3

Vegetable Flavors and Sensory Characteristics

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3.1 Introduction

Vegetables are edible plants that are usually consumed with main course dishes (USDA 2014). According to this definition, some fruits, for example, cucumber, okra, pepper, pumpkin, squash, and tomato, are considered as vegetables. The primary selection criteria of food choices are availability, health benefits, nutrition, price, and sensory qualities. Among these, flavor is the key sensory attribute that drives consumer acceptability. Vegetable flavors have received a lot of attention in order to increase consumer consumption and purchase intent. Food flavor is determined by the compounds that elicit smell, taste, and trigeminal senses. All aroma components are volatiles, but not all volatiles are aroma-active compounds. Taste compounds, such as sugars, amino acids, and phenolic components, are water-soluble nonvolatile substances.

Vegetable flavors have been well discussed in the literature (Takeoka 1999; Husain 2010; Ong and Liu 2011) usually focusing on flavor constituents. This chapter reviews vegetable flavors determined by sensory evaluation (direct method) and by instrumental analysis of flavor components (indirect method). Not only aromas but also taste compounds are addressed here.

3.2 Vegetable Flavors

3.2.1 Vegetable Flavor Biogenesis

Most vegetable flavors are secondary metabolites that are the results of enzymatic reactions in intact tissues. In general, nonvolatile precursors in vegetable tissue are separate from enzymes. Enzymatic reactions occur when the tissues are damaged or disrupted by chewing, crushing, cutting, or peeling. It is also known that flavor substances in plants are generated for plant defense from environmental stress or to attract beneficial insects. Flavors of fruits and vegetables are the degradation products from amino acid, carbohydrate, or fatty acid metabolic pathways, a fact that is well documented (Reineccius 2006; Schwab et al. 2008).

3.2.1.1 Flavor Derived from Amino Acid

Various sulfur-containing flavor compounds in Allium and Brassica vegetables are metabolites from cysteine sulfoxides. In garlic, the precursor alliin, the sulfur-containing compound, and enzyme alliiinase are located in different areas. Once the tissue is crushed, intermediate allicin is rapidly formed and
converts to more stable products that are responsible for the characteristic note of garlic. The pungent flavor and bitter taste of many vegetables, particularly cole crops, are due to glucosinolates. These thio-glucosides are hydrolyzed by myrosinase (thioglucosidase) to form isothiocyanates, nitriles, and thiocyanates. Further reactions yield many flavor compounds.

### 3.2.1.2 Flavor Derived from Carbohydrate

Mono- and sesquiterpenes are the major chemical classes of terpenoids. They are present in herbs, spices, fruits, and vegetables. For example, the highest abundant headspace (HS) volatiles of celery are limonene, followed by myrcene and γ-terpinene (Tirillini et al. 2004). Terpenoids are synthesized from acetylcoenzyme A (acetyl-CoA) and pyruvate. Geranyl diphosphate, farnesyl diphosphate, and geranylgeranyl diphosphate are the precursors of monoterpines, sesquiterpenes, and diterpenes, respectively. Sesquiterpenes further undergo metabolism to triterpenes, whereas diterpenes react to form tetraterpenes. Carotenoids, the tetraterpenoids, can convert to norisoprenes, such as, 6-methyl-5-hepten-2-one, geranylacetone, and β-ionone in tomatoes (Buttery et al. 1988). Furanoe® (2,5-dimethyl-4-hydroxy-3(2H)-furanone, DMHF) in tomato is another common example of an aroma compound derived from the deoxy analogues of d-fructose.

### 3.2.1.3 Flavor Derived from Fatty Acid

Saturated and unsaturated fatty acids are the precursors of abundant volatile compounds with diverse chemical structures. The degradation of fatty acids occurs mostly by oxidation reactions including (1) α-oxidation, (2) β-oxidation, and (3) in-chain oxidation via a lipoxygenase (LOX) pathway. Aldehydes, with one carbon less from parent fatty acids, are the degradation products of α-oxidation reactions, whereas, β-oxidation reactions involve acetyl-CoA and yield flavor compounds with two carbons less. Short chain (six- and nine-carbon) saturated and unsaturated aldehydes and alcohols, which are responsible for green notes, are the conversion volatiles from linoleic and linolenic acids via LOX pathway.

### 3.2.2 Factors Influencing Vegetable Flavors

Vegetable flavors are dynamic and complex, and it is difficult to compare results among research studies since amounts of flavor compounds are reported as relative concentrations. The major compounds and the flavor-active compounds are considered as evidence of each factor. Since enzymatic reactions involve biogenesis of vegetable flavor compounds, different flavor qualities are mainly due to (1) availability of substrates and specific enzymes, (2) enzymatic activities (stability, as well as optimum condition), and (3) approachability of enzymes and substrates. Cultivars, edible parts, growing conditions, maturity, and postharvest handing, as well as processing, have been investigated as to the impact on flavor quality of vegetables. Genetic is the most important factor resulting in typical flavor characteristics. Different species contain diverse precursors and enzymatic activities. Flavor compounds, especially aroma components, are biosynthesized in specific organs. The pH values in altered edible parts (bulbs, immature flower buds, immature and mature fruits, leaf, roots, seeds, stems, and tubers) and planting temperature may differ from optimum conditions of enzymatic activity. Accumulation of nutrients (flavor precursors) is affected by fertilization and maturation. Changes in environmental conditions cause variations in precursor content. Stress from other factors results in different flavor qualities as well. The influencing factors of some specific vegetables are highlighted in the next section.

### 3.3 Characteristic Flavors of Some Vegetables

The vegetables in this chapter are divided by botanical classification into 12 families. The first three categories, Alliaceae, Asparagaceae, and Gramineae belong to the subclass Monocotyledoneae, while Brassicaceae, Chenopodiaceae, Compsitae, Convolvulaceae, Cucurbitaceae, Leguminosae, Malvaceae,
Solanaceae, and Umbelliferae families are the subclass Dicotyledoneae. Although mushrooms (edible fungi) and seaweeds are separate from plants, they receive attention as the key ingredients in vegetarian diets. Typical flavors and off-flavors of some interesting vegetable are reviewed here.

### 3.3.1 Alliaceae

Alliaceous vegetable (allium family) plants have different pungency precursors that result in different flavor characteristics (Yoo and Pike 1998). For example, chive contains $\text{S}$-methyl-$\text{L}$-cysteine sulfoxide (MeCSO) as a major precursor, while $\text{S}$-2-propenyl(allyl)-$\text{L}$-cysteine sulfoxide (AICSO) is a general substrate in onion, leek, and shallot. Precursor $\text{S}$-1-propenyl-$\text{L}$-cysteine sulfoxide (PeCSO) is found mainly in garlic.

#### 3.3.1.1 Garlic (Allium sativum L.)

Diallyl disulfide is the most abundant compound in fresh garlic bulbs accounting for 30% of total volatiles (Mazza et al. 1992). The level of sulfur-containing compounds, namely diallyl disulfide, diallyl trisulfide, allyl methyl disulfide, and allyl methyl trisulfide, increases during maturation. This is because alliins are at a higher level in leaves during the early growing stage, and then accumulate in the bulb during development of the bulb (Bloem et al. 2004). The reduction of total volatile compounds in garlic is the result of thermal processing (Kim et al. 2011). Diallyl disulfide decreases after autoclaving and high-temperature aging (aged-back garlic). 2,4-Dimethylthiazole disappears in cooked garlic, while dimethyl disulfide is formed by heat treatment. Diallyl disulfide also dramatically decreases after $\gamma$-irradiation, and then increases during storage (Wu et al. 1996).

Although garlic has health benefits, some people avoid consuming garlic due to its strong and long-lasting flavor. Interestingly, a recent study demonstrates that deodorization of garlic breath aroma can be facilitated by foods and beverages (Munch and Barringer 2014). Concentration of garlic aroma, including ally methyl disulfide, diallyl disulfide, allyl mercaptan, and allyl methyl sulfide, dramatically declines after consumption of apple (raw and microwaved), green tea, parsley, spinach, mint, and lemon juice. The probable cause is polyphenolic compounds, oxidized polyphenols by enzymatic reactions, and acids in foods and beverages.

#### 3.3.1.2 Leek (Allium ampeloprasum L.)

The content of $\text{S}$-alk(en)yl-$\text{L}$-cysteine sulfoxides in white bulb leek is higher than in green upper leaf leek (Doran et al. 2007). The major volatile compounds in fresh leek are 2-methyl-(E)-2-pentenal, hexanal, (E)-2-hexenal, dipropyl disulfide and (E,E)-2,4-decadienal (Nielsen et al. 2003). Total concentration of volatiles decreases after frozen storage for 12 months. Loss of major components is observed over storage time, except for hexanal and (E,E)-2,4-decadienal. Moreover, ketones and alcohols are generated during frozen storage due to LOX activity. Gas chromatography-olfactometry (GCO) analysis shows that (Z)-3-hexenol, propanethiol, allyl methyl disulfide, methyl propyl disulfide, dipropyl disulfide, dipropyl trisulfide, and methyl propyl trisulfide are the odor-active compounds contributing to characteristic aroma of Allium porrum L. (Schreyen et al. 1976a,b).

#### 3.3.1.3 Onion (Allium cepa L.)

Flavor precursors of onion, including pyruvate and alk(en)yl cysteine sulfoxides, are higher in the top/bottom parts of onion compared to the dry brown skin, outer and inner fleshly leaf parts (Bacon et al. 1999). The content of these precursors accumulates during storage at 0°C in the dark (commercial storage condition). Thiopropanal $\text{S}$-oxide is the most abundant HS volatile formed rapidly after slicing yellow onion, and subsequently disappearing (Järvenpää et al. 1998). In contrast, dipropyl disulfide, which cannot be detected at the beginning, becomes the major volatile 170 min after cutting. Onion flavor is also isolated by ethanol and water extractions (Ueda et al. 1994). The major sulfur compounds in ethanol extract of onion are trans-(+)
\footnote{\textit{PeCSO} and its $\gamma$-glutamyl peptide ($\gamma$-Glu-PeCSO). On the
other hand, the boiled water extract of onion contains cycloalliin, a thermal degradation product of 3-Mercapto-2-methylpentan-1-ol has been identified as the potent odourant of onion (Wirder et al. 2000). Its aroma quality at low concentration (0.5 ppb) is meat broth, sweaty, onion, and leek-like, while it is reminiscent quality, at high concentration (1 ppm), is sulfuric, burnt gum, sweaty, and onion-like. Its odor threshold in water is 0.15 µg/L. This compound also presents in shallot, chive, scallion, and leek, but it is not detected in garlic (Granvogl et al. 2004). In addition, its content in cooked samples is significantly higher than in raw plants. Glucose is the predominant sugar in sweet onion (also called short-day onion), followed by fructose and sucrose (Yoo et al. 2012). The concentration of reducing sugars drops during storage at 24°C and 30°C, while sucrose content increases over time.

3.3.2 Asparagaceae

3.3.2.1 Asparagus (Asparagus officinalis L.)

Asparagus stem is a wealth of dietary fiber and vitamins A and C. However, storage at 1°C or 20°C causes significant reduction of flavor acceptability due to loss of sweetness from the spear tips (King et al. 1987). Fructose and glucose are the main sugars in asparagus, and sucrose is the minor sugar the content of which is influenced by cultivars (Brueckner et al. 2010). The volatile flavor components in cooked white asparagus are mainly derived from (1) oxidation of fatty acids, (2) thermal degradation of S-methylmethionine, asparagusic acid, p-coumaric acid, and ferulic acid, and (3) Maillard reactions (Tressl et al. 1977a). The steam distillation extraction of asparagus, followed by Charm analysis, shows the importance of nitrogen- and sulfur-containing compounds (Ulrich et al. 2001). The most potent odorant is 2-methoxy-3-isopropyl pyrazine that is responsible for the green and germ-like notes. In addition, 3-(methylthio) propanal (cooked potato), 2,3-octanedione (mushroom-like), 2,6-dimethyl pyrazine (nutty) and hexanal (green) have moderate potency. Dimethyl sulfide that has been reported as a cooked asparagus note may also contribute to the overall aroma of asparagus.

Asparagus taste has been greatly studied by Dawid and Hafmann (2012a,b, 2014). Taste of raw and cooked asparagus is described as astringent, bitter (off-flavor), sour, salty, sweet, umami, and buttery mouth-coating. The buttry mouth-coating is an effect of sulfur-containing compounds, namely 1,2-dithiolane-4-carboxylic acid 6-δ-α-glucopyranose ester and 1,2-dithiolane-4-carboxylic acid 6-β-β-glucopyranose ester. The recognition taste threshold of the component mixture in 2% aqueous ethanol solution (pH 5.9) is 276.8 µmol/L. Asparagusic acid (1,2-dithiolane-4-carboxylic acid) is responsible for the astringent flavor, and its threshold is 132.9 µmol/L. This acid is a sulfur-containing component derived from l-valine (Tressl et al. 1977b). In addition, bitterness perception is due to the presence of saponins. The bitter saponins identified in white asparagus are 3-O-[α-L-rhamnopyranosyl-(1→2)-α-L-rhamnopyranosyl-(1→4)-β-D-glucopyranosyl]-26-O-[β-D-glucopyranosyl]-25R-22-hydroxyfurost-5-ene-3β,26-diol (protodioscin, 1a), 3-O-[α-L-rhamnopyranosyl-(1→2)-α-L-rhamnopyranosyl-(1→4)-β-D-glucopyranosyl]-26-O-[β-D-glucopyranosyl]-25S-22-hydroxyfurost-5-ene-3β,26-diol (neoprotodioscin, 1b), (25R)-furost-5-ene-3β,22,26-triol-3-O-[α-L-rhamnopyranosyl-(1→4)-β-D-glucopyranoside]-26-O-β-D-glucopyranoside ((25R)-ASP-II, 2a), (25S)-furost-5-ene-3β,22,26-triol-3-O-[α-L-rhamnopyranosyl-(1→4)-β-D-glucopyranosyl]-26-O-β-D-glucopyranoside (ASP-II, 2b), (25R)-furostane-3β,22,26-triol-3-O-[α-L-rhamnopyranosyl-(1→4)-β-D-glucopyranoside]-26-O-β-D-glucopyranoside ((25R)-dihydro-ASP-II, 3a), (25S)-furostane-3β,22,26-triol-3-O-[α-L-rhamnopyranosyl-(1→4)-β-D-glucopyranoside]-26-O-β-D-glucopyranoside ((25S)-dihydro-ASP-II, 3b), 3-O-[[δ-D-glucopyranosyl-(1→2)] [[β-D-xyllopyranosyl-(1→4)] β-D-glucopyranosyl] (25S),5β-spirostan-3β-ol (AS-1, 4), 3-O-[α-L-rhamnopyranosyl-(1→2)-α-L-rhamnopyranosyl-(1→4)-β-D-glucopyranosyl]-25S-spirostan-5-ene-3β-ol (AS-2-I, 5a) and 3-O-[α-L-rhamnopyranosyl-(1→2)-α-L-rhamnopyranosyl-(1→4)-β-D-glucopyranosyl]-25S-spirostan-5-ene-3β-ol (diosein, 5b). The recognition thresholds of 1a/b, 2a/b, 3a/b, 4, and 5a/b in 2% aqueous ethanol solution (pH 5.9) are 65.9, 10.9, 25.5, 199.7, and 70.6 µmol/L, respectively. The key bitter tastants in raw asparagus are monodesmosidic saponins including dioscin (5b) and AS-2-I (5a), while bidesmosidic saponins contribute the bitter
perception in cooked stem. Four major bitter components, after cooking, are protodioscin (1a), neoprotodioscin (1b), (25R)-ASP-II (2a), and ASP-II (2b). Interestingly, the content of mono- and bidesmosidic saponins is low in spear tip as compared to the other parts, but the panelists rate the spear tip with the highest score of bitter intensity. Further research should be conducted to investigate the other bitter compounds.

3.3.3 Gramineae

3.3.3.1 Bamboo (Phyllostachys pubecense)

Bamboo shoot is a budding sprout that is a good source of dietary fiber. Consumption of cooked and fermented young shoot is common in Asia. However, inappropriate cooking process leads unpleasant flavor described as acrid and bitter. Acrid flavor still remains after blanching, but boiling for a longer time can remove it. Bitter taste is present in fresh harvested shoots, and develops during storage. Bitterness of bamboo shoot is due to a natural toxic substance, namely cyanogenic glycoside taxiphyllin (Choudhury et al. 2012).

Volatile compounds in bamboo shoots harvested during spring and winter are comprised of hydrocarbons, aldehydes, ketones, alcohols, esters, ethers, and oximes (Chung et al. 2012). The most abundant HS volatiles as analyzed by solid-phase microextraction (SPME) are methoxy-phenyl oxime, n-hexanol and (Z)-3-hexenal. 1-Octen-3-ol is found in winter bamboo shoot, while esters and ethers are identified in spring shoot. Steaming for 60 min can reduce the content of 1-octen-3-ol, which expresses a mushroom note.

HS aroma of fermented Phyllostachys pubecense shoots is contributed by 29 odorants (Fu et al. 2002). The most potent components, analyzed by Osme time-intensity technique, are p-cresol (responsible for barn-like note), 2-heptanol (mushroom, earthy), acetic acid (vinegar) and 1-octen-3-ol (mushroom, plastic). In addition, methional (potato, fermented), linalool (floral, perfume), and (E,Z)-2,6-nonadienal (cucumber, green) are important aroma-active compounds in fermented product.

3.3.3.2 Sweet Corn (Zea mays L.)

The identified HS volatiles of canned and frozen sweet corn are acetaldehyde, ethanol, acetic, ethanethiol, dimethyl sulfide, and hydrogen sulfide (Flora et al. 1977). Dimethyl sulfide is estimated to be an important aroma compound in cooked corn because of its low odor threshold (Bills and Keenan 1968). It is the degradation product of S-methyl-methionine sulfonium salt. HS concentrations of dimethyl sulfide in cooked sweet corn is 0.43–17.0 ppm, and seems to vary across cultivars, maturities, harvest time, and process (Flora and Wiley 1974). Process is the most important factor causing significant differences in dimethyl sulfide levels. Canning results in fourfold increase of dimethyl sulfide compared to fresh corn, while frozen corn contains a lower content. 2,5-Dimethyl pyrazine (harsh) and 3,6-dimethyl-2-ethyl pyrazine (green, oxidized oil) are the thermally induced off-aromas in canned sweet corn (Lee 1978). Although peroxidase is not deactivated to prevent off-flavor, overall acceptability score of unblanched corn is higher than that of blanched kernel after up to 8 months of frozen storage (Collins et al. 1996). When high β-carotene sweet corn is developed for nutritional purposes, there is concern that some low odor threshold volatiles derived from carotenoids will affect overall aroma. However, a sensory panel could not distinguish the aroma of raw corn containing high carotenoid from white corn with no detectable β-ionone (Gallon et al. 2013). This may confirm the importance of other aroma components in sweet corn.

The overall acceptability of sweet corn is significantly influence by taste and texture, and shows a slight impact from aroma (Azanza et al. 1996). The main sugar in sweet corn is sucrose that constitutes up to 80%–90% of sugars (Olsen et al. 1990). Fructose and glucose are in the minority and present in the same proportion. Total sugars decline over storage time as a result of conversion to starch. Storing sweet corn at higher temperatures leads to a faster degradation rate of sugars. Furthermore, sucrose content in mature sweet corn is lower in comparison to the early harvested and late harvested kernels (Hale et al. 2005).
3.3.4 Brassicaceae

3.3.4.1 Bok Choy (Pac Choi) (Brassica rapa var. Mei Qing Choi)

Trained panelists describe bok choy flavor and texture by 21 attributes (Talavera-Bianchi et al. 2010a). The sensory characteristics are influenced by the stage of planting. The flavor of bok choy at an early stage of development is expressed as green-unripe, musty/earthy, lettuce-like, and sweet. The panelists rate higher intensities of green-grassy/leafy, bitter, cabbage-like, and sulfur attributes in mature bok choy that are a result of glucosinolate-derived compounds. Green-grass/leafy, piney, and pungent flavors are perceived higher in conventional bok choy grown in the field as compared to the high tunnel grown bok choy (Talavera-Bianchi et al. 2010b). The intensity of green-unripe and green-peapod increases during cold storage at 4°C, while that of overall sweet and umami qualities are reduced (Talavera-Bianchi et al. 2011). Moldy is an additional term to express the off-flavor in 18-day stored sample.

HS volatile flavor compounds of bok choy are determined using GC-mass spectrometry (GC-MS) (Talavera-Bianchi et al. 2011). The volatile compounds in high abundance are 4-ethyl-5-methylthiazole, (E)-2-hexenal, 4-isothiocyanato-1-butene and (Z)-3-hexenal. The content of these components, except (Z)-3-hexenal, is higher in organic bok choy in comparison to conventional vegetable. However, changes of volatile compounds in both organically and conventionally grown bok choy during storage have similar trends. For example, the level of volatile flavor compounds related to the green note decreases as storage time progresses.

3.3.4.2 Broccoli (Brassica oleracea L.)

Sulfur compounds are the main HS volatiles of fresh broccoli, of which dimethyl disulfide is the major part (Vidal-Aragón et al. 2009), while pentanol, pentanal, nonanal, hexanal, and heptanal are the dominant volatiles in cooked buds (Hansen et al. 1997). The HS odorants of fresh broccoli with the most impact are 2-methoxy-3-isopropyl pyrazine (pea, earthy), hexanal (green, grassy), 1-penten-3-one (chemical, green), and two unknowns (Ulrich et al. 1998). 2-(Methylthio)ethanol is a minor volatile formed from methionine during boiling (Rössner et al. 2002). This aroma is expected to be a potent odorant (burnt, earthy, sulfury) because of its lower odor threshold (0.1 ppb in water).

Stinky, undesirable odor in broccoli stored under anaerobic atmosphere or low-oxygen condition has been investigated (Forney et al. 1991; Pentima et al. 1995). Methanethiol, dimethyl disulfide, and dimethyl sulfide are identified as the off-flavor compounds. The first two volatiles are generated from l-methionine and S-methylcysteine, while dimethyl sulfide is derived from S-methylmethionine. Hot-water treatment at high temperature (52°C for 3 min) to inhibit yellowness causes formation of off-flavor as well (Forney and Jordan 1998). GCO analysis indicates that (Z)-3-hexen-1-ol, dimethyl trisulfide and dimethyl disulfide are the off-note volatiles in broccoli treated with hot water. The studies of Buck and Joslyn (1953, 1956) also investigate development of off-odor and bitter taste in frozen broccoli when blanching pretreatment is inadequate. Aldehyde content in undercooked broccoli remains about the same during frozen storage, whereas accumulation of acetoin and diacetyl is detected after storage.

The major sugars in broccoli are fructose, followed by glucose, but Chinese broccoli has a reverse trend (Schonhof et al. 2004). The sugar level of broccoli harvested in spring/summer is greater than in summer/winter (Rosa et al. 2001). Furthermore, the content of free sugars, except sucrose, shows greater in secondary inflorescences. The dominant glucosinolates in broccoli are glucoraphanin, followed by glucobrassicin, neoglucobrassicin, and progoitrin (Lewis and Fenwick 1987; Baik et al. 2003), but glucoraphanin is the most abundant component in Chinese broccoli (Schonhof et al. 2004).

3.3.4.3 Brussels Sprout (Brassica oleracea)

Sprout flavor, sweetness, bitterness, earthy, and off-flavor are used to evaluate the sensory flavor profile of frozen Brussels sprouts (Lyon et al. 1988). The external color, internal color, and texture are also included to determine quality. Off-flavor and brownness intensities increase during frozen storage, especially at −6°C. The sensory quality without off-flavor remains the same during storage at −29°C for 140 weeks or at −18°C for 32–40 weeks.
Aroma compounds of Brussels sprouts are mainly derived from MeCSO. Conversion of this precursor to methanethiosulfinate by enzymatic reaction occurs more at basic pH than acidic pH (Marks et al. 1992). Other sulfur-containing flavor compounds, such as dimethyl trisulfide and pyruvate, are also formed via cysteineylase-mediated enzymatic reaction.

The bitterness of Brussels sprouts is due to glucosinolates, namely, sinigrin and progoitrin (van Doorn et al. 1998). Glucobrassicin, glycoiberin, glucoraphanin, gluconapin, glucoalyssin, 4-methoxyglucobrassicin, and neoglucobrassicin are also present in Brussels sprouts with glucobrassicin being the most abundant in sprouts from Australia and the United States (Zabaras et al. 2013). In addition, this study shows that bitterness is influenced by sugar content. Brussels sprouts contain 12.6 mg/g of free sugars. Fructose and glucose are the major free sugars, followed by sucrose. Adding sucrose, saccharin, aspartame, or sucralose suppresses bitterness of Brussels sprouts (Wilkie et al. 2013). Sucrose and sucralose can increase acceptability of the sprouts as well.

3.3.4.4 Cabbage (Brassica oleracea L.)

The majority of volatile chemical classes in cabbage are sulfur-containing compounds and saturated alcohols (MacLeod and Nussbaum 1977). The most abundant volatile is dimethyl sulfide that accounts for 34% of total volatiles. The other major components are allyl isothiocyanate, 1-cyano-2,3-epithiopropane, methanol, acetaldehyde, acetone, propanal, 3-pentanone, and (Z)-3-hexenol (MacLeod and Nussbaum 1977; Chin et al. 1996). Ally isothiocyanate and hydrogen sulfide are promptly generated after disruption of cabbage tissue (Chin and Lindsay 1993). The latter volatile disappears after 40 min, while accumulation of subsequent reaction products, namely dimethyl disulfide and dimethyl trisulfide, is observed until 100 min. In addition, methanethiol-related compounds are formed after 10 min. Allyl isothiocyanate, derived from sinigrin, is noted as a potent odorant in fresh cabbage because of its high odor unit and characteristic note (pungency, cabbage-like) (Chin et al. 1996). Although dimethyl trisulfide and 2,4-decadienal are the minor volatile components in cabbage, they are high potent contributors of cabbage aroma when considering their very low-odor threshold values in water (0.01 and 0.07 ppm, respectively) (Buttery et al. 1976a).

3.3.4.5 Cauliflower (Brassica oleracea L.)

The main volatile classes in Romanesco cauliflower are sulfur-containing compounds and fatty acid-derived compounds that contribute to the green note (Valette et al. 2003). The highest concentration of volatile in fresh cauliflower is dimethyl disulfide, followed by dimethyl trisulfide and (Z)-3-hexenol. Dimethyl disulfide and dimethyl trisulfide are also the major compounds in ripening and frozen inflorescence, while (Z)-3-hexenol content is very low. The major volatiles in vacuum steam distilled cauliflower are 3-methylthiopropyl isothiocyanate and nonanal (Buttery et al. 1976a). Dimethyl trisulfide, however, is more important since its odor threshold in water is very low (0.01 ppb). The potency of nonanal should also be considered since it presents at high concentration and its odor threshold is 1 ppb. In contrast, ally isothiocyanate (odor threshold 375 ppb) and but-2-enyl isothiocyanate (threshold 380 ppb) are probably not contributors of cauliflower overall aroma.

Bitterness, sweetness, cauliflower flavor, green/grassy flavor, pungent flavor, crispiness, juiciness, bitter aftertaste, and pungent aftertaste are used to describe the sensory quality of white, green, pyramidal, and purple cauliflower (Brückner et al. 2005). Among these attributes, sweetness, juiciness, and cauliflower flavor are the most important descriptors for consumer preference. The bitterness off-flavor in cooked cauliflower is due to its various glucosinolates. The most potent odorants in sulfur off-note cauliflower are allyl isothiocyanate (sulfur, garlic, pungent), dimethyl trisulfide (sulfur, cauliflower, cabbage), dimethyl sulfide (cabbage, cooked cauliflower), and methanethiol (sulfur, cooked cabbage) (Engel et al. 2002). These aroma-active compounds are derived from MeCSO, S-methylmethionine and sinigrin. The sulfur characteristic may also be contributed by methyl ethyl sulfide, dimethyl disulfide, and butyl isothiocyanate.

3.3.4.6 Kale (Brassica oleracea L.)

Volatile in kale leaves are classified into alcohols, aldehydes, esters, ketones, norisoprenoid derivatives, terpenes, and sulfur- and nitrogen-containing compounds (Fernandes et al. 2009). The number of volatile
components rises during the planting stage, particularly aldehydes, esters, ketones, norisoprenoid derivatives and terpenes. Some compounds present only in mature leaves, such as \((E,E)-2,4\)-heptadienal, \((E,Z)-2,6\)-nonadienal and eucalyptol. On the other hand, isothiocyanates and nitrogen-containing compounds almost fade in fully developed leaves. The content of these compounds accumulates during germination to sprout, and then disappears. Only three sulfur- and nitrogen-containing volatiles, namely allyl isothiocyanate, phenylethyl isothiocyanate, and benzothiazole, can be detected in mature leaves.

3.3.4.7 Radish (Raphanus sativus L.)

Radish is a common vegetable, and white radish is widely consumed in Asia as fresh and dried root. The volatile constituents in fresh radish root are in glycoside and free forms (Blažević and Mastelić 2009). The volatile profile extracted by hydrodistillation is comprised of alkanes, alcohols, aldehydes, fatty acids, esters, isothiocyanates, nitriles, and other sulfur- or nitrogen-containing compounds. The major components are hexadecanoic acid, 4-(methylthio)butyl isothiocyanate, methyl linolenate, 5-(methylthio)-4-pentenenitrile, dimethyl trisulfide, 5-(methylthio)pentyl isothiocyanate, 4-(methylthio)-3-butenyl isothiocyanate, and 2-phenylethyl isothiocyanate. The pungent flavor of radish has been studied (Coogan et al. 2001; Coogan and Wills 2002, 2008). The pungent aroma, 4-methylthio-3-transbutenyl isothiocyanate, accumulates during growing and then declines. The maximum level is detected in 9-week root planted in fall and winter, and 13-week root growth during spring and summer. This pungent compound decreases after the drying process being affected by the drying temperature.

3.3.4.8 Rocket Salad (Diplotaxis and Eruca spp.)

Rich peppery taste is the flavor characteristic of rocket salad (Eruca vesicaria) and wild rocket salad (Diplotaxis tenuifolia) (Pasini et al. 2011). The sensory flavor profile of rocket salad includes herbaceous aroma, bitterness, and pungency. These flavor attributes are related to the content of a phenolic compound, namely kaempferol-3-(2-sinapoyl-glucoside)-4′-glucoside. Although progoitrin/epiprogoitrin is a minor glucosinolate in rocket salad, this substance and dimeric glucosativin (common glucosinolate in this vegetable) are responsible for its bitter taste. The amount of total glucosinolates correlates strongly with pungency flavor.

3.3.4.9 Turnip (Brassica oleracea)

With turnip or kohlrabi, it is the stem that is usually consumed as a cooked vegetable. Dimethyl trisulfide is the most abundant aroma compound in green turnip, followed by dimethyl disulfide (MacLeod and MacLeod 1990). However, 57% of total volatile content is glucosinolates and derived compounds. Several glucosinolates are detected in green turnip, and the major components are 4-(methylthio)butylglucosinate, 3-(methylthio)propylglucosinolate and 2-phenethylglucosinolate. Green turnip flavor is characterized by 16 attributes, such as green/grassy, mustard oil/mustard greens, smoky, peppery/pungent, sweet potato, boiled cabbage/sulfur, bitter, and salt (Jones and Sanders 2002). The variety and maturity impact on the intensity of bitterness, as well as mustard oil/mustard greens flavor.

3.3.5 Chenopodiaceae

3.3.5.1 Beet (Beta vulgaris L.)

Off-flavor of beet puree that usually occurs after processing has been described as bitter, burnt, medicinal, metallic, and phenolic. Shallenberger and Moyer (1958) reported the presence of pyrrolidonecarboxylic acid (PCA) in bitter puree sample. This acid is the degradation product of glutamine. The study demonstrates that sensory panelists can differentiate between the flavors of puree that contains 50 mg PCA (in 100 g sample) and nonbitter puree. Increasing concentration of PCA to 200 mg/100 g puree leads to off-flavor. In addition, the panel describes salt aqueous solutions of PCA as bitter or medicinal.
3.3.5.2 Spinach (*Spinacia oleracea* L.)

Sensory characteristics including bitterness, sweetness, sourness, green/grassy, earthy, musty, nutty, decayed, burn, and astringent are used to evaluate the flavor quality of fresh baby spinach treated with electron beam irradiation during storage (Neal et al. 2010). The acceptability of spinach is related to the level of 6-n-propylthiouracil that is responsible for bitter taste (Turnbull and Matisoo-Smith 2002). The main aroma compounds in spinach leaves obtained by simultaneous distillation-extraction are (*E*)-2-hexenal and (*E*)-2-hexenol (Näf and Velluz 2000). The additional degradation products from fatty acids that contribute green note, such as hexanal, (*Z*)-3-hexenal, (*Z*)-2-hexenal, hexanol, (*E*)-3-hexenol, and (*Z*)-3-hexenol are identified. The spinach extract also contains sulfur-containing aroma-active compounds. The potency of odor-active compounds in raw and boiled spinach is also studied (Masanetz et al. 1998). The most potent odorants in raw spinach are (*Z*)-3-hexenal (green, grassy), methanethiol (cabbage-like) and (*Z*)-1,5-octadien-3-one (geranium-like), whereas dimethyl sulfide (cabbage-like, spicy), methanethiol, dimethyl trisulfide (sulfurous, cabbage-like), methional (boiled potato), and 2-acetyl-1-pyrrrole (roasty) have high potency in boiled spinach. Off-flavor is detected in dried spinach stored for 7–11 months. It is expressed as sulfurous/cabbage-like, malty, buttery, grassy/green, metallic, hay-like/strawy and fishy. The off-flavor compounds are identified by the application of HS dilution technique and odor activity value. A mixture of (*Z*)-1,5-octadien-3-one and methional at a ratio 1:100 causes an undesirable fishy note, and 3-methyl-2,4-nonanedione is responsible for hay-like. Extraordinarily, the fishy note in fresh spinach is also a result of trimethylamine (TMA) that is usually found in fish (Shim and Baek 2012). The formation of TMA occurs at only basic pH.

3.3.6 Compositae (Asteraceae)

3.3.6.1 Globe Artichoke (*Cynara scolymus*)

The immature flower bud is the edible part of globe artichoke that is usually eaten as a cooked vegetable. The abundant volatiles in cooked artichoke are β-selinene and caryophyllene both of which are sesquiterpenes (Buttery et al. 1978). When relative odor unit is taken into account, oct-1-en-3-one (mushroom-like) is the most potent odorant because of its extremely low-odor threshold (0.005 ppb in water). The other important odorants are hex-1-en-3-one, decanal, non-trans-2-enal, and phenylacetaldehyde.

It has been noted that drinking water after eating artichoke can induce sweetness of water. The reason is the presence of active compounds in artichoke (Bartoshuk et al. 1972). Chlorogenic acid (3-cafeoylquinic acid) and cyanarin (1,5-dicaffeoylquinic acid) are extracted from the buds, and the potassium salts of these acids have been evaluated by sensory panels. These active compounds are not sweet, but they can induce sweetness by modifying the tongue. The mechanism is not proposed, so it should be considered for further study.

3.3.6.2 Jerusalem Artichoke (*Helianthus tuberosus* L.)

This plant is eaten as raw or cooked vegetable for nutty flavor and crispness. It is rich in prebiotic inulin, which is a fructose polymer. The organoleptic test of raw and boiled Jerusalem artichoke has been evaluated (Bach et al. 2013b). Typical flavor of Jerusalem artichoke, green nut flavor, sweetness, and color descriptors are highly correlated with acceptability of raw tube, while celeriac aroma, sweet aroma, sweetness, and color attributes relate to the liking score of boiled artichoke. Among several flavor attributes, sweetness is positively correlated to acceptability. The total sugar content in Jerusalem artichoke ranges from 18.1 to 20.8 g/kg edible part, and the level of total sugar and fructose is not affected by boiling. Fried aroma is added to describe the flavor quality of baked tube (Bach et al. 2013a). Loss of pea flavor can be used to differentiate baked tube from boiled tube, and presence of celeriac aroma can be used to discriminate cooked tube from raw tube.

3.3.6.3 Lettuce (*Lactuca sativa*)

(*Z*)-3-Hexenal, (*E*)-2-hexenal, (*Z*)-3-hexenol, elemene/caryophyllene, and 2-methoxy-3-isopropylpyrazine are identified as aroma-active compounds in iceberg lettuce that responsible for green leafy note (Deza-Durand and Petersen 2014). Lettuce grown in warmer temperatures and lower precipitation has a high
level of 2,3-butanedione (sweet, caramel), β-selinene (spoiled vegetables, flowers), caryophyllene and β-elemene (strong chemical, grass, chili). In contrast, cooler weather and longer hours of sunshine induce biogenesis of 2-methoxy-3-isopropylpyrazine (grass, soil) and dimethyl sulfide (off-odor, broccoli, shellfish). During storage, over-mature lettuce produces a higher level of six-carbon aldehydes than mature leaves, and branch chain aldehydes become the major group. 1-Penten-3-ol (flower) disappears after 1-day storage, while β-selinene (spoiled vegetables, flowers) is observed in 11-day stored lettuce. The level of (Z)-3-hexenol of iceberg lettuce packed in a low oxygen modified atmosphere also increases over storage time (Tudela et al. 2013). Dramatic increase of (Z)-3-hexenal, β-elemene, ethyl acetate, and dimethyl sulfide results in unpleasant overall flavor. Among various volatiles, dimethylphenol and ester pentanoic acid can be used as freshness biomarkers of butterhead lettuce packed in modified atmosphere, whereas (Z)-3-dodecene and β-elemene are used as quality loss indicators (Lonchamp et al. 2009).

### 3.3.7 Convolvulaceae

#### 3.3.7.1 Sweet Potato (Ipomoea batatas L.)

The high abundance volatile components in baked sweet potato are furfuraldehyde, benzaldehyde, nonanal, and β-ionone (Purcell et al. 1980). Furan and its derivatives also present after baking as the result of an increase of carbonyl groups from starch conversion. Diacetyl (buttery), n-hexane (objectionable), 2-furyl methyl ketone (baked potato), trimethylbenzene (carnation, milkweed), 2-pentylfuran (fresh flower, pungent aroma), and β-ionone (violet) are intense odorants in baked sweet potato (Tiu et al. 1985).

Overall acceptability of baked sweet potato is positively correlated with sweetness (Chan et al. 2012). Sucrose is the major sugar component in raw sweet potato. Glucose, fructose, and maltose are present in the tube as well. Significant increase of maltose content is detected after baking. Although maltose turns into the main sugar in baked sweet potato, the overall liking is related to sucrose concentration. Sensory flavor characteristics of boiled sweet potato are earthy, sweet potato aroma and flavor, burn, yellow vegetable/pumpkin flavor, brown sugar, dried apricot/floral, vanilla, sweet, sour, bitter, umami, and astringent (Leighton et al. 2010; Leksrisompong et al. 2012). The intensity of sweetness and yellow vegetable flavor in orange-fleshed sweet potato is higher than the white-fleshed variety. Similarly, cooked orange-fleshed sweet potato has a higher pumpkin-like flavor and sucrose level compared to cooked cream-fleshed tube (Laurie et al. 2013). Earth aroma is also rated at higher intensity in baked orange sweet potato than in purple and yellow varieties (Leksrisompong et al. 2012). The baked yellow potato does not have sourness, and only baked purple tuber has bitterness and umami. In addition, the intensity of sweetness and chestnutty flavor in sweet potato dramatically decreases after 7-day storage at 26°C (van Oirschot et al. 2003).

### 3.3.8 Cucurbitaceae

#### 3.3.8.1 Cucumber (Cucumis sativus L.)

Biogenesis of saturated and unsaturated aldehydes in cucumber from fatty acids is well discussed by Phillips and Galliard (1978). (Z)-3-Nonenal and hexanal are derived from linoleic acid, while (Z,Z)-3,6-nonadienal and (Z)-3-hexenal are generated from linolenic acid. Subsequent enzymatic reactions convert (Z)-3-aldehydes to (E)-2-nonenal, (E,Z)-2,6-nonadienal and (E)-2-hexenal. Propanal in cucumber is also a degradation product of linolenic acid (Grosch and Schwarz 1971).

Among numerous compounds, (E)-2-nonenal and (E,Z)-2,6-nonadienal are the most abundant volatiles and recognized as cucumber flavor (Kemp et al. 1974; Palma-Harris et al. 2001; Sotiroudis et al. 2010). The stability of latter aroma and activity of enzymes extracted from cucumber fruit has been studied (Buescher and Buescher 2001). (E,Z)-2,6-nonadienal is developed by endocarp tissue greater than mesocarp, and a sevenfold lower level is produced by exocarp tissue. The optimum pH for enzymatic reaction is 5.7–7.0. The stability of this volatile is pH and temperature dependent. The aroma compound in cucumber juice (pH 5.8) almost disappears after storage at 5°C for 14 days, while a 35% loss is detected in juice acidified to pH 2. The degradation rate of this odorant in juice stored at 5°C is about fourfold lower as compared to 25°C. (E)-2-Nonenal is also not stable. The content of (E)-2-nonenal and (E,Z)-2,6-nonadienal in cucumber juice decreases more than 90% after 4 h at 30°C (Cho and Buescher 2011).
Cold storage influences the volatile profile of cucumber fruit. The content of \((E, Z)-2,6\)-nonadienal and \((E)-2\)-nonenal significantly decreases during storage at 4.4°C, while an increase of 2-hexenal and hexanal is observed (Geduspan and Peng 1986).

### 3.3.8.2 Pumpkin/Squash (Cucurbita maxima)

Although pumpkin fruit is consumed worldwide, there is little information on its flavor. Some studies have determined the volatile compounds in pumpkin seeds. Kebede et al. (2014) reported the HS volatiles including aldehydes, alcohols, and terpenes in blanched and cooked pumpkin. These compounds are derived from carotenoid degradation, unsaturated fatty acid degradation, and Strecker degradation. 2-Methylbutanal and 3-methylbutanal, the Strecker degradation products, are induced by thermal processing. Nonanal and hexanal generated from oxidative degradation reactions of unsaturated fatty acids are significantly increased by high pressure high temperature treatment (HPHT) in comparison to the conventional thermal process.

Acceptability of buttercup squash is influenced by sweetness (Corrigan et al. 2000). The major sugars in various buttercup squash cultivars are glucose and fructose, followed by sucrose. The proportion of glucose and fructose is about 1:1. Although sucrose is the minor sugar, its content highly correlates with sweetness intensity. Sucrose content declines during storage, accompanied by an increase of glucose and fructose.

### 3.3.9 Leguminosae

#### 3.3.9.1 Edamame (Glycine max (L.) Merrill)

Attributes used to express flavor of edamame (green vegetable soybean) are raw bean, cooked bean, green complex, fruity complex, nutty/almond, brothy, sulfur, salty, sweet, sour, bitter, umami, astringent, and metallic (Krinsky et al. 2006). Bitterness is probably due to saponins and isoflavonoids that have been identified in soybean products. Sweet taste of edamame is contributed by sucrose content. The major free sugar in edamame is sucrose, followed by maltose, fructose, and glucose (Sugimoto et al. 2010). Concentrations of these sugars deteriorate during storage. In addition, sweetness and chewiness vary among different varieties (Wszelaki et al. 2005).

#### 3.3.9.2 Green Bean (Phaseolus vulgaris L.)

Degradation compounds from fatty acids are the major volatiles found in fresh green beans (also called French beans, dry beans, and common beans). Among them, hexanal is the most abundant HS volatile (Oomah et al. 2007). Odor-active compounds in rehydrated green beans are 2-methylpropanal (chocolate), 2-/3-methylbutanal (chocolate, sweet), 2,3-butanedione (caramel), hexanal (grassy), 2-methyl-2-butenal (sweet, chemical), 1-octen-3-one (mushroom, metal), and dimethyl trisulfide (rotten, metal) (van Ruth et al. 1996a). Increasing of rehydration time leads to higher levels of 2-butenal, 2-methyl-2-butenal, and 1-octen-3-one (van Ruth et al. 1996b). The flavor characteristics of green bean treated with \(\gamma\)-irradiation at 1–2 kGy are not significantly different from the untreated bean (Armelim et al. 2006). Conversely, decrease in burned, bitter, fresh, metallic, and warmed up flavors is a result of high-dose usage.

#### 3.3.9.3 Pea (Pisum sativum L.)

The major volatile constituents of lipid-derived compounds, particularly six-carbon atoms, are the major HS volatiles in blanched green peas (Jakobsen et al. 1998). Hexanal (green, strong) is the key aroma-active compound that presents in highest concentration. Additional odor-active compounds are hexyl acetate (sweet, perfume), octanal (orange, sweet), 1-octen-3-one (mushroom, strong), dipropyl disulfide (sulfurous, sour), 3-isopropyl-2-methoxyprazine (pea pod, bell pepper, blanched peas), 5- or 6-methyl-3-isopropyl-2-methoxyprazine (dry grass, spruce), 3-sec-butyl-2-methoxyprazine (green) and 3-isobutyl-2-methoxyprazine (green, peas, bell pepper). 1-Propanol, 1-butanol, 1-pentanol, 2-penten-1-ol, 3-octen-1-ol, 1-heptanol, 3-hepten-1-ol, 2-hepten-1-ol, and 2-octen-1-ol are also major constituents of distilled green peas (Shipton et al. 1969).

Blanching peas by steam, water, and microwave before freezing causes changes in the flavor profile (Lin and Brewer 2005). In general, blanching leads to an increase of potato aroma and flavor and a
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decrease of fruity aroma, umami, bitter flavor, and astringency. There is, however, no significant difference in terms of grainy aroma, sulfur aroma, grassy aroma, earthy aroma, sweetness, fruity flavor, and buttery flavor. Bitterness of dry peas is due to monodesmoside saponins, namely 2,3-dithydro-2,5-dihydroxy-6-methyl-4H-pyran-4-one and saponin B. The former bitter component presents at a higher level than the latter in all varieties (Heng et al. 2006). In addition, this tastant is perceived more bitter than saponin B.

3.3.9.4 Petai Bean (*Parkia speciosa*)

Petai bean or stink bean is widely consumed in Southeast Asia. 1,2,4-Trithiolane is the most abundant and highest intensity aroma compound in cooked petai beans (Frérot et al. 2008). The other potent odorants are 1,3-dithiabutane, 1,2,4,5-tetrathiane, 1-octen-3-one, and 1,2,4,6-tetrathiepane.

3.3.10 Malvaceae

3.3.10.1 Okra (*Hibiscus esculentus* L.)

Okra originates in Africa. Its green pods (immature fruit) are eaten as a vegetable or used as a thickening agent (Ames and Macleod 1990). The overall perception of okra extract in this study is described as green, slightly cereal-like and floral. Monoterpenes are the major class of volatile in okra. Pyrroles, pyrazines, and other furan derivatives are also identified. 2-Methoxy-4-vinylphenol (*p*-vinylguaiacol) is the most abundant aroma compound having musty, linseed oil and camphor characteristic notes. Additional main aroma components are dimethyl sulfide (decaying vegetables, cabbage-like, sulfurous), pyridine (unpleasant, pyridine-like), 2-actylfuran (burnt, fetid), 5-methyl-2-furaldehyde (roasted, gravy-like), linalool (sweet, fruity, floral), eugenol (roasted, cloves, musty), β-damascenone (sap-like, green, rotting grass, compost), and β-caryophyllene (fruity, hay-like, unroasted cereal).

Boiled okra prepared from fresh, frozen, and rehydrated pods are evaluated using a 9-point hedonic scale (Falade and Omojola 2010). Aroma and taste of rehydrated okra are rated as less appreciated than those of fresh. On the other hand, freezing does not affect the aroma acceptability of okra. Blanching okra before drying can decrease the intensity of hay-like aroma and flavor (Stone et al. 1986). Moreover, blanched okra, as reported by sensory panels, is sweeter than unblanched pods.

3.3.11 Solanaceae

3.3.11.1 Pepper (*Capsicum annuum* L.)

Formation of aroma compounds related to the green note occurs quickly in jalapeno pepper, and the maximum level of these volatiles is detected within a couple of minutes after tissue disruption (Azcarate and Barringer 2010). Volatile sulfur compounds, including aliphatic saturated and unsaturated thiols, and mercapto-ketones are identified in red bell pepper as well (Naef et al. 2008; Starkenmann and Niclass 2011). 2-Methoxy-3-isobutylpyrazine is a major aroma in distilled green bell pepper (Buttery et al. 1969). It is thought to be the most important aroma compound because of its extremely low odor threshold (0.002 ppb in water) and aroma description (green bell pepper-like). Another important aroma compound in bell pepper is 4-butyl-5-propylthiazole with bell pepper note and 0.003 ppb odor threshold in water (Buttery et al. 1976b).

Bitterness, grassy, and cucumber-like are main sensory characteristics of green bell pepper, while red pepper is rated higher in sweetness and sourness (Luning et al. 1994a). Green bell pepper has a larger content of volatile compounds than red bell pepper (Wampler and Barringer 2012). The odor-active compounds related to green note, such as (Z)-3-hexenal, (Z)-3-hexenol, 1-hexanol, 2-sec-butyl-3-methoxy pyrazine and linalool in green bell pepper decrease during ripening, and lose aroma potency at red stage (Luning et al. 1994b). Whereas the potency of 3-carene (red/green bell pepper, rubbery) and 2-isobutyl-3-methoxy pyrazine (green/red bell pepper, lettuce) remains the same in all maturations (green, turning and red). Another study shows a 70% reduction of LOX activity as green pepper turns to
red pepper (Luning et al. 1995). Decrease of most volatiles as well as increase of (Z)-3-hexenal, (E)-2-
hexenal, hexanal, hexenol, and hexanol at early frozen storage is detected in whole blanched pepper
(Azcarate and Barringer 2010). Most volatile compounds decrease after blanching, particularly (Z)-3-
hexenal (Wampler and Barringer 2012).

3.3.11.2 Potato (Solanum tuberosum L.)
Glutamate and 5′-guanosine monophosphate (5′-GMP) are the most important umami components in
potato flavor (Morris et al. 2007). The level of 5′-GMP and 5′-adenosine monophosphate (5′-AMP)
increases during boiling and steaming. The main volatile constituents in potato are 1-octen-3-ol, (E)-2-octenal, (E)-2-octenol, geraniol, 2-pentylfuran, phenylacetaldehyde, (E)-2-nonenal, furfural, hexanal, and pyridine (Buttery et al. 1970). In
addition, methyl mercaptan and dimethyl disulfide are abundant volatiles, among several sulfur-containing
compounds, in cooked potato (Gumbmann and Burr 1964). Volatile aroma compounds in baked potato are
mainly derived from lipid oxidation and Maillard reaction. 2-Isobutyl-3-methoxy-pyrazine, 2-isopropyl-
3-methoxy-pyrazine, β-damascenone, dimethyl trisulfide, decanal and 3-methylbutanal contribute baked
potato flavor (Pareles and Chang 1974; Duckham et al. 2001). In contrast, the typical aroma of boiled potato
is significantly influenced by methional (boiled potato), trans-4,5-epoxy (E)-2-decenal (metallic), Furaneol
(caramel-like), sotolon (spicy, seasoning-like), vanillin (vanilla-like), dimethyl trisulfide (sulfury), dimethyl
sulfide (sulfury), and 3-isopropyl-2-methoxy-pyrazine (green, pea-like) (Mutti and Grosch 1999).
2-Methoxy-3-isopropylpyrazine is the key volatile responsible for typical earthy aroma (Buttery and
Ling 1973). The severe off-flavor, addressed as earthy, musty, and potato bin-like, is due to the charac-
teristic notes of 2-octenal, 2-methoxypyrazine, and several unidentified compounds (Mazza and Pietrzak
1973). Musty off-odor in potato is a result of 2,4,6-trichloroanisole that develops from pesticide-treated
soil (Daniels-Lake et al. 2007). Off-flavor is also detected in boiled potato as well. Off-note of boiled
potato, defined as cardboard-like, occurs after storage (Petersen et al. 1999). Application of GCO and
reconstruction model reveals that eight key odor-active compounds, namely pentanal, hexanal, nonanal,
(E)-2-octenal, (E,E)-2,4-heptadienal, (E)-2-nonenal, (E,E)-2,4-nonadienal, and (E,E)-2,4-decadienal, are
responsible for this objectionable odor. Cardboard off-flavor note in boiled potato is also associated with
a high level of 2-pentenal, 2-hexenal, 2-heptenal, 2-pentylfuran, and 2-decenal (Blanda et al. 2010). Using
sodium pyrophosphate before storage can prevent the off-note without causing any other undesirable fla-
vors. Storing boiled potato at lower temperatures can also reduce the formation of volatiles derived from
lipid oxidation (Blanch et al. 2009). Furthermore, lower temperature results in higher sugar content.

3.3.11.3 Tomato (Solanum lycopersicum L.)
Sensory attributes, including aromas (tomato, browned, cardboard, decaying vegetation, green-viney), flavors
(tomato, browned, cardboard, fermented, fruity, green-viney, musty/earthy, ripeness, cooked, umami), basic
tastes (bitter, chemical, overall sweet, salty, sour, sweet), and mouthfeels (astringent, chemical, metallic), are
developed to describe the flavor of fresh and processed tomatoes (Hongsoongnern and Chambers IV 2008). The
most abundant HS volatiles in fresh tomato are 6-methyl-5-hepten-2-one, followed by acetaldehyde
and benzyl alcohol (Marković et al. 2007). The former compound also presents at highest concentration in
tomato products including juice, paste, puree, and canned diced tomatoes. Furthermore, (Z)-3-hexenal is
detected only in fresh tomato, while furfural presents only in tomato products. Other research reveals that
the major volatile components in common and cherry tomatoes are six-carbon aldehydes and alcohols (Zhang
et al. 2008). Hexanal, (E)-2-hexenal and (E)-2-octenal are abundant volatiles in both tomatoes. The different
between common and cherry tomatoes is that 6-methyl-5-hepten-2-one and (E,E)-2,4-hexadienal are higher
in common tomato, whereas 3-hexenol and 1-hexanal are larger in cherry tomato. Xu and Barringer (2010)
studied tomato volatiles in mouth after swallowing. The results indicate that methylbutanal, hexanal and
nonanal last longer than (Z)-3-hexenal, (E)-2-hexenal, 1-penten-3-one and isobutyl alcohol.
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The important aromas in tomato are 3-methylbutanal, hexanal, (E)-2-hexenal, (Z)-3-hexenal, (Z)-3-hexenol, 1-penten-3-one, 1-octen-3-one, methional, β-damascenone, β-ionone, trans-4,5-epoxy-(E)-2-decenal and Furaneol (Buttery et al. 1987; Krumbein and Auerswald 1998; Mayer et al. 2008). Methional is a degradation product of methionine, while trans-4,5-epoxy-(E)-2-decenal converts from linoleic acid (Mayer et al. 2008). Furaneol is a potent odorant in processed tomato as well (Buttery et al. 1995). Its odor threshold in water is pH-dependent (60 ppb at pH 7, 31 ppb at pH 4.5, and 21 ppb at pH 3).

Volatile aroma compounds in tomato also present in glycoside form. Rhamnos is the main sugar of glycoside volatiles, followed by arabinose, glucose, and xylose (Ortiz-Serrano and Gil 2010). The major glycoside components are 3-methylbutyric acid, hexanal, (E)-2-hexenal, phenylacetaldehyde, β-damascenone, 4-vinylguaiacol, 2-phenylethanol, benzyl alcohol, and 2-methyl-1-butanol (Buttery et al. 1990; Marlatt et al. 1992). Both bound and free volatiles in tomato develop during ripening (Ortiz-Serrano and Gil 2010). Hexanal, (Z)-2-hexenal, 2-iso-butythiazole, 2-methyl-2-hepten-6-one, geranylacetone, and farnesylacetone increase during ripening (Hayase et al. 1984). Volatile aroma compounds, particularly (Z)-3-hexenal, accumulate mainly in pulp and skin (Buttery et al. 1988). Cold storage at 2°C influences reduction of (Z)-3-hexenal in fresh tomato (Buttery et al. 1987). Volatile compounds in dehydrated cherry tomato, including 1-butanol, 2-methyl-2-butenal, 3-hydroxy-2-butanol, furfural, and acetoinitrile, are the degradation products of carotenoids, fatty acids, and Maillard reactions (Heredia et al. 2012).

3.3.12 Umbellifarae

3.3.12.1 Carrot (Daucus carota L.)

Mono- and sesquiterpenes are the major volatile components in carrots. Terpinolene is the most abundant volatile compound accounting for 38% of total volatiles in steam distilled carrot (Buttery et al. 1968). However, 2-nonenal has a higher potency because its odor threshold in water (0.08 ppb) is very low in comparison to terpinolene (200 ppb). Terpinolene, as well as γ-terpinene, β-caryophyllene and (E)-γ-bisabolene, are also highly abundant compounds in purple, orange, red, yellow, and white carrots (Kreutzmann et al. 2008b). GCO analysis and odor activity value indicate that sabine, β-myrcene, and p-cymene, which have carrot-top note, may contribute to the characteristic of carrot flavor (Kjeldsen et al. 2003). One unknown is evaluated by GCO as moderately intense raw carrot-like, and considered to be a contributor of carrot aroma (Buttery et al. 1979). It was recently identified as linden ether (3,9-epoxy-1,4-(8)-p-menthadiene), and it is proved to be the most potent odorant in cooked carrot (Buttery and Takeoka 2013). The additional impact odorants are β-damascenone, β-ionone, heptanal, (E)-2-nonenal, and (E,E)-2,4-decadienal.

There is a lot of research on what influences carrot flavor. Accumulation of terpenes is higher in the root crown than in the middle and tip parts (Simon et al. 1980). Higher planting temperature increases the concentration of terpenes, such as α-terpinene, β-myrcene, trans-caryophyllene, farnesene, and α-humulene (Rosenfeld et al. 2002). Accumulation of these terpenes enhances bitterness, but suppresses sweet taste perception. In contrast, extension of the harvest time results in an increase of sweetness and a decrease of bitterness (Suojala and Tupasela 1999). Formation of aldehydes from lipid degradation and reduction of terpenes are observed in 3-month stored carrots (Varming et al. 2004). Furan content in carrot increases during air-drying, while most other volatiles decrease (Duan and Barringer 2012). In addition, the generation rate of furan is higher when the moisture content is below 40%.

Undesirable flavors of carrot have been studied. Ink-like and harsh off-flavors of carrot are related to high content of monoterpenes (Fukuda et al. 2013). Eugenin, gazarin, 6-methoxymellein, falcarniol, falcarnidiol, and falcarnidiol 3-acetate are the major bitter taste components in carrot (Czepa and Hofmann 2003). Among these constituents, falcarnidiol is the most important bitter tastant. In contrast, eugenin and gazarin are not considered to be the key compounds because of low concentration and high taste threshold. High accumulation of falcarnidiol and other polyacetylenes, except falcarniol, is detected in the peel of raw carrot root (Kreutzmann et al. 2008a). The study also shows that the bitterness of carrot is suppressed by high content of sugars. Sucrose is the major sugar in carrot, followed by fructose, glucose, and maltose (Rosenfeld et al. 2002). Proportion of fructose and glucose is about the same. Sugar content increases as the growing temperature increases.

Flavor characteristics such as earthy, fruity, nutty, sweetness, and bitterness are used to distinguish between cultivars and planting locations (Varming et al. 2004). Purple root has a higher intensity of
sickly sweet and nutty flavors, but lower level of terpene aroma, green note, bitterness, and burning aftertaste (Kreutzmann et al. 2008b). While strong intensity of carrot, green, terpene, bitterness, and burning is perceived in red carrot.

### 3.3.12.2 Celery (Apium graveolens L.)

Celery leaves and stems are eaten as both raw and cooked vegetables. MacLeod et al. (1988) isolated volatile aroma constituents in fresh celery by high vacuum-low temperature distillation. The main volatile components, comprising of 70% of total volatiles, are 3-butyltetrahydrophthalide (sedanodile), 4,7-dimethoxy-5′-(prop-2-enyl)benzo-1,3-dioxolan (apiole), and 3-butyphthalalde. Limonene, myrcene, and γ-terpinene are also present in high concentration (MacLeod and Ames 1989; Tirillini et al. 2004). From GCO analysis, the several odor-active compounds having a celery note are alkyl phthalide, 3-butyhexahydrophthalalde, methyl 6-pentanoylcyclohex-1-enoe, (Z)-3-butyldenedephalthalide, phthalide, (E)-3-butilidenehalthalide, 3-butil-4,5-dihydrophthalalde (sedanenolide), cis-3-butil-3a,4,5,6-tetrahydrophthalide (cis-sedanalide), (Z)-3-butilidene-4,5-dihydrophthalide ((Z)-ligustilide), trans-3-butil-3a,4,5,6-tetrahydrophthalide (trans-sedanalide), and (E)-3-butilidene-4,5-dihydrophthalide ((E)-ligustilide) (MacLeod and Ames 1989). Among these aromas, 3-n-butyphthalide, sedenалide, and trans- and cis-sedanolides are the most potent odorants in raw and boiled celery (Kurobayashi et al. 2006). This indicates that boiling temperature does not impact phthalide content. This component presents in fresh celery in the form of glycoside and aglycone (Tang et al. 1990). Aroma of raw celery leaves is influenced by (Z)-3-hexenal (green) and (Z)-3-hexenol (green) as well, whereas 3-methylbutanoic acid (valeric), sotolone (sweet, spicy), 2-methylbutanoic acid (valeric), vanillin (sweet), and β-damascenone (sweet, fruity) are important in boiled leaves (Kurobayashi et al. 2006). In addition, (Z)-3-hexenal and (Z)-3-hexenol that are related to the green note are at a higher potency in leaves than in stalks.

Sensory terms including sharp, grassy green, green spicy, complex, mellow, sweet, and soupy are used to express the flavor quality of raw and boiled celery (Kurobayashi et al. 2006). Application of low-dose γ-irradiation improves sensory qualities, including color, texture, and aroma of diced celery during storage at 5°C (Prakash et al. 2000). The acceptability of irradiated celery also significantly higher than that of acidified, blanched, and chlorinated vegetables in term of appearance, color, off-aroma, celery flavor, texture, and overall acceptance.

### 3.3.13 Mushroom

The aroma characteristic of mushroom is due to the presence of eight-carbon (C₈) volatile components and sulfur compounds. Aliphatic C₈ constituents are also a major class in wild mushrooms (Malheiro et al. 2013). The major HS volatiles in fresh champignon (Agaricus bisporus L.) are 1-octen-3-one, 1-octen-3-ol, 3-octanone, 3-octanol, and benzaldehyde (Costa et al. 2013). Although 1-octen-3-one (mushroom-like) is an abundant volatile, it has moderate potency in raw champignon compared to methional (cooked potato-like), 3-methylbutanal (malty), phenylacetaldehyde (flowery, honey-like), sotolone (seasoning-like), and phenylacetic acid (honey-like) (Grosshauser and Schieberle 2013). In contrast, 1-octen-3-one, ethyl 2-methylbutyrate (floral and sweet), 3-octanol (mushroom-like, buttery), methional and linalool (citrus-like) are the key aroma compounds in raw pine-mushroom (Tricholoma matsutake Sing.) (Cho et al. 2006). These aroma components also contribute to the overall aroma of cooked pine-mushroom with significantly higher potency of methional compared to raw mushroom.

Mushroom is widely used to enhance umami taste since it contains amino acids and 5′ nucleotides. Glutamic acid, aspartic acids, 5′-GMP, 5′-inosine monophosphate (5′-IMP), 5′-xanthosine monophosphate (5′-XMP), and 5′-AMP, which have umami taste, have been identified in shiitake mushroom (Lentinus edodes). The amino acids responsible for sweetness (alanine, glycine, proline, serine, and threonine) and bitterness (histidine, allo-isoleucine, isoleucine, leucine, methionine, phenylalanine, tryptophan, and valine) are also found in dried shiitake mushroom (Dermiki et al. 2013). Soluble sugars/polyols and organic acids also contribute mushroom flavor (Li et al. 2014). Trehalose, sometimes called mushroom sugar, is the main sugar among several soluble sugars/polyols in dried mushrooms, but mannitol is the major sugar in dried Agaricus blazei. Citric acid is the abundant organic acid in dried mushrooms.
Water of soaked dried mushroom contains not only taste components but also volatile aroma compounds, such as the common C₈ volatiles, sulfur-containing compounds, and other aldehydes (Dermiki et al. 2013). The variation of flavor content in aqueous extract is due to temperature and time of soaking. Higher temperatures significantly increase the level of tastants in the extract, while most volatile aroma compounds are lost. The content of amino acids having umami and bitter tastes in mushroom Russula griseocarnosa decreases during maturity, particularly at the cap entirely open stage (Ming et al. 2014). Processing and storage lead to a remarkable reduction of amino acids and 5′ nucleotides in champignon mushroom (Liu et al. 2014). The content of amino acids having umami taste is greatly decreased by the salting process, followed by canning and freezing processes. In addition, frozen mushroom has a higher content of 5′ nucleotides than salted and canned mushrooms.

3.3.14 Seaweed

Kelps Laminaria (kombu) and Undaria (wakame) are common brown seaweeds with high consumption, particularly in Japanese cuisine. Green and red algae are also consumed. Ethanol is the most abundant HS volatile compound in water extract of Sea tangle (Laminaria japonica), but isovaleric acid, allyl isothiocyanate, octanal, and acetaldehyde are even more important, based on the concept of expected odor intensity (Seo et al. 2012). Aldehydes and alcohols derived from unsaturated fatty acids are also identified in green, brown, and red seaweed (Kajiwara et al. 2006). Kuo et al. (1996) reported LOX activity in green seaweed (Enteromorpha intestinalis) that confirms biogenesis of volatile aroma compounds in algae. For example, dried green seaweed has a typical algae-like odor, while pickled seaweed has an oyster-like note. Seaweed extract treated with linoleic acid results in aroma compounds responsible for fresh apple-like, green, cucumber-like, mango-like, and algal tonalities. Aroma of five Aonori (dried Japanese green seaweed) samples are described as animalic, floral, spicy, fatty, green note, marine-like, fresh (watery), powdery, and leather-like (Yamamoto et al. 2014). The common dominant volatile compound is 7-heptadecene, whereas benzaldehyde derived from amino acid is the major volatile in green algae from Shizuoka.

3.4 Conclusion

Flavors of vegetables are complex and influenced by many factors. The researches of vegetable flavors, including biogenesis, flavor chemistry, factors affecting flavor and sensory properties, have been studied for many decades. Flavor information of some vegetables, however, is still limited and should be considered for further study. Understanding of vegetable flavors can help scientists develop desirable aromas and tastes that will increase consumer demand. For example, vegetables with palatable flavor received more acceptances and that affects purchasing decisions. Vegetables with high-flavor quality are important not only to consumers, particularly children, but also to farmers to gain market share.

REFERENCES

Bacon JR, Moates GK, Ng A, Rhodes MJC, Smith AC, Waldron KW. 1999. Quantitative analysis of flavour pre-
Baik HY, Juvik JA, Jeffery EH, Wallig MA, Kushad M, Klein BP. 2003. Relating glucosinolate content and
Science 178:988–990.
Blanch GP, Flores G, Castill MLRD. 2009. Effect of temperature on lipid-derived volatile compounds in boiled
Blažević I, Mastelić J. 2009. Glucosinolate degradation products and other bound and free volatiles in the
1:309–312.
Buck PA, Joslyn MA. 1956. Formation of alcohol, acetaldehyde, and acetoin in frozen broccoli tissue. J Agric
Buescher RH, Bueschar RW. 2001. Production and stability of (E,Z)-2,6-nonadienal, the major flavor volatile
Buttery RG, Black DR, Haddon WF, Ling LC, Teranishi R. 1979. Identification of additional volatile constitu-
Chem 26:791–793.
Buttery RG, Guadagni DG, Ling LC, Seifert RM, Lipton W. 1976a. Additional volatile components of cabbage,
Buttery RG, Guadagni DG, Lundin RE. 1976b. Some 4,5-dialkylthiazoles with potent bell pepper like aromas.
Buttery RG, Takeoka GR. 2013. Cooked carrot volatiles; AEDA and odor activity comparisons; identification
Buttery RG, Teranishi R, Ling LC, Flath RB, Stern DJ. 1988. Quantitative studies on origins of fresh tomato
and their effects on sensory attributes of baked sweet potatoes. J Food Sci Technol 51:4072–4077. doi
10.1007/s13197-012-0900-z.
Chin HW, Lindsay RC. 1993. Volatile sulfur compounds formed in disrupted tissues of different cabbage cul-


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