

Book Chapter

Vegetables and Medicinal-Aromatic Plants: Volatile and Non-Volatile Fingerprints

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Abstract

Aroma and flavor compounds play a critical role in the quality of vegetables, medicinal and aromatic plants (MAPs), being two of the most important sensory attributes for consumer's preferences. Throughout the last decades, many studies have correlated the presence of bioactive compounds with consumer's choices or with their beneficial health properties. The purpose of this review is to provide an updated overview regarding the presence of volatile and non-volatile compounds in some of the most economically relevant vegetables and MAPs. Particular emphasis is placed on bioactive polyphenols, polyphenols as prebiotics, and discuss the most important factors that affect the content and profile of the volatile and non-volatile compounds responsible for the aromatic features of vegetables and MAPs. The new challenges and future perspectives for science will also be reported in improving and intensifying the aroma and flavors of vegetables and MAPs.

Keywords

Plant Breeders; Consumers; Volatile Compounds; Flavor Compounds; Aroma Compounds; Bioactive Phenolic Compounds

Introduction

The concept of “quality” is wide, but in horticulture, it can be defined as the degree of excellence given by the combination of different attributes or characteristics that give to each product a value in terms of its proposed use [1]. This concept can include the visual appearance, ability to endure postharvest processing operations, chemical, and nutritional composition, and aroma [2]. More recently, advances have been made in horticultural breeding. Now it is possible to find fruits and vegetables with characteristics that growers and retailers desire, such as high yield, high resistance to pests' attack and disease occurrence, attractive appearance, and capacity to support different handling and processing operations. However, most of the time, many of these horticultural crops fail to achieve top nutritional and flavor

characteristics [3]. Increasing horticultural crops' flavor by breeding is still a challenging task. Many factors affect the synthesis of volatile and non-volatile compounds like climate, cultural practices, the agricultural production system (organic *vs* conventional), or pre and postharvest processing operations [4]. Also, the astringency, dryness, viscosity, heat, coolness, often referred to as the 'texture' of foods, can affect the flavor of vegetables and medicinal and aromatic plants (MAPs) [5]. This review presents a discussion of the most important factors that affect the content and profile of the volatile and non-volatile compounds responsible for the aroma and flavor of vegetables and MAPs, as well as the recent advances in plant breeding regarding the achievement of chemical compounds responsible for the typical aroma and flavor sensory attributes.

Plant Bioactive Phenolic Compounds

Bioactive compounds are defined as compounds that are present in nature and are part of the food chain. More than 8,000 different phenolic compounds have been identified in the plant kingdom, one of the most numerous and distributed classes of plant secondary metabolites [6]. Vegetables and MAPs are important sources of bioactive phenolic compounds. They can interact with one or more compounds of the living tissue by showing an effect on human health [6,7]. Phenolic bioactive compounds are secondary metabolites possessing health benefit effects [8]. They might be produced from two distinct pathways: (i) shikimic acid (phenylpropanoids) and (ii) acetic acid (phenols) [9]. Due to their abundance of vegetables and MAPs, the study of phenolic compounds (simple phenolics, coumarins, lignans, flavonoids, isoflavonoids, anthocyanins, proanthocyanidins, and stilbenes) effects on health have increased in recent years, due to the growing evidence indicating that polyphenols are a major class of bioactive phytochemicals [10]. Their consumption may play a role in the prevention of several chronic diseases as a potent antioxidant agent, prevention of illnesses induced by oxidative stress and some specific cardiovascular (mainly high cholesterol levels, high blood pressure) and neurodegenerative diseases (such as Alzheimer's or Parkinson's, type II diabetes, cancers, and urinary tract

infections) [11-15]. However, the health effects of phenolic compounds are dependent on their type, quantity consumed, as well as on their bioavailability.

The amount of total phenolic compounds is greater in dark vegetables, such as red kidney beans, a variety of the common bean (*Phaseolus vulgaris*), black beans, and black gram (*Vigna mungo*). Bravo [11] determined the content of total phenolic compounds in several vegetables such as black gram (540–1200), chickpeas (78–230), cowpea (175–590), common beans (34–280), green gram (440–800), pigeon peas (380–1710), Brussel sprouts (6–15), cabbage (25), leek (20–40), onion (100–2025), parsley (55–180), and celery (94) (dry matter, mg/100 g).

Phenolic acids are non-flavonoid polyphenolic compounds that have been widely studied because of their potential protective roles [16]. They have a benzene ring, a carboxylic group, and one or more hydroxyl and/or methoxyl groups. They are usually divided into benzoic acid derivatives (i.e., hydroxybenzoic acids, C6-C1) (Figure 1a) and cinnamic acid derivatives (i.e., hydroxycinnamic acids, C6-C3) (Figure 1b), based on the constitutive carbon structures. The content of hydroxybenzoic acid (C6-C1 derivatives) (e.g., gallic acid, salicylic acid, salicylaldehyde, and protocatechuic acid) is typically low in edible plants [17]. Phenolic acids may make up about one-third of the phenolic compounds in the human diet; these compounds have a powerful antioxidant activity that may help protect cells from damage caused by free radicals [11,18].

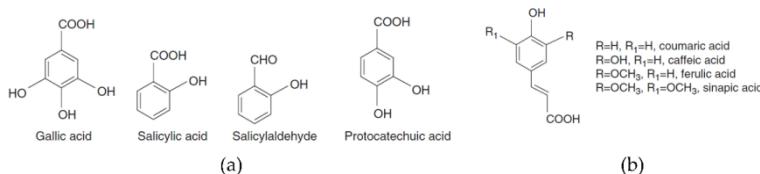


Figure 1: Chemical structures of hydroxybenzoic acids (a) and hydroxycinnamic acids (b).

According to Khadem and Marles [19], gallic acid has antineoplastic and bacteriostatic activities, and salicylic acid exerts anti-inflammatory, analgesic, antipyretic, antifungal, and

antiseptic properties. Protocatechuic acid has also been described as having several bioactivities such as anti-inflammatory, antifungal, and antioxidant ones [20]. For instance, *p*-hydroxybenzoic acid has been isolated from many sources including carrot (*Daucus carota*) [21] and protocatechuic acid from onion, garlic, and relatives (*Allium spp.*) [22].

The hydroxycinnamic acids (C6-C3 derivatives) are more abundant than hydroxybenzoic acids. The four most common hydroxycinnamic acids are ferulic acid, caffeic acid, coumaric acid, and sinapic acid. These acids are frequently present in plants in the combined forms such as glycosylated derivatives or esters of tartaric acid, shikimic acid, and quinic acid rather than in the free form. Hydroxycinnamic acids are recognized as powerful antioxidants playing an essential role in protecting the body from reactive oxygen species (ROS). Several hydroxycinnamic acid derivatives, such as caffeic acid, chlorogenic acid, ferulic acid, *p*-coumaric acid, and sinapic acid, present strong antioxidant activity by inhibiting lipid oxidation and scavenging of ROS [12]. Chlorogenic acid and caffeic acid inhibit the N-nitrosation reaction and prevent the formation of mutagenic and carcinogenic N-nitroso compounds [23].

Rosemary (*Rosmarinus officinalis* L.) is a plant of Mediterranean origin that has been distributed throughout different areas of the world [24]. It has many medicinal properties, and its extracts have been used (mainly orally) in folk medicine as a diuretic, analgesic, expectorant, antirheumatic, and antimutagenic agents. Caffeic acid and its derivatives, such as rosmarinic acid (Figure 2) and chlorogenic acid, have been thought to be the most important ones responsible for the therapeutic properties of rosemary extracts, as they have antioxidant effects and contribute to the bioactive function of rosemary [25].

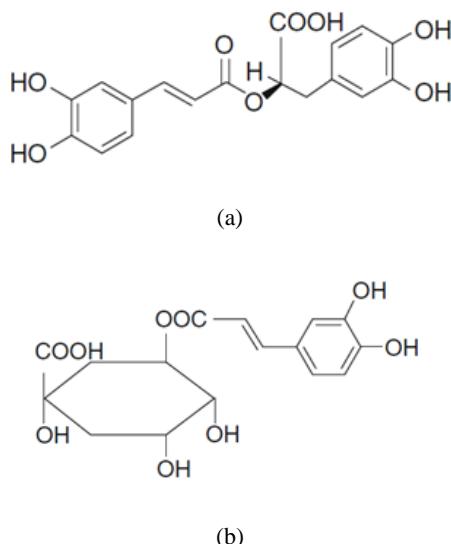


Figure 2: Chemical structures of rosmarinic acid (a) and chlorogenic acid (b).

Among the phenolic compounds identified by Zheng and Wang [26], rosmarinic acid was the predominant phenolic compound in *Salvia officinalis* and *Thymus vulgaris* (Table 1).

Table 1: Phenolic compounds in *Salvia officinalis*, *Thymus vulgaris*, and *Rosmarinus officinalis* (mg/100 g of fresh weight). Adapted from Zheng and Wang [26].

Phenolic compounds	<i>Salvia officinalis</i>	<i>Thymus vulgaris</i>	<i>Rosmarinus officinalis</i>
Vanillic acid	2.27±0.48		1.73±0.08
Caffeic acid	7.42±0.35	11.7±1.04	2.95±0.12
Luteolin	33.4 ±1.32	39.5±1.53	
Rosmarinic acid	117.8±1.01	91.8±2.75	32.8±1.69
Hispidulin	16.3±1.07	20.8±0.96	19.7±1.12
Cirsimarinin	14.3±0.83		24.4±0.87
Carnosic acid			126.6±6.00
Apigenin	2.4±0.07		1.1±0.15
Naringin			53.1±2.09
Rosmanol			124.1±3.19

Total phenolic (mg of GAE/g of fresh weight)	1.34±0.09	2.13±0.11	2.19±0.15
ORAC (Oxygen Radical Absorbance Capacity) (µmol of TE/g of fresh weight)	13.28±0.40	19.49±0.21	19.15±0.63

In previous years, the use of phenolic acids, such as chlorogenic, ferulic, cinnamic, and rosmarinic acids in food have increased [26].

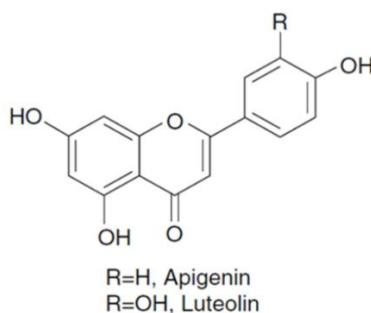
Coumarins are a large class of C6-C3 derivatives belonging to the benzo- α -pyrone group, which exist in free or combined form as heterosides and glycosides in certain plants; most of them are isolated from chlorophyll-containing plant materials [27]. Species-rich in coumarins included *Aesculus hippocastanum* (Horsechestnut), *Passiflora incarnata* (Passionflower), *Lawsonia inermis* (Henna), *Hypericum perforatum* (Saint John Wort), *Tilia cordata* (Lime Tree), and *Uncaria tomentosa* (Cat's Claw) [28]. Naturally-occurring coumarins can be categorized into four types. Simple coumarins are the hydroxylated, alkoxylated, and alkylated derivatives of the benzene ring of coumarin, and the corresponding glycosides. Furanocoumarins compounds consist of a five-member furan ring attached to the coumarin nucleus, divided into linear and angular types with a substituent at one or both remaining benzenoid positions. Pyrano coumarins are analogous to the furanocoumarins but contain a six-member ring. The last type is coumarins substituted in the pyrone ring [29]. Several products that contain a coumarin moiety show excellent biological activities such as antitumor, antibacterial, antifungal, anticoagulant, vasodilator, analgesic, and anti-inflammatory activities [27,30,31].

Lignans are a diverse group of bioactive phenolic compounds formed of two β - β -linked phenylpropane units; they are present in different parts of plant species in free form or combined form as glycoside derivatives. Lignans are found in vegetables such as in the Brassicaceae family, where fresh edible weights (mg/100 g) between 0.185 to 2.32 can be found, for instance, for broccoli (98.51), Brussels sprouts (50.36), cauliflower (9.48), green

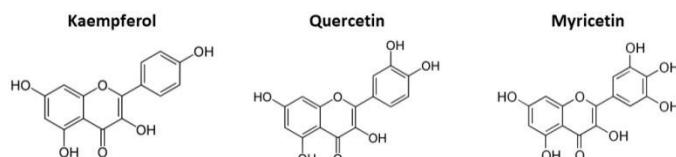
cabbage (0.03), red cabbage (18.1), white cabbage (21.51), and kale (63). They can also be found in green beans (22.67), tomato (2.15), cucumber (3.8), zucchini (7.02), green lettuce (1.17), and carrot (7.66). However, spinach, white potatoes, and mushrooms contain an amount below 0.1 mg/100 g (fresh edible weight) of lignin [32,33]. Lignan presents a great antioxidant activity and may be effective in the treatment of cardiovascular disease, coronary heart disease, and diabetes [34].

Flavonoids have the general structural C6-C3-C6, in which the two C6 units are phenolic and linked by a C3 group. In most of the cases, three or more -OH groups are linked to their backbone structure [35], and can occur as aglycones or as conjugated to organic acids and/or sugars [36,37]. The degree and pattern of hydroxylation, alkalization, prenylation, or glycosylation reactions modify the primary structure of the molecule [36]. The substitution of chemical groups in the flavonoid structures is correlated to the corresponding chemical and/or biological properties and bioavailability [38]. They can be divided into flavones, flavonols, flavanones, and flavanols, according to the oxidation state of the central pyran ring, and anthocyanins and isoflavonoids with different antioxidants, antibacterial, antiviral, and anticancer activities [18,37].

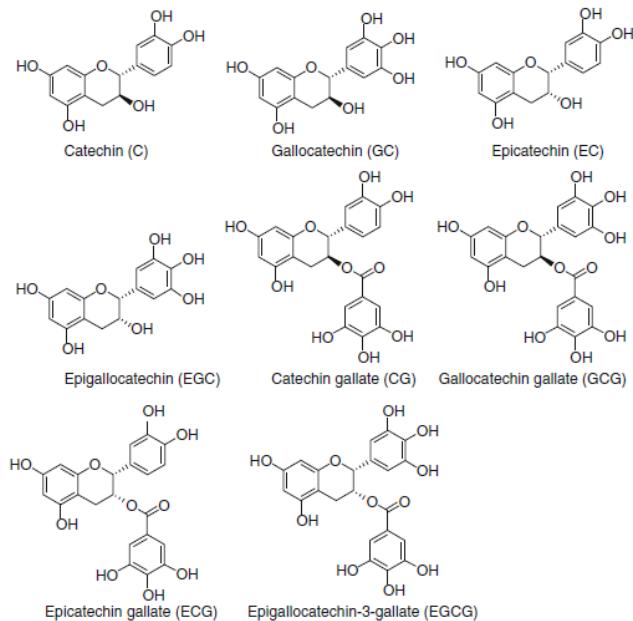
Flavones usually occur as glycosides of apigenin and luteolin in plants (Figure 3). Flavones are found in celery (22–108 mg/kg fresh weight) and are able to lower the levels of total and low-density lipoprotein (LDL) cholesterol, having anti-inflammatory and anticancer activities [39]. In other vegetables, the contents are (mg/kg of luteolin and apigenin, respectively): 0.41 and 0.05 in water spinach; 0.09 and 0.03 in cucumber; 0.16 and 1.07 in purple cabbage; 1.18 and 0.31 in Chinese cabbage; 0.16 and 0.92 in white cabbage and 0.22 and 0.04 in onion [40].

**Figure 3:** Structures of the major flavones.

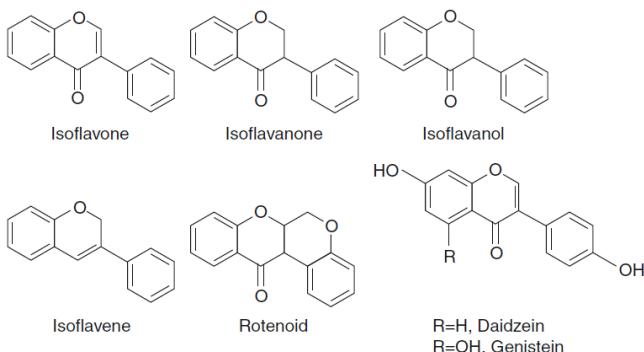
Flavonols have been extensively studied and are widely distributed in plants [41–50]. They are frequently the conjugated form of glycosides such as kaempferol, quercetin, and myricetin (Figure 4). Quercetin levels in the edible parts of most vegetables are generally (of fresh weight, mg/kg) below 10, except for onions (284–486), kale (110), broccoli (30), French beans (32–45), and slicing beans (28–30) [41]. Kaempferol could only be detected (fresh edible weight, mg/kg) in kale (211), endive (15–91), leek (11–56), and turnip tops (31–64) [41]. A rich source of flavonols are onion leaves that contain (fresh weight, mg/kg) 1.497 quercetin and 832 kaempferol [43], and also sweet potato leaves (purple) showed 156 mg/kg of myricetin and 267 mg/kg of quercetin [40]. According to Erlund [51], quercetin is an antioxidant protecting against reactive oxygen species and shows antiatherosclerosis, anticancer, anti-inflammatory, and cholesterol-lowering properties. Flavanones are colorless compounds characterized by the absence of a double bond in the 2, 3-position of the pyrone ring, and are isomeric with chalcones. Low concentrations of flavanones, namely naringenin, are found in tomatoes [52].

**Figure 4:** Structures of the major flavonol aglycones.

Monomeric flavan-3-ols include (+)-catechin, (-)-epicatechin, (+)-gallocatechin, (+)-catechin gallate, (-)-epicatechin gallate, (-)-epigallocatechin, (-)-epigallocatechin gallate, and (-)-gallocatechin gallate (Figure 5). (+)-Catechin and (-)-epicatechin are the most abundant flavanols found in fruits, while in seeds of some leguminous, the most abundant flavonols are (+)-gallocatechin, (-)-epigallocatechin, and (-)-epigallocatechin gallate [53]. In fava beans (*Vicia faba* L.), (-)-epicatechin and (-)-epigallocatechin were detected by Helsper et al. [54]. A general trend of increasing “total catechin equivalent” content with increasing darkness of the legumes within one family can be observed [55,56]. All types of beans, and mature seeds contain flavan-3-ols (mg/100 g, edible portion)—namely, (+)-catechin (1.66); (-)-epicatechin (0.35) [57] and beans, pinto, mature seeds, raw (*Phaseolus vulgaris*) (+)-catechin (5.07); (-)-epicatechin (0.14); (-)-epigallocatechin (0.05 mg/100 g) [58], broad beans, immature seeds, raw (*Vicia faba*), (-)-epicatechin (28.96); (-)-epigallocatechin (15.47); (+)-catechin (14.29); (+)-gallocatechin (4.15) [51,52]. (+)-Catechin prevents protein oxidation by its free radical scavenging capacity. Furthermore, it possesses the ability to reduce the covalent modification of protein induced by ROS or by-products of oxidative stress [59].

**Figure 5:** Structures of monomeric flavan-3-ols.

Isoflavonoids are flavonoids that have their B ring fused with the C3 position of ring C, which are phenolics with phytoestrogenic activity (Figure 6). The concentrations of isoflavones in soybean products ranged from 580 to 3800 mg/kg of fresh weight [60].

**Figure 6:** Chemical structures of isoflavonoids.

The basic structures of anthocyanins are anthocyanidins, in which the two aromatic rings A and B are linked by a heterocyclic ring C that possesses oxygen. More than 23 different anthocyanidins have been found with pelargonidin, cyanidin, peonidin, delphinidin, petunidin, and malvidin being the most common (Figure 7). Anthocyanins are natural water-soluble pigments occurring in plants mainly in a conjugated form as glycosides. Monomeric anthocyanin changed the hydroxylation and methoxylation patterns on the B ring; the nature, position, and the number of conjugated sugar units; the nature and number of conjugated aliphatic or aromatic acid groups; the existence or lack of an acyl aromatic group in the molecule [61]. Most of the anthocyanins occur as acylated by organic acids (*p*-coumaric, caffeic, ferulic, or sinapic acids) via ester bonds [62]. They are usually present in any pink to purple vegetables such as black beans (*Phaseolus vulgaris*) (delphinidin (11.98); malvidin (6.45); petunidin (9.57) in mg/100 g, edible portion); kidney red beans (*Phaseolus vulgaris*) (pelargonidin (2.42); cyanidin (1.19) in mg/100 g, edible portion) [63]; common raw beans (*Phaseolus vulgaris* var. Zolfino) (delphinidin (2.50); malvidin (0.10); petunidin (0.14) in mg/100 g, edible portion) [38]; redraw cabbage (*Brassica oleracea*) (cyanidin (72.86), delphinidin (0.01); pelargonidin (0.02) in mg/100 g, edible portion) [48,63] and in cowpeas (blackeyes, crowder, southern) (*Vigna unguiculata*) (cyanidin (94.72); delphinidin (94.60); malvidin (34.28); peonidin (11.07); petunidin (27.82) in mg/100 g, edible portion) [64]. The pharmacological effects associated with consumption of anthocyanin-rich foods include antiedema, antioxidant, anti-inflammatory, and anticarcinogenic activities [65].

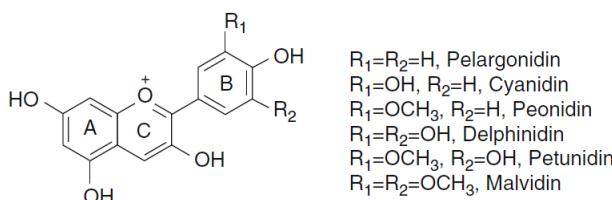
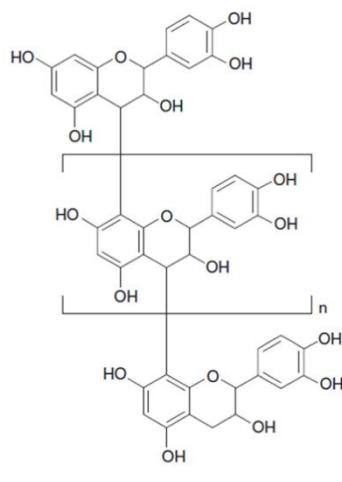


Figure 7: Chemical structures of anthocyanidins.

Condensed tannins, also recognized as proanthocyanidins, mainly comprise a flavan-3-ol unit to form dimers, oligomers, and polymers of up to 50 monomer units (Figure 8). Proanthocyanidins have complex structures depending on the number of the flavan-3-ol units, the location, and type of interflavan linkage in the molecule, and nature and position of substituents on the flavan-3-ol unit. Proanthocyanidins can be classified into procyanidins and prodelphinidins based on their hydroxylation patterns of A and B rings [39]. The proanthocyanidin contents in spinach (*Spinacia oleracea*) and radish leaves (*Raphanus sativus*) are 88.46 and 13.57 proanthocyanidins in mg/100 g fresh weight, respectively [66]. Proanthocyanidins have antioxidant activity responsible for cardioprotection, cancer chemoprevention, and lowering cholesterol amounts [39].



Procyandins: $n > 0$

Oligomeric procyandins: $n = 0-7$

Figure 8: Chemical structure of procyandins.

Quinones are phenolic compounds with conjugated cyclic dione structures, such as that of benzoquinones, derived from aroma compounds by the conversion of an even number of $-\text{CH}=$ groups into $-\text{C}(=\text{O})-$ groups with any necessary rearrangement of double bonds. The most common skeletal structures of

quinones found in plants are *p*-quinone, *o*-quinone, anthraquinone, naphthoquinone, and naphtodianthrone (Figure 9).

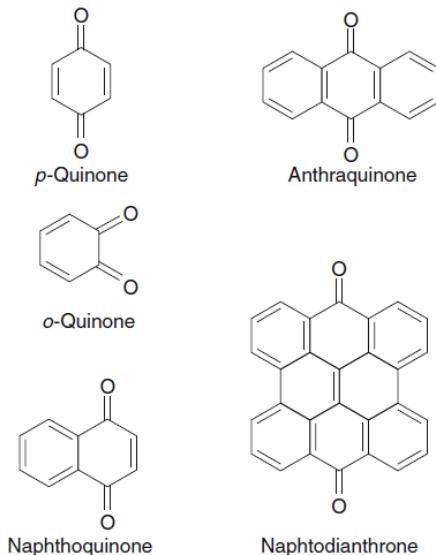


Figure 9: Quinone structures.

Stilbenes are a group of phenolic compounds that share a similar chemical structure to flavonoids, in which the two aromatic rings (A and B) are linked by a methylene bridge. One of the stilbenes mostly present in glycosylated forms is *trans*-resveratrol (Figure 10). Resveratrol is a phytoalexin that has been particularly studied as it shows several biological activities, reduces the formation of atherosclerotic plaque, presents neuroprotective, antidiabetic, anti-inflammatory, antioxidant, anticarcinogenic effects, and antiviral activity [67,68]. It was also shown in several studies that *trans*-piceid a 3- β -glucosylated form of *trans*-resveratrol could inhibit platelet aggregation [69,70] and oxidation of human low-density lipoprotein (LDL). Peng et al. [71] showed that *trans*-piceid was the major form existing in most vegetables, and most of the samples contained higher *trans*-piceid than *trans*-resveratrol. The concentration of *trans*-resveratrol in $\mu\text{g}/100 \text{ g}$ fresh weight lies between 1.14 and 0.70 in cauliflower and 1.78 and 23.12 in celery, as well as 8.8 and

19.74 in black soya bean. As for *trans*-piceid, it is between 43.04 and 783.29 in celery, 0.80 and 9.22 in leaf lettuce, 1.10 and 12.0 in tomato, and 18.16 and 194.40 in red radish [71]. According to Sebastià et al. [72], the concentration of *trans*-resveratrol in tomatoes is 0.2 µg/g.

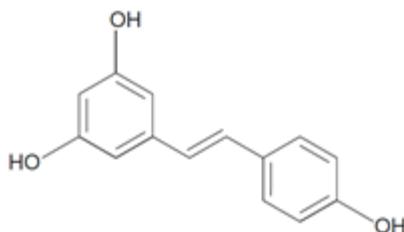


Figure 10: Chemical structure of resveratrol.

Flavonoids are largely distributed in vegetables, and they have been studied mainly because of their potential health benefits as antioxidants and chemopreventive agents [54]. However, until now no recommended daily intake of these compounds has been established mainly because the composition data are incomplete, the biological activities are not well determined, and especially because the bioavailability and pharmacokinetic data are inconclusive. Emerging science from some studies suggests that flavonoid-rich diets may lower the risk of some diet-related chronic degenerative diseases [73-75], but a few clinical and laboratory reports indicate that very high doses of certain flavonoids may have adverse effects [76,77]. Therefore, it is important to accurately assess flavonoid intakes from the perspectives of both disease prevention and safety [78,79]. The specific action of each phenolic compound from vegetables and medicinal and aromatic plants are not easy to measure since only a small part of it is truly absorbed and, also, it may potentially transform [80]. Numerous dietary phenolic compounds are antioxidants able to quench ROS and toxic free radicals formed from the peroxidation of lipids and, consequently, have anti-inflammatory and antioxidant properties. Flavonoids are recognized as preventing the production of free radicals by chelating iron and copper ions to directly scavenge ROS and toxic free radicals and inhibit lipid peroxidation, which may

damage DNA, lipids, and proteins, linked to aging, atherosclerosis, cancer, inflammation, and neurodegenerative diseases [81].

Many of these reported biological functions have been attributed to free radical scavenging activity, and there has been intensive research on the natural antioxidants derived from plants [37,82–84]. Hundreds of epidemiological studies have correlated the antioxidant, anticancer, antibacterial, cardioprotective, anti-inflammation, and immune system promoting roles of plants enhanced by phenolic content. Tables 2 and 3 summarize important bioactivities related to the presence of phenolic identified in vegetables and MAPs widely consumed in the world. For example, Salem et al. [85] found that extracts of artichokes rich in polyphenols were capable of inhibiting the production of histamine, bradykinin, and chemokines. These authors discovered that polyphenols present in extracts were capable of acting synergistically, enhancing their anti-inflammatory potential. Additionally, Sharma et al. [86] observed that extracts of onion could inhibit the bacterial growth of *Staphylococcus* sp. and *Escherichia coli*, due to the presence of quercetin aglycone, quercetin-4'-*O*-monoglucoside, and quercetin-3,4'-*O*-diglucoside. However, the intensity of the antagonistic effect was dependent on the concentration of each compound in each onion variety assessed. In 2018, Dzotam et al. [87], using extracts of nutmeg rich in 7-trihydroxyflavone, observed an antibacterial activity of such extracts against the multidrug-resistant Gram-negative bacteria *Providencia stuartii* and *Escherichia coli*. A recent study showed that thymus extract rich in rosmarinic acid and 3,4-dihydroxybenzoic acid could exhibit antiradical and antioxidant properties and enhanced gastrointestinal digestion [88].

Table 2: Phenolic compounds present in some vegetables consumed worldwide and the main bioactivities pointed.

Vegetables	Main Phenolics	Bioactivities Pointed	Ref.
Artichoke (<i>Cynara scolymus</i> L.)	Hydroxytyrosol, verbascoside, apigenin-7-glucoside, oleuropein, quercetin, pinoresinol, and apigenin	Anti-inflammatory activities of <i>C. scolymus</i> were found due to the synergistic effect of phenolic compounds. Inhibitory action of artichoke extracts in the inflammatory process such as histamine, bradykinin, and chemokine mediators' processes were related to the phenolic content.	[85]
Broccoli florets (<i>Brassica oleracea</i> L. var. <i>italica</i>)	Hydroxybenzoic acid, hydroxycinnamic acid, flavone, polymethoxylated flavone, kaempferol glycosylated and kaempferol derivatives, quercetin-3- <i>O</i> -glucoside and derivatives, isorhamnetin-3- <i>O</i> -rutinoside, isorhamnetin glucoside, and related compounds	Hydroalcoholic extracts were capable of directly reacting with and quenching DPPH and Oxygen (ORAC) radicals. Flavonoids and derivatives showed significant positive correlations to DPPH and ORAC.	[89]
Celery (<i>Apium graveolens</i> L.)	High content of apiaín, apigenin, and rutin, 3,7-dihydroxyflavone, cyanidin and diosmetin, and terpenes (α -ionone)	Antioxidant activity was highly correlated with the presence of apiaín, apigenin, and rutin, mainly due to the lower BDE of O–H bonds in their B rings, which enhanced their H atom donating ability.	[90]
Garlic (<i>Allium sativum</i> L.)	The high content of total phenolic compounds, vanillic acid, caffeic acid, <i>p</i> -coumaric acid, ferulic acid, sinapic acid, cyanidin-3-(6'-malonyl)-glucoside)	A positive and significant correlation between the content of total phenolic content and antimicrobial and antioxidant activity was found. The highest total phenolics content was significantly correlated with the lowest EC50 values for all the tested antioxidant activity assays.	[91,92]
Ginseng leaves (<i>Panax ginseng</i> C. A. Mey.)	Gallic acid and galangin	The antioxidant capacity in the lipophilic fraction was higher than those in hydrophilic fractions and positive correlations between antioxidant capacity and total phenolic content, gallic acid, and galangin were found.	[93]
Leek (<i>Allium porrum</i> L.)	Rosmarinic acid, quercetin, and apigenin glycosylated forms and respective derivatives	Extracts showed a favorable antimicrobial activity against <i>Staphylococcus aureus</i> , <i>Bacillus subtilis</i> , and <i>Aspergillus niger</i> . Extracts inhibit Hep2c, L2OB, and RD tumor cells in a dose-dependent manner after 48 h treatment period.	[94]
Onion (<i>Allium cepa</i> L.)	Quercetin aglycone, quercetin-4'- <i>O</i> -monoglucoside, and quercetin-3,4'- <i>O</i> -diglucoside	The antioxidant activity of onions was dependent on variation in the contents of quercetin compounds in all onion varieties assessed. Antibacterial activity against <i>Staphylococcus</i> sp. and <i>Escherichia coli</i> was dependent on variation in both phenolic profile and content.	[86]
Watercress (<i>Nasturtium officinale</i> L.)	Coumaric acid, sinapic acid, caftaric acid, quercetin, and quercetin derivatives were the major phenolic compounds identified	The radical scavenging activity (RSA) of root, stem, and leaves of watercress methanolic extracts were highly correlated with the variation of phenolics. Watercress leaves had a similar antioxidant potential to that of tocopherol.	[95]

Table 3: The key role of some important phenolics identified in some medicinal and aromatic plants (MAPs) species extracts and respective bioactivities.

MAPs Extracts	Main Phenolics Identified	Bioactivities Pointed	Ref.
Fern (<i>Asplenium nidus</i> L.)	7-O-hexoside and quercetin-7-O-rutinoside	Antimicrobial activity against <i>Proteus mirabilis</i> Hauser, <i>Proteus vulgaris</i> Hauser, and <i>Pseudomonas aeruginosa</i> (Schroeter). Migula was shown when fern extracts were applied at different concentrations.	[96]
Ginkgo leaves (<i>Ginkgo biloba</i> L.)	Quercitin-3-O-glucoside	Ginkgo leaf extracts were capable of decreasing sunburn symptoms in UVB-induced skin <i>in vivo</i> models.	[97]
Green tea (<i>Camellia fangchengensis</i> Liang and Zhong)	Procyanidin B1, B2, B3, procyanidin trimer, fangchengbisflavan A and B, (+)-catechin 7-O-β-glucopyranoside, (-)-epicatechin, (-)-epicatechin gallate, epigallocatechin, and epicatechin 3-(3-O-methyl) gallate	Antiradical and antioxidant activity against <i>in vitro</i> studies were shown.	[98]
Haskap berry (<i>Lonicera caerulea</i> L.)	Cyanidin-3-O-glucoside, cyanidin-3-O-rutinoside, chlorogenic acid, quercitin-3-O-rutinoside, quercitin-3-O-glucoside, and catechin	Extracts exhibited comparable anti-inflammatory effects to diclofenac which is a COX inhibitory medicine.	[99]
Nutmeg (<i>Myristica fragrans</i> Houtt)	30,40,7-trihydroxyflavone	Antibacterial activity of nutmeg extracts against the multidrug-resistant Gram-negative bacteria <i>Providencia stuartii</i> Ewing and <i>Escherichia coli</i> was observed.	[87]
Lavandula (<i>Lavandula pedunculata</i> Mill.)	Caffeic acid, luteolin-7-O-glucuronide, and rosmarinic acid	Exhibited highest anti-inflammatory activity in rat RAW 264.7 macrophages by inhibiting nitric oxide production.	[100]
Rosemary (<i>Rosmarinus officinalis</i> L.)	Isorhamnetin-3-O-hexoside, carnosic acid, carnosol, rosmanol, epirosmanol, rosmaridiphenol, rosmarinic acid, and their methoxy derivatives	Antioxidant and antiradical activities were observed. Exerted a direct cytoidal effect via upregulation of nitric oxide (NO) in cancer cells, which in turn acts in a pro-apoptotic manner and induces cell apoptosis.	[101]
Oregano (<i>Origanum vulgare</i> L.)	Rosmarinic acid, 3,4-dihydroxybenzoic acid	The hydroalcoholic extract shows antioxidant activity in <i>in vitro</i> and <i>in vivo</i> models. The oral formulation of oregano preserves antioxidant activity from gastrointestinal digestion.	[88]
Thymus (<i>Thymus algeriensis</i> Boiss. and Reut)	Rosmarinic acid, caffeoyl rosmarinic acid, eriodictyol hexoside, kaempferol-O-hexoside, kaempferol-O-hexuronide, luteolin-O-hexuronide, apigenin-C-di-hexoside, and apigenin-O-hexuronide	Methanolic extracts were found to possess substantial antioxidant and antiacetylcholinesterase activities which were correlated to their phenolic contents; however, significant variations were observed between populations.	[102]
Sage (<i>Salvia officinalis</i> L.)	Apigenin, carnosic acid, carnosol, rosmanol, epirosmanol, rosmarinic acid, and their methoxy derivatives	Antioxidant and antiradical activities were observed. Sage extracts were capable of exerting a direct cytoidal effect via upregulation of nitric oxide (NO) in cancer cells, in a pro-apoptotic manner which induced cell apoptosis.	[101]

Polyphenols as Prebiotics

As mentioned previously, polyphenols are natural compounds present in many vegetables and MAPs. In the human body, the majority of polyphenols has poor absorption. They are retained in the intestine for more time, promoting beneficial effects, specifically by affecting the gut microbiota [100-102]. The polyphenols are biotransformed into low-molecular-weight phenolic metabolites by gut microbiota resulting in the increased bioavailability of polyphenols, responsible for the health effects derived from polyphenol-rich plants consumption, may differ from the native compound found in plants [101,103-106]. The properties of polyphenols depend on bioactive metabolites produced when they are metabolized by microbiota [107]. At the same time, specific polyphenols can frequently modulate the gut microbial composition by the inhibition of pathogenic bacteria and increase the growth of beneficial bacteria resulting in changes in gut microbial composition [108-111]. Finally, they may act as prebiotic metabolites and enhance the beneficial bacteria. It was demonstrated in animal studies that the consumption of polyphenols, especially catechins, anthocyanins, and proanthocyanidins, increases the abundance of *Lactobacillus*, *Bifidobacterium*, *Akkermansia*, *Roseburia*, and *Faecalibacterium* spp. [112]. Prebiotics are defined in 1995 as “nondigestible food constituents that beneficially act the host by selectively stimulating the growth and/or activity of one or a limited number of bacterial species already resident in the colon”[113]. Later in 2010, prebiotics was defined as “a selectively fermented ingredient that allows specific changes, both in the composition and/or activity in the gastrointestinal microflora, benefits upon host well-being and health”[114]. The bioavailability of polyphenols is influenced by their structural characteristics, mainly by their degree of polymerization [115,116]. For example, proanthocyanidins are not absorbed by intestinal mucosa [116]. Only aglycones and some of few glucosides can be absorbed [117]. Also, the prebiotic effect of each polyphenol can be influenced by the plant source and the chemical structural characteristics of the compound, besides the individual differences in the gut microbiota composition [118,119].

Advances in Phenolic Compounds and Future Research Perspectives

As the plant bioactive phenolic compounds have received in recent years increasingly attention [120,121], the research concerning their biosynthesis, biological activities, extraction, purification processes, and chemical characterization are of utmost interest. New analytical strategies, such as NMR and MS, have demonstrated help in the identification of new molecular structures and characterization of plant phenolic profiles [122]. Recently, Jacobo-Velázquez et al. [123] focused on the most recent advances in plant phenolic research as the functional characterization of enzymes involved in the biosynthesis of flavonoids; the evaluation of pre-and postharvest treatments to increase the phenolic concentration of different plants, and the chemical description of the phenolic profiles from different plants and the evaluation of their bioactivity. Therefore, the development of analytical methods for exploring qualitative or quantitative approaches to analyzing these bioactive phenolic compounds in different plants are essential. Starting with sample preparation and optimization of the extraction process (solid-liquid extraction, ultrasound-assisted extractions, microwave-assisted extractions, supercritical fluid extraction) is essential for achieving higher accuracy in results [124-126]. According to Swallah et al. [127], it is difficult to choose a universal method of preparation and extraction of phenolic compounds from different plants, as they exhibit different polarity, have a different molecular structure, different hydroxyl groups number and positions, and several aromatic rings involved. Followed by their analysis using different methods such as spectrophotometry, gas chromatography, liquid chromatography, thin-layer chromatography, capillary electrophoresis, and near-infrared spectroscopy, developing rapid, sensitive, and reliable methods are still required [128,129]. Another challenge is the analysis of polymeric phenolic compounds, as their polydispersity results in poor resolution and detection. An example is proanthocyanidins, of such polydisperse structures for which method development is needed. Consequently, characterizing the unknown phenolic is, therefore, one of the main challenges in the research on plant polyphenols [122].

Vegetables Aroma and Flavor Compounds

The word ‘vegetables’ comprises a wide variety of plant species with different kinds of uses but, in general, this designation includes over-wintering storage organs like bulbs, tubers, roots, seeds, leaves, stems, and some modified flowers, with a variety of colors, flavors, tastes, and aromas. These descriptors associated with their nutritional value are critical for their success and thus determinant for consumer’s choice. Like in fruits, in vegetables, aroma and flavor are determined by taste and odor-active compounds and perceived by the tongue and olfactory systems. The biggest issue is to interpret the results since many compounds are difficult to detect, others to identify and others not perceived (not flavor-active) [130]. Therefore, it is important to have efficient methods to detected them. Specific instrumental methods have been developed to analyze food aroma and flavor [131,132]. However, classical methods based on a sensory panel of experts are still used [133]. Although it is often considered that flavor and aroma are set by nature, other factors, like cultural practices, genetics, maturity degree, growing conditions, postharvest handling operations, and cooking is also a critical causes with significant effect on these attributes [134,136].

More than 730 flavor compounds have been identified [134,137], including some non-volatile compounds. For example, in tomatoes are known more than 400 volatile and non-volatile compounds, although only 30 are present in concentrations higher than one $\mu\text{L/L}$, as summarized in different studies [138,140]. In pepper, the ‘sweetness’, ‘spicy’, ‘floral’, ‘herbal’ is given by a mixture of volatile compounds (Z)-3-hexenal, 2-heptanone, (Z)-2-hexenal, (E)-2-hexenal, hexanol, (Z)-3-hexanol, (E)-2-hexenol, and linalool and non-volatile compounds (fructose and glucose) [141]. In vegetables, the presence of flavor and non-flavor compounds are diverse, but the major volatile compounds related to the typical sensory properties of vegetables are summarized in Table 4.

Table 4: Key volatile and nonvolatile compounds present in some vegetables largely consumed worldwide. The sensory attributes were adapted from Parker et al. [131] and Maarse [142].

Vegetables	Key-Volatile Compounds	Sensory Attributes	Ref.
Broccoli (<i>Brassica oleracea</i> L. var. <i>italica</i>)	Methanethiol, hydrogen sulfide, dimethyl disulfide, trimethyl disulfide, dimethyl sulfide, hexanal, (<i>Z</i>)-3-hexen-1-ol, nonanal, ethanol, 4-methylthiobutyl isothiocyanate, butyl isothiocyanate, 2-methyl butyl isothiocyanate, and 3-isopropyl-2-methoxypyrazine	“Cabbage”, “radish”	[143]
Cabbage (<i>Brassica oleracea</i> L. var. <i>capitata</i>)	2-Propenyl isothiocyanate, methanethiol, dimethyl sulfide, dimethyl trisulfide, ethanol, methyl acetate, ethyl acetate, hexanal, (<i>E</i>)-2-hexenal, and (<i>Z</i>)-3-hexen-1-ol	“Sulfury”, “onion”, “sweet corn”	[144,145]
Cauliflower (<i>Brassica oleracea</i> L. var. <i>botrytis</i>)	2-Propenyl isothiocyanate, dimethyl trisulfide, dimethyl sulfide, and methanethiol	“Sulfury”, “cauliflower”, “putrid”	[146,147]
Carrot (<i>Daucus carota</i> L. subsp. <i>sativus</i>)	α -Pinene, sabinene, myrcene, limonene, β -ocimene, γ -terpinene, <i>p</i> -cymene, terpinolene, β -caryophyllene, α -humulone, (<i>E</i>)- γ -bisabolene and β -ionone, 3-sec-butyl-2-methoxypyrazine	“Earthy”, “fruity”, “citrus-like”, “woody”, and “sweet”	[142]
Celery (<i>Apium graveolens</i> L.)	3-Butylphthalide and 3-butyltetrahydrophthalide (sedanolide), (<i>Z</i>)-3-hexen-1-ol, myrcene, limonene, α -pinene, γ -terpinene, 1,4-cyclohexadiene, 1,5,5-trimethyl-6-methylene-cyclohexene, 3,7,11,15-tetramethyl-2-hexadecen-1-ol, and α -humulene	“Herbal”	[148,149]
Cucumber (<i>Cucumis sativus</i> L.)	3-Isopropyl-2-methoxypyrazine, (<i>E</i> , <i>Z</i>)-2,6-nonadienal, and (<i>E</i>)-2-nonenal	“Fatty”, “green”, “cucumber”	[148,150]
Garlic (<i>Allium sativum</i> L.)	Allicin, <i>S</i> -alk(en)yl-cysteine sulfoxides, di-2-propenyl disulfide, methyl 2-propenyl disulfide, dimethyl trisulfide, methyl 2-propenyl trisulfide, and di-2-propenyl trisulfide	“Ammonia”, “sulfur-like smell”	[151]
Leek (<i>Allium porrum</i> L.)	1-Propanethiol, dipropyl disulfide, dipropyl trisulfide, methyl(<i>E</i>)-propenyl disulfide, and propyl (<i>E</i>)-propenyl disulphide	“Onion”, “green”	[152,153]
Onion (<i>Allium cepa</i> L.)	<i>S</i> -alk(en)yl-cysteine sulfoxides, thiopropanal- <i>S</i> -oxide (the lachrymatory factor) 3,4-dimethyl-2,5-dioxo-2,5-dihydrothiophene, propyl methanethiosulfonate, and propyl propanethiosulfonate	“Ammonia”, “sulfur-like smell”	[152]
Pea (<i>Pisum sativum</i> L.)	Hexanal, (<i>E</i>)-2-heptenal, (<i>E</i>)-2-octenal, 1-hexanol, (<i>Z</i>)-3-hexen-1-ol, 3-alkyl-2-methoxypyrazines, 3-isopropyl-2-methoxypyrazine, 3-sec-butyl-2-methoxypyrazine, 3-isobutyl-2-methoxypyrazine, 5-methyl-3-isopropyl-2-methoxypyrazine, and 6-methyl-3-isopropyl-2-methoxypyrazine	“Green”, “herbal”	[154]
Pepper (<i>Capsicum annuum</i> L.)	(<i>Z</i>)-3-hexenal, 2-heptanone, (<i>Z</i>)-2-hexenal, (<i>E</i>)-2-hexenal, hexanol, (<i>Z</i>)-3-hexanol, (<i>E</i>)-2-hexenol, and linalool, 2-Isobutyl 3-methoxypyrazine	“Green pea”, “green bell pepper”, “spicy”, “herbal”	[141]
Tomato (<i>Solanum lycopersicum</i> L.)	Hexanal, <i>cis</i> -3-hexenal and <i>trans</i> -2-hexenal, hexanol, <i>cis</i> -3-hexenol, 1-penten-3-one, 2-isobutylthiazole, 6-methyl-5-hepten-2-one, β -ionone, 3-methylbutanal, 3-methyl butanol, 2-pentenal, acetone, ethanol and fureanol, (<i>Z</i>)-3-hexenal	“Green”, “wasabi”, “privet”, “tomato leaf” “Green”, “fatty”, “grassy”	[155,156]

Table 5 shows some examples of compounds responsible for typical aroma and flavor found in vegetables.

Table 5: The key role of some volatile compounds responsible for the sensory attributes of some vegetable species adapted from Parker et al. [131] and Maarse [142].

Vegetables	Volatile compound	Sensory attributes
	Alcohols	
Watermelon	(Z, Z)-3,6-Nonadienol	“Fatty”, “soapy”, “cucumber”, “watermelon”, “rind”
	Aldehydes	
Cucumber	(E)-2-Nonenal	“Fatty”, “green”, “cucumber”
Tomato	(Z)-3-Hexenal	“Green”, “fatty”, “grassy”
Celery	Lactones; 3-Butylphthalide	“Herbal”
	Pyrazines	
Green bell pepper, peas	2-Isobutyl 3-methoxypyrazine	“Green pea”, “green bell pepper”, “spicy”, “herbal”
Carrot	3-Sec-butyl-2-methoxypyrazine	“Earthy”, “fruity”, “citrus-like”, “spicy”, “woody”, and “sweet”
	Terpenoids	
Red beet	Geosmin	“Freshly plowed soil”, “earthy”
	Sulfur compounds	
Asparagus and cabbage	Dimethyl sulfide	“Sulfury”, “onion”, “sweet corn”
Tomato	2-Isobutyl thiazole	“Green”, “wasabi”, “privet”, “tomato leaf”
Turnip	3-Butenyl-glucosinolate	“Bitter taste and aftertaste”
Broccoli	4-Methylthiobutyl isothiocyanate	“Cabbage”, “radish”
Onion	Propyl propanethiosulfonate	“Roasted alliaceous”
Radish	4-Methylthio-3-butenyl-isothiocyanate	“Sharp taste”, “mustard/horseradish-like”
Garlic and onion	S-alk(en)yl-cysteine sulfoxides	“Ammonia”, “sulfur-like smell”

Branched-chain alcohols, a result of amino acid deamination and decarboxylation [147,157], are common in plant materials. (*Z, Z*)-3,6-Nonadienol (Figure 11) has been described as having “fatty”, “soapy”, “cucumber”, “watermelon”, and “rind” sensory attributes, in watermelon, but also “boiled leaf-like” and “grassy” attributes in fresh-cut melon [158] or “muskmelon-like” and “musky” flavors in cantaloupe [159].

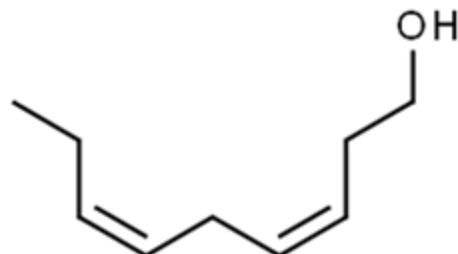


Figure 11: Chemical structure of (*Z, Z*)-3,6-nonadienol.

Volatile aldehydes, also a chemical class formed by the lipoxygenase pathway from fatty acids [147,157], are well-known for their green note odor. Many of these compounds can be found in camellia (*Camellia oleifera* Abel, *Theaceae*) seed, which can be used to produce camellia oil, a popular edible oil in China (Figure 12). Jia et al. [160] found a total of 66 volatile compounds in camellia oil, identified using gas chromatography–mass spectrometry–olfactometry.

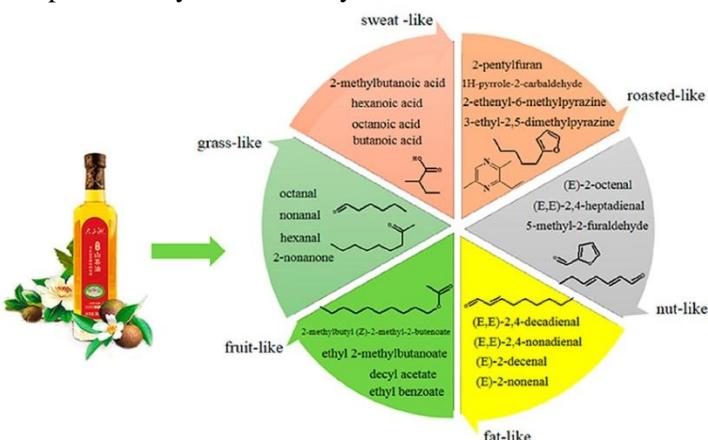


Figure 12: Schematic representation of virgin camellia oil aroma compounds composition and their sensory descriptors [160].

(*E*)-2-Nonenal and (*Z*)-3-hexenal (Figure 13), originate from different fatty acids ((*E*)-2-nonenal, from linoleic acid and (*Z*)-3-hexenal from linolenic acid) and are described as presenting other sensory attributes. “Penetrating”, “waxy” [158] or “fatty” [161] characteristics have been linked to (*E*)-2-nonenal, while, for (*Z*)-3-hexenal, “leafy”, “powerful”, “strawberry leaf”, “winey”, “green leaves”, “apple-like”, “leaf-like” and “cut grass” attributes have also been linked.

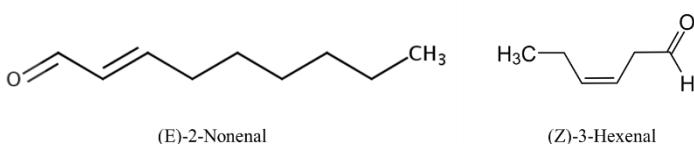


Figure 13: Chemical structure of (*E*)-2-nonenal and (*Z*)-3-hexenal.

Sesquiterpene lactones are among the most prevalent and biologically significant classes of secondary metabolites found across the plant kingdom, comprising over 5000 known compounds, being most common in families such as *Cactaceae*, *Solanaceae*, *Araceae*, and the *Euphorbiaceae*. 3-Butylphthalide (Figure 14) is one of the most known lactones, and besides the “herbal” note associated with it, it is also mainly responsible for the “celery” aroma [162].

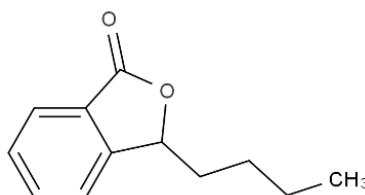


Figure 14: Chemical structure of 3-butylphthalide.

Pyrazines are heterocyclic nitrogen-containing heterocyclic compounds found in a wide variety of processed foods, grapes, and wines [163], and are mostly associated with nutty and roasty flavors, as well as those of green vegetables, like green pepper. 2-Isobutyl 3-methoxypyrazine and 3-sec-butyl-2-

methoxypyrazine (Figure 15) are two well-known pyrazines that present low sensory detection thresholds, making them very important, as they can be the compounds responsible for the dominating aromatic features in several vegetables [164]. However, in some cases, their flavor can be considered a defect denominated as the “potato taste defect” (PTD), many times found in East African coffee beans [165].

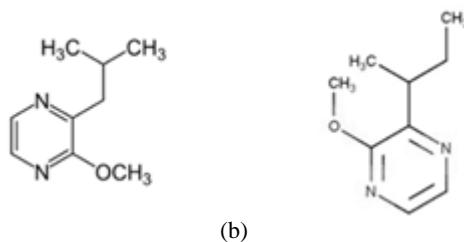


Figure 15: Chemical structure (a) 2-isobutyl 3-methoxypyrazine and (b) 3-sec-butyl-2-methoxypyrazine.

The chemical class of terpenoids includes compounds widely distributed in plants and fruits and they can be divided into two major groups: monoterpenes and sesquiterpenes or irregular terpenes, which are mostly synthesized in catabolic reactions and/or by autoxidation [166]. Geosmin (Figure 16) is an irregular terpene, and its major sensory attributes, as referred to, are “earthy” and “freshly plowed soil”.

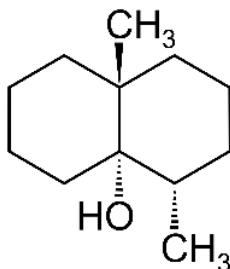


Figure 16: Chemical structure of geosmin.

Sulfur-containing compounds (Figure 17) are synthesized from methionine and cysteine and can be emitted due to an increased

accumulation of free methionine. They are key trace volatiles and are a major factor in the sensory properties of fruits and vegetables [167,168].

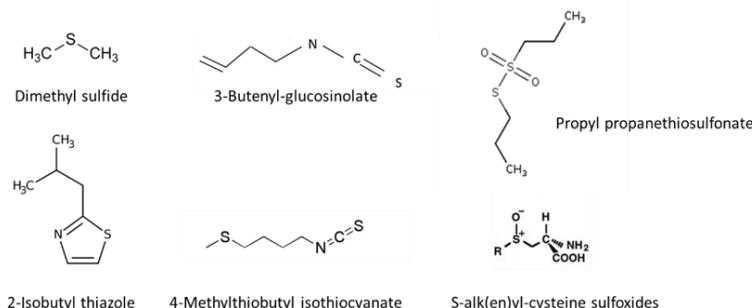


Figure 17: Chemical structure of sulfur-containing volatile compounds.

The origin of volatile and non-volatile compounds is diverse, due to the multitude of molecules that convey flavor. In general, they are synthesized from terpenoid, apocarotenoid, and lipoxygenase pathways and derived from amino and fatty acids [142,169] (Figure 18).

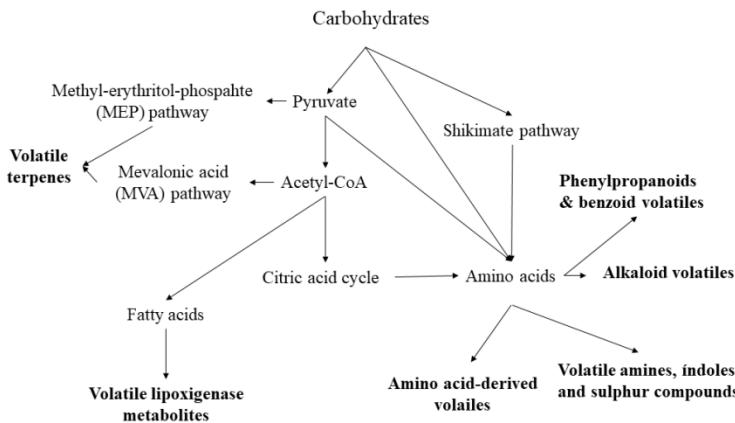


Figure 18: Generalized pathway for the synthesis of plant volatiles. In bold are presented the names of the type of the volatile compound. Adapted from [169].

Although many of the volatile and non-volatile flavor and aroma compounds have been identified, many of their biochemistry

pathways are still not well clarified. Nevertheless, several metabolic pathways are involved in the biosynthesis of flavor, aroma, and taste compounds in vegetables. Many volatile compounds are synthesized from fatty acids, amino acids, and carotenoids pathways [138,170], others from isoprenoid substrates. However, it is well known that primary metabolism is fundamental for the formation of non-volatile compounds, which also contribute to the flavor, aroma, and taste of vegetables [170] (Figure 19). Among these, are included sugars, organic acids, free amino acids, pro-vitamins, minerals, and salts [171]. For example, sweetness is determined by the concentrations of the predominant sugars, while sourness, is determined by the concentrations of the predominant organic acids [172].

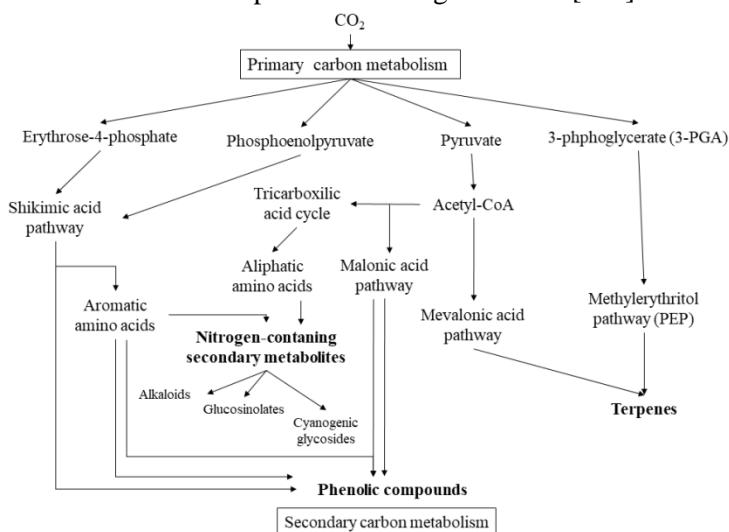


Figure 19: Generalized pathways for the synthesis of some of the non-volatile compounds present in plants. In bold are presented the names of the main non-volatile type compounds. Adapted from Ncube and Staden [173].

In tomatoes, their characteristic sweet-sour taste is due to a combination of the sugars and organic acids, and positive correlations between perceived sweetness, reducing sugar content and soluble solids have been found [174]. Therefore, defining what compounds are more critical to flavor is more complex than expected. Additionally, when vegetables are harvested, a catabolic process starts due to the disruption of plant

tissues, affecting their aroma and transforming their key flavor into another compound. Some of them may even turn into a new biologically active compound. For example, in Brassica vegetables, operations like cutting, chewing, cooking, or even fermentation [175] have an uncontrolled effect on volatile compounds due to the mixture of enzymes. The Brassica vegetables typical odor and taste are mainly due to the presence of glucosinolates, which when in contact with the enzyme myrosinase (EC 3.2.1.147, thioglucoside glucohydrolase) are hydrolyzed into new groups of breakdown products such as isothiocyanates, organic cyanides, oxazolidinethiones, and thiocyanate [174], affecting their aroma and transforming their key flavor into a different one. A similar situation occurs with *Allium* species, like onion, shallots, garlic, leek, and other related, that have in common the presence of the sulfur-based S-alk(en)ylcysteine sulfoxide (alliin, I) in their composition. In damaged or disrupted tissue transformation into several other compounds, via alliinase occurs [176]. The initial hydrolysis products are ammonia, pyruvate, and an alk(en)ylthiosulphinate (allicin, II) and can undergo further non-enzymatic reactions to yield a variety of compounds such as thiosulfate [III] and di- and trisulfides [IV] [177], which gives to Allium species their typical odor of sulfur-like smell. Although the majority of such compounds are related to odor and flavor, some of them are also involved in important biochemical activities. Epidemiological studies have shown that glucosinolate hydrolysis products (responsible for the bitterness and mustard/horseradish-like flavor) may act as an anti-carcinogen agent and can exert antibacterial and antifungal activity against diverse human and plant pathogens [178]. Recently, allicin, a derived compound from alk(en)ylcysteine sulfoxide in Allium species shown antimicrobial and anti-carcinogenic activities (nºs). Compounds like lycopene and carotene, largely present in tomatoes, carrots, and spinaches, have been associated with anti-inflammatory properties [179].

MAPs Aroma and Flavor Compounds

Plants provide multiple ranges of aromas and flavors well notice by the most sensitive human senses, taste, and odor [180]. Over

time, many plant species have been used to produce foods and medical or herbal formulations [181,182]. The use of MAPs began as an unselective wild-harvested of plants, moving into a selective collection and then to the cultivation of the most useful. From ancient times to the present, plants have been used as medicine and food preservers [183,184]. Nowadays, their cultivation, pharmacognosy, phytochemistry, biology, conservation, and sustainable use are matters of interest [185]. MAPs yields a wide variety of natural compounds, produced and stored in glands located in different parts of the plant: leaves, flowers, fruits, seeds, barks, and roots [186,187]. These natural compounds, most of which are essential oils, are volatile at room temperature, important for plant adaptation and survival, namely as pollinator attractants, herbivores restraints, or as a defense against pathogenic microorganisms. Because of their biological activities, they are also important to Man, in both commercial and industrial resources, namely in traditional medicine [186], which also provides raw materials for use in the pharmaceuticals, cosmetics, food, and chemical industries [187].

What are MAPs? According to Maiti and Geetha [188], MAPs are plants that provide ‘medicines’ to humans that prevent disease, maintain health, or cure illnesses, so ‘let food be your medicine’ attributed to Hippocrates, 460-377 B.C., is again a popular concept. New designations have emerged to classify the beneficial effects of the use of some plants or plant parts and products. According to [186], MAPs can be divided into four groups, based on their final usage (Figure 20).

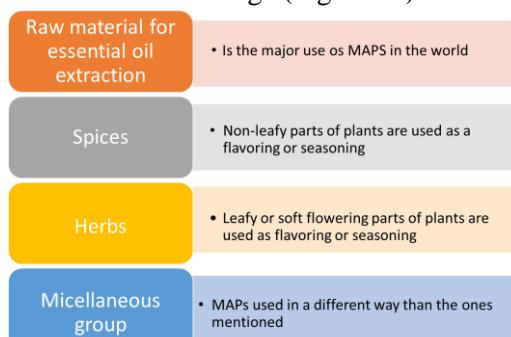


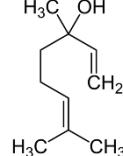
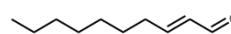
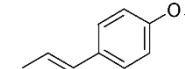
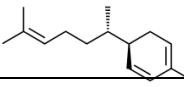
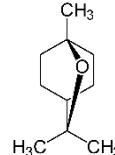
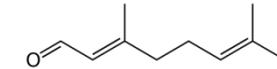
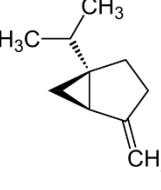
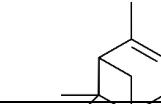
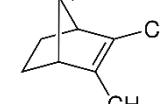
Figure 20: MAPs groups based on how they are utilized. Adapted from [186].

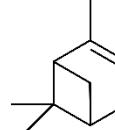
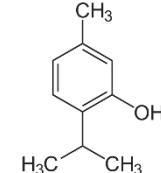
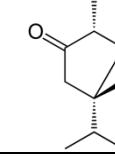
The International Union for Conservation of Nature and the World Wildlife Fund estimated that about 50,000-80,000 flowering plant species are used in medicinal formulation across the world. Among these, only 1 to 10% has been studied chemically and pharmacologically for their potential value [189,190]. MAPs contain a wide variety of bioactive secondary metabolites, such as essential oils, alkaloids, phenolics (such as flavonoids), steroids, terpenes, sesquiterpenes, diterpenes, and saponins [191], that find uses in several perfumeries, flavoring, and pharmaceutical compounds [192]. Many secondary metabolites include aromatic substances and phenolic compounds or their oxygen-substituted derivatives such as tannins [193]. Several of these compounds have anti-inflammatory and antioxidant properties. Plant secondary metabolites are characterized by exhibiting chemical polymorphism, which causes the occurrence of several chemotypes within the same species [194]. The chemotypes are of extreme importance when considering the safety, quality, and efficacy of herbal products derived from the MAPs. There are numerous cases of plant species showing a great variety of chemotypes. The genus *Thymus* shows many examples since the large majority of *Thymus* species are chemically heterogeneous. *Thymus vulgaris* is among the most popular plants having chemotypes. Six different chemotypes are known, depending on the main component of the essential oil: thymol, carvacrol, linalool, geraniol, borneol, sabinene hydrate, and multiple component chemotypes [195]. Table 6 summarizes some important MAPs and their main volatile compounds. Regarding the data presented in this table, a different type of compound is responsible for the aromatic features of MAPs. For example, Lee et al. [196] identify a high content of linalool, methyl cinnamate, estragole, eugenol, and 1,8-cineole compounds in basil cultivars and reported that these compounds were responsible for their typical aroma perceived by consumers. Similar results were presented by Shahwar et al. [197], who reported that the distinct aroma of coriander is due to a mixture of different compounds in which decennial and related compounds (Table 6) assume a high preponderance. Several other authors [196–206] have reported that the typical aromatic features exhibited by MAPs result from a combined effect of several compounds rather than a single

compound, as shown by Kizhakkayil and Sasikumar [200] for ginger. These authors reported that the typical “spicy” and “fresh” aromas exhibited by ginger are due to the simultaneous presence of zingiberene, 6-gingerol, 8-gingerol, 10-gingerol, 6-shogaol, 8-shogaol, geranial, and neral. Even in lower amounts, these compounds, are critical for the consumer to perceive the typical aroma of ginger and all of them are important to define the ginger “bouquet”.

For better exploitation of any MAP species, it is necessary to evaluate the genetic stability of their populations, i.e., whether such populations continue to produce the same characteristic products after being transplanted to and grown in habitats with different edaphoclimatic conditions. In all, for each particular species, it is crucial to perform a detailed study, which addresses, for instance, the influence of seasonal and geographic variations and local environmental conditions. The results obtained will provide the scientific basis for the selection and cultivation of species showing better qualities, thus bringing some economic and social benefits for local growers.

Table 6: Key volatile compounds present in some medicinal and aromatic plants (MAPs). In bold, the major volatile compounds of each MAP.

MAPs	Main volatile compounds	Chemical structure of major volatile compounds	Ref.
Basil (<i>Ocimum basilicum</i> L.)	Linalool , methyl cinnamate, estragole, eugenol, and 1,8-cineole		[193]
Coriander (<i>Coriandrum sativum</i> L.)	(E)-2-Decenal , linalool, (E)-2-dodecenal, (E)-2-tetradecenal, 2-decen-1-ol, (E)-2-undecenal, dodecanal, (E)-2-tridecenal, (E)-2-hexadecenal, pentadecenal and α -pinene		[194]
Fennel (<i>Foeniculum vulgare</i> (Mill.)	trans-Anethole , estragole, fenchone, and 1-octen-3-ol		[195]
Ginger (<i>Zingiber officinale</i> Rosc.)	Zingiberene , 6-gingerol, 8-gingerol, 10-gingerol, 6-shogaol, 8-shogaol, 10-shogaol, geranial, neral, 1,8-cineole, β -bisabolene, β -sesquiphellandrene, (E)(E)- α -farnesene, viridiflorol and (E)(E)-farnesal		[196,197]
Lavender (<i>Lavandula angustifolia</i> Mill.)	1,8-Cineole , camphor and borneol		[198]
Melissa (<i>Melissa officinalis</i> L.)	Geranial , neral, alloaromadendrene, geranyl acetate, 6-methyl-5-hepten-2-one, and β -caryophyllene		[199]
Oregano (<i>Origanum vulgare</i> L.)	Sabinene , 1,8-cineole, caryophyllene oxide, (E)- β -caryophyllene, <i>p</i> -cymene, α -terpineol, and germacrene D		[200]
Parsley (<i>Petroselinum crispum</i> (Mill.) Nym. Ex A.W.Hill	α-Pinene , sabinene, myrcene, β -pinene, <i>cis</i> -3-hexenyl acetate, α -phellandrene, <i>p</i> -cymene, limonene, β -phellandrene, <i>trans</i> - β -ocimene, γ -terpinene, terpinolene, 1,3,8-p-menthatriene, α -terpineol, <i>trans</i> - β -caryophyllene, germacrene-D, nerolidol and myristicin		[201]
Peppermint (<i>Mentha x piperita</i> L.)	Santene , camphene, β -pinene, myrcene, <i>cis</i> -3-hexenyl acetate, <i>p</i> -cymene, α -terpinene, limonene, <i>trans</i> - β -ocimene, γ -terpinene, <i>trans</i> -sabinene hydrate, nonanal, linalool, <i>cis</i> -limonene oxide, <i>trans</i> -limonene oxide and <i>cis</i> - <i>p</i> -mentha-2,8-dien-1-ol		[201]

Rosemary (<i>Rosmarinus officinalis</i> L.)	α-Pinene , myrcene, 1,8 cineole, camphor, caryophyllene, α -humulene, nerolidol, spathulenol and rosmarinic acid		[202]
Thymus (<i>Thymus vulgaris</i> L.)	Thymol , carvacrol, linalool, geraniol, borneol, and sabinete hydrate		[192]
Sage (<i>Salvia officinalis</i> L.)	α-Thujone , 1,8 cineole, β -caryophyllene, α -humulene, α -pinene, β -thujone, β -pinene, camphene, camphor, and <i>p</i> -cymene		[203]

Advances in Aromatic Features and Future Research Perspectives

From aroma and flavor perspectives, the actual challenges in research are multifold: (a) overcome the crop defects; (b) refinement of aroma deviations; (c) modulate volatile and non-volatile compounds biosynthesis to produce high-potency aromas and flavors; (d) increase the accuracy of aroma and flavor signature; and (e) understand how preharvest and postharvest factors can affect vegetables and MAPs aroma, flavor or taste. The flavor results from a complex metabolic network that can be influenced by several factors, such as genetics, environment, agricultural practices, and postharvest handling and storage. However, recent findings show that the biosynthesis of the compounds can be remarkably influenced by other factors, like enzyme specificity of gene adaptation [35,207] leading the research of new steps. Until recently, the research focus was to understand how agriculture practices affect plant composition and interfere in the consumer's perception of aroma and flavor [131,208], but the latest research studies are shifting from yield to quality factors. Nowadays, the trends in consumption is defined in their majority by consumer's preferences (sustainability, nutrition, flavor, aroma, novelty) and not exclusively by the producer's priorities [208].

The genomic and metabolomic analysis with clarification of fundamental metabolism of flavor and aroma compounds, its biosynthetic mechanism, regulation, and localization is a hot topic [208]. So, linkages of flavor and aroma biosynthesis with enzymatic endogenous processes will provide new insights into the flavor control mechanism. Moreover, the association of genome and metabolome analysis with the identification of key-enzymatic changes that occurred in physiological processes would address new opportunities to increase the content of specific compounds, particularly those with importance for consumer acceptance. This approach will open the possibility to produce vegetables and MAP species with an enhanced content of a specific volatile or non-volatile compound, with greater biological properties. Also, it will speed up the discovery of new or unknown chemosensory-active molecules and to

understanding their biochemical interactions with main food matrix constituents. Likewise, it will open ways of direct improvement of foods by adapting processing parameters that can help to overcome taste defects or undesirable aromas and flavors, without the addition of any artificial ingredients.

Final Remarks

The nutritional value of vegetables and MAPs can be accessed in many ways, including by their aroma and flavor. This work overviews a large amount of information available in these characteristics of vegetables and MAPs. Nonetheless, all this information is still limited to completely understand all the processes behind the formation of volatile and non-volatile compounds, their interaction with other compounds, but, more important, how they will influence the consumer's perception of aroma and flavor, and, finally, how they influence the human tendency to buy vegetables and MAPs. This is true to all plant species reported in this work, and those not included here. A continuous effort to identify volatile and non-volatile compounds for flavor and aroma is not studied species must be undertaken. Furthermore, the improvement of flavor and aroma are fundamental but must be achieved without compromising other quality traits.

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