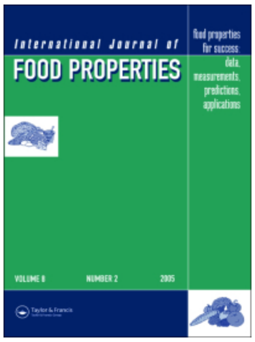

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Antioxidant-rich natural fruit and vegetable products and human health

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ABSTRACT
Antioxidants are important ingredients that are present in fruits and vegetables (FAV). With increased consumption of FAV in its raw and processed form, a predominantly plant-based diet rich in FAV could reduce the risk of the development of chronic human diseases. This review highlights the potentials of the various types of antioxidants containing FAV; their impact on human health as nutraceuticals, pharmaceuticals, and phytoceuticals; as well as prospects in tackling some chronic human diseases. The structures and activity relationship of the antioxidant compounds, as well as their mechanism of action, are examined from current scientific investigations. Information provided herein will give more insight into the roles of antioxidant ingredients present in FAV.

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Fruits; vegetables; phytochemicals; antioxidants; human health; diets

Introduction

Among the various food plants, fruits and vegetables (FAV) are reported to have health-improving benefits.[1–3] Some FAV such as the citrus fruits (orange, grapefruit, lime, lemon), grapes, pomegranates, apples, dates, green and yellow vegetables (peppers), cabbage, strawberries, carrots, dark leafy greens, and banana,[4–6] have been known worldwide to contain antioxidants. A characteristic of antioxidants is that they exert both additive and synergistic effects in reducing the risk of chronic diseases.[7–9] Fruits and vegetables, therefore, exert protective roles against chronic diseases such as cardio- and cerebrovascular, ocular and neurological diseases, strokes, cancer, diabetes, hypertension, and blood-related diseases.[10–15] Several epidemiological studies have presented compelling evidence that the potential of FAV to combat the majority of these health conditions are associated with the natural compounds found in them.[1,4] Low intake of FAV was estimated to be responsible for 31% of ischemic heart disease and 11% of stroke worldwide.[2] In the report of the joint FAO/WHO consultation on diet, nutrition, and prevention of chronic diseases, a minimum daily intake of 400–500 g per day of FAV was recommended for the prevention of high blood pressure, stroke, cardiovascular diseases, and other micronutrient related deficiencies.[2,7] Inadequate intake of FAV is therefore a significant risk-factor that causes several nutritionally related non-communicable diseases (NCDs).[2,7,13,16]

The protective effect of FAV has generally been attributed to their antioxidant constituents (natural radical terminators) such as vitamins A, C (ascorbic acid), E (α-tocopherol), β- and α-carotene and glutathione.[17,18] Alkaloids, trepenoids, sulfur-containing compounds, phenolic and polyphenolic compounds (Figure 1) are other antioxidants present in FAV,[15] which reduces oxidative damage by neutralizing the activities of free-radicals.[13] These bioactive, non-nutritive plant compounds generally called phytochemicals further engage in

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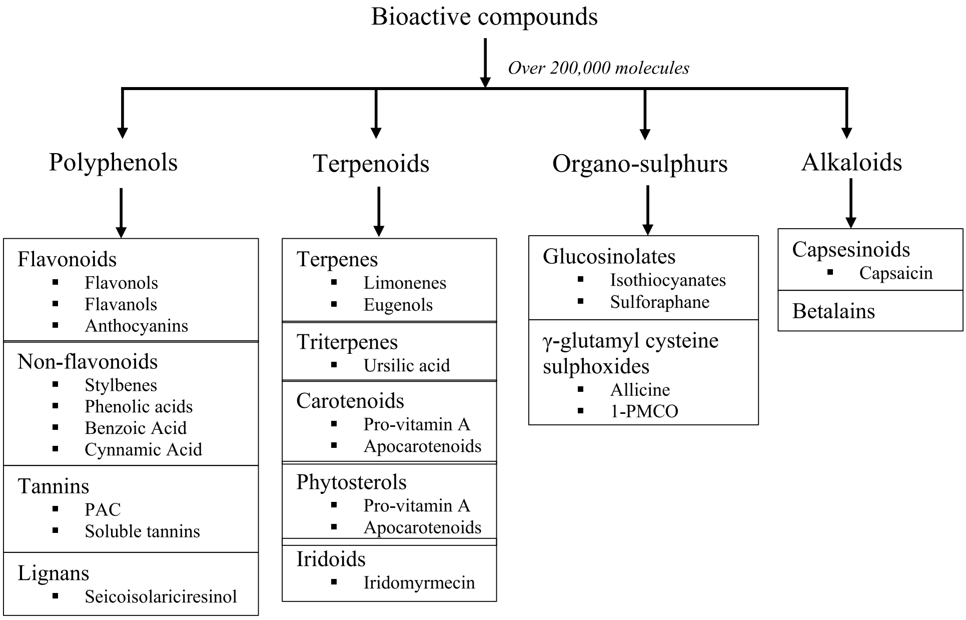

Figure 1. Groupings of bioactive compounds present in fruits and vegetables. Source: Desjardins.[19] β-carotene α-carotene.

the termination of chain reactions by removing the free radical intermediates.[18] Niki and Noguchi[20] noted that carotenoids, a significant bioactive present in FAV, are particularly effective at inhibiting the oxidation caused by singlet oxygen. Polyphenolic flavonoids, another group of bioactives, are plant metabolites that exert numerous biological and pharmacological properties.[21,22] Flavonoids consisting of anthocyanins, anthocyanidins, flavonols, flavones, and flavanones have been shown to possess antioxidant,[23] anti-inflammatory,[24] antimutagenic,[25,26] and anticarcinogenic properties.[27,28] Trombino et al.[29] and Marinova et al.[30] further reported a synergistic interaction between phenolic acid, β-carotene, and ascorbic acid, as well as between flavonoids and tocopherols inherent in FAV.

Fruits and vegetables when consumed separately provide known bioactive that exert beneficial health effects. However, processing which is one of the means of improving the consumption of FAV in combination will further synergistically enhance the effects of bioactives on molecular mechanisms that are important for disease preventions.[31] Combined foods such as salads, ready-to-eat meals, and mixtures of fresh vegetables or fruit ingredients[32] will enhance the synergistic action of the different phytochemicals. Lichtenthaler and Marx[33] postulated that processed products from FAV, such as juice, are rich sources of bio-accessible antioxidants, though their bioavailability is said to be relatively low. Septembre-Malaterre et al.[34] investigated FAV as a source of nutritional compounds and phytochemicals as well as their changes during fermentation. It was observed that though FAV serves as a source of phytochemicals in their raw and unprocessed state, fermentation ensures changes in the forms and profiles of these bioactive, thereby leading to modifications of their health-related properties. This review thus highlights bioactive non-nutrient compounds in FAV in their raw and processed forms, to elucidate their roles in disease prevention and health.

High antioxidant fruits and vegetables

Fruits and vegetables are edible plant parts including roots, stalks, tubers, bulbs, leaves, stems, fruits, and flowers.[35,36] Fruits irrespective of their level of consumption contain varying antioxidant constituents (Table 1). However, the distinct antioxidants that can be derived from FAV include vitamins C and E, carotenoids, and phenolic compounds. Research has further shown that FAV acts as a major source of

Table 1. Comparative list of selected fruit and vegetables (FAVs) phytochemicals and their antioxidant-richness.

Fruit and vegetables	Phytochemical class	Phytochemical subclass	Antioxidants	References
Fruits				
Apple	Triterpenoids	Sterols	Campesterol, β-sitosterol	[31]
	Flavonoids	Anthocyanins	Cyanidin, delphinidin	
		Flavanols	Catechin	
		Flavonols	Quercetin, kaemferol	
		Dihydrochalcones	Phloretin	
	Phenolic acids	Hydroxycinnamic acids	Ferulic acid, chlorogenic acid	
		Salicylates		
Apricot	Tetrapenoids	Carotenoids	α-carotene, β-carotene, lycopene	[31]
	Flavonoids	Flavonols	Quercetin, kaempferol	
		Dihydrochalcones	Phloretin	
Banana	Phenolic acids	Hydroxybenzoic acids	Gallic acid	[31,37–43]
	Flavonoids	Flavanols	Catechin, epicatechin, epigallocatechin	
		Flavonols	Myricetin	
	Lignans		Pinoresinol	
	Triterpenoids	Sterols	Campesterol	
Berries	Phenolic acids	Hydroxybenzoic acids	Gallic acid	[31,43]
	Flavonoids	Flavanols	Catechin	
		Flavonols	Quercetin, kaempferol	
		Anthocyanins	Cyanidin, delphinidin	
	Stilbenoids		Resveratrol, pterostilbene, piceatannol	
Carrot	Flavonoids	Anthocyanins	Cyanidin, delphinidin	[31]
		Flavones	Apigenin	
	Lignans		Pinoresinol	
	Monoterpenoids		Limonene	
	Tetrapenoids	Carotenoids	α-carotene, β-carotene, lycopene	
Grape	Phenolic acids	Hydroxybenzoic acid	Gallic acid, protocatechuic acid	[44]
		Hydroxycinnamic acid	Caffeic acid, *p*-coumaric acid, ferulic acid, chlorogenic acid	
	Flavonoids	Flavanols	Catechin, epicatechin, epigallocatechin	
		Flavonols	Myricetin-3-*O*-glucoside, myricetin-3-*O*-glucuronide, kaempferol, quercetin, isorhamntin-3-*O*-Glucoside	
		Anthocyanins	Cyanidin, delphinidin	
Mango	Tetrapenoids	Carotenoids	α-carotene, β-carotene, β-cryptoxanthin, lycopene, xanthophylls	[31,35,45]
Orange	Monoterpenoids		Limonene	[31,35,45–48]
	Tetrapenoids	Carotenoids	α-carotene, β-carotene, β-cryptoxanthin, lycopene, xanthophylls	
	Flavonoids	Flavonones	Eriodictyol, hesperetin, chrysin, luteolin, naringenin	
	Organic acids	Aldonic acids	Vitamin C	
	Organic acids	Aldaric acids	Tartaric acid	
		Aldonic acids	Vitamin C	
Papaya	Tetrapenoids	Carotenoids	β-carotene, β-cryptoxanthin, xanthophylls	[31,35,45,46]
	Organic acids	Aldonic acids	Vitamin C	
Pomegranate	Phenolic acid	Hydroxybenzoic acids	Gallic acid, ellagic acid	[31]
	Triterpenoids	Sterols	Campesterol	
Vegetables				
Asparagus	Triterpenoids	Sterols	Campesterol, β-sitosterol	[31]

(*Continued*)

Table 1. (Continued).

Fruit and vegetables	Phytochemical class	Phytochemical subclass	Antioxidants	References
Broccoli	Tetrapenoids	Carotenoids	α-carotene, β-carotene, lycopene, xanthophylls	(8,35,40,46,47,49–58)
		Quinones	Phylloquinone, menadione	
	Triterpenoids	Tocopherols & tocotrienols	α-tocopherol, β-tocopherol, α-T3, β-T3, α-tocotrienol, β- tocotrienols	
		Sterols	Sitosterol, β-sitosterol, sitostanol, campesterol, brassicaterol, stigmasterol, campestanol	
	Flavonoids	Anthocyanins	Cyanidin,	
		Flavanols	Catechin, luteolin, pelargonidin, butein	
		Flavonols	Quercetin, kaempferol,	
	Tanins	Condensed tannins	Procyanidin A_1, procyanidin B_2	
		Glucosinolates	Progoitrin, sinigrin, glucoiberin, glucoraphanin, glucoalyssin, gluconasturtiin, gluconapin	
Brussels sprout	Tetrapenoids	Carotenoid	β-carotene	[40,46,50,54,57,58]
	Triterpenoids	Tocopherols and tocotrienols	α-tocopherol, β-tocopherol, α-T3, β-T3, α-tocotrienol, β- tocotrienols	
		Sterols	Campesterol, β-sitosterol, sitostanol, stigmasterol, brassicasterol,	
	Lignans		Lariciresinol, pinoresinol, secoisolariciresinol, matairesinol	
		Glucosinolates	Progoitrin, sinigrin, glucoiberin, glucoraphanin, glucoalyssin, gluconapin, gluconasturtiin	
Cabbage	Glucosinolates	Aromatic glucosinulates	Glucobrassicin	[31]
		Aliphatic glucosinulates	Sulforaphane	
	Phenolic acids	Hydroxycinnamic acids	Ferulic acid, chlorogenic acid	
	Lignans		Pinoresinol	
	Tetrapenoids	Carotenoids	α-carotene, β-carotene, lycopene	
Eggplant	Phenolic acids	Hydroxycinnamic acids	Chlorogenic acid, caffeoylquinic acid	[34,59]
	Flavonoids		Kaempferol, quercetin, apigenin, isorhamnetin, rutin	
		Anthocyanins	Delphinidin, nasunin,	
		Carotenoids	Lutein, zeaxanthin	
	Glycoalkaloids		α-solamargine, α-solasonine	
Onion	Triterpenoids	Sterols	Campesterol, β-sitosterol	[31]
	Sulfur compounds	Thiosulfinates	Allicin	
	Flavonoids	Anthocyanins	Cyanidin, delphinidin	
		Flavonols	Quercetin, kaempferol	
	Lignans		Pinoresinol	
Spinach	Triterpenoids	Phenolic terpenes	Vitamin E	[31]
	Tetrapenoids	Carotenoids	α-carotene, β-carotene, lycopene	
Vanilla grass	Coumarins		Coumarin	[31]

vitamins, polyphenols, carotenoids, glucosinolates, saponins, and sterols when consumed in sufficient amounts.[60–63] Some tropical and subtropical fruits such as guava, mango, passion fruit, pineapple, banana, litchi, papaya, passiflora, *kiwano*, carambola, feijoa, star fruit, lime, and longan are utilized as ingredients in the diets of food consumed in North America and Europe.[64–66] Burton-Freeman[67] stated that consumption of FAV, apart from increasing the antioxidant capacity of the human blood, counterbalances the negative effects of high fat and carbohydrate meals.

From a taxonomical viewpoint and as shown in the works of Carlsen et al.,[68] FAV and its plant parts contain variant levels of bioactive compounds that often result in some FAV recording higher concentration of antioxidants than others. Antioxidants present in FAV include the primary and secondary metabolites of plants.[8] Secondary metabolites constitute most of the antioxidant compounds and they are classed into terpenoids, phenolics, alkaloids, and sulfur-containing compounds[8] based on their chemical structures.[69] Primary metabolites with antioxidant activity include vitamin

B complex, protein and nonprotein amino acids, fatty acids, and organic acids. Although substantive information has been provided about the occurrence and content of different chemical compounds in FAV, it is yet to be effectively systemized.[8,9]

Table 2 shows the antioxidant contents of FAV in mg/100 g of fresh food. The citrus family consists of fruits that are made up of high nutritional and antioxidant properties.[60] Rich in ascorbic acid, citrus fruits also contain flavanone glycosides (hesperidin, narirutin, and naringenin), limonoids, flavones (sinensetin and nobiletin), and phenylpropanoids such as hydrocinnamates.[13,81,82] Lako et al.[80] who investigated the phytochemical flavonols, carotenoids, and the antioxidant properties of a wide selection of Fijian fruit, vegetables, and other readily available foods, showed that green leafy vegetables had the highest antioxidant capacity followed by fruits and root crops. Anyasi et al.[83] also reported that banana ('Muomva-red cultivar') contains a high content of total polyphenols which is an indication that the banana could be a source of bio-nutrients with great medicinal and health functions. A different class of flavonoids has been reported in *Opuntia cactus* with types and concentration varying according to variety, tissue type, and maturation.[84] Other reports have indicated that plants in the *Cactaceae* family produce flavonol 3-O-glycosides (quercetin, kaempferol, and isorhamnetin), dihydroflavonols, flavanones, and flavanonols.[85] Nearly all reports on flavonoids found in *Opuntia cacti* have dealt with extraction from the floral tissue.

High antioxidant-rich fruits

Fruits with a documented high concentration of antioxidants belong to the plant members of *Rosaceae* (dogrose, sour cherry, blackberry, strawberry, and raspberry), *Empetraceae* (crowberry), *Ricaceae* (blueberry), *Grossulariaceae* (blackcurrant), *Juglandaceae* (walnut), *Asteraceae* (sunflowerseed), *Punicaceae* (pomegranate), and *Zingiberaceae* (ginger).[86] Pomegranate, grape, orange, plum, pineapple, lemon, date, kiwi, clementine, and grapefruit have been identified with high antioxidant properties.[35,86] Other fruits associated with a high amount of antioxidants include dog rose, sour cherry, blackberry, strawberry, raspberry, cloudberry, and rowanberry. Among these fruits, berries account for the highest antioxidant content and dog rose has the highest compared to others such as crowberry, wild berry, black currant, sour cherry, wild blackberry, wild strawberry, cultivated blackberry, and cowberry/cranberry. Berries have a high content of phytochemicals such as flavonoids, tannins, stilbenoids, phenolic acids, and lignans.[87]

Table 2. Antioxidant contents of some fruits and vegetables in mg/100 g fresh food.

FAVs	Flavanols	β-carotene	Lycopene	Isoflavones	Anthocyanins	Flavan-3-ols	Proanthocyanidins	References
Fruits								
Apple	2.0–26.0	-	-	-	1.8–17.0	2.3–7.3	7.5–141.0	[70–73]
Avocado	-	-	-	-	-	0.1	0.02–7.4	[71–73]
Banana	25.2–58.8	-	-	-	-	0.1	4.0	[71–73]
Kiwi	-	-	-	-	-	-	3.7–13.9	[73]
Mango	-	-	-	-	-	-	12.8	[73]
Orange	-	173–211[a]	-	-	-	-	-	[74]
Papaya	-	471[a]	-	-	-	-	-	[74]
Passion fruit	-	1362[b]	-	-	-	-	-	[75]
Peach	0.3	-	-	-	4.7	1.2	7.4–67.3	[70,71,73,76]
Pear	0.3–4.5	-	-	-	-	0.9	1.1–42.3	[70,71,73]
Pineapple	-	-	-	-	11.6 [c]	-	-	[75]
Watermelon	-	616–1040[a]	11,378[a]	-	-	-	-	[74]
Vegetables								
Broccoli	10.2	-	-	13.7	113.0	-	-	[70,76,77]
Cauliflower	0–3.1	-	-	-	-	-	-	[72]
Eggplant	-	-	-	7.9	35.1	-	-	[76,77]
Lettuce	0.9–7.4	-	-	-	1.5	-	-	[70–73,76]
Onion	1–135.9	-	-	17.6	38.8	-	-	[70,76–78]
Peas	0.3–14.5	-	-	54.1–477	-	-	-	[70,77–78]
Spinach	0.3	-	-	-	-	0.01	-	[71,79]
Sweet potato	-	13.0	-	-	-	-	-	[80]
Tomatoes	0.2–7.4	-	-	32.5	-	-	-	[70,72,77,78]

[a]1 g/serving of edible portion; [b] μg/100 g dry basis; [c] mg/100 g dry basis.

High antioxidant-rich vegetables

Broccoli, brussels sprout, green cabbage, tomato, cauliflower, spinach, leek, lettuce, and sweet pepper have been reported with different antioxidant levels.[8,88] Hounsome and Hounsome[8] showed that the phytochemical α-carotene and antioxidant β-carotene (Figure 2) are richly found in broccoli (1 and 779 mg/100 FW), carrot (4.6 and 8.8 mg/100 FW), tomato (112 and 393 mg/100 FW), pea (19 and 485 mg/100 FW), and sweet pepper (59 mg/100 FW, β-carotene only). These phytochemicals were reported to vary in structure and function from vegetable to vegetable and from cultivar to cultivar, with the level of maturity, postharvest handling, and processing among other factors having a significant impact on their variability.[89,90] Vegetables rich in ascorbic acid include beans, broccoli, cabbage, cauliflower, cress, pea, spinach, spring onion, and sweet peppers.[49] Asparagus, brussels sprout, cabbage, carrot, cauliflower, kale, lettuce, spinach, sweet potato, and turnip are rich sources of vitamin E.[8] Red pepper has also been reported to have a high content of vitamin C (144 mg/100 g).[91]

Fruits and vegetable phytochemicals and human health

There is an array of evidence that consumption of FAV is important for human health as they are richly endowed with health-improving nutrients.[6,92–95] Burton-Freeman[67] postulated that antioxidant-rich FAV increases the antioxidant capacity of the blood, thus decreasing the risk of developing diseases such as cancer, diarrhea, coronary atherosclerosis, and gastrointestinal tract diseases. Results from epidemiological and laboratory studies conducted by Eckert,[96] Harding et al.[97] and Rouanet[98] supported the hypothesis that consumption of FAV will prevent and significantly reduce cancer, Alzheimer's diseases, diabetes, and heart diseases.

Further epidemiological studies have proposed an inverse correlation between high intake of FAV and many degenerative and aging diseases.[16,99–101] Improvement in diabetes mellitus, digestive problems, immune disorder, cataract, bronchitis, asthma, and other respiratory syndromes have all been reported upon regular intake of FAV. Butt and Sultan[95] also suggested that humans relying on FAV have a 10–15% lower risk of developing cataracts than those who consumed lower proportions of FAV. Jaganath and Crosier[7] indicated that a proper balance between oxidants and antioxidants is necessary to maintain health as alterations to this balance often leads to pathological responses that result in functional disorders and diseases. It has also been postulated that a non-vegetarian diet may

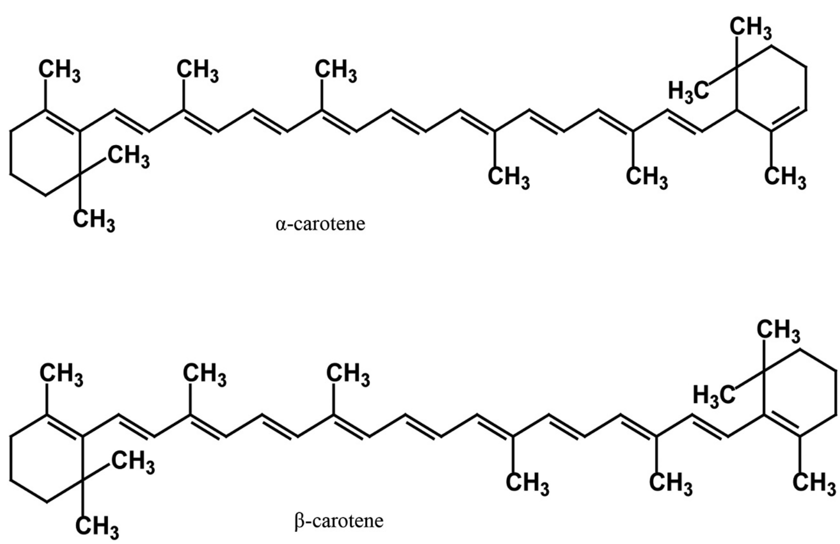

Figure 2. Chemical structure of carotene.

alter hormone production, metabolism, or action at the cellular level thereby increasing the incidence of breast, colorectal, and prostate cancer.[102] The health functions of FAV are therefore based on their phytochemical content, which in their various chemical forms, possess antioxidative, antiviral, anti-inflammatory, antimicrobial, anti-carcinogenic, antiangiogenic, antibiotic, and antithrombotic properties.[8,103,104]

Baskar et al.[105] demonstrated that regularly, free radicals are synthesized in the body either naturally or through external factors such as environmental stress, thus resulting in various degenerative diseases that harm the body. Though the body has an inbuilt defense mechanism to scavenge these radicals, there is a need for the utilization of additional antioxidants available in FAV.[106] Diseases such as cancer, Alzheimer's disease, Parkinson's disease, arthritis, atherosclerosis, and aging are formed in the body as a result of these radicals.[105] Antioxidants especially those synthesized by FAV therefore play a vital role in ensuring that these free radicals are scavenged, thereby preventing them from causing harm.[106] This is especially more important due to the increased emphasis on the consumption of antioxidants from natural sources as used for preventive and therapeutic medicine.[107]

Dietary antioxidants are defined as food compounds that significantly reduce the deleterious effects of ROS, RNS, or both, on the normal physiological function in humans.[94,108] ROS (oxygen ions, free radicals, and peroxides) and RNS (nitrous anhydride, peroxynitrite, and nitrogen dioxide radicals) cause oxidation, nitration, halogenation, and deamination of biomolecules of all types, including lipids, proteins, carbohydrates, and nucleic acids, with the formation of toxic and mutagenic products.[109,110] Pathogenesis of non-communicable and non-nutritionally related human diseases such as brain stroke, diabetes mellitus, rheumatoid arthritis, Parkinson's disease, Alzheimer's disease and cancer have been associated with the oxidative damage of these oxidants to cells[9,111] of which FAV phytochemicals are counter-intuitive. Examples include lycopene: the principal carotenoid in tomatoes,[112] a very efficient quencher of singlet oxygen in the biological system. Another example is vitamin E, a major lipid-soluble chain-breaking antioxidant in humans, that protects the DNA, low-density lipoproteins, and polyunsaturated fatty acids from free radical-induced oxidation.[8]

Vitamin C

Bruno et al.[113] stated that the roles of vitamin C include the regulation of cell growth, cell signaling, apoptosis, antioxidants, and as cofactors for enzymes. Vitamin C occurs mainly in FAV and it is reduced by heat during processing; hence, its nutrient density in raw FAV is higher than in processed forms.[114] Vitamin C scavenges reactive oxygen species (ROS) and reactive nitrogen species (RNS) and also regenerates α-tocopherol and coenzyme Q from α-tocopherol and coenzyme Q radical. This resultant action helps in maintaining the antioxidant activities of α-tocopherol and coenzyme Q.[114] The studies by Lee et al.[115] and Chen et al.[116] postulated that ascorbate induces lipid hydroperoxide decomposition to genotoxins in the absence of redox-active metal ions and also leads to a reduction in the growth of aggressive tumor xenografts. As documented in studies conducted on animal species, consumption of FAV rich in vitamin C will greatly help protect the body against cardiovascular disorders, gastrointestinal disorders, cancer, skin infections, and diabetes through the reduction of insulin glycation and an increase in glucose homeostasis.[117]

Vitamin E

Consisting of eight different types: α-, β-, γ- and δ-tocopherols and the α-, β-, γ- and δ-tocotrienols, vitamin E can be obtained from vegetable oils, nuts, and seeds of different fruits.[114] Experimental model studies *in vitro* and *in vivo* have shown the antioxidative, pro-antioxidative, anti-inflammatory, modulation of cell signaling, antiproliferation, antiangiogenesis, and apoptosis induction effects of vitamin E. Other works have also shown that α-tocopherol is the major form in human tissues.

Accounting for more than 90% of the literature on vitamin E studies, α-tocopherol is the most studied vitamin E isoform.[118] α-tocopherols, and other forms of vitamin E play crucial roles in protection against lipid peroxidation, scavenging of peroxyl radicals,[119] reaction with ROS and RNS and reduction in the synthesis of ROS from NADPH oxidase.[120] The pro-oxidant effect of α-tocopherol also includes its ability to reduce redox-active metals such as copper and iron.

When present in the human skin, vitamin E serves as a vital line of dermal antioxidant protection. Its isoforms such as tocopherols and tocotrienols can protect the skin against disease conditions such as dermatitis, UV-irradiation induced skin injury, and chemically induced oxidative stress in animal models.[121] Thus, vitamin E obtained from FAV has found application as cosmetics due to its protective dermal effects.[122]

Carotenoids

Carotenoids consist of a group of lipophilic pigmented compounds that is made up of over six hundred fat-soluble plant pigments. They are chiefly responsible for colors such as yellow, red, and orange present in FAV and from which the compounds are derived. Major carotenoids present in human diets are α-, β-carotene, lutein, lycopene, zeaxanthin, astaxanthin, and β-cryptoxanthin, with these compounds playing an active role in the protection of plants from the damaging and scourging effects of exposure to sunlight.[114,123] Carotenoids function in the body as a precursor of vitamin A, thus preventing vitamin A deficiency in the body.[124] Carotenoids further undertake antioxidant activities by scavenging reactive species, oxides, and radicals,[125] suppressing inflammatory responses in both *in vivo* and *in vitro* systems, as well as assisting in the modulation of cell signaling and induction of apoptosis.[126,127] This is apart from their roles in cardiovascular protective activities, obesity, cancer, and gastrointestinal disorders.[128–135]

Phenolic compounds

Stalikas[136] showed that phenolic compounds are secondary metabolites of plant origin that carry one (phenols) or several (polyphenols) hydroxyl moieties in their aromatic ring. Among the major dietary sources are FAV, with an average daily consumption of approximately 1 g/day.[137,138] Phenolic compounds consist of approximately 8,000 naturally occurring metabolites which are divided into two main groups; flavonoids and non-flavonoids.

The flavonoids, a member of the polyphenols, are planar molecules whose varied structure arises partially due to methoxylation, prenylation, glycosylation, or hydroxylation. Their heterocyclic six-member ring with oxygen is encased by two aromatic rings (Figure 3). Uppu and Parinandi[139] reported that flavonoids are derived from two biosynthetic pathways: the shikimate and the acetate

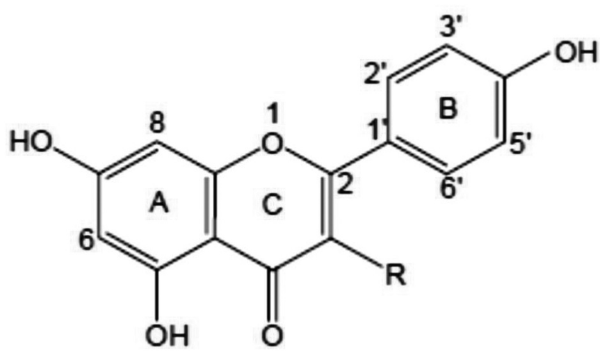

Figure 3. Basic structure of flavonoids. R = OH: flavonols; R = H: flavones.Source: Stalikas[136].

pathways. As natural pigments in FAV, they occur in colors such as yellow in flavonols and flavones; orange, blue, purple, red, and violet in anthocyanins.[140] Flavonoids can be classified as flavones, flavonols, flavan-3-ols, flavanones, anthocyanidins, proanthocyanidins, isoflavones, and dihydroflavanols. The nonflavonoids (Figure 4) comprise simple phenols, hydrolyzable tannins, cinnamic acid, coumarins, xanthones, stilbenes, lignans, secoiridoids, benzophenones, acetophenones, phenylacetic, and benzoic acids. Classification of the nonflavonoids is dependent on the number of carbon frameworks present in the organic acids.[136]

Phenolic compounds undertake antioxidant, pro-oxidant, anti-inflammatory activities and also exert great influence on the bioavailability of nitric oxide in humans.[114] Stoclet et al.[141] and Mann et al.[142] demonstrated that bioavailability of nitric oxide involves a reduction in nitric oxide bioavailability by phenols, a step which is vital in the reduction of cardiovascular diseases. Its antioxidant activities involve ROS, RNS, and other reactive species scavenging activities; the inhibition of ROS synthesis from cells; and the induction of endogenous cellular antioxidant enzymes.[143–146] The scavenging activities have been attributed largely to their redox properties which enable them to function as reducing agents, singlet oxygen quenchers, and hydrogen donors.[147]

Determination of the antioxidant capacity of fruits and vegetables

The concentration of antioxidants in FAV varies in their degree of activity and mode of action, hence the difficulty in their analysis. Various methods exist for the determination of the antioxidant capacity of FAV.[23,80,148,149] However, there are known factors that affect the determination of the antioxidant capacity in fruits and such factors include geographical location, agricultural and farming practices, the season of cultivation, particle size, amount of extraction steps, sample to solvent ratio, and temperature of the process. [140,150,151] Sample preparation is therefore a critical step in the total determination of antioxidants in FAV.[136] Established protocols for the analysis and determination of antioxidant capacity in FAV (Table 3) include oxygen radical absorbance capacity (ORAC), Trolox equivalent antioxidant capacity (TEAC), 2,2-azino-bis-3-ethylbenzthiazoline-6-sulfonic acid (ABTS), 1,1-diphenyl-2-picrylhydrazyl (DPPH), ferric reducing ability of plasma (FRAP), and vitamin C equivalent antioxidant capacity (VCEAC). The ORAC method is one of the most widely used methods for evaluating antioxidant capacity (AOC) due to known and unknown antioxidants present in tested foods.[157] Peroxyl radical-scavenging activities of water-soluble and lipid-soluble antioxidants in samples are evaluated by the hydrophilic ORAC (H-ORAC) and lipophilic ORAC (L-ORAC) methods, respectively.

Mechanism of action of fruits and vegetable phytochemicals

The protective effect of FAV has generally been attributed to their antioxidant constituents (natural radical terminators) from known sources as well as from other unidentified compounds.[17,18] Niki

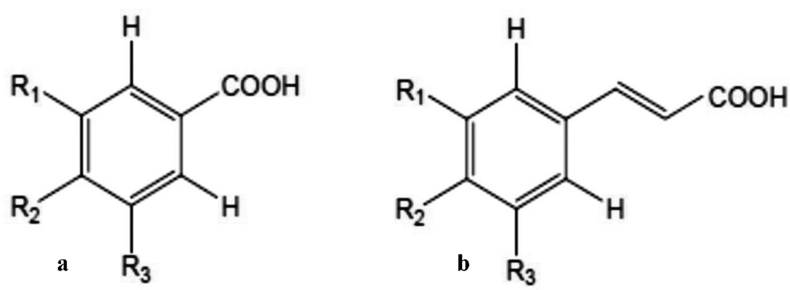

Figure 4. Structures of naturally occurring phenolic acids. **A**, Hydroxybenzoic; and **B**, hydroxycinnamic structures. R1, R2, and R3 represents H, OH, and OCH3. Source: Stalikas[136].

Table 3. Analytical methods for determination of antioxidant properties of fruits and vegetables.

Method of determination[1]	Antioxidants determined	References
HPLC	Phenolic compounds; chlorogenic acid, (-)-epicatechin, (+)-catechin, caffeic acid, rutin, quercetin-glycosides and phloridzin, lycopene, beta-carotene	[72,152]
ABTS assay	Antioxidant compounds, antioxidant capacity	[151,153]
DPPH assay	Antioxidant compounds, antioxidant capacity	[151,153]
FRAP	Antioxidant compounds	[151,154]
ORAC	Antioxidant compounds: ascorbic acid, α-tocopherol, β-carotene, glutathione, bilirubin, uric acid, melatonin, flavonoids	[43,154]
TEAC	NA	[151,154]
VCEAC	Determination of vitamin C equivalent	[151]
Folin-Ciocalteau method	Total phenols	[151,152]
Vanillin assay	Total flavan-3-ols, proanthocyanidins	[152]
GC-MS, LC-MS	Flavonoids; isoflavones, flavonones, anthocyanins, flavonols, flavones	[140]
β-carotene method	β-carotene	[155]
PSC	Total phenolics	[156]

[1]ABTS, 2,20-azino-bis-3-ethylbenzthiazoline-6-sulfonic acid; DPPH, 1,1-diphenyl-2-picrylhydrazyl; ORAC, oxygen radical absorbance capacity; FRAP, ferric reducing antioxidant power; TEAC, Trolox equivalent antioxidant capacity; VCEAC, vitamin C equivalent antioxidant capacity; HPLC, high-performance liquid chromatography; GC-MS, gas chromatography-mass spectrometry; LC-MS, liquid chromatography-mass spectrometry; PSC, peroxyl radical-scavenging capacity; NA, not available.

and Noguchi[20] stated that carotenoids are particularly effective at inhibiting the oxidation caused by singlet oxygen. Gil et al.[23] postulated that flavonoids possess antioxidant properties, anti-inflammatory,[24] antimutagenic[25,26] and anticarcinogenic properties.[27,28] Antioxidants delay the onset of free radical formation by their ability to donate hydrogen atom (or electron/proton) or chelation of metals involved in the formation of ROS.[7,8] The operational mode of antioxidants in negating the impact of free radicals to cells involves a combination of different mechanisms which include direct termination of the free radicals,[158] and post-modification of the active compounds during metabolism.[111,159,160] The latter mechanism often results in metabolites that are chemically, biologically, and in several instances, functionally distinct from the dietary form and such features underpin their bioactivity.[161] Williams and Spencer[162] hypothesized that cells respond to phytochemicals mainly through direct interactions with receptors, enzymes involved in signal transduction, or through modifying gene expressions which may result in modification of the redox status of the cell that may induce series of redox-dependent reactions.

Williams and Spencer[162] also postulated that there is now emerging evidence that phytochemicals such as flavonoids may play an important role as modulators of intracellular signaling cascades, which are pivotal to the cell machinery. Intracellular signaling cascades are major routes of communication between the plasma membrane and regulatory targets in various intracellular compartments.[7] These signaling cascades seem to consist of up to five tiers of protein kinases that sequentially activate each other by phosphorylation, which consequently affects the activity of transcription factors that regulates gene expression.[163] Jaganath and Crosier[7] showed that the presence of these cascades enables the cells to respond to variant stresses and signals which in turn regulate numerous cell processes, including growth, proliferation, and death (apoptosis). Phytochemicals can exert modulatory effects in cells through selective actions on different components of the signaling cascades.[164,165] The intracellular concentration of phytochemicals required to affect cell signaling pathways is considerably lower than those required to have an impact on cellular anti-oxidant capacity and their metabolites may still retain the ability to interact with cell signaling proteins, even if their antioxidant activity is diminished.[160,166]

Flavonoids are abundant in plants and the majority of plant tissues possess the ability to synthesize flavonoids.[167] In plants, the leaves, flowers, and fruits contain flavonoid glycosides; the woody tissue contains aglycone; and the seeds may contain either the flavonoid glycosides or aglycones. Apigenin, a flavone present in parsley and celery hinders proinflammatory cytokines and HIFR, VEGF, and COX-2 expression through the inhibition of nuclear factor-κB (NF-κB), PI3K/Akt, and ATF/cyclic

AMP responsive element signaling pathways.[168–170] Tangeretin, a polymethoxylated flavone that is abundant in peels of citrus fruits serves as an anticarcinogenic agent by suppressing IL-1β-induced COX-2 expression through the inhibition of p38 MAPK, c-Jun N-terminal kinase (JNK), and Akt activation.[171] Kaempferol, a flavonol in broccoli and tea diminishes the activity of inflammation-related genes such as iNOS and COX-2 by blocking signaling of STAT-1, NF-κB, and AP-1 in activated macrophages[172] and human endothelial cells.[173] Quercetin, another flavonol present in leafy green vegetables, onions, broccoli, apples, and grapes acts as a potent antioxidant and anti-inflammatory agent. Quercetin inhibits the expression of pro-inflammatory cytokines in mast cells[174] and suppresses TNF-induced NF-κB and CBP/p300 recruitment to pro-inflammatory gene promoters.[175] Furthermore, quercetin diminishes total cholesterol, triglycerides, and low-density lipoprotein and reduces glycemia as well as high-density lipoprotein levels through the inhibition of 11β-hydroxysteroid dehydrogenase type 1.[176,177]

Hamalainen et al.[172] stated that naringenin, a flavanone occurring in oranges inhibits iNOS protein and gene expression by blocking the activation of NF-κB. Naringenin-7-*O*-glucoside is reported to stop cardiomyocytes from doxorubicin-induced toxicity through the induction of endogenous antioxidant enzymes by phosphorylation of extracellular signal-regulated kinases 1 and 2 (ERK1/2) and nuclear translocation of Nrf2[178] and through the stabilization of the cell membrane as well as the reduction of reactive oxygen species generation.[179] Cyanidin, an anthocyanidin inherent in cherries and strawberries was shown to inhibit tumor promoter-induced carcinogenesis and tumor metastasis *in vivo* through the modulation of the expression of COX-2 and TNF-R.[180] Cyanidin-3-*O*-rutinoside retards *in vivo* absorption of carbohydrates through the inhibition of α-glucosidase.[181] Delphinidin, another anthocyanidin present in dark fruits has been found to contribute antiangiogenic activity through the inhibition of the PDGF-BB/PDGF receptor (PDGFR)-β in smooth muscle cells.[182] Anthocyanins suppress lipid peroxidation in caco-2 cells[183] and reduce ethanol-induced migration of breast cancer cells through blockage of ethanol-induced activation of ErB2/cSrc/FAK pathway essential for cell migration.[184] Furthermore, anthocyanins suppress benzo[a]pyrene-7,8-diol-9,10-epoxide-induced cyclooxygenase-2 (COX-2) expression mostly by hindering the activation of the Fyn signaling pathway;[185] prevent nitric oxide synthase and COX-2 and reduction in nitric oxide and prostaglandin E2 production (PGE2);[186] as well as inhibit IκBα phosphorylation, thus suppressing NF-κB activity in cell and in vivo models,[187–189] thereby contributing to its chemopreventive ability.

Carotenoids such as lycopene present in papaya, tomatoes, watermelon, oranges, and pink grapefruit reduce inflammatory response through the lowering of iNOS and COX-2 gene expression[190] as well as IL-12 production through blocking MAPK signaling and the activation of NF-κB in murine dendritic cells.[191] Similarly, β-carotene inherent in fruits such as carrots, palm fruits, mangoes, papayas, and green leafy vegetables inhibits LPS-induced iNOS, COX-2, and TNF-α expression by decreasing phosphorylation and degradation of IκBR and nuclear translocation of NF-κB in macrophages.[192] Lutein, a yellow pigment present in leafy vegetables such as spinach and kale was reported to inhibit LPS- and H_2O_2-induced pro-inflammatory gene expression by decreasing the activity of PI3K and NF-κB inducing kinase (NIK) and phosphorylation of Akt in RAW264.7 cells.[193]

Fruits and vegetable phytochemicals and cancer

Cancer, a degenerative disease across the world and one of the leading causes of death,[95,101,194] has been associated with lifestyle, environmental and dietary factors. The pathogenesis is attributable to genetic mutation, smoking, heavy metal ingestion, and lack of proper diet.[95] Studies conducted by Lee and Smith[195] and Wolfe et al.[196] have shown that about one-third of all cancer cases and one-half of hypertension and cardiovascular infections are diet-related. However, Willett[197] stated that appropriate dietary intake can prevent more than 30% of cancerous cell growth. Similarly, Amiot and Lairon[198] and Butt and Sultan[95] reported that about 30–40% chances of cancer can be prevented by adopting a proper physical and dietary lifestyle. Consumption of vegetables rich in dietary antioxidants has been linked to a lower risk of different types of cancer,[199] especially the mouth, pharyngeal, esophageal, lung, stomach, and colon cancer.[95,200] Fahey[57] explained that the anti-carcinogenic effect of glucosinolates is due to the activation of enzymes involved in the detoxification of carcinogens, inhibition of enzymes modifying steroid hormone metabolism, and protection against oxidative damage. Isothiocyanates resulting from glucosinolate hydrolysis possess antioxidative and anti-proliferative activities.[201] Sulforaphane, an isothiocyanate found in broccoli, cauliflower, collard green, and turnips, is effective in reducing the risk of certain types of cancer such as breast and colon cancer.[11,95] Garlic, onions, chives, leek, and scallions are good sources of sulfur-containing compounds and are effective in reducing the risk of certain cancers.[95]

Hollman and Kitan[202] demonstrated that vegetables rich in flavonoids such as bean, broccoli, endive, leek, onion, and tomato were able to impact positively on cancerous conditions as they stimulate enzymes involved in detoxification of carcinogenic substances and inhibit inflammation associated with local production of free radicals. Similarly, tomatoes and their lycopene-rich products have the potential for minimizing certain forms of cancer. Sterols which are essential for the synthesis of prostaglandins and leukotriene are important components of the immune system.[8] They are richly found in broccoli, brussels sprout, carrot, cauliflower, celery, tomato, soy, and spinach.[203] Due to the structural similarity of sterols to cholesterol, sterols are also reported to inhibit cholesterol absorption.[8] Also, of their cholesterol-lowering effects, plant sterols may possess anticancer, anti-atherosclerosis, anti-inflammation, and antioxidant properties.[103,104] Although dietary phytoestrogens have been reported to help reduce the risk of certain hormone-stimulated malignancy such as breast and prostate cancers,[204] their anti-carcinogenic properties still await further confirmation.[95]

In humans, lignans possess antioxidant and (anti) estrogenic properties and may reduce the risk of certain cancers.[8] Reduced cancer risks have also been associated with higher urinary lignan excretion.[205] Lignans formed by oxidative dimerization of two phenylpropane units are present in nature in the free form, while their glycoside derivatives exist in minor forms.[206] Lignans are secondary plant metabolites that serve as an important source of phytoestrogens.[207] These secondary plant metabolites are present in fruits such as pears, plums, raspberries, strawberries, grapes, kiwi, and apricot and in vegetables such as asparagus, carrot, cabbage, broccoli, and garlic.[34,207] The different types of lignans (Figure 5) that occur in foods include medioresinol, syringaresinol, sesamin, and the lignan precursor sesamolin.[207,209,210] Heinonen et al.[208] postulated that lignans are considered phytoestrogens due to their being metabolized into enterodiol and enterolactone in the intestinal microflora. Phytoestrogens which are present in apples and vegetables have shown protective potential against cancer, CVD, menopausal symptoms, and osteoporosis.[34,211] Prasad[212] and Saleem et al.[213] reported that epidemiological and pharmacological studies on lignan presented it to be beneficial in the prevention of cancer, atherosclerosis, reduction of inflammation, and risk factors for oxidative stress and stroke. In a study that examined the relationship between plasma lignan concentration and the incidence of colon cancer in over 57,000 participants between the age of 50–64, higher concentrations of lignans were seen to lower the risk of colon cancer in women.[207,214]

Fruits and vegetables and cardiovascular diseases

Cardiovascular disease (CVD) is one of the leading causes of death globally and has other health contributing risk factors such as obesity and type II diabetes mellitus. Experimental studies conducted by Brigelius-Flohe and Frebar,[215] and Butt and Sultan[95] showed that greater intake of FAV proffers great coronary care and regulation of blood cholesterol levels, which helps in the prevention of CVDs. Dietary fibers in artichoke, sweet potato, and turnip,[95] flavonoids in bean, broccoli, leek, endive, and tomatoes,[8] all have potential in the suppression of CVDs. FAV has been shown (Table 4) to contain lots of phytonutrients and in amounts that contribute to the prevention of degenerative diseases in the body.[13]

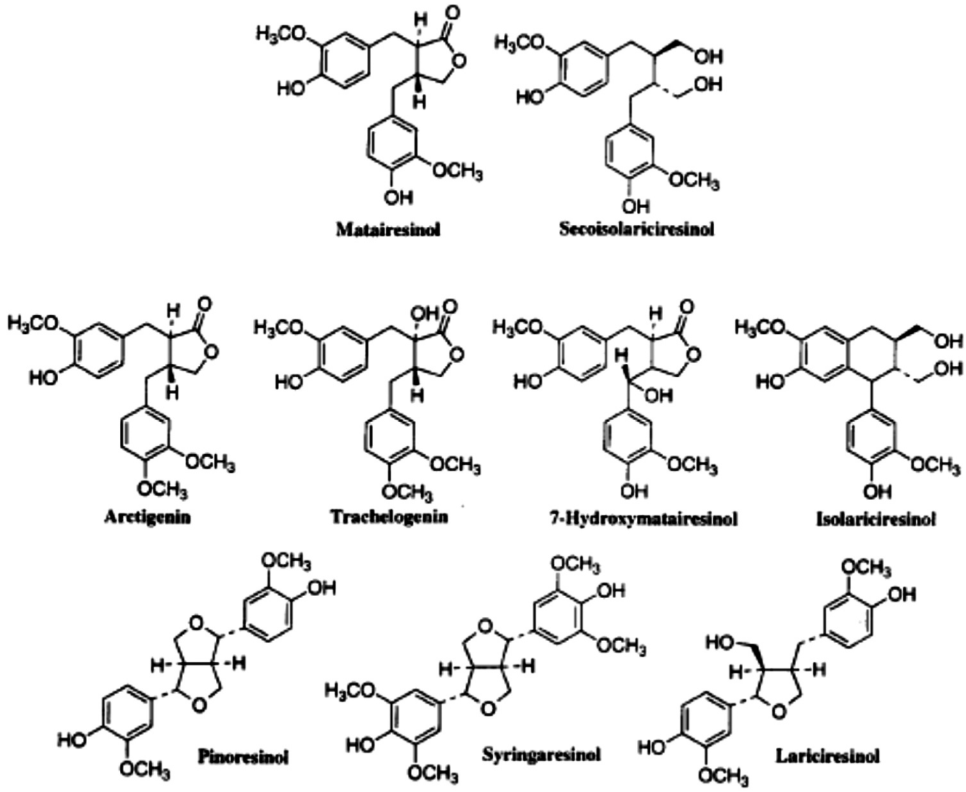

Figure 5. Structures of plant lignans present in fruits and vegetables. Source: Heinonen et al.[208].

Antioxidant-fortified fruit and vegetable products and human health

In both developed and developing countries, there is increasing interest in "natural" products, their content of phytochemicals and antioxidants[250] in the fight against human ailments. Some of these antioxidant-rich natural products include tea, shrubs, wine, and fruit juice.[92,250,251] There are many novel high antioxidant fruit ingredients, for example, acai berries and wolfberries, concentrations, and extracts of pomegranate, cranberry, and blueberry. Acai berries are similar to other dark-colored fruits because they are rich in anthocyanins, while wolfberries are rich in carotenoids, lutein, and zeaxanthin. Other emerging functional ingredients of beverages include sea buckthorn and baobab fruit powder. Gao et al.[252] showed that sea buckthorn contains significant amounts of tocopherols, tocotrienols, and carotenoids. Processed vegetable products do contain these nutrients in portions from which the body can derive immense benefits when consumed.

Vitamin C has been found useful in the biofortification of fruit juice and drinks. Related works conducted by Biesalski[253] and Mann et al.[142] have elaborated the beneficial role of carotenoids in cardiovascular pathophysiology, when used as dietary supplements. Ascorbate can also be obtained through supplements especially in the juice where it is often added, as its deficiency in the body has been known to result in scurvy, anemia, blotchy bruises, poor wound healing, and susceptibility to diseases.[114] However, natural antioxidants obtained from plants and dependent on the dose of consumption are said to be more safe and healthy than artificially synthesized antioxidants. Fan et al.[254] hypothesized that fruits such as blue honeysuckle, blueberry, and lingberry which contain high amounts of anthocyanins can be utilized in replacing the red, blue, purple, and black artificially synthesized colorants of FAV products in the food industry.

Table 4. Fruits and vegetables and their health functions.

Fruits and vegetables	Available antioxidants	Health functions	References
Fruits			
Acai	Flavonoids; orientin, homoorientin, vitexin, chrysoeriol, quercetin and dihydrokaemferol.	Reduction of reactive oxygen species (ROS) formation in polymorphonuclear (PMN) cells. Alleviation of oxidative stress in aging	[154]
Apple	Anthocyanins, flavonol glycosides, chlorogenic and ρ-coumaroylquinic acid, phloretin glucoside, xyloglucoside, (-)-epicatechin, (+)-catechin, procyanidins and vitamin C.	Inhibit cancer cell proliferation, decrease lipid oxidation, reduces risk of some cancers, cardiovascular disease, asthma, diabetes and lower cholesterol	[216,217]
Avocado	Serotonin 5-hydroxytryptamine, sterols, monounsaturated FAs; linoleic, palmitoleic, cis-vaccenic and γ-linolenic acids.	Reduces the risk of cardiovascular disease, functions as neurotransmitter	[154,218]
Berries	Ascorbic acid, carotenoids, flavonoids, phenolic acids, and tocopherols	Exhibits chemopreventive and chemotherapeutic activities *in vitro* and *in vivo* and inhibition of proliferation of the human lung epithelial cancer cell line A549	[219,220]
Citrus fruit	Pectin, limonoids; limonin and nomilin, flavonoids; hesperidin and naringin	Possess anti-inflammatory, anticancer, antiviral and antiatherogenic properties and an ability to inhibit human platelet aggregation	[221,222]
Durian	n-3 fatty acids, caffeic acid, quercetin.	Cholesterol reduction in the body	[154]
Grape	Phenolic acid, stilbenes, flavonols, flavanols, viniferin and anthocyanins	Reduction of low-density lipoprotein, inhibition of platelet aggregation and antifungal agent	[223,224]
Graviola	Folic acid, vitamin C	Maintains intestinal flora, functions as a good diuretic (juice), promotes weight loss, used in normalizing acidity of the stomach, possess anti-rheumatic and anti-inflammatory properties	[154]
Guava	Vitamin C, polyphenols	Normalizes body blood pressure	[225,226]
Kiwano	Rutin, myricetin, quercetin, caffeic acid, ascorbic acid, malic acid and oxalic acid	Anti-inflammatory, spasmolytic, capillary protective and blood platelet aggregation inhibitory activities	[154]
Kiwifruit	Afzelin, astragalin, quercitrin, isoquercitrin, rutin, epicatechin, catechin, procyanidins, quercetin and kaempferol	NA	[227]
Litchi	(-)-epicatechin and procyanidin	NA	[154]
Mango	Ascorbic acid, β-carotene, polyphenols; mangiferin, catechins, quercetin, kaempferol, rhamnetin, anthocyanins, gallic acid, ellagic acids, propyl gallate, methyl gallate, protocatechuic acid	Protect human cells against damage, helps to combat degenerative diseases like cancer and heart disease.	[228,229]
Persimmon	β-carotene, polyphenols; ρ-coumaric acid, catechin, epicatechin, epigallocatechin and condensed proanthocyanidins	NA	[230]
Pineapple	Epicatechin, ferulic acid, gallic acid, catechin, sterols, bromelain	Anti-inflammatory, anti-invasive, anti-metastatic, anti-tumor	[154,231]
Prickly pear	Vitamins, β-carotene, betanin and indicaxanthin	Undergoes radical-scavenging and reducing properties	[232,233]
Star fruit (Carambola)	Anthocyanins, catechins, epicatechin, gallic acid	Halt hemorrhages, mitigate liver problems, diarrhea, counteracts fever and hangover after excessive alcohol	[234,235]
Stone fruit	β-carotene, β-cryptoxanthin, caffeoyltartaric acid, 3-*p*-coumaroylquinic acid, ascorbic acid, hydroxycinnamic acid, chlorogenic and neochlorogenic acid	Scavenge hydroxyl radicals, inhibition of LDL oxidation	[236]
Vegetables			

(*Continued*)

Table 4. (Continued).

Fruits and vegetables	Available antioxidants	Health functions	References
Allium (onions & garlic)	Diallyl sulfide and allylmethyl trisulfide	Inhibits LDL oxidation, cell proliferation and growth, enhance the immune system, alters carcinogen activation, stimulate detoxification enzymes, and reduces carcinogen-DNA binding	[237,238]
Beetroot	Betalains, polyphenols	Inhibition of LDL oxidation	[239]
Carrot	β-carotene, linolenic acid and vitamin A,		[240]
Cruciferous vegetables (cabbage, broccoli, cauliflower, brussels sprouts, Kale)	Glucosinolates and *S*-methylcysteine sulfoxide	Cancer chemo-preventive effects, prevention of lipid peroxidation	[241,242]
Lettuce	Polyphenols	Inhibition of LDL oxidation	[240]
Pepper	Vitamin A and C, phenolic compounds provitamin A, β-carotene, α-carotene, and β-cryptoxanthin and xanthophyll	Acts as pro-oxidants	[243,244]
Potato	Ascorbic acid, α-tocopherol, violaxanthin, lutein and polyphenolic compounds	NA	[245,246]
Spinach	Polyphenols	Inhibition of LDL oxidation	[240]
Tomato	Vitamins A C and E, β-carotene, lycopene, potassium, flavonoids and folic acid	Prevention of cancer and heart diseases, acts as pro-oxidant in a lipid environment	[247–249]

NA, not available.

Natural-antioxidant fruit and vegetable products

Preference for the use of natural products is due largely to their minimal side effects and the increasing preference for natural product used in preventive and therapeutic medicine. There is increasing advocacy and the use of natural vitamins C and E as protection from ultraviolet radiation in the skin and other cosmetic products. Processed food drinks such as fruit juice and wine are presently supplemented with ascorbic acid that is derived from fruits. Natural carotenoid-derived colorants obtained from FAV are increasingly in use to replace artificially synthesized colorants in the manufacture of food products by food processors. Berries and their products are potentially excellent antioxidant sources. However, during the processing of berries to jams, total phenol content is reduced resulting in lower antioxidant values in processed berry products than in fresh berries.[80]

Future direction on natural antioxidant-rich fruits and vegetables

The health claims, *in vitro*, from antioxidants present in fruits are still being conducted in experimental models, with many of the claims on their therapeutic effects yet to be verified. Research on phenolic compounds is of growing interest because of the vital biological and pharmacological characteristics which these antioxidants have shown in human health.[136] Hence, bioactives are the topic of discussion at most food and health-related conferences. Further research is therefore needed to verify these health claims and to ascertain antioxidant contents of most pre-packed fresh-cut versus whole FAV,[255] as well as dried FAV that is incorporated into other food products. Recent research revealed that fruit peels and seeds, such as grape seeds and peels, pomegranate peel, wampee peel, and mango seed kernel may potentially possess antioxidant properties. Valorization of the entire plant parts of FAV including peels, rind, seeds, core, rag, stones, pods, vine, skin, pomace, shell, and stem to ensure extraction and utilization of these antioxidants in different food systems are currently ongoing.[256,257] With the increasing preference and advocacy for natural and minimally processed food products, more studies are ongoing on the antioxidant compounds and their functional, nutraceutical, and prebiotic roles in humans to push forward against cancer, neurodegenerative, and cardiovascular diseases.[258] One of such is the postulation by Suntres[259] that antioxidant liposomes hold an important role in future research on antioxidants. Genetic engineering has also been suggested as one of the research areas that should aim at breeding genetically modified plants that can produce higher quantities of specific compounds, yielding higher quantities of antioxidants. Traditional and exotic fruits as well as ornamental plants are receiving attention more than ever before, all in an attempt to maximize their benefits and significance on human health. Instrumental methods of assessing antioxidant activity are likely to become more important in the future as methods that do not require the use of chemical reagents or solvents reduce waste disposal problems. Thus, different mechanisms of extraction of the antioxidants inherent in FAV aside from the known conventional methods are presently being explored in the food processing industry. These unconventional extraction techniques such as supercritical fluid, pulsed electric field, microwave-assisted, ultrasound-assisted, and enzyme-assisted extraction methods are advantageous due to their high yield, use of organic solvent, low process time, reduced use of energy, and less waste generation.[257,260]

Conclusion

Though some FAV serves as food mostly in tropical countries, several studies have shown that the consumption of FAV worldwide is insufficient to meet the daily nutritional needs for human health and wellness. With the many health claims attributed to the antioxidant content of FAV, sustained and increased production will lead to increased consumption by humans and an effect of a decrease in degenerative disorders. However, with the increasing world population, there would continually be a reliance on synthetic antioxidant supplements. Therefore, scaling up of production and increased consumption in both scenarios may lead to a reduction of terminal and degenerative diseases.

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