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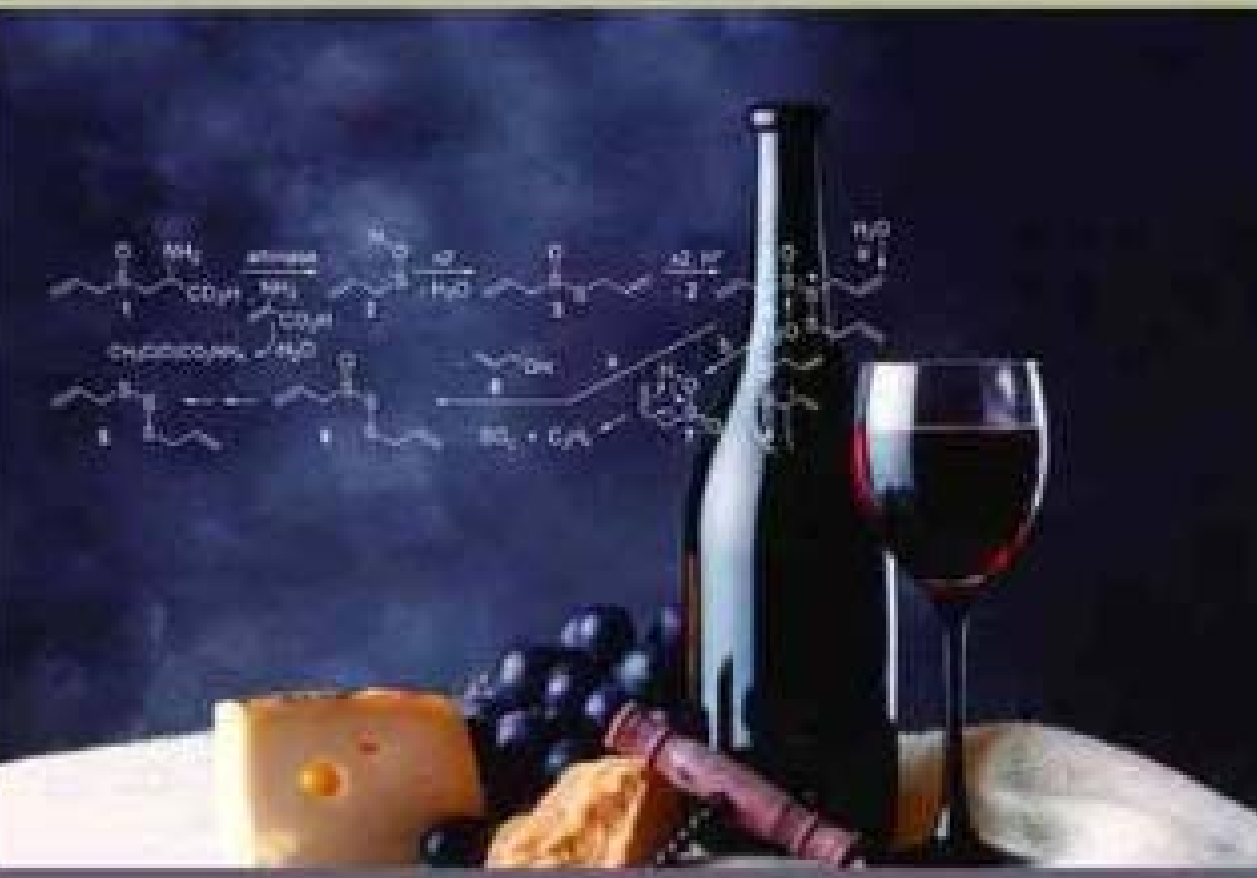
Volatile Sulfur Compounds in Food



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Volatile Sulfur Compounds in Food

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Chapter 1

The Significance of Volatile Sulfur Compounds in Food Flavors

An Overview

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Volatile sulfur compounds are important contributors to the characteristic flavors and off-flavors of many foods. As a class, sulfur-containing flavor volatiles have low sensory detection thresholds, are present in low concentration and are often chemically labile, which can present measurement challenges. Advances in analytical separation techniques and instrumentation have enabled understandings of their occurrence and contributions to their relative sensory significance.

Relating the chemistry and sensory contributions of volatile sulfur compounds to food flavor is an ongoing endeavor. The preminent quest in flavor research is to identify and categorize chemical constituents which provide unique sensory characteristics to the aroma and flavor of foods. Sulfur compounds contribute enzymatically-derived flavors in the *Allium* species (garlic, onion, chive) or *Cruciform* families (Brussels sprouts, broccoli, cabbage, cauliflower), and thermally-generated flavors such as roasted meat, chicken, seafood, and coffee. Volatile sulfur compounds play an important role in the aromas of bread, popcorn, nuts, potato products and wine, and contribute subtle flavor characteristics to cheddar cheese, chocolate and tropical fruit flavors, to name a few examples. Additional understandings of biosynthetic pathways, fermentation mechanisms, or thermal processes continue to evolve by which sulfur flavor constituents can be

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produced. As a result, new knowledge of unique sulfur flavor chemicals and their generation pathways facilitates improved quality of food processing, storage, and flavor systems.

Significant progress has been made with investigations of sulfur compounds since the previous ACS Symposium Series book devoted to this topic over 17 years ago (*1*). The intent of this chapter is to provide an updated summary of volatile sulfur compounds that are important contributors to the flavor of meats, seafood, fruits, vegetables and beverages.

Sensory Impact of Sulfur Volatiles

Volatile constituents of food flavors occur as complex mixtures in concentrations ranging from low parts-per-million to parts per trillion. As a class, sulfur flavor compounds are typically present in foods at extremely low levels, often at sub parts-per-billion concentrations. Some of these volatile components provide background sensory nuances to the flavor, while others provide unique flavor characterizing identities to the foods they occur in. The latter unique flavor substances are referred to as "character-impact compounds", and have been recently reviewed (*2*).

When smelled or tasted, a single character-impact chemical or blend of characterizing chemicals contributes a recognizable sensory impression at the typically low concentration levels in natural flavors. Examples of sulfur-containing character-impact compounds include diallyl disulfide (garlic), allyl isothiocyanate (mustard), and 2-furfurylthiol (coffee) (*2*). In some situations, flavor concentration and food context influence sensory perception. For example, at high concentrations dimethyl sulfide conveys an odor reminiscent of cabbage, but when present at reduced levels in the context of heat-treated corn, it conveys the typical flavor impression of canned corn. The relative sensory impact of a flavor compound depends on its individual odor threshold and its concentration in the food. As a class, volatile sulfur compounds exhibit sensory potency at low concentrations due to their low aroma and taste thresholds. In most foods, sulfur compounds contribute appropriate flavor character at low concentrations (< 1 μg/kg), but at higher concentrations, their aromas are perceived as sulfurous and objectionable. The olfactory perception (character and intensity) of sulfur compounds also depends on their diastereomeric and enantiomeric form, if they are able to exist as chiral isomers.

An indirect method to assess whether thiols are contributors to flavor impact is to simply add copper to samples. This methodology was used to assess the organoleptic role of thiols in beer flavor, because copper is selectively able to trap them into odorless chemical complexes (*3*)

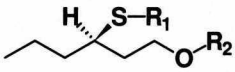
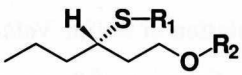
Enantiospecific Odor Differences

It is known that the enantiomers of chiral flavor compounds often have different sensory properties (*4*). In some cases, one chiral form may exhibit a lower flavor threshold relative to its epimer. In other situations, the aroma may

change flavor character between the two enantiomeric forms, or shift in character from odor to odorless. The sensory properties of enantiomers of sulfur volatile compounds have been described and compared (*4–6*).

An example of the enantiomeric differences among 3-thio-1-hexanols and their esters, which contribute to the odor and taste properties of yellow passion fruits, is shown in Table I. In general, the (*R*)-enantiomers have a tropical fruit aroma, whereas the (*S*)-enantiomers are sulfur and herbaceous. The stereodifferentiation and odor assessments of naturally occurring chiral sulfur volatiles should provide better insights of their relative flavor impact.

Table I. Sensory Properties for Enantiomeric 3-Thio- and 3-Methylthiohexanols and their Esters. (Adapted from reference (*4*). Copyright 2006 American Chemical Society)

	 **(*R*)-isomer**	 **(*S*)-isomer**
	(R)-isomer	***(S)-isomer***
$R_1 = R_2 = H$	intense sulfur odor[a]	intense sulfur odor[a]
$R_1 = H, R_2 = COCH_3$	tropical fruit	sulfur, herbaceous
$R_1 = H, R_2 = CO\text{-}Pr$	tropical fruit	sulfur, oniony
$R_1 = H, R_2 = CO\text{-}Amyl$	herbaceous,fresh sulfur	burnt sulfur
$R_1 = CH_3, R_2 = H$	herbaceous, weak	exotic, fruity
$R_1 = CH_3, R_2 = COCH_3$	fruity	int. sulfur, herbaceous
$R_1 = CH_3, R_2 = CO\text{-}Pr$	fruity, very weak	oniony
$R_1 = CH_3, R_2 = CO\text{-}Amyl$	fruity, very weak	weak oniony, roasty

[a] No odor difference.

Analytical Measurements

Sulfur compounds have long been the target of study of flavor chemists, however they have presented unique analytical challenges to surmount during the isolation and identification process (*7*, *8*). Specific issues are the tendency of reduced sulfur compounds (e.g., thiols) to oxidize, rearrange, or isomerize under mild heating conditions or during concentration from food matrices (*8*).

Analytical methods employed to identify volatile sulfur compounds in foods and beverages have been recently reviewed (*9*). Several current isolation and concentration techniques will be discussed.

Extraction of Thiols

p-Hydroxymercuribenzoic acid (*p*HMB) is used for selective trapping of thiols. This organomercury compound has been applied to determine polyfunctional thiols in beer (*10*, *11*), hops (*11*, *12*), and cheese (*13*). Typically, the sodium salt of *p*HMB is used to directly extract thiols from aqueous samples, while *p*HMB is used to concentrate thiols from organic solvent extracts of flavor compounds. The thiol-*p*HMB complexes are loaded on a strongly basic anion-exchanger column, and volatile thiols are released by percolating a hydrochloride L-cysteine monohydrated solution. Elution of beverages (e.g., wine) through a column containing a *p*HMB absorbent is an alternate approach (*14*). Thiols in flavor extracts can also be enriched on agarose gel grafted with *p*-aminophenyl-mercuric acetate, then desorbed with a 10 mM dithiothreitol solution (*15*).

Isolation of Sulfur Volatiles

Selection of flavor extraction and isolation procedures for sulfur compounds depends on the type of matrix and relative volatility of compounds of interest. Consequently, there is not a universal flavor isolation method. Several reviews have summarized analytical techniques for isolation and quantification of volatile flavor compounds (*16–18*). These include solid-phase micro-extraction (SPME) (*19*), stir bar sorptive extraction (SBSE) (*20*), headspace adsorption, vacuum distillation, simultaneous distillation/extraction, and solvent-assisted flavor evaporation (SAFE). Because reduced sulfur compounds are labile to oxidation and thermal rearrangements, care must be taken during isolation procedures to avoid formation of artifacts. It is recommended that borosilicate glass vials and contact surfaces, such as the GC injection liner, should be silylated to deactivate reactive sites prior to chromatographic analysis (*21*).

Multidimensional GC-MS

The separation and identification of trace sulfur compounds in complex food matrices generally requires numerous purification steps to suppress major volatile compounds (*19*, *22*). Multidimensional gas chromatography, especially heart-cut bidimensional gas chromatography, now offers an elegant alternative approach for identifying trace odorants. This hyphenated technique, combined with olfactometry, has recently been used to identify sulfur flavors in wines (*23*) and beer (*11*), thus suggesting new solutions for trace analysis.

Two-Dimensional GC

Comprehensive two-dimensional gas chromatography (GCxGC) is a powerful analytical tool for enhancement of separation capacity and mass spectral resolution (*24*). This hyphenated technique, often used in tandem with mass spectrometry, provides more accurate and sensitive quantification for improved characterization of flavor volatiles in complex mixtures. Advantages to this technique are that it

considerably shortens the identification process and, of particular importance for reactive sulfur compounds, it avoids enrichment steps that might result in artifact formation. GCxGC-TOFMS recently was used to identify a novel *O,S*-diethyl thiocarbonate in Indian cress (*25*).

GC Detectors

Gas chromatography with pulsed flame photometric detection (GC-PFPD) is a sulfur-specific detector with detection limits of 1 pg (10^{-12} g). A comparison of linear range, detection limits and selectivity of sulfur detectors has been described (*9*). The PFPD detector provides enhanced sensitivity relative to flame photometric detectors, and lower cost than atomic emission detection. PFPD has been recently utilized to measure sulfur compounds in cheese (*26*, *27*), wine (*21*), and strawberry (*28*, *29*) flavors.

Olfactometry

In recent studies, potent sulfur aroma compounds have been identified using sensory-focused analytical methods such as gas chromatography-olfactometry (GC-O) (*30*, *31*). Three variants of this technique include Charm Analysis™, aroma extract dilution analysis (AEDA), and OSME analysis. The potent sulfur compounds that are identified by these methods represent significant contributors to the flavors of the foods they represent. In some instances, these sensory-focused analytical techniques have led to the discovery of new character-impact sulfur compounds. However in other situations, important sulfur volatiles have been identified that, while they do not contribute character impact, impart significant nuances to the overall flavor.

Artifacts

Because sulfur flavor compounds tend to be thermally unstable, prone to oxidative reactions and present at low concentrations, often challenges occur during their isolation and identification (*8*). Previously, artifacts have been noted as a consequence of high temperatures encountered during sample concentration or in the gas chromatograph (GC) injector or mass spectrometry transfer column. It has been suggested that many reported "novel" sulfur compounds were actually secondary reaction products of fragile sulfur-containing flavorants (*7*). Volatile sufur compounds (e.g., methane thiol, dimethyl sulfide) can undergo thermal oxidation to form dimethyl disulfide and dimethyl sulfoxide, respectively, unless suitable analytical conditions are employed. Changes in dimethyl sulfide/disulfide/trisufide were reported in strawberry puree as a result of heating (*29*). Thermal reactions were reported to influence formation of sulfur compounds in Welsh onions and scallions during their identification; branched polysulfides were found in volatile distillates (*32*), but were absent in solvent extracts (*32*). Conversely, methyl methane thiosulfinate and dialk(en)yl thiosulfonates were predominant in key volatiles from solvent extracts (*32*). More recently, 3-propyl-1,2-oxothiolane identified in Sauternes botrytized wine was

shown to be produced from thermal oxidative degradation of 3-sulfanylhexanol disulfide in the GC injector (*23*). To minimize these situations, flavor chemists should utilize sulfur standards and analytical calibration curves to verify recovery. Alternative low-temperature isolation methods or cool on-column GC injection can often mitigate artifact formation.

Sulfur Constituents of Food Flavors

Key sulfur-containing aroma compounds have been identified in herbs and seasonings, fruit, vegetable, meat, seafood, dairy, and Maillard-type flavors. The occurrence of volatile sulfur compounds in food flavors is the subject of several recent reviews (*33–41*).

Herbs, Spices and Seasonings

A variety of sulfur aroma compounds are present in the isolates of spices and herbs, which are commonly used as seasonings in foods. The *Allium* family includes garlic, onion, leek, and chive, all of which are comprised of sulfur-containing character impact compounds. The aroma impact constituents of garlic include diallyl disulfide and the corresponding thiosulfinate derivative (allicin), which are enzymatically released from a sulfoxide flavor predursor (alliin) during the crushing of garlic cloves (*35*). A listing of character-impact sulfur compounds found in herb and seasoning flavors is presented in Table II.

The flavor chemistry of sulfur compounds in onion is quite complex (*32*, *43*, *44*). Early reports of polysulfides and thiosulfinates were later demonstrated to be thermal artifacts from gas chromatographic analysis (*44*). Character impact sulfur compounds have been proposed for fresh, boiled, and fried onion. In raw, fresh onion, propyl propanethiosulfonate, propenyl propanethiosulfonate thiopropanal S-oxide, and propyl methanethiosulfonate are impact contributors (*32*, *35*, *43*). Several compounds contribute to the aroma character of cooked onion, of which dipropyl disulfide and allyl propyl disulfide provide key impact (*35*). Fried onion aroma is formed by heating the latter compound, and is characterized by 2-(propyldithio)-3,4-dimethylthiophene, which has an odor threshold of 10-50 ng/l in water. More recently, a new highly potent aroma compound, 3-mercapto-2-methylpentan-1-ol, was identified in raw onions (*45*), with an odor threshold of 0.03 μg/L (*46*). The flavor impact of this mercaptyl alcohol is strongly dependent on concentration; at 50 μg/L, it provides a pleasant meat broth-like, onion, and leek-like flavor, while at high levels it gives a strong, unpleasant onion-like quality. Higher concentrations are formed in cooked onions, and it was also found in other *Allium* species including chives, onions, and leeks but not garlic (*47*). Representative structures for sulfur impact compounds in herbs and seasonings are shown in Figure 1.

Table II. Character-Impact Sulfur Compounds in Herbs and Seasonings

Character impact compound (s)	*Odor description*	*Occurrence*	*Reference*
Benzenemethanethiol	garden cress seed	garden cress	(*50*)
Diallyl disulfide	garlic	garlic	(*35*)
Diallylthiosulfinate (allicin)		garlic	(*35*)
4-Pentenyl isothiocyante	mustard/horseradish	horseradish	(*35*)
O,S-Diethyl thiocarbonate	red fruit, sulfury	Indian cress	(*25*)
Allyl isothiocyanate	mustard-like	mustard	(*42*)
Propyl propanethiosulfonate	roasted alliaceous	onion, raw	(*32*)
Propyl methanethiosulfonate		onion, raw	(*32*)
3-Mercapto-2-methylpentan-1-ol	broth, onion, leek	onion, raw	(*45*)
Allyl propyl disulfide	cooked onions	onion, cooked	(*32*)
Dipropyl disulfide	burnt green onion	onion, cooked	(*32*)
2-(Propyldithio)-3,4-Me_2thiophene		onion, fried	(*35*)
Bis(methylthio)methane	sulfury, truffle	truffle	(*48*, *49*)
1,2,4-Trithiolane		truffle	(*48*)

Unique sulfur compounds were identified as providing key aromas in black and white truffles (*48*, *49*) The predominant sulfur component in black and white truffle aroma is dimethyl sulfide, however bis(methylthio)methane and 1,2,4-trithiolane are reported as unique to white truffle aroma (*48*). 1-(Methylthio)propane and 1-methylthio-1-propene were newly identified in black truffle.

Isothiocyanates are character-impact constituents which provide pungency and typical flavor to mustard (allyl isothiocyanate), radish, *trans*-4-(methylthio)-3-butenyl and *trans*-4-(methylthio)butyl isothiocyanate) and horseradish (4-pentenyl and 2-phenylethyl isothiocyanate) (*35*). Garden cress (peppergrass) is classified in the *Brassica* (*Cruciferae* /mustard) family, and its leaves and seeds were historically used as a spicy condiment to contribute "peppery" flavor. Benzenemethanethiol was identified as the character-impact flavor for the unique flavor of garden cress (*Lepidium sativum*) seed, and also occurs in the volatile extracts of potatoes (*50*). Recently, a novel sulfur volatile, *O,S*-diethyl thiocarbonate was identified in Indian cress (*Tropaeolaceae* family), providing a "red fruity-sulfury" character (*25*). A series of thiocarbonate homologues were synthesized with "sulfury", "fruity" and "pineapple" aromas.

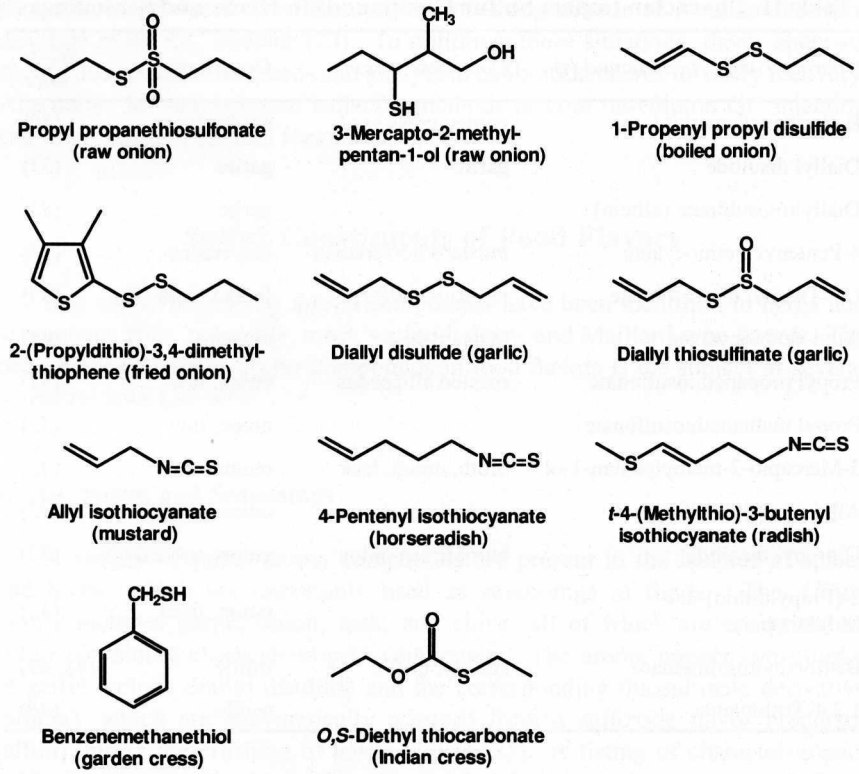


Figure 1. Character-impact sulfur flavor compounds in herbs and seasonings.

Fruit Flavors

The volatile composition of fruit flavors is extremely complex, and non-characterizing volatile esters are common across species. However, trace sulfur volatiles have been identified which play significant roles in the flavor of grapefruit, wine, strawberry, passion fruit, and other tropical fruits. A compilation of character-impact sulfur compounds in fruit flavors is summarized in Table III.

Ethyl 3-mercaptopropionate provides the pleasant fruity fresh grape aroma in Concord grape at low parts-per-million levels (*51*). It is well-established that characteristic wine flavors are produced from secondary metabolites of grapes and yeast during the fermentation process, which increase the chemical and aroma complexity of wine (*52*). For example, in wines, there is no single compound that characterizes its fruity aroma, but rather a complex blend of odorants (*53*). Wines made from certain *vinifera* grape varieties possess unique "fruity, fresh, green" character contributed from polyfunctional thiols, including 2-furfurylthiol, benzyl mercaptan, 3-mercaptohexan-1-ol, and 3-mercaptohexyl acetate in white and rose′ wines ((*54*) *and references cited therein.*). The latter two mercaptans are discussed in more detail below in the context of tropical fruit flavor character. Hydrogen sulfide, methanethiol, and methylthioacetate were measured at low-ppb

levels in Pinot Noir, Cabernet Sauvignon, Pinot Grigio, and Chardonnay wines; methionol was present at ppm levels. At these concentrations, they contribute a positive background impression to wine aroma, however at higher amounts they are responsible for "reduced", "rotten egg" sulfury off-flavors (*21*).

4-Mercapto-4-methyl-2-pentanone (cat ketone) provides "catty" character and typical flavor of Sauvignon blanc wine (and also Scheurebe) at an aroma perception threshold below 3 ppt (*54–57*). It is also a characteristic flavorant in Japanese green tea (sen-cha) (*58*), a main contributor to the "fruity" aroma in beer made with certain hops (*11*), and contributes significantly to the flavor of hand-squeezed grapefruit juice (*59*). Representative chemical structures for sulfur-containing character-impact compounds in fruits are shown in Figure 2.

Table III. Character-Impact Sulfur Compounds in Fruits

Character impact compound (s)	*Odor description*	*Occurrence*	*Reference*
4-Methoxy-2-methyl-2-butanethiol	blackcurrant, sulfur	blackcurrant	(*35*)
8-Mercapto-*p*-menthan-3-one	blackcurrant, catty	blackcurrant (synthetic)	(*34*)
4-Mercapto-4-methyl-2-pentanone	cat urine	grape, Sauvignon	(*55*)
		grapefruit	(*59*)
1-*p*-Menthene-8-thiol	juicy grapefruit	grapefruit	(*62*)
Ethyl-3-mercaptopropionate	fresh grape, foxy	grape, Concord	(*51*)
3-Methylthiohexan-1-ol	green, vegetable	passion fruit	(*33*)
2-Methyl-4-propyl-1,3-oxathiane	tropical, green	passion fruit	(*63*)
3-Mercaptohexan-1-ol	citrus, tropical fruit	passion fruit, wine	(*54, 64*)
3-Mercaptohexylacetate	black currant	Riesling, pink guava	(*33, 70*)
Ethyl 3-(methylthio)propionate	sulfury pineapple	pineapple	(*74, 75*)
	green, fresh melon	muskmelon	(*72, 73*)
Methyl thioacetate	cheesy, garlic	strawberry	(*29*)
Methyl thiobutanoate	cheesy, cabbage	strawberry	(*29*)
3,5-Dimethyl-1,2,4-trithiolane	sulfury, onion	durian	(*77*)

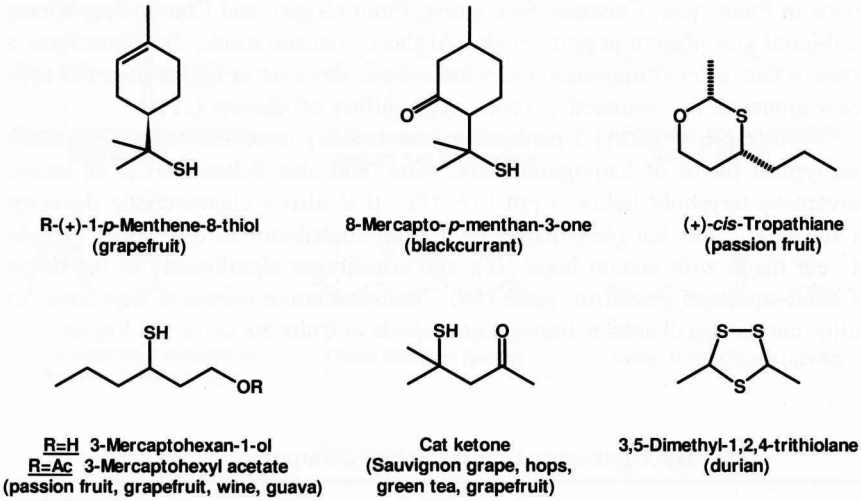


Figure 2. Representative character-impact sulfur flavor compounds in fruits.

Blackcurrant flavor is popular in Europe, and is associated with numerous health-related functional foods and alcoholic drinks (cassis liqueur). The key aroma component in blackcurrant is 4-methoxy-2-methyl-2-butanethiol (*35*). The "catty/ribes" flavor of blackcurrant (*Ribes nigrum*) was earlier attributed to "cat ketone", but it was later shown to be absent during flavor and sensory analysis of blackcurrant juice concentrates (*60*). 2-Methyl-3-furanthiol ("cooked meat") was among the five most potent aroma compounds recently identified by GC-olfactometry in blackcurrant juice (*61*). The flavor chemical 8-mercapto-*p*-menthan-3-one contributes a powerful blackcurrant, cassis and catty-like aroma character, however it has not been identified in the natural fruit (*34*). This unique mercaptan is synthesized by reaction of hydrogen sulfide with (-)-pulegone from buchu leaf oil.

The fresh juicy note of grapefruit juice is attributable to 1-*p*-menthene-8-thiol. This compound has a detection threshold of 10^{-1} parts-per-trillion (ppt), among the lowest values reported for aroma chemicals (*62*). The (+)-R-isomer was found to have a lower aroma threshold in water than the racemic mixture, and it imparts a pleasant, fresh grapefruit juice character, as opposed to the extremely noxious sulfur note contributed by the (-)-S-epimer.

The "tropical fruit" category is one of the most important areas for new discoveries of key impact flavor compounds. Analyses of passion fruit have produced identifications of many potent sulfur aroma compounds (*33*). Among these is tropathiane, 2-methyl-4-propyl-1,3-oxathiane, which has an odor threshold of 3 ppb (*63*). 3-Mercapto-1-hexanol is a powerful odorant reminiscent of citrus and tropical fruit. It was first isolated from passion fruit and contributes to its character impact (*64*, *65*). It has been extensively studied in wine flavor, and identified as one of the key aroma compounds in Sauvignon blanc, Riesling, Gewurztraminer, Cabernet Sauvignon, and Merlot wines (*23*). Its acetate derivative (3-mercaptohexyl acetate) provides a characteristic

"Riesling-type note" (*33*). 3-Mercapto-1-hexanol and its acetate were also reported in fresh grapefruit juice, where they contribute "grapefruit, passion fruit, box tree-like" aromas (*66*). Recent studies have identified a series of C_5-C_7 3-mercaptyl-1-alcohols in wines made from *Botrytis*-infected grapes (*67*). All contribute citrus-like aromas, except the branched 3-mercapto-2-methylbutanol isomer, which is "raw onion". 3-Mercaptohexan-1-ol is especially impactful to tropical fruit aroma in this wine, and its disulfide oxidation product has been identified in passion fruit (*65*) and Sauternes botrytized wine (*23*). In Sauternes wine, polyfunctional thioaldehdyes, (e.g., 3-mercaptoheptanal "fruity, lemon"; 3-methyl-3-mercaptobutanal "petroleum, bacon") were shown to decrease during bottle aging, and most thiols were lost during 1-2 years of storage (*68*). 2-Methylfuran-3-thiol contributes an interesting "bacon" note to this wine (*68*). 3-Mercapto-3-methylbutanol ("cooked leeks") was identified in Sauvignon blanc wine, however it was deemed unimportant to the aroma character since its concentration was significantly below its 1500 ng/L detection threshold (*69*). A new citrus odoriferous component, 3-propyl-1,2-oxathiolane, was shown to be produced by thermal oxidative degradation of the disulfide in the GC injector (*23*). In pink guava fruit, 3-mercapto-1-hexanol ("grapefruit") and 3-mercaptohexyl acetate ("black currant") contribute significantly to the strong and characteristic tropical fragrance of the fresh fruit in a nearly racemic ratio. Both 3-mercapto-1-hexanol enantiomers have extremely low odor thresholds of 70-80 pg/L (*70*). 2-Pentanethiol, which was previously attributed to guava fruit character (*71*), was not detected in these recent studies.

Sulfur esters have been identified in other tropical/subtropical fruits including melon, pineapple, kiwifruit, and durian. For muskmelon, ethyl 3-(methylthio)propionate is an important supporting character impact compound, contributing green, fresh melon notes (*72*, *73*). Additional thioether esters in melons include methyl 2-(methylthio)acetate, ethyl (methylthio)acetate, and the corresponding thioether alcohols. In pineapple, methyl 3-(methylthio)propionate and ethyl 3-(methylthio)propionate provide background green notes, however their contribution to the fruit aroma was considerably lower relative to the most odor-active volatiles (*74*, *75*). Methyl (methylthio)acetate and ethyl (methylthio)acetate have been identified in kiwifruit (*76*) and Indonesian durian in which sulfur volatiles dominate the overall aroma perception (*77*). From flavor extract dilution analysis, 3,5-dimethyl-1,2,4-trithiolane was identified as the most potent odorant in durian.

Freshly-picked lychee (var. litchi) fruit has a distinct sulfurous aroma character which diminishes upon storage. Sulfur volatiles and their individual sensory contribution in three lychee cultivars were identified as hydrogen sulfide (sulfur), dimethyl sulfide ("cabbage"), diethyl disulfide ("moldy, sulfur"), 2-methyl thiazole ("fresh garlic spice"), 2,4-dithiopentane ("burnt tire, cabbage"), dimethyl trisulfide ("cabbage, sulfur"), methional ("boiled potato"), and 2-acetyl-2-thiazoline ("nutty-woody") (*78*).

Methyl thioacetate ("cheesy, garlic") and methyl thiobutanoate ("cheesy, garlic, cabbage") were reported in strawberry as aroma-active sulfur volatiles with very low thresholds at relatively high concentrations (*29*). Recently, a series of novel thioesters were reported in fresh strawberry, including methyl

(methylthio)acetate, ethyl (methylthio)acetate, methyl 2-(methylthio)butyrate (fruity, floral, garlic), methyl 3-(methylthio)propionate, ethyl 3-(methylthio) propionate, methyl thiopropanoate, methyl thiohexanoate, and methyl thiooctanoate (fruity, pineapple) (*28*). Except as indicated, the aroma character of these esters was principally "cheesy/onion/garlic/sulfurous".

Table IV. Character-Impact Sulfur Compounds in Vegetables

Character impact compound (s)	*Odor description*	*Occurrence*	*Reference*
Dimethyl sulfide		asparagus	(*85*)
	cabbage	cabbage	(*80*)
	canned corn	corn	(*81*)
	sulfury, tomato	tomato paste	(*79*)
2-iso-Butylthiazole	tomato leaf	tomato (fresh)	(*79*)
1,2-Dithiacyclopentene		asparagus, heated	(*80*)
4-Methylthiobutyl isothiocyanate	cabbage, radish	broccoli	(*81*)
Methyl methanethiosulfinate		Brussels sprouts	(*82*)
		sauerkraut, cabbage	(*83*)
Allyl isothiocyanate	horseradish	cabbage, raw	(*81*)
	sulfur, garlic	cauliflower, cooked	(*84*)
3-(MeS)propyl isothiocyanate	pungent, horseradish	cauliflower	(*81*)
2-Acetyl-2-thiazoline	popcorn, roasty	corn, fresh	(*81*)
3-Methylthiopropanal	cooked potato	potato (boiled)	(*35*)
2-Heptanethiol	bell pepper, fruity	bell pepper	(*86*)
(E)-3-Heptene-2-thiol	sesame, green	red bell pepper	(*15*)
(E)-4-Heptene-2-thiol	sesame, coffee	red bell pepper	(*15*)

Vegetable Flavors

In vegetables, the contribution of sulfur flavor impact compounds depends considerably on how they are prepared (cutting, blending), and the form in which they are consumed (raw vs. cooked). For example, the character impact of fresh tomato is delineated by 2-*iso*-butylthiazole and (Z)-3-hexenal, with modifying effects from β-ionone and β-damascenone (*79*). Alternatively, dimethyl sulfide is a major contributor to the flavor of thermally-processed tomato paste (*79*, *80*). Dimethyl sulfide is also a flavor impact compound for sweet corn, while hydrogen

sulfide, methanethiol and ethanethiol may further contribute to its aroma due to their low odor thresholds (*81*). A summary of sulfur character-impact compounds for vegetable flavors is outlined in Table IV.

Among the Cruciform vegetables, cooked cabbage owes its dominant character impact flavor to dimethyl sulfide. In raw cabbage flavor, allyl isothiocyanate contributes sharp, pungent horseradish-like notes (*81*). Methyl methanethiosulfinate was observed to provide the character impact of sauerkraut flavor, and occurs in Brussels sprouts and cabbage (*82*, *83*). Compounds likely to be important to the flavor of cooked broccoli include dimethyl sulfide and trisulfide, nonanal, and erucin (4-(methylthio)butyl isothiocyanate) (*80*). Cooked cauliflower contains similar flavor components as broccoli, with the exception that 3-(methylthio)propyl isothiocyanate is the characterizing thiocyanate (*80*). Allyl isothiocyanate, dimethyl trisulfide, dimethyl sulfide, and methanethiol were the key odorants of cooked cauliflower "sulfur" odors (*84*). Key volatile sulfur compounds were recently identified in the flavor of cooked asparagus (*85*).

2-Heptanethiol was recently reported as a new flavor compound in cooked red and green bell peppers (*86*). Subsequently, a series of newly-reported thiols, mercapto ketones, mercapto alcohols, and methylthio-thiols were identified in red bell pepper which cover a palette of organoleptic properties (*15*). Their flavor descriptors range from "berry/tropical fruit", to "green/vegetable-like, meaty, onion-like, sesame, peanut, coffee, and roasted." Characteristic bell pepper notes could be attributed to (*E*)-3-heptene-2-thiol ("sesame, green, bell peppers, fresh") and (*E*)-4-heptene-2-thiol ("sesame, coffee, bitterness of peppers"). It was reported that few of the new compounds identified have unpleasant "rubbery/rotten" notes that are notorious for sulfur compounds. Representative structures for character-impact sulfur compounds in vegetables are presented in Figure 3.

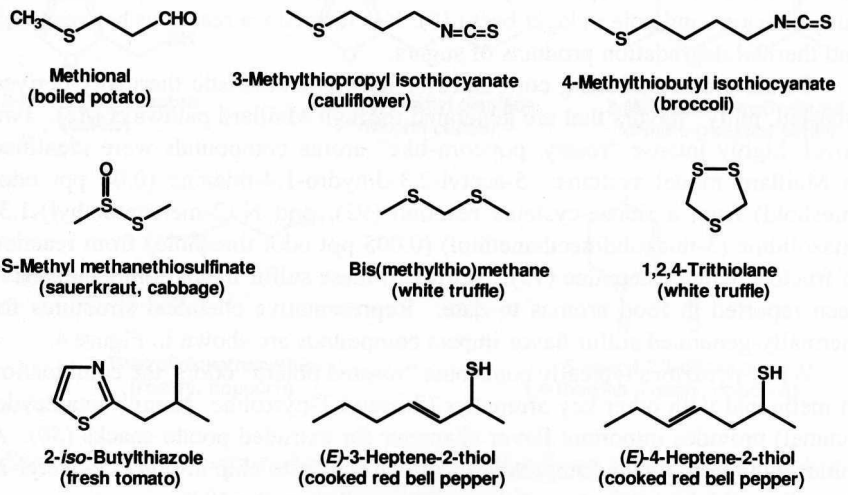


Figure 3. Representative character-impact sulfur flavor compounds in vegetables.

Maillard-Type, Brown and Cereal Flavors

Characteristic heated flavor compounds arise via the Maillard pathway, the thermally-induced reaction between sulfur amino acids (cysteine/cystine, methionine) and reducing sugars. Sulfur heterocyclic constituents that contribute aromas of coffee, toasted cereal grains, popcorn and roasted meats are products of Maillard reactions (*87*). 2-Furfurylthiol is the primary character impact compound for the aroma of roasted Arabica coffee (*88*). It has a threshold of 5 ppt and smells like freshly brewed coffee at concentrations between 0.01 and 0.5 ppb (*89*). At higher concentrations it exhibits a "stale coffee, sulfury" note. Other potent odorants in roasted coffee include 5-methylfurfurylthiol (0.05 ppb threshold), which smells meaty at 0.5-1 ppb, and changes character to a sulfury mercaptan note at higher levels (*89*). Furfuryl methyl disulfide has a sweet mocha coffee aroma (*63*). While other sulfur compounds such as 3-mercapto-3-methylbutyl formate and 3-methyl-2-buten-1-thiol were previously thought to be important factors for coffee aroma, recent studies have confirmed that the flavor profile of brewed coffee is primarily contributed by 2-furfurylthiol, 4-vinylguaiacol, and "malty"-smelling Strecker aldehydes, among others (*88*, *90*). In the volatile fraction of roasted hazelnuts, both 2-furfurylthiol and 2-thienylthiol contribute "coffee-like, sulfury" notes with high odor activities (*91*). For wines and champagnes aged in toasted oak barrels, 2-furfurylthiol and 2-methyl-3-furanthiol have been identified as providing their "roast-coffee" and "cooked meat" aroma characters, respectively (*14*). A summary of character-impact sulfur compounds for thermally generated flavors is outlined in Table V.

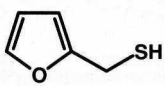
Thiols of branched and linear C_5-C_6 alcohols and ketones are produced during fermentation of fresh lager beers, including 3-mercaptohexanol, 2-mercapto-3-methylbutanol, and 3-mercapto-3-methylbutanol (*10*) These hop-derived thiols contribute subtle background characters such as "rhubarb", "onion/sulfur" and "broth/onion/sweat", respectively. 2-Methyl-3-furanthiol contributes a "meaty/ nutty" background note in lager beer (*10*). It is formed via reactions between H_2S and thermal degradation products of sugars.

Cereal grains including corn and rice have characteristic thermally-derived "toasted, nutty" flavors that are generated through Maillard pathways (*87*). Two novel, highly intense "roasty, popcorn-like" aroma compounds were identified in Maillard model systems: 5-acetyl-2,3-dihydro-1,4-thiazine (0.06 ppt odor threshold) from a ribose-cysteine reaction (*92*); and N-(2-mercaptoethyl)-1,3-thiazolidine (3-thiazolidineethanethiol) (0.005 ppt odor threshold) from reaction of fructose with cysteamine (*93*). Neither of these sulfur flavor compounds have been reported in food aromas to date. Representative chemical structures for thermally-generated sulfur flavor impact compounds are shown in Figure 4.

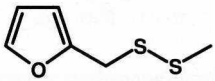
While pyrazines typically contribute "roasted potato" odors, the combination of methional with other key aromatics (2-acetyl-1-pyrroline, phenylacetaldeyde, butanal) provides important flavor character for extruded potato snacks (*50*). A minor but potent flavor component identified in potato chip aroma is 2-acetyl-2-thiazoline which contributes a "roasty, popcorn" character (*94*).

Table V. Character-Impact Sulfur Compounds in Cooked Flavor Systems

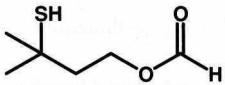
Character impact compound (s)	*Odor description*	*Occurrence*	*Reference*
2-Furfurylthiol	fresh brewed coffee	coffee	(*88*)
	coffee-like, sulfury	hazelnut, roasted	(*91*)
	roast-coffee	wine (barrel-aged)	(*14*)
5-Methylfurfurylthiol	meaty	coffee	(*89*)
2-Thienylthiol	coffee-like, sulfury	hazelnut, roasted	(*91*)
Furfuryl methyl disulfide	mocha coffee	coffee	(*63*)
2-Methyl-3-furanthiol	cooked meat	wine (barrel-aged)	(*14*)
	meaty, nutty	beer, lager	(*10*)
3-Mercaptohexanol	rhubarb, fruity	beer, lager	(*10*)
2-Mercapto-3-methylbutanol	onion, sulfur	beer, lager	(*10*)
3-Mercapto-3-methylbutanol	broth, onion, sweat	beer, lager	(*10*)
2-Acetyl-2-thiazoline	roasty, popcorn	potato chip	(*94*)
5-Acetyl-2,3-dihydro-1,4-thiazine	roasty, popcorn	Maillard model system	(*92*)
3-Thiazolidineethanethiol	roasty, popcorn	Maillard model system	(*93*)



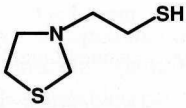
2-Furfuryl mercaptan (coffee)



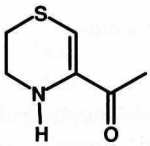
Furfuryl methyl disulfide (mocha coffee)



3-Mercapto-3-methylbutyl formate (roasted coffee)



3-Thiazolidineethanethiol (roasty, popcorn)



5-Acetyl-2,3-dihydro-1,4-thiazine (roasty, popcorn)

Figure 4. Representative character-impact sulfur flavor compounds in cooked foods.

Meat and Seafood Flavors

Sulfur-containing heterocyclic compounds are associated with meaty characteristics. Two compounds with the most potent impact include 2-methyl-3-furanthiol (1 ppt) and the corresponding dimer, bis-(2-methyl-3-furyl) disulfide (0.02 ppt) (*35*). Both substances have been identified in cooked beef and chicken broth, and have a strong meaty quality upon dilution. 2-Methyl-3-furanthiol also occurs in canned tuna fish aroma (*95*). The disulfide has a recognizable aroma character of "rich aged-beef, prime-rib" (*63*). Both compounds are produced from the thermal degradation of thiamin (*96*). A related sulfur volatile, 2-methyl-3-(methylthio)furan, is the character impact compound for roast beef (*35*). Besides 2-methyl-3-furanthiol, additional potent sulfur-containing odorants 2-furfurylthiol, 2-mercapto-3-pentanone, and 3-mercapto-2-pentanone were identified in heated meat (*97*). A summary of character-impact sulfur compounds for meat and seafood flavors is shown in Table VI.

Table VI. Character-Impact Sulfur Compounds in Meat and Seafood

Character impact compound (s)	*Odor description*	*Occurrence*	*Reference*
Dimethyl sulfide	stewed clam	clam, oyster	(*108*)
Methional	boiled potato	boiled clam	(*102*)
		crustaceans	(*104*)
Pyrrolidino-2,4-(Me_2)dithiazine	roasted	boiled shellfish	(*107*)
2-Acetylthiazole	popcorn	boiled clam	(*102*)
2-Acetyl-2-thiazoline	roasty, popcorn	roasty (beef)	(*98*)
		cooked chicken	(*99*)
	nutty, popcorn	crustaceans	(*104*)
4-Me-5-(2-hydroxyethyl)thiazole	roasted meat	Maillard reaction	(*63*)
2-Methyltetrahydrofuran-3-thiol	brothy, meaty	Maillard reaction	(*63*)
2-Methyl-3-furanthiol	roasted meat	meat, beef	(*35*)
	meat, fish, metallic	canned tuna fish	(*95*)
Bis-(2-methyl-3-furyl) disulfide	rich aged-beef	aged, prime-rib	(*35*)
2-Methyl-3-(methylthio)furan	beefy, coffee	roast beef	(*35*)
2,5-Dimethyl-1,4-dithiane-2,5-diol	chicken broth	Maillard reaction	(*63*)

In cooked meats and other thermally-processed foods, the key aroma compound 2-acetyl-2-thiazoline imparts a potent "roasty, popcorn" note that enhances meaty and roast flavors. It was first identified in meat systems among the flavor volatiles of beef broth, and later reported as one of the character-impact compounds of roasted beef (*98*). 2-Acetyl-2-thiazoline was subsequently detected as a potent odorant of chicken broth and cooked chicken (*99*). Representative structures for meat and seafood sulfur flavor impact compounds are shown in Figure 5.

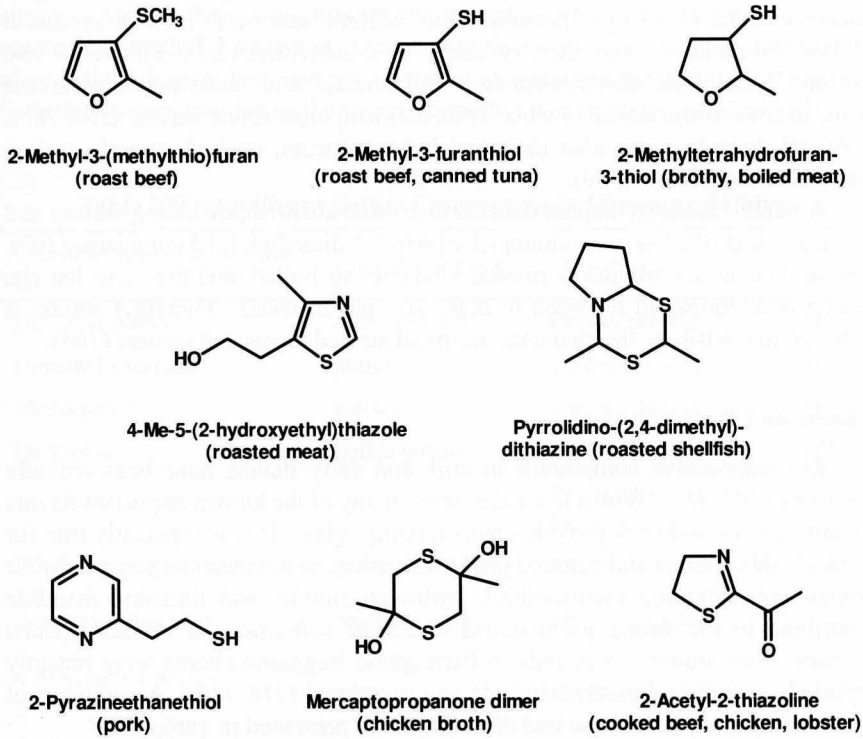


Figure 5. Representative character-impact sulfur flavor compounds in meat and seafood.

A brothy compound associated with boiled beef, 4-methyl-5-(2-hydroxyethyl)lthiazole (sulfurol), is a "reaction flavor" product from hydrolysis of vegetable protein. It is suspected that a trace impurity (2-methyltetrahydrofuran-3-thiol) in sulfurol is the actual "beef broth" character impact compound (*63*). Another reaction product flavor chemical, 2,5-dimethyl-1,4-dithiane-2,5-diol (the dimer of mercaptopropanone), has an intense chicken-broth odor. A series of C_4-C_9 3-(methylthio)aldehydes have been reported in cooked beef liver (*100*) and other highly thermally processed foods (fried potatoes, tomato paste, dried squid) (*101*). Unlike methional, which is derived from the amino acid methionine, these sulfur compounds are likely formed via reaction of methyl mercaptan with unsaturated aldehydes. Volatile

isolation employed techniques such as Likens-Nickerson for identification of these 3-(methylthio)aldehydes, so the possibility that they are artifacts needs to be further investigated.

Fish flavors are primarily composed of noncharacterizing "planty" or melon-like aromas from fatty acid-derived unsaturated carbonyl compounds. Three notable sulfur volatiles in boiled clam were determined to be principal character-impact compounds by AEDA: 2-acetyl-2-thiazoline ("roasted"), 2-acetylthiazole ("popcorn") and 3-methylthiopropanal (methional) ("boiled potato") (*102*). Because 2-acetyl-2-thiazoline is readily degraded by heating in aqueous media (*103*), it is presumed that acetylthiazoline is initially produced at low temperature, and then oxidized to 2-acetylthiazole. Methional and 2-acetyl-2-thiazoline also contribute to the "meaty" and "nutty/popcorn" aroma notes in cooked crustaceans such as crab, crayfish, lobster, and shrimp (*104*, *105*). 2-Acetyl thiazoline was also identified in boiled trout, cooked mussels, turbot, and boiled carp fillet. (*106*).

A potent character-impact odorant in cooked shellfish, including shrimp and clam, was identified as pyrrolidino[1,2-*e*]-4*H*-2,4-dimethyl-1,3,5-dithiazine (*107*). This dithiazine contributes a roasted character to boiled shellfish, and has the lowest odor threshold recorded to date, 10^{-5} ppt in water. Dimethyl sulfide is reported to contribute the character aroma of stewed clams and oysters (*108*).

Cheese and Dairy Flavors

Key odor-active compounds in milk and dairy flavors have been recently reviewed (*109–113*). With a few exceptions, many of the known important flavors in dairy products do not provide characterizing roles. This is especially true for milk, cheddar cheese and cultured products, such as sour cream and yogurt. Sulfur compounds including methanethiol, hydrogen sulfide, and dimethyl disulfide contribute to the strong garlic/putrid aroma of soft-smear or surface-ripened cheeses. Key aroma compounds in Parmigiano Reggiano cheese were recently reported, including dimethyltrisulfide and methional (*114–116*). A summary of sulfur compounds for cheese and dairy flavors is presented in Table VII.

By a wide margin, cheddar is the most popular cheese flavor in North America. While its flavor is described as "sweet, buttery, aromatic, and walnut," there is no general consensus among flavor chemists about the identity of individual compounds or groups of compounds responsible for cheddar flavor.

At present, it is thought to arise from a unique balance of key volatile components, rather than a unique character impact compound. Sensory-guided flavor studies concluded that the important sulfur contributors to cheddar cheese aroma are methional, dimethyl sulfide, dimethyl trisulfide, and methanethiol (*117*, *118*). Two recent studies confirmed that hydrogen sulfide and dimethyl disulfide only increased during initial stages of cheddar cheese aging, whereas dimethyl sulfide, dimethyl trisulfide, and methanethiol continued to develop throughout the aging process (*25*, *26*). A desirable "nutty" flavor supports "sulfur" and "brothy" characters in a quality aged cheddar cheese sensory profile. 2-Acetyl-2-thiazoline (*117*, *119*) contributes "roasted, corny" flavors in synergy with 2-acetyl-1-pyrroline, which were suggested to be related to the "nutty"

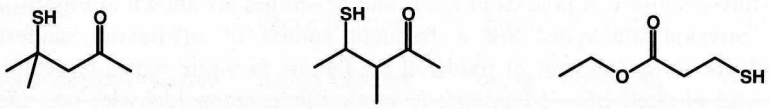
flavor. In cheddar cheese powders, dimethyl sulfide imparts a desirable "creamed corn" flavor (*120*). Representative structures of significant sulfur volatiles in cheese are shown in Figure 6.

A thiolester, ethyl 3-mercaptopropionate, was reported for the first time in Munster and Camembert cheeses (*13*). This sulfur volatile was described at low concentrations as having pleasant "fruity, grapy, rhubarb" characters. It has previously been reported in wine and Concord grape (*51*) but was never mentioned before in cheese.

Novel polyfunctional thiols were recently reported in aged cheddar cheese. Among these were 4-mercapto-4-methyl-2-pentanone ("catty") and 4-mercapto-3-methyl-2-pentanone ("cooked milk, sweet") (*121*). Other tentatively identified thiols include 4-mercapto-2-pentanol, 4-mercapto-3-methylpentan-2-ol, 5-methyl-4-mercapto-hexan-2-one, and 5-methyl-4-mercaptohexan-2-ol (*121*).

Table VII. Significant Sulfur Compounds in Cheese and Dairy

Character impact compound (s)	*Odor description*	*Occurrence*	*Reference*
Dimethyl sulfide	creamed corn	cheese, cheddar	(*117*)
Dimethyl trisulfide	putrid	cheese, cheddar	(*117*)
Methanethiol	sulfury	cheese, cheddar	(*117*)
Methional	boiled potato	cheese, cheddar	(*117*)
		Parmigiano Reggiano	(*114–116*)
Ethyl-3-mercaptopropionate	grapy, rhubarb	cheese, Camembert	(*13*)
2-Acetyl-2-thiazoline	roasted, corny	cheese, cheddar	(*117, 119*)
4-Mercapto-4-Me-2-pentanone	catty	cheese, cheddar	(*121*)
4-Mercapto-3-Me-2-pentanone	cooked milk, sweet	cheese, cheddar	(*121*)
2-Methyl-3-furanthiol	brothy, burnt	whey protein	(*122*)



4-Mercapto-4-methyl-2-pentanone cheddar cheese (catty) | **4-Mercapto-3-methyl-2-pentanone cheddar cheese (cooked milk, sweet)** | **Et-3-mercaptopropionate Munster, Camembert cheese (fruity, grapy, rhubarb)**

Figure 6. Representative sulfur flavor compounds in cheese.

Key aroma-active compounds have been reported in dried dairy products including nonfat milk and whey powders. A supporting role was provided by the sulfur flavor impact compound. 2-methyl-3-furanthiol ("brothy/burnt") identified in whey protein concentrate and whey protein isolate (*122*).

Sulfur Volatile Contributions to Off-Flavors and Taints

Exposure of beer to light generates 3-methyl-2-butene-1-thiol, which provides a skunky off-flavor in "sun-struck" or "light-struck" ales (*123*, *124*). This mercaptan has a sensory threshold of 0.05 ppb in beer. It derives from complex photo-induced degradations of isohumulones (hop-derived, bitter iso-acids) to form free-radical intermediates, which subsequently react with the thiol group of cysteine. Lightstruck off-flavor can be controlled in beer through packaging technology (colored glass bottles), use of chemically- modified hop bitter acids, antioxidants, or its precipitation with high molecular weight gallotannins and zinc salts (*125*). In addition to dimethyl sulfide, thioesters have been reported to contribute a "cabbagy, rubbery" off-note that sometimes are derived from hops in beer, the most significant being S-methyl hexanethioate, which has a detection threshold of 1 ppb (*126*). A summary of off-flavor impact sulfur compounds in foods and beverages is presented in Table VIII.

Another staling off-flavor in beer is described as "catty/ribes", whose character comes from 4-mercapto-4-methyl-2-pentanone (cat ketone). This off-flavor can develop rapidly in beers that are packaged and stored with significant quantities of air in the headspace (*127*). A similar "catty/ribes" off-flavor in aged lager beer was attributed to 3-mercapto-3-methylbutyl-formate (*128*). 2-Mercapto-3-methylbutanol was detected in a Finnish beer characterized by an intense "onion-like" off flavor and suggested that it likely was derived from hops (*129*).

Sulfur compounds present in wine can have a detrimental effect on aroma character, producing odors described as "garlic, onion and cauliflower," the so-called Boeckser aromas. This sulfurous character is correlated with 2-methyl-3-hydroxythiophene, 2-methyl-3-furanthiol and ethanethiol. Their concentrations in wine are influenced by winery practices and the use of certain winemaking yeasts (*130*). Off-flavors in European wines were associated with the non-volatile bis(2-hydroxyethyl) disulfide, a precursor to the "poultry-like" character of 2-mercaptoethanol and hydrogen sulfide (*131*). Examples of off-flavor sulfur compounds in foods and beverages are shown in Figure 7.

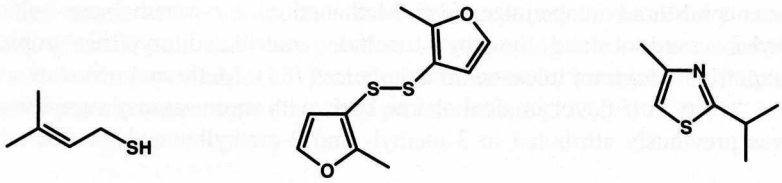
Strecker aldehydes are a frequent source of off-flavors in fermented products. Development of oxidized off-flavors in white wines typically marks the end of shelf life. Methional (3-methylthiopropionaldehyde) was identified as producing a "cooked vegetables" off-flavor character in a young white wine that had undergone spontaneous oxidation (*132*). Methional levels increased in wines spiked with methionol or methionine, suggesting its formation via direct peroxidation or Strecker degradation of methionine. The importance of methional in the development of characteristic oxidation notes in white wine was further demonstrated (*133*). Methional and 2-methyl-3-furanthiol are purported off-flavor

components in stored orange juice (*134*). Methanethiol, 1-*p*-menth-1-ene-8-thiol, 2-methyl-3-furanthiol, and dimethyl trisulfide contributed atypical "tropical fruit/grapefruit" character to canned orange juice (*135*). Methional was shown to impart a "worty" off-flavor in alcohol-free beer, with more sensory significance than was previously attributed to 3-methyl- and 2-methylbutanal for this taint (*136*).

A vitamin-derived off-odor problem was described in which a pineapple fruit juice beverage was fortified with riboflavin. The "vitamin, cabbage, brothy, vegetable soup" off-odor was characterized as 4-methyl-2-isopropylthiazole, which resulted from riboflavin-sensitized Strecker degradation of valine, cysteine and methionine, followed by reaction of the resulting aldehydes with ammonia and hydrogen sulfide (*137*).

Table VIII. Off-Flavor Impact Sulfur Compounds in Foods and Beverages

Impact compound (s)	*Off-flavor description*	*Occurrence*	*Reference*
3-Methyl-2-butene-1-thiol	skunky, plastic	beer (light-struck)	(*123*, *124*)
S-Methyl hexanethioate	cabbagy, rubbery	beer	(*126*)
3-Mercapto-3-methylbutyl-formate	cat urine, ribes	beer, aged	(*128*)
4-Mercapto-4-methyl-2-pentanone	cat urine, ribes	beer, aged	(*127*)
2-Mercapto-3-methylbutanol	onion-like	beer	(*129*)
Methional	worty	beer (alcohol-free)	(*136*)
	cooked vegetables	oxidized white wine	(*132*)
	cooked potato	orange juice, aged	(*134*)
	potato	UHT-milk	(*142*)
Dimethyl disulfide	sunlight off-flavor	milk	(*138*)
2-Methyl-3-furanthiol	meaty/vitamin B	orange juice, aged	(*134*)
Benzothiazole	sulfuric, quinoline	milk powder	(*139*)
Bis(2-methyl-3-furyl)disulfide	vitamin B_1 odor	thiamin degradation	(*140*)
4-Methyl-2-isopropylthiazole	vitamin, cabbage	orange juice (vit B_2)	(*137*)



3-Methyl-2-butene-1-thiol lightstruck beer | **Bis-(2-methyl-3-furyl)disulfide vitamin B_1 (thiamin)** | **4-Methyl-2-iso-propylthiazole vitamin B_2 (fort. orange juice)**

Figure 7. Representative off-flavor impact sulfur compounds in foods and beverages.

Sunlight off-flavor in milk ("cardboard-like") can result from milk exposed to high intensity fluorescent light or sunlight, which generates dimethyl disulfide from photooxidation of methionine (*138*). Part of a characteristic off-flavor in spray-dried skim milk powder is contributed by benzothiazole (sulfuric, quinoline) as low ppb levels (*139*).

While bis(2-methyl-3-furyl)disulfide contributes a desirable aged, prime rib flavor in beef, it is the principal "B-vitamin" off odor resulting from thiamin degradation (*140*).

Character compounds which contribute positive flavor impact at low levels can become off-flavors when they occur at higher concentrations. For example, dimethyl sulfide provides an appropriate "corn-like" background character to beer flavor at low levels, however it contributes a highly undesirable "cooked vegetable" or "cabbage-like" malodor when present at levels significantly above its sensory threshold (30-45 ppb) (*141*). Similarly for cheddar cheese flavor, it imparts a rotten vegetable taste when present at high levels (*118*).

In ultra-high temperature (UHT) processed milk, the "UHT milk flavor" character is contributed by methional plus pyrazines (*142*). Additionally, dimethyl sulfide was reported as one of the significant flavor components of UHT milk off-flavor (*143*). Methional, methanethiol, and dimethyl sulfide are the source of "sulfur" and "cooked" off flavors in ultrahigh-temperature (UHT) processed soy milks (*144*).

Conclusion

In the 17 years since the previous review, there have been significant strides in the flavor chemistry of volatile sulfur compounds due to analytical advancements in sulfur-specific detectors and limits of detection. Greater awareness and care is being taken to prevent isomerization of reactive sulfur flavor compounds during their analysis. New key aroma compounds containing sulfur have been discovered in fruits, vegetables, dairy products, wine, beer, and heated foods. Traditionally, sulfur compounds have been associated with unpleasant, noxious off-flavors, however recent discoveries indicate that a positive perspective is developing towards the role of sulfur volatiles in tropical, fruity, and savory character of food flavors. Undoubtedly, flavor research on sulfur volatiles will

continue to accelerate given these recent discoveries and a new appreciation of their sensory significance in foods.

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