compounds $(C_5H_8)_n$ formed by connecting isoprene (C_5) in a head-to-head or head-to-tail manner. It is a class of those compounds with the largest structure and quantity among plant secondary metabolites, including sesquiterpenoids, monoterpenoids, sesquiterpenes, diterpenoids, triterpenoids, polypentenols, phytosterols, and brassinosteroids, and involves the biosynthesis of carotenoids and their decomposition products, which include cytokinins, gibberellins, chlorophyll, tocopherol, and plastin[30]. Terpenoids are all derived from a common five-carbon structural unit, which is isopentenylpyrophosphate (IPP), and its allyl isomer dimethylallyl diphosphate (DMAPP). The biosynthesis pathways of terpenoids are mainly the cytosolic mevalonic acid (MVA) pathway and the plastidial methylerythritol methylerythritol 4-phosphate (MEP) pathway.

Among them, carotenoids are the second largest class of natural pigments on the earth, which belong to tetraterpenoids, and there are more than 750 kinds of carotenoids. Carotenoid pigments are mainly C_{40} lipophilic isoprenoids. Carotenoids range in color from colorless to yellow, orange, and red, making up the colors of many fruits, flowers, and vegetables. During the synthesis of carotenoids, many intermediate products and derivatives are produced. For example, phytoene is a kind of colorless carotenoid with three conjugated double bonds. Phytoene is gradually desaturated to form lycopene by generating phytofluene, ζ-carotene, etc. Lycopene is catalyzed by lycopene cyclase to produce carotenoids with cyclic terminal end groups, such as α-carotene and β-carotene. β-carotene is hydroxylated to form zeaxanthin, which is cyclized to form zeaxanthin Zx, which is then catalyzed twice to produce violaxanthin and other compounds[2]. β-carotene in carrots and sweet potatoes, lycopene in tomatoes and watermelons, capsanthin in red peppers, lutein in marigold flowers, as well as carotenoids and their oxidative and enzymatic cleavage products are crucial for various plant species' biological processes.

The structures of terpenoids contained in different fruits and vegetables are relatively complex, and the types and contents vary greatly. There are still many terpenoids that have not been isolated and identified. Usually, organic solvents are used to extract terpenoids in fruits and vegetables, and after separation and purification via a silica gel column or chromatographic column, they are identified using mass spectrometry or nuclear magnetic resonance spectroscopy. Tai and Chen[31] isolated and identified 14 carotenoids in daylily, namely neoxanthin, violaxanthin, violeoxanthin, lutein, 13-cis-Lutein 5, 6-epoxide, lutein 5,6-epoxide, zeaxanthin, β-cryptoxanthin, and all-trans-β-carotene and its cis isomers. Montesano et al.[32] found that pumpkin is rich in a variety of biologically active terpenoids, including triterpenoids (such as cucurbitacin), sesquiterpenes, and tetraterpenes (such as carotenoids). Kikuchi et al.[33] extracted 7-oxomultiflor-8-ene-3α, 29-diol3-acetate-29-benzoate with a potential anticancer activity from pumpkin seeds, as well as six other multiflorane-type triterpenes. Szewczyk et al.[34] analyzed the essential oil components obtained from the distillation of daylily and found that its main component is the oxygenated monoterpene 1,8-cineole, which has a high antioxidant activity. Qin et al.[35] extracted triterpenoid limonoid from pummelo with acetone, which has various biological activities, such as anti-cancer, antioxidant, and anti-virus.

2.4. Polysaccharides

Polysaccharides are polymeric carbohydrates composed of more than 10 monosaccharides. The structure of polysaccharides generally includes the type and sequence of monosaccharides constituting the sugar chain, the type of saccharide ring, the anomeric carbon configuration of the glycosidic bond, the branching site, and the spatial conformation. Although the structures of plant polysaccharides vary widely, the synthesis pathways are basically the same. The biosynthetic pathway of plant polysaccharides includes three steps: 1) sucrose undergoes a series of transformations to produce uridine diphosphate glucose (UDP)-glucose, uridine diphosphate glucose-mannose, and guanosine diphosphate-fucose-fucose; 2) UDP-glucose is converted into other nucleoside diphosphate (NDP) monosaccharides; and 3) finally, monosaccharides are incorporated from sugar nucleotide donors into growing polysaccharide polymers by different glycosyltransferases, and then these repeating units are polymerized to form plant polysaccharides. UDP-glucose is the basis for the synthesis of other NDP monosaccharides in the polysaccharide synthesis pathway and plays a vital role in the entire synthesis process. Fruits and vegetables contain a lot of natural polysaccharides, such as starch, cellulose, pectin, hemicellulose, xyloglucan, and inulin. Active polysaccharides have the following characteristics: the primary main chain structure has β(1→3)-D-glucan with a moderate branching degree, molecular weight within a certain range, and good solubility; active hydroxyl groups on monosaccharides are replaced by functional groups, such as phosphoric acid groups, sulfuric acid groups, and methylated groups; and the advanced structure has a specific ordered spatial conformation[36]. There are often a large number of side chains on the main chain of polysaccharides. The monosaccharides that make up the sugar chains mainly include glucose, rhamnose, arabinose, mannose, xylose, fucose, etc. Different types of complexes formed by them together form the complex structure of polysaccharides.

The structure, composition, and function of polysaccharides are often affected by material pretreatment and extraction and separation methods. Generally, crude polysaccharides of fruits and vegetables are obtained via water extraction and ethanol precipitation and then purified using a DEAE cellulose anion exchange column chromatography and Sephadex dextran gel column chromatography, etc., to prepare homogeneous polysaccharides. Gong et al.[24] dried and crushed *Lycium barbarum* fruit to obtain crude polysaccharides through distilled water extraction, ethanol precipitation, and other processes. Different retentates were obtained through membrane dialysis, and homogeneous polysaccharides were obtained through gel permeation using a Sephadex G-100 column. In the study by Teng et al.[25], passion fruit was extracted with hot water, mixed with ethanol, and placed overnight to precipitate polysaccharides, which were dialyzed with molecular weight cutoff of 3500 Da and freeze-dried to obtain refined polysaccharides. Bensaci et al.[26] stirred hawthorn fruit pulps with distilled water for a total of 24 hours, which were filtered and precipitated with ethanol to obtain crude water-soluble polysaccharide substances. Ultrasound-assisted extraction was used to improve the yield of polysaccharides. Nie et al.[20] used ultrasound-assisted phosphate buffer to extract crude polysaccharides in okra, which were separated and purified using a DEAE column and collected by eluting with deionized water and 0.1mol/L NaCl solution to obtain okra polysaccharides. The activity and function of polysaccharides are not only related to the composition of polysaccharides but also affected by physical structure characteristics. The study of the fine structure of fruit and vegetable polysaccharides will help to further elucidate their structure-activity relationship. Due to the high heterogeneity and complexity of polysaccharides, the analysis of polysaccharide composition, glycosidic bond configuration, connection mode, spatial structure, polymers, and other fine structures requires some modern instrumental analysis methods, such as high-performance anion exchange chromatography (HPAEC), high-performance size-exclusion chromatography (HPSEC), gas chromatography–mass spectrometry (GC-MS), LC-MS, and nuclear magnetic resonance spectroscopy.

3. Main functions of bioactive components in fruits and vegetables

The functions of bioactive components in fruits and vegetables have been fully studied, and they generally have antioxidant, anti-tumor, anti-inflammatory, and antibacterial functions. However, the specific functional properties of different types of bioactive components are quite different. The main functions of bioactive components in fruits and vegetables are shown in **Table 2**.

Table 2. Main functions of bioactive components in fruits and vegetables.

Type	Source	Extraction method	Function	Mechanism of action	Reference
Phenolic acids	Pomegranate peel	70% ethanol	Anti-tumor	Promoted apoptosis of colorectal cancer cells, mitigated inflammation, suppressed tumor cell proliferation, inhibited Wnt/β-Catenin signaling pathway	[37]
		70% methanol	Anti-inflammatory, antioxidant	Protected erythrocytes from free radical-induced lysis and down-regulated over-expression of pro-inflammatory mediators NFκB, iNOS, and IL-6	[38]
		50% methanol	Anti-inflammatory	Reduced pain and inflammation associated with arthritis by inhibiting TNF-R1, TNF-α, IL-1β, IL-6, and NF-κB oxidative stress markers	[39]
Polyphenols	Mulberry	Water extraction	Anti-tumor	Delayed tumor growth in TSGH 8301 xenograft model	[40]
	Lychee pulp	95% ethanol	Hypolipidemic	Down-regulated mRNA and corresponding protein expression levels of fatty acid synthase (FAS)	[41]

Table 2. (*Continued*).

Type	Source	Extraction method	Function	Mechanism of action	Reference
Polyphenols	Grape skin	Acetone-water extraction	Anti-oxidant	Ortho-dihydroxy phenols and gallate groups, malvidin anthocyanins, flavonoids, phenolic acids, such as p-coumaric acid and ferulic acid, were oxidized or antioxidant activity of malvidin anthocyanins was increased	[28]
	Passion fruit peel	60% ethanol	Anti-obesity	Inhibited weight gain and fat content in obese rats and reduced inflammatory cytokines in serum and thiobarbituric acid reactive substances in liver	[42]
	Mango pulp	80% ethanol	Anti-atherogenic	Increased apolipoprotein A1/B ratio in rats, regulated high-density lipoprotein metabolism, and reduced non-alcoholic steatohepatitis.	[43]
Flavonoids	Citrus peel	70% ethanol	Hypolipidemia	Reduced body weight gain, liver weight, and epididymal white adipose tissue (eWAT) weight in HFD mice	[44]
		Methanol	Antioxidant	Had strong DPPH and superoxide radical scavenging activity	[45]
	Grape stem bark	Ethanol extraction, silica gel column purification	Neuroprotection	Resveratrol activated CaMKII signaling pathway, increased hippocampal synaptic plasticity and CREB transcription, and slowed down Alzheimer's disease progression	[46]
	Pomelo peel	Ultrasonic-assisted extraction	Hypolipidemia	Reduced body weight, liver organ index, serum triglyceride, low-density lipoprotein cholesterol, and total cholesterol levels in hyperlipidemic mice and increased serum high-density lipoprotein cholesterol levels, and reduced degenerative damage of fatty liver cells in hyperlipidemic mice	[47]
	Peel of Citrus *changshan-huyou*	Extracted with 0.1% calcium carbonate solution and eluted resin with ethanol	Anti-inflammatory	Inhibited IL-1β, IL-6, IL-12, TNF-α and IFN-γ; significantly suppressed systemic and intrahepatic inflammation; and showed hepatoprotective and anti-inflammatory effects by suppression of phosphorylated NF-κB and MAPK	[48]
	Orange peel	Ethanol extraction	Antibacterial	Extract had inhibitory effects on *Staphylococcus aureus*, *Enterococcus faecalis,* Pseudomonas aeruginosa, *Escherichia coli*, *Salmonella typhimurium*, and *Candida albicans*	[49]
Terpenoids	Citrus peel	Hydrodistillation	Antioxidant	Showed strong DPPH scavenging ability and effectively inhibited lipid peroxidation	[50]
	Pummelo seeds	Acetone extraction, silica gel column purification	Antioxidant	Limonin enhanced transcription of *Nrf2* and its downstream genes *HO-1* and *NQO1*, activated Nrf2-ARE pathway, and promoted expression of antioxidant-related genes	[35]
	Carrot	Soxhlet extraction	Immunomodulatory	Feeding carotenoids can enhance immunity of mice, promote increase of lymphocytes, etc., as well as carotenoid complex, which consists of α-carotene, β-carotene, zeaxanthin, and lycopene, and extract had stronger immunomodulatory effects than extracts containing only α-carotene and β-carotene	[51]

Table 2. (*Continued*).

Type	Source	Extraction method	Function	Mechanism of action	Reference
Terpenoids	Mamey sapote	Hexane/acetone/ethanol extraction	Antioxidant	Carotenoids had free radical scavenging activity. Lutein and β-cryptoxanthin content are positively correlated with ABTS antioxidant activity.	[52]
Polysaccharides	Onions	Sequentially extraction	Antibacterial	Antibacterial activities of four polysaccharides against *Staphylococcus aureus*, *Escherichia coli*, *Bacillus subtilis*, and *Salmonella typhimurium* ranked in descending order: DASS > CHSS > HBSS > CASS	[53]
	Longan pulp	Distilled water	Immunomodulatory	Enhanced phagocytosis of macrophages of mice	[54]
	Longan pulp	Ultrasonic extraction	Anti-tumor	Enhanced delayed hypersensitivity and phagocytosis of peritoneal macrophages in mice, enhanced proliferation of splenic lymphocytes, and had strong inhibitory effect on S180 tumors	[55]
	Blueberry pulp	Water extraction and alcohol precipitation	Anti-fatigue	Can prolong exhaustive swimming time of mice and improve exercise endurance	[56]
	Fruit of *Nitraria*	Water extraction and alcohol precipitation	Hypolipidemia	Prevented fat accumulation in liver and reduced hyperlipidemia	[57]
	Jujube	Water extraction and alcohol precipitation	Hypolipidemia	Reduced triglyceride content and alanine aminotransferase activity and inhibited lipid accumulation	[58]
	Fortunella margarita (Lour.) juice	Heat precipitation	Hypolipidemia	Reduced cholesterol content, inhibited formation of lipid peroxides, and reduced blood lipids by scavenging free radicals in body	[59]
	Fresh okra fruit	Water extraction and alcohol precipitation	Against gastric irritation and inflammation	Had anti-adhesion activity against *Helicobacter pylori* and ability to block specific surface receptors of *Helicobacter pylori*	[60]
	Okra fruit	Ultrasound-assisted extraction	Improve gut flora	Promoted growth of probiotics and used by probiotics to maintain survival and metabolic activities	[20]
	Rosa laevigata Michx fruits	Water extraction, DEAE-52 ion exchange cellulose column purification, Sephadex G-200 column purification.	Antioxidant	Enhanced antioxidant enzyme activity and total antioxidant capacity, suppressed malondialdehyde levels, and protected SH-SY5Y cells from H_2O_2-induced damage	[61]

3.1. Antioxidant effect

Under normal circumstances, the production and removal of free radicals in the body's cells are in a state of dynamic balance, but with aging or due to external stress, the excessive accumulation of free radicals in the body breaks this balance, which will cause oxidative damage and rapid aging of cells, leading to the occurrence of various diseases. The chemical components in fruits and vegetables generally have an antioxidant activity, which can regulate the body's antioxidant metabolic system and maintain cell redox homeostasis and lipid membrane stability. In particular, polyphenols, vitamin C, etc., can easily scavenge free radicals through self-oxidation and directly or indirectly inhibit lipid peroxidation. The main components of active ingredients extracted from citrus peels by Lu et al.[50] were monoterpenes, of which limonene was the main compound substance. This citrus peel extraction had a relatively strong 1,1-diphenyl-2-trinitrophenylhydrazyl (DPPH) scavenging ability and effective inhibition of lipid peroxidation. Apraj and Pandita[45] prepared methanol extracts of citrus peels. The main components of the extracts were polymethoxyflavones, including D-limonene, 4H-pyran-4-one, 2,3-dihydro-3, 5-dihydroxy-6-methyl, 2-methoxy-4-vinylphenol, n-hexadecanoic acid, etc. The citrus peel extracts had strong DPPH and superoxide radical scavenging activities, as well as anti-collagenase and anti-elastase potential, and can be used as a powerful anti-wrinkle agent in anti-aging skin care formulations. A passion fruit peel extract prepared by Vuolo et al.[42] can increase the activities of glutathione reductase, glutathione peroxidase, GSH-Px, and superoxide dismutase, as well as SOD in the liver, and can reduce lipid absorption, lipid peroxidation levels, and fat accumulation. Benbouguerra et al.[28] found that the antioxidant capacity of grape skin extracts was highly correlated with the content of phenolic substances. Phenols, such as ortho-dihydroxy phenols and gallate groups, malvidin anthocyanins, flavonoids, p-coumaric acid, and ferulic acid oxidation, or the second oxidation of malvidin anthocyanins, cause an increase in the antioxidant activity. Wang et al.[14] found that the contents of phenolic acids, flavonoids, anthocyanins, and flavanols in red-fleshed apples were higher than those in white-fleshed apples, and the extracts of red-fleshed apples had a stronger ability to scavenge free radicals, thus reflecting a strong antioxidant activity. Cichewicz and Nair[62] discovered a new naphthalene glycoside stelladerol in freeze-dried day lily, which had a strong antioxidant activity. In-vitro experiments showed that 10μmol/L stelladerol inhibited lipid oxidation by up to 94.6%±1.4%, much higher than that of vitamin E. Liu et al.[61] isolated polysaccharides from *Rosa laevigata* Michx, and the selenium polysaccharides contained in it had antioxidant effects, can reduce lipid peroxidation, and enhanced the body's resistance to oxidative damage.

3.2. Anti-tumor and anti-cancer effects

Cancer or malignancy is a series of diseases caused by gene mutations that lead to abnormal cells or uncontrolled growth[63]. After inflammation occurs in cells, pro-tumor inflammatory factors promote cancer by blocking anti-tumor immunity and exerting direct tumor-promoting signals and functions onto epithelial and cancer cells[64]. Common anti-tumor mechanisms include cell cycle arrest, anti-angiogenesis, and apoptosis, which can directly exert tumor-killing abilities[65]. Polyphenols, flavonoids, polysaccharides, and anthraquinones in fruits and vegetables can exert anti-tumor and anti-cancer effects by blocking the cell cycle, inducing apoptosis, and inhibiting related signaling pathways. Zhong et al.[55] found that longan polysaccharides had an inhibitory rate of 85% on tumors in S180 tumor-bearing mice, which may be related to the significant enhancement of delayed hypersensitivity and phagocytosis of peritoneal macrophages and the proliferation of splenic lymphocytes. Ahmed et al.[37] identified components of the ethanol extract of a pomegranate peel, which contained gallic acid, protocatechuic acid, catechin, rutin, etc., and can promote the apoptosis of colorectal cancer cells induced by administering N-methylnitrosourea intrarectally, inhibit the proliferation of inflammation and tumor cells, and inhibit the Wnt/β-Catenin signaling pathway. Cichewicz et al.[66] reported that anthraquinones in the methanol extract of daylily root inhibited the proliferation of breast cancer and lung cancer cells and did not show cytotoxicity. The possible mechanism is to show an anti-proliferative activity by inducing the differentiation of cancer cells. Chen et al.[40] found that a mulberry water extract as a supplement synergistically treated the TSGH 8301 human bladder cancer cell line with paclitaxel, enhanced the cytotoxicity of paclitaxel, and induced severe G2/M arrest, mitotic catastrophe, and subsequent apoptosis. It can also delay tumor growth in a TSGH 8301 xenograft model by activating the expressions of PTEN (phosphatase and tensin homolog) and caspase 3.

3.3. Anti-inflammatory effect

Inflammation is an adaptive response, triggered by harmful stimuli and conditions, such as infection and tissue damage. Acute inflammation and local chronic inflammation are mostly related to tissue damage, while systemic chronic inflammation is related to tissue dysfunction[67]. Fruit and vegetable extracts have shown a significant anti-inflammatory effect, and the effect was more obvious than that of a single extracted component.

The main way of action is to inhibit the release of pro-inflammatory cytokines by inhibiting the NF-κB (nuclear transcription factor kappa B) signaling pathway and macrophage inflammatory response. Ramlagan et al.[38] studied the protective effects of a pomegranate mesocarp extract (PME) in a cell model with simulated diabetes-like oxidative stress exposed to advanced glycation end products (AGEs) and hydrogen peroxide (H_2O_2). It was found that the polyphenol-rich PME protects erythrocytes from the 2,2'-azobis(2-amidinopropane) dihydrochloride (AAPH) radical-induced lysis, preventing the decline in the activity of antioxidant enzymes and inhibiting the production of reactive oxygen species (ROS). The PME had an anti-inflammatory effect on preadipocytes by inhibiting the secretion of interleukin-6 (IL-6). The PME can down-regulate the over-expressions of pro-inflammatory mediators NF-κB, inducible nitric oxide synthase (iNOS), and IL-6 after an AGE treatment. The PME reduced oxidative stress and inflammation at the adipose tissue level, with a tendency to alleviate obesity-related diseases, such as insulin-resistant and type II diabetes. Karwasra et al.[39] studied the inhibitory effect of the methanol-water extract of a pomegranate peel on inflammation and found that the total punicalagin content in the pomegranate extract was 11.8% (w/w) and that the extract also contained gallic acid and ellagic acid. The pomegranate peel extract inhibited tumor necrosis factor-α (TNF-α), TNF receptor-1 (TNF-R1), interleukin-1β (IL-1β), IL-6, and NF-κB oxidative stress markers and helped reduce arthritis pain and inflammation. Liu et al.[68] established a chronic unpredictable mild stress model and found that the ethanol extract of day lily may exhibit an anti-inflammatory effect by improving the monoamine and neurotrophic factor systems and had an effect on IL-1β, IL-6, and TNF-α expression levels in the frontal cortex and hippocampus of rats. Lengsfeld et al.[60] found that okra polysaccharides had an antiadhesion activity against *Helicobacter pylori*, had the ability to block specific surface receptors of *Helicobacter pylori*, and can fight against inflammatory diseases. Jiang et al.[48] reported that flavonoids from *Qu Zhi Ke* (peel of Citrus *changshan-huyo*u) can inhibit IL-1β, IL-6, IL-12, TNF-α, and IFN-γ; significantly inhibit systemic and intrahepatic inflammation; and inhibit phosphorylated NF-κB and mitogen-activated protein kinase (MAPK) to exert hepatoprotective and anti-inflammatory effects, thereby reducing hepatic lesion. Xiao et al.[69] found that a litchi methanol extract can improve antioxidant status, reduce nuclear factor E2-related factor 2 (NF-E2-related factor 2, Nrf2) nuclear translocation, reduce the expression of Nrf2 target genes in the liver, and can be used to prevent and control the alcoholic-related liver disease; the lychee methanol extract inhibited the expression of lipid synthesis genes and increased the expression of fatty acid β-oxidation genes, thereby improving the level of triglyceride metabolism. A passion fruit peel extract prepared by Vuolo et al.[42] reduced inflammatory cytokines in serum and thiobarbituric acid reactive substances in the liver, reducing the inflammatory response.

3.4. Hypolipidemia and cardiovascular disease prevention

Hyperlipidemia is one of the main risk factors for the development of cardiovascular diseases, such as hypertension and atherosclerosis. One of the characteristics of cardiovascular diseases is vascular dysfunction, mainly involving complex interactions between modified plasma lipoproteins, vascular endothelial and smooth muscle cells, migratory cells, and the molecules produced by these cells. Polysaccharides extracted from fruits and vegetables can regulate lipoprotein metabolism and exhibit significant blood lipid-lowering function. Crude *Nitraria retusa* fruit polysaccharides (NRFPs) prepared by Rjeibi et al.[57] had the function of hypolipidemia, and 250mg/kg NRFPs had protective effects on hyperlipidemia and hepatotoxicity induced by Triton X-100. The liver structure of NRFP-treated hyperlipidemic mice was improved. NRFPs can significantly reduce malondialdehyde (MDA) levels and prevent lipid peroxidation in the liver and heart, as well as maintaining the membrane integrity and reducing the activity of related enzymes in oxidative damage. Zeng et al.[59] found that feeding *Fortunella margarita* (Lour.) polysaccharides can reduce blood lipids in rats and reduce lipid peroxidation of cell membranes, which may be related to increasing the activity of lipase in the body, thereby accelerating the decomposition of triglycerides (TG) and reducing cholesterol levels. And it may also be related to enhancing the activities of SOD, GSH-Px, and glutathione-S-transferase and inhibiting the formation of lipid peroxides. *Pyrus ussuriensis* Maxim pear dietary fibers can reduce blood lipid levels by reducing the absorption of fatty acids and cholesterol in food, interfering with bile acid metabolism, and improving liver lipid metabolism, thereby significantly reducing the weight gain and lipid and cholesterol levels in high-fat-diet (HFD)-induced obese mice[70].

In addition, secondary metabolites, such as polyphenols and flavonoids, can also reduce blood lipid levels and play a protective role in vascular function. Gao et al.[44] purified and enriched polymethoxyflavones (PMFs) from 70% ethanol extracts of citrus peels, and the purified PMFs could effectively alleviate the hyperlipidemia induced by an HFD in mice. The PMFs also significantly reduced low-density lipoprotein cholesterol (LDL-C) levels in HFD mice, ameliorated hepatic steatosis, and reduced adipose tissue in mice. Yu et al.[47] extracted naringin from a pomelo peel and found that naringin could significantly reduce body weight, liver organ index, and the levels of serum TG, LDL-C, and total cholesterol (TC), while increasing the level of serum high-density lipoprotein cholesterol and significantly increasing the activities of GSH-Px and SOD. Liver histopathological analysis showed that naringin could alleviate the degenerative damage of fatty liver cells in hyperlipidemic mice. Domínguez-Avila et al.[43] identified the main components of an 80% ethanol extract of mango pulp as chlorogenic acid, gallic acid, vanillic acid, and protocatechuic acid. After feeding Wistar rats with the mango pulp extract, it was found that it had anti-atherogenic and hepatoprotective functions, can increase the ratio of apolipoprotein A1/B, regulate high-density lipoprotein metabolism, and reduce non-alcoholic steatohepatitis. The study by Su et al.[41] showed that a 95% ethanol extract of fresh lychee pulp significantly reduced the HFD-induced increase of serum total cholesterol and triglyceride levels in mice.

3.5. Immunomodulatory effect

Immune function is important for preventing and eliminating infections. The immune system is the first line of defense against pathogens, providing protection before the body's functions are compromised. Among them, innate immunity is mainly represented by macrophages, dendritic cells, and natural killer (NK) cells. Bioactive substances can play an immunomodulatory role by upregulating anti-inflammatory cytokines, stimulating the synthesis of antibodies, affecting the phagocytic activity of NK cells and macrophages, and promoting the proliferation of T and B lymphocytes[29]. Natural products, such as fruits and vegetables polysaccharides and carotenoids, could play an immunomodulatory role by stimulating the phagocytic activity of macrophages. Deng et al.[71] extracted and separated crude polysaccharides from *Momordica charantia*, purified them using DEAE anion exchange columns, and used them for intraperitoneal injection in mice. The results showed that polysaccharides from *Momordica charantia* can directly stimulate lymphocytes and effectively enhance the cellular and humoral immune functions of immunosuppressed mice. In addition, *Momordica charantia* polysaccharides were able to stimulate the proliferation of normal and ConA-induced splenic lymphocytes and could be used as an effective immunostimulant. Rong et al.[54] studied the effect of longan polysaccharides on mouse macrophage phagocytosis and found that 6.25–50 μg/mL of longan polysaccharides can enhance macrophage phagocytosis in a dose-dependent manner. Among them, a 50μg/mL LPD2 treatment increased the phagocytic ability of macrophages to 205.1%±9.3% of that of the control group.

3.6. Neuroprotective effect

Neuroprotection refers to the use of certain substances that can reverse some nerve damage or prevent the further deepening of nerve damage. These substances often have the function of preventing cell degeneration in neuron cells[72]. Phenolic substances, alkaloids, steroidal saponins, polysaccharides, and other substances in fruits and vegetables can regulate related signaling pathways or protein expression to exert a neuroprotective effect. Choi et al.[46] used ethanol to extract resveratrol from grape stembark, which could activate the CaMKII signaling pathway, thereby increasing hippocampal activity through a brain-derived neurotrophic factor (BDNF)-dependent pathway. Synaptic plasticity and transcription of cyclic-AMP response binding protein (CREB) may mediate the formation of long-term potentiation in the hippocampus by regulating the CaMKII-BDNF-CREB-dependent signaling pathway, thereby delaying the occurrence of Alzheimer's disease and exerting neuroprotective effect. Liu et al.[61] found that selenium-containing polysaccharides of *Rosa laevigata* Michx can upregulate Nrf2 and heme oxygenase-1(HO-1) in human neuroblastoma cells by activating typical antioxidant responses. It stimulated the signaling pathway Nrf2/HO-1 and played a neuroprotective role. Savla et al.[5] investigated the effectiveness of carpain, a methanol extract of papaya leaves, as a neuroprotective candidate. Carpain inhibited Aβ-42 aggregation, had a neuroprotective effect against nerve-growth-factor (NGF)-induced cytotoxicity in PC12-derived neurons, and conferred significant stability to intracellular microtubules. Wang et al.[73] studied the neuroprotective effect of lychee seed saponins (LSS) and its related mechanisms. The LSS significantly improved cognitive function and reduced neuronal damage by inhibiting hippocampal cell apoptosis in rats with Alzheimer's disease. The LSS down-regulated the mRNA expression of caspase-3 and the protein expression of Bax (BCL2-associated X), while the protein expression of Bcl-2 (B-cell lymphoma-2) and the ratio of Bcl-2/Bax increased. The LSS significantly improved the cognitive function and prevented the neuronal damage in rats with AD by modulating the apoptotic pathway.

3.7. Anti-fatigue effect

Fatigue is caused by many factors, such as the accumulation of metabolites, the consumption of energy and substances, and the generation of a large number of free radicals after strenuous exercise. It is not only a symptom but may also lead to a series of serious secondary problems, such as anxiety, depression, cognitive impairment, etc., and may even lead to serious diseases related to biological regulation and the immune system[73]. A variety of natural ingredients in fruits and vegetables can exert anti-fatigue effects. Wang et al.[74] found that flavonoids in parsley can significantly alleviate the fatigue symptoms of mice caused by swimming exercise, and its mechanism of action may be related to the regulation of Keap1/Nrf2 and AMPK/PGC-1α pathways to improve the antioxidant capacity. Blueberry polysaccharides prepared by Bo[56] can prolong the exhaustive swimming time of mice; reduce the content of blood urea nitrogen, blood lactic acid, and MDA; and significantly increase the levels of liver glycogen and muscle glycogen and the activities of SOD and lactate dehydrogenase. Blueberry polysaccharides can also improve the aerobic metabolism and exercise endurance of the mice.

3.8. Antibacterial effect

Microbial drug resistance is an important issue currently, and the emergence and spread of multidrug-resistant microbial strains pose a severe challenge to global public health[49]. Most biologically active substances in fruits and vegetables have certain antibacterial activities, which are an important source for the development of safer and more efficient natural antibacterial agents. Ma et al.[53] extracted onion polysaccharides with 70% ethanol-water solution and found that the extract had antibacterial activity against *Staphylococcus aureus*, *Escherichia coli*, *Bacillus subtilis*, and *Salmonella typhimurium*, and the antibacterial activity may be related to sulfate. Sulfate can improve the ability to disrupt cell walls and cytoplasmic membranes and inhibit the growth of bacteria. Szewczyk et al.[34] extracted essential oil components from different varieties of day lily and found that the main component of the essential oil was oxygen-containing monoterpene 1,8-cineole and that the essential oil contained a large number of unknown components. Negative bacteria showed strong antibacterial activity. Oikeh et al.[49] found that a fresh orange peel extract had inhibitory effects on *Staphylococcus aureus*, *Enterococcus faecalis*, *Pseudomonas aeruginosa*, *Escherichia* *coli*, *Salmonella typhimurium*, and *Candida albicans*. Flavonoids in the orange peel extract had the ability to regulate enzyme activity and inhibit cell proliferation, which had a defensive effect on invading pathogens. Tannins can form complexes with proline-rich proteins, inhibit cell protein synthesis, and inhibit the growth of pathogens. Alexandre et al. studied the antibacterial activity of phenolic compounds in pomegranate extracts and found that the pomegranate peel extracts had selective antibacterial effects on various pathogenic bacteria, such as *Staphylococcus aureus*, *Bacillus cereus*, and *Pseudomonas aeruginosa*. But it did not affect beneficial bacteria.

3.9. Effect of improving intestinal flora

Gut flora refers to microorganisms that live in the digestive tract of humans and other animals, including some insects. Regulating gut microbiota to a more favorable state and maintaining homeostasis are associated with a reduced risk of developing various metabolic, immune, and neurological disorders and may also enhance intestinal barrier functions and reduce the incidence of chronic inflammation[75]. Dietary fibers, polysaccharides, polyphenols, flavonoids, and other natural products in fruits and vegetables can regulate the composition of intestinal microorganisms and increase the diversity of flora, and thus play a role in improving intestinal flora. Jiang et al.[76] found that hawthorn polysaccharides can promote the secretion of nitric oxide, IL-2, IL-6, and TNF-α; increase the abundance of Bacteroidetes and Verrucomicrobia; and reduce the abundance of Proteobacteria. Hence, regulating gut microbiota plays a role in immune regulation. Peng et al.[70] reported that the dietary fiber intervention of *Pyrus ussuriensis* Maxim pear improved the diversity of intestinal microbiota in mice, adjusted the composition of intestinal microbiota, increased the abundance of some key bacteria (such as those producing short-chain fatty acids), and also increase the relative abundance of *Firmicutes*, *Bacteroidetes*, *Akkermansia*, *Parabacteroides*, *Alistipes*, and *Alloprevotella*, thereby having a positive effect on alleviating hyperlipidemia and improving the intestinal bacterial ecosystem. Liu et al.[77] found that the water-holding, oil-holding, and swelling capacities of the dietary fiber of the pomelo fruit retarded the diffusion of glucose, inhibited α-amylase, and affected the formation of cholesterol micelles. The soluble dietary fiber decreased the total cholesterol content and the abundance of *Bacteroidetes*, *Proteobacteria*, and *Ruminococcaceae*, but increased the abundance of *Firmicutes*, *Lactobacillus*, and *Prevotellaceae* in hyperglycemic mice. Jiang et al.[76] found that *Durio zibethinus* Murr rind polysaccharides (DZMPs) could significantly increase the intestinal transit rate and the estrogen, gastrin, and short-chain fatty acid concentrations in rats, as well as reducing body protein levels and improving rat gastrointestinal motility. The Shannon index and Chao1 index of intestinal flora in high-dose DZMP rats were higher than those in constipation rats, and the relative abundance of Desulfovibrio decreased significantly. It can be seen that DZMPs can improve constipation by regulating intestinal flora. Jing et al.[78] fed HFD rats with low-molecular-weight polysaccharides from *Rosa laevigata* Michx, which could significantly reduce the ratio of *Firmicutes/Bacteroidetes*, increase the relative abundance of *Alistipes*, *Prevotella*, and *Akkermansia*, and regulate intestinal tract microbiome. Wang et al.[73] studied flavonoids in parsley and found that flavonoids also played an important role in the regulation of intestinal microecology.

4. Conclusion and prospect

The nutritional health of the global population is facing the dual problems of undernutrition and overnutrition, and metabolic syndrome problems, such as obesity, diabetes, hypertension, and hyperlipidemia, are prominent. The World Health Organization proposes that each person needs to eat at least 400 g (that is, five kinds) of fruits and vegetables per day in its recommendation to promote a healthy diet for humans. With the development of the social economy and the improvement of people’s living standards, the effect of fruits and vegetables on human body health will receive more and more attention.

The basic structure of biologically active substances in fruits and vegetables has been widely determined, and specific components have been continuously separated, purified, and identified, mainly including phenolic acids, flavonoids, anthraquinones, terpenoids, alkaloids, and steroidal saponins. The bioactive functions of these natural products have also been continuously explored and verified. The relevant research results provide an important basis for clarifying the functional characteristics of fruits and vegetables and their effects on the body. However, there are many kinds of fruits and vegetables, and there are still many functional active ingredients in fruits and vegetables that have not been identified and analyzed. The main active ingredients and related mechanisms of functional substances of fruit and vegetable extracts still need to be further explored. In addition, most studies focus on in-vitro experiments or experimental animals, while human-based clinical trials are still relatively scarce, and there is little consideration about the stability of active substances and safe dosages during use. In addition, different types of bioactive components in fruits and vegetables may have crossover and overlapping effects in functions (**Figure 1**), but there is still a lack of infiltration studies on the functions of complex bioactive components.

In recent years, network pharmacology has become one of the frontiers and hotspots in the field of bioactive functional ingredients. Based on the principles of network pharmacology[79] and on the basis of high-throughput omics data analysis, virtual computing, and database retrieval, the screening and compounding of bioactive substances in fruits and vegetables and the construction of active functional networks can extensively reveal the biological activities of fruits and vegetables, such as the availability, toxicity, and metabolic properties of bioactive ingredients. With the deepening of the research system, the relationship between the bioactive components of fruits and vegetables and human health will be fully explained, and their bioactive functions and healthcare value will be fully excavated, deeply developed, and comprehensively utilized.

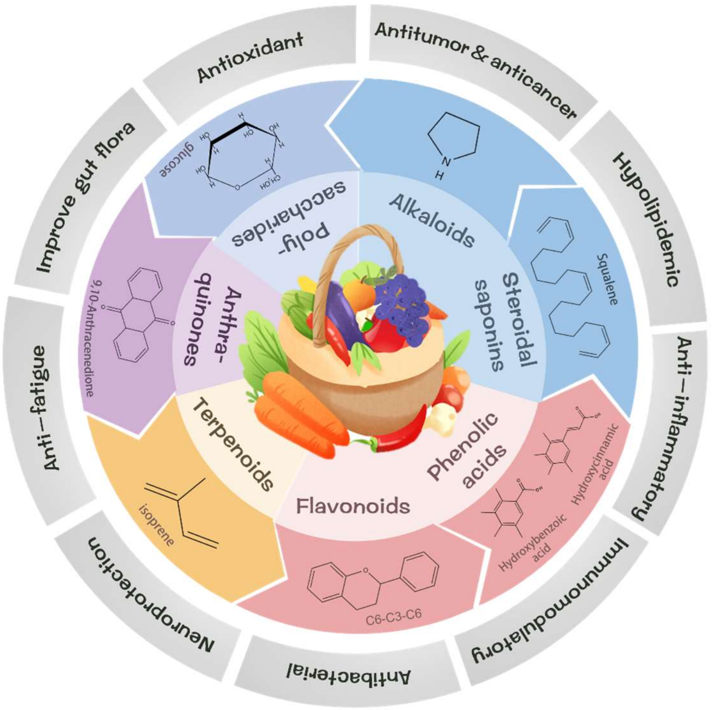

Figure 1. Bioactive components and functions of fruits and vegetables.

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Conflict of interest

The authors of the article have no conflicts of interest to declare.

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