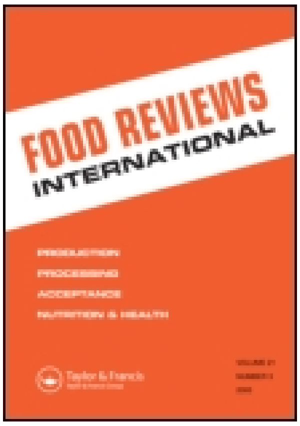

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Sensorial Contribution and Formation Pathways of Thiols in Foods: A Review

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Sensorial Contribution and Formation Pathways of Thiols in Foods: A Review

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Since the mid-1990s, more than 300 publications have been devoted to the organoleptic relevance of thiols in foods (meats, wines, fruits). The available data about their physicochemical and sensorial properties, occurrence in foods, and potential formation pathways are compiled in this article.

Keywords Sulfur compounds, Thiols, Flavor, Aroma, Odor threshold, Catty, Blackcurrant, Food occurrence

Introduction

Flavors are certainly one of the most important determinants of food quality and acceptance (Mestress et al., 2000). In a few cases, the presence of a single compound (character impact substance) is sufficient to impart the typical note of the matrix (Buettner and Schieberle, 1999). More frequently, however, several compounds are needed to mimic the overall aroma. GC olfactometry (AEDA, CHARM) is probably the most useful way to find those key flavors. Unfortunately, the quality of the results depends strongly on the representativity of the analyzed extract (Bouchilloux et al., 1998b; Buettner and Schieberle, 2001; Darriet et al., 1993; Manning and Price, 1977). Extraction of thiols without artefacts is very difficult, especially when all chemical families are needed at the same time. By means of either efficient extraction procedures specific to thiols or isotopic dilution, it is possible to determine thiol concentrations accurately and to compare them with sensory thresholds

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(Manning and Price, 1977). Unfortunately, commercial thiols with sufficient olfactive purity for sensory threshold determination are usually unavailable for such experiments (Meilgaard, 1975). Too often neglected, moreover, especially when GC olfactometry is used, are the interactions of thiols with the matrix and their qualitative or quantitative synergistic effects with other odorants (Bezman et al., 2001; Marais and Swart, 1999). For example, 3-mercaptohexanol, known for its typical grapefruit flavor, surprisingly boosts the ''red fruit'' character when present in wine (Blanchard et al., 1999), whereas 4-mercapto-4-methyl-2-pentanone, famous for its catty or blackcurrant odor, enhances the ''citrus fruit'' note in grapefruit juice (Buettner and Schieberle, 2001; Gora and Brud, 1983).

Among chemicals, sulfur-containing molecules and especially thiols are probably the most famous key flavors in many foods and beverages. They are often characterized by sensorial thresholds as low as the ppt level. In some cases, thiols are described by fruity notes, highly desired by the consumers. For instance, 4-mercapto-4-methyl-2-pentanone appears to be crucial in white wines where the Sauvignon typicity (boxtree/blackcurrant aroma) is required. However, their occurrence is not recommended when exhaling pungent and objectionable odors (Mestres et al., 2000). Surprisingly, a few of them are considered as pleasant in some foods and damaging in others. For example, 3-methyl-2-butene-1-thiol is essential for the coffee flavor acceptance, but it is the worst enemy in beer. This article aims to compile all current data on their physical, chemical, and sensorial properties, their occurrence in foods, and formation pathways.

Physical and Chemical Properties

By definition, thiols are sulfur compounds possessing a SH functional group in their chemical structure. Because of the high polarisability of their sulfur atom (Blanchard, 2000), they are more acidic (pK_a: 9–12) than their corresponding alcohols (pK_a: 15). This property is often used in chemical syntheses involving a nucleophilic attack of the sulfur atom. In this kind of reaction, it is common to add a base such as piperidine in order to obtain the S^- form, which is much more nucleophilic than the SH one.

Thiols usually exhibit very strong antioxidant activity [free radical trapping (Naim et al., 1993, 1994), quinone or H_2O_2 reduction (Bandaranayake and Wickramasinghe, 1996; Negishi and Ozawa, 2000)]. They are easily oxidizable and convert quickly to disulfide forms (Ferreira et al., 2003; Haye et al., 1977; Hofmann et al., 1996; Mestress et al., 1997, 2000; Mottram and Madruga, 1995; Mottram and Whitfield, 1994). This phenomenon can be catalyzed by cupric ions (Fig. 1a). The resulting disulfides can be hydrolyzed to their corresponding thiols (Guth et al., 1995; Rauhut, 1993). In the absence of water, they are split to thiyl radicals and converted to thiols by other antioxidants (Guth et al., 1995). This well-known interchange reaction, between protein sulfhydryl groups (cysteine residue) and disulfides for instance (Fig. 1b; Adams et al., 2001; Axelsson and Mannervik, 1975; Bel Rhlid et al., 1999b; Bücking and Steinhart, 2002; Chen and Schofield, 1995; Friedman, 1994; Lavigne and Dubourdieu, 1996; Morel et al., 2000; Mottram and Madruga, 1995; Mottram et al., 1996, 1998; Nedjma, 1997; van Seeventer et al., 2001) is pH dependent (a higher pH involving greater disulfide loss) and temperature dependent (a higher temperature increasing interchanges). In the latter case, heat denaturation of proteins probably maximizes availability of

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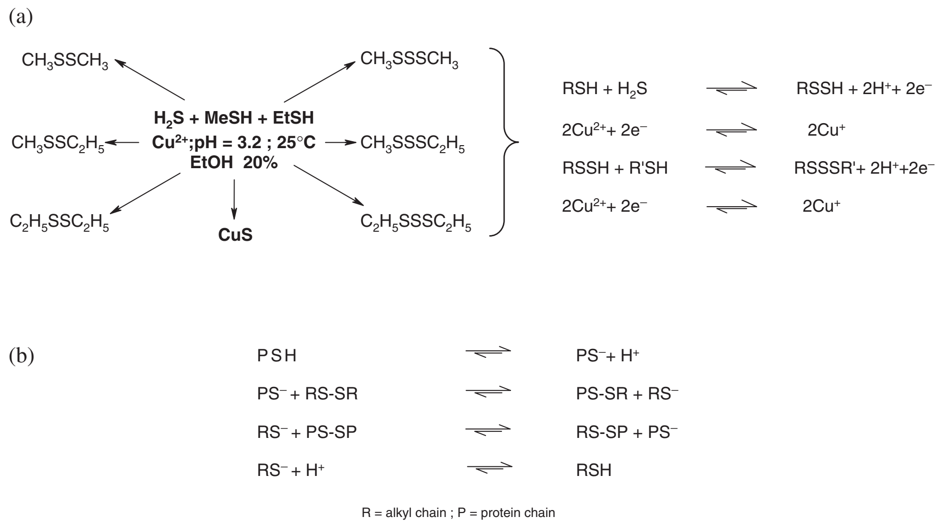

Figure 1. Thiol oxidation (a) and interchange reactions with proteins (b).

sulfhydryl groups (Adams et al., 2001; Morel et al., 2000). Yet, although thiols are suspected of being thermally unstable (Blank et al., 1992; Hofmann, et al., 1996; Lin et al., 2002; Maga, 1976; Mottram et al., 1998; Vermeulen and Collin, 2002b), food processing such as pasteurization does not always alter the thiol content (Bezman et al., 2001).

This type of interchange reaction with yeast cell-wall mannoproteins can induce organoleptic evolution in fermented beverages [e.g., thiol trapping by lees in wines (Lavigne and Dubourdieu, 1996; Maujean, 2001; Tominga et al., 2003b) or H_2S removal during secondary fermentation in beer]. In living cells, glutathione with its SH moiety is also able to form mixed disulfides with proteins (Axelsson and Mannervik, 1975).

Some strong antioxidants (e.g., 2-furfurylthiol) can also sometimes act as prooxidants by promoting Fenton reactions after ferric ion reduction (Blank et al., 2002).

Thiols are also known to bind to metals such as Cu (Bouchilloux et al., 1998b, 1999; Darriet et al., 1993, 2001a, 2001b; Hatzimiditriou et al., 1996; Lavigne et al., 1993, 1998; Naim et al., 1997; Nedjma, 1997; Rauhut, 1993; Rigaud et al., 1986; Walker, 1995), Ag (Walker, 1995), Zn (Walker, 1995), Pb (Walker, 1995), and Hg (Darriet et al., 1995; Manning and Price, 1977; Mestres et al., 1997). This type of reaction has been used many times to extract thiols selectively from a complex matrix (e.g., reversible combination with *p*-hydroxymercuribenzoate) (Bouchilloux et al., 1996; Darriet et al., 1995; Dubourdieu and Darriet, 1993; Lavigne et al., 1993, 1998; Mestres et al., 1997; Tominaga, 1998; Tominaga and Dubourdieu, 1997; Tominaga et al., 1998b, 2003b). This thiol propensity to react with metallic ions also explains why the spraying on vine of antifungal agents containing Cu^{++} is unsuitable, especially when Sauvignon typicity is required (Darriet et al., 2001a).

Like other powerful nucleophiles (Edwards and Wedzicha, 1997; Heusinger and Mosandl, 1984; Naim et al., 1993, 1994; van Seeventer et al., 2001; Vermeulen and

Collin, 2002b), thiols can degrade unsaturated carbonyls (e.g., mesityl oxide), lactones (e.g., aflatoxins), and halogenous toxicants (Badings et al., 1976; Friedman, 1994; Takabe et al., 1970). More recent studies suggest that thiols could also be used as additives for prevention of browning in foods and beverages. For instance, fortification of orange juice and other foods with cysteine (Naim et al., 1993, 1994, 1998; Negishi and Ozawa, 2000; Voldrich et al., 1995), glutathione (Naim et al., 1997, 1998; Voldrich et al., 1995), or *N*-acetyl-cysteine (Naim et al., 1998; Voldrich et al., 1995) has proved an appropriate means of preventing Maillard reactions and browning, where thiols enter into competition with amino groups for carbohydrate reactivity (Edwards and Wedzicha, 1997; Friedman, 1994). Nevertheless, the fact that these three compounds can be a source of objectionable flavor must be taken into account (Mestres et al., 2000; Naim et al., 1997). Likewise, thiols are prone to react with polyphenols and quinones (Blanchard, 2000; Darriet et al., 2001b; Dubourdieu, 1995; Nedjma, 1997), and this explains why consumption of raw apple, pear, and prune containing significant amounts of polyphenols deodorizes bad breath after garlic consumption (Negishi et al., 2002). In the mouth, thiols can also be degraded by saliva enzymes (Buettner, 2002).

Finally, some research mentions interactions with melanoidins (Hofmann and Schieberle, 2002; Hofmann et al., 2001) or lipids (Bücking and Seinhart, 2002), the latter explaining why milk has a drastic effect on coffee sulfur notes (Bücking and Steinhart, 2002).

Sensorial Properties and Food Occurrence

As depicted in Tables 1–9, the thiols depicted in Figs. 2–5 are widespread in vegetables, fruits, beverages, meats, dairy products, and other foods. Most of them are characterized by a very low perception threshold (sometimes below the ppt level; Aznar et al., 2001; Demole et al., 1982; Gora and Brud, 1983; Maga, 1976; Mestres et al., 1999; Mottram et al., 1998; Reiners and Grosch, 1998) or BE-GC-LOADS (Best Estimated-Gas Chromatography-LOwest Amount Detected by Sniffing) (sometimes far below 1 ng; (Vermeulen and Collin, 2000b; Vermeulen et al., 2001). Therefore, it is often difficult to identify or quantify them in a complex matrix; the detection thresholds of most common detectors can only be reached with intense concentration steps (Tominaga et al., 1998b).

Colorimetric tests that use either 4,4′-bis-dimethylaminodiphenylcarbinol (Rohrbach et al., 1973) or 5-5′-dithiobis-(2-nitrobenzoic)-acid (Voldrich et al., 1995) are sometimes used to check for the presence of thiols in a medium (Fig. 6). These reactants are often sprayed on chromatographic thin layers to follow the progression of a chemical synthesis of thiols (Vermeulen et al., 2003a). By this way the spots corresponding to thiols are revealed by a change in color [from blue to colorless for the 4,4′-bis-dimethylaminodiphenylcarbinol and from colorless to yellow for the 5-5′-dithiobis-(2-nitrobenzoic)-acid].

Thiols are usually evil smelling, and therefore, are considered as detrimental to flavor (Bezman et al., 2001; Beloqui and Bertrand, 1995b; Block, 1992; Dan et.al., 1999; Hugues, 1998; Kadota and Ishida, 1972; Mestres et al., 1997; Mottram and Whitfield, 1995b; Walker and Gray, 1970). Nevertheless, minute concentrations of some polyfunctional thiols are required for the acceptability of some foods and beverages (Bel Rhlid et al., 1999a; Fitz et al., 2001; Helmlinger et al., 1976; Kumazawa et al., 2000a; Lüntzel, et al., 2000b; Masuda et al., 1988; Menneer et al.,

Table 1
Beverage/food occurrence, perception threshold, and odor of mercapto-alcohols illustrated in Fig. 2

No.	Matrix–concentration	Perception threshold	Odor
3	In vegetables: Onion (Maga, 1976; Shankaranarayana et al., 1982)	—	—
4	In beverages: Wine—0–400 ppb (Beloqui and Bertrand, 1995a; Ferreira et al., 2003; Guedes de Pinho and Bertrand, 1995; Lavigne et al., 1998;Mestres et al., 2002; Rauhut, 1993; Tominaga et al., 1998a)	In water + 15% ethanol: 1–10 ppm (Beloqui and Bertrand, 1995b; Lavigne et al., 1998; Rauhut, 1993). In water + 20% ethanol: 100 ppb (Ferreira et al., 2003). In wine: 0.13–10 ppm (Mestres et al., 2000)	Alliaceous (Guedes de Pinho and Bertrand, 1995; Mestres et al., 2000) Poultry (Beloqui and Bertrand, 1995a, b; Ferreira et al., 2003; Mestres et al., 2000). Rubber, burnt (Ferreira et al., 2003). Stale, off-flavor, unpleasant (Guedes de Pinho and Bertrand, 1995; Mestres et al., 2002; Tominaga et al., 1998a)
5	In beverages: Beer—7 ppb (Olsen, 1988)	In water: < 1 ppb (Olsen, 1988)	Onion (Olsen, 1988)
6	In vegetables: Onion (Lüntzel et al., 2000c; Widder et al., 2000)	BE-GC-LOADS: 0.004–0.007 ng (Vermeulen et al., in press) In air: 2(R)-3(S): 0.00007–0.0002 ppt (Lüntzel et al., 2000c) 2(S)–3(R): 0.003–0.007 ppt (Lüntzel et al., 2000c) In water: 0.15 ppb (Widder et al., 2000) 0.63 ppb (Widder et al., 1999) 2(R)–3(R): > 12 ppb (Lüntzel et al., 2000c) 2(R)–3(S): 0.04 ppb (Lüntzel et al., 2000c) 2(S)–3(R): 0.03 ppb (Lüntzel et al., 2000c) 2(S)–3(S): > 30 ppb (Lüntzel et al., 2000c)	Burnt plastic, gas, citrus fruit, greenery, vinaigrette (Vermeulen et al., in press) Meat broth, sweat, leek (Lüntzel et al., 2000c; Widder et al., 1999, 2000). Onion (Widder et al., 2000). Sulfury, burnt gum, metallic, roasted (Widder et al., 1999)

(*continued*)

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Table 1
Continued

No.	Matrix–concentration	Perception threshold	Odor
7	In beverages: Wine—0.25–10 ppb (Acuna et al., 2000; Blanchard et al., 1999; Bouchilloux et al., 1998a, b, 1999, 2000; Darriet et al., 2001a)	BE-GC-LOADS: 0.07 ng (Vermeulen et al., in press) In air: 0.004-0.4 ppt (Acuna et al., 2000) In water: 3 ppb (Bouchilloux et al., 1998b; Mestres et al., 2000) (R): 3–7 ppb (Bouchilloux et al., 2000) (S): 35–40 ppb (Bouchilloux et al., 2000) In water + 12% ethanol: 20 ppb (Blanchard et al., 1999). (R): 20–27 ppb (Bouchilloux et al., 2000). (S): 0.12–0.13 ppm (Bouchilloux et al., 2000)	Broth, sweat (Acuna et al., 2000; Blanchard et al., 1999; Bouchilloux et al., 1998b; Mestres et al., 2000) Fruity, animal (Mestres et al., 2000) Herbaceous, exotic fruit, gassy, cooked vegetable (Acuna et al., 2000) Leek, onion (Acuna et al., 2000; Vermeulen et al., inpress) Roasted meat (Acuna et al., 2000; Blanchard et al., 1999)
8	In beverages: Coffee—50–1500 ppb (Acuna et al., 2000; Blank et al., 1992; Boelens and van Gemert, 1993; Buettner, 2002; Holscher et al., 1990, 1992; Tominaga and Dubourdieu, 2000; Tominaga et al., 1998a; van de Waal et al., 2002), wine—1.6–327 ppt (Acuna et al., 2000; Bouchilloux et al., 1998a, b; Mestres et al., 2000; Peyrot des Gachons et al., 1999; Spinnler and Bonnarme, 2002; Tominaga and Dubourdieu, 2000; Tominaga et al., 1998a, b, 2000a; van de Waal et al., 2002)	BE-GC-LOADS: 0.2 ng (Vermeulen et al., in press) In water: 1.3 ppb (Tominaga et al., 1998a, 2000a) 2–6 ppb (Holscher et al., 1992) 2.1 ppb (Buettner, 2002) In water + 12% ethanol: 1.5 ppb (Mestres et al., 2000; Peyrot des Gachons et al., 1999; Tominaga et al., 1998a, b, 2000a)	Broth, meaty (Blank et al., 1992) Catty (Buettner, 2002) Leek (Mestres et al., 2000; Peyrot des Gachons et al., 1999; Spinnler and Bonnarme, 2002; Tominaga et al., 1998a, 2000a) Onion, tartare, chervil (Vermeulen et al., in press) Soup (Acuna et al., 2000; Holscher et al., 1990, 1992) Sweet, spicy, cooked food (Holscher et al., 1990, 1992)

9	In beverages: Wine—250 ppt–12.8 ppb (Acuna et al., 2000; Blanchard et al., 1999; Bouchilloux et al., 1996, 1998a, b, 1999; Darriet et al., 2001a, b; Dubourdieu, 1995; Ferreira et al., 2001, 2002; Hatzimiditriou et al., 1996; Kotseridis and Baumes, 2000; Kotseridis et al., 2000; Lin et al., 2002; Masneuf et al., 1999, 2002; Mestres et al., 2000; Murat et al., 2001a, b, c, d; Peyrot des Gachons et al., 1999, 2000; 2002a, b, Spinnler and Bonnarme, 2002; Tominaga and Dubourdieu, 2000; Tominaga et al., 1995, 1996, 1998a, b, c, 2000a, b, 2003b; van de Waal et al., 2002) In fruits: Grapefruit (Lin et al., 2002), passion fruit—38 ppb (Acuna et al., 2000; Bouchilloux et al., 1998a, b; Dubourdieu, 1995; Engel and Tressl, 1991; Kotseridis et al., 2000; Lin et al., 2002; Tominaga and Dubourdieu, 2000; Tominaga et al., 1996, 1998a, b, 2000b; Weber et al., 1994, 1995; Werkhoff et al., 1998) In miscellaneous matrices: Yeast extract (Kotseridis and Baumes, 2000)	BE-GC-LOADS: 0.004 ng (Vermeulen et al., in press) In water: 12–1 ppt (Bouchilloux et al., 1998b; Mestres et al., 2000) 17 ppt (Tominaga et al., 1998a, 2000a) In water + 12% ethanol: 0.8 ppt (Darriet et al., 2001a; Masneuf et al., 2002) 4 ppt (Lin et al., 2002; Peyrot des Gachons et al., 1999) 60 ppt (Blanchard et al., 1999; Ferreira et al., 2002; Mestres et al., 2000; Murat et al., 2001b; Peyrot des Gachons et al., 2002a; Tominaga et al., 1998a, b, 2000a, 2003b)	Asparagus (Kotseridis and Baumes, 2000) Broom, box tree, animal, grape (Mestres et al., 2000) Citric note (Ferreira et al., 2002) Fruity (Ferreira et al., 2002; Mestres et al., 2000; Murat et al., 2001a) Grapefruit (Acuna et al., 2000; Blanchard et al., 1999; Bouchilloux et al., 1998b; Kotseridis and Baumes, 2000; Kotseridis et al., 2000; Murat et al., 2001b; Peyrot des Gachons et al., 1999, 2002; Spinnler and Bonnarme, 2002; Tominaga et al., 1998a, b, 2000a; Werkhoff et al., 1998) Passion fruit (Acuna et al., 2000; Kotseridis and Baumes, 2000; Kotseridis et al., 2000; Marais and Swart, 1999; Masneuf et al., 2002; Mestres et al., 2000; Murat et al., 2001b; Peyrot des Gachons et al., 1999, 2002a, b; Tominaga et al., 1998a, b, 2000a, b, 2003b) Rhubarb, lime (Vermeulen et al., in press) Sweat (Dubourdieu, 1995; Tominaga et al., 1995) Tropical fruit, guava, mango, blackcurrant, buchu (Werkhoff et al., 1998) Vegetable, dry (Aznar et al., 2001; Ferreira et al., 2001)
10	In beverages: Wine (Lavigne et al., 1998)	BE-GC-LOADS: 0.2 ng (Vermeulen et al., in press)	Potato, broth (Vermeulen et al., in press)

(*continued*)

Table 1
Continued

No.	Matrix–concentration	Perception threshold	Odor
11	In beverages: Wine—122 ppb (Bouchilloux et al., 1998a, b; Lin et al., 2002; Mestres et al., 2000; Murat et al., 2001c; Peyrot des Gachons et al., 1999, 2000, 2002a, b; Spinnler and Bonnarme, 2002; Tominaga et al., 1998a, b, c, 2000a; van de Waal et al., 2002)In fruits: Grapefruit (Lin et al., 2002)	BE-GC-LOADS: 0.009 ng (Vermeulen et al., 2001, in press) In water: 20 ppt (Tominaga et al., 1998a, 2000a) In water + 12% ethanol: 55 ppt (Lin et al., 2002; Mestres et al., 2000; Peyrot des Gachons et al., 1999, 2002a; Tominaga et al., 1998a, b, 2000a)	Blackcurrant, solvent (Vermeulen et al., 2001, in press) Broom, box tree (Mestres et al., 2000; Vermeulen et al., 2001, in press) Citrus zest (Lin et al., 2002; Mestres et al., 2000; Peyrot des Gachons et al., 1999, 2002a, b; Spinnler and Bonnarme, 2002; Tominaga et al., 1998a, b, 2000a) Grapefruit (Lin et al., 2002) Passion fruit (Marais and Swart, 1999; Mestres et al., 2000)

BE-GC-LOADS, Best Estimated-Gas Chromatography-LOwest Amount Detected by Sniffing.
ppm, mg/L; ppb, µg/L; ppt, ng/L.

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Table 2
Beverage/food occurrence, perception threshold, and odor of mercapto-aldehydes illustrated in Fig. 3

No.	Matrix–concentration	Perception threshold	Odor
12	In fruits: Passion fruit (Engel and Tressl, 1991), tomato (Engel and Tressl, 1991) In meats: Beef liver (Werkhoff et al., 1996)	BE-GC-LOADS: 0.003 ng (Vermeulen and Collin, 2002b)	Citrus fruit peel (Vermeulen and Collin, 2002b) Sulfury, fruity, herbaceous, juicy, sweet, tropical fruit, passion fruit, guava, mango, buchu, blackcurrant, durian (Werkhoff et al., 1996)
13	In vegetables: Onion (Widder et al., 2000)	BE-GC-LOADS: 0.003–0.1 ng (Vermeulen and Collin, 2002b) In water: 0.95 ppb (Widder et al., 2000)	Meaty, onion, meat broth (Lüntzel et al., 2000; Vermeulen and Collin, 2002b; Widder et al., 2000) Pepper (Vermeulen and Collin, 2002b) Sulfury, pungent, sweat (Widder et al., 2000)

BE-GC-LOADS, Best Estimated-Gas Chromatography-LOwest Amount Detected by Sniffing.
ppb, µg/L.

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Table 3
Beverage/food occurrence, perception threshold, and odor of mercapto-ketones illustrated in Fig. 3

No.	Matrix–concentration	Perception threshold	Odor
14	In meats: Pork (Liu et al., 2001)	—	—
15	In meats: Beef liver (Werkhoff et al., 1996), pork (Güntert et al., 1990) In miscellaneous matrices: Roasted sesame (Werkhoff et al., 1996)	In air: 1.7–6.8 ppt (Hofmann and Schieberle, 1995)	Meaty, pickled (Güntert et al., 1990; Werkhoff et al., 1996) Sulfury (Güntert et al., 1990; Hofmann and Schieberle, 1995; Werkhoff et al., 1996)
16	In meats: Beef liver (Werkhoff et al., 1996)	BE-GC-LOADS: 0.009 ng (Vermeulen et al., in press)	Cheese, solvent, skunky, pungent (Vermeulen et al., in press) Sulfury, onion, durian, rubber (Güntert et al., 1992; Werkhoff et al., 1996)
17	In beverages: Wine (Pripis-Nicolau et al., 1999) In meats—0–70 ppt (Madruga and Mottram, 1995; Mottram and Madruga, 1994): Beef—20–44 ppb (Kerscher and Grosch, 1998), lamb—10 ppb (Kerscher and Grosch, 1998), pork—11–14 ppb (Kerscher and Grosch, 1998) In poultry: Chicken—13 ppb (Kerscher and Grosch, 1998) In miscellaneous matrices: Yeast extract (Kerscher and Grosch, 1998)	In air: 0.6 ppt (Kerscher and Grosch, 1998)	Broth, mashed potato (Mottram and Madruga, 1994) Garlic (Kerscher and Grosch, 1998) Onion (Pripis-Nicolau et al., 1999) Rotten meat, hydrogen sulfide (Mottram and Madruga, 1995) Sulfury (Kerscher and Grosch, 1998; Mottram and Madruga, 1995; Pripis-Nicolau et al., 1999)
18	In meats—0–70 ppt (Madruga and Mottram, 1995; Mottram and Madruga, 1994): Beef liver (Werkhoff et al., 1996) In miscellaneous matrices: Wheat flour (Bredie et al., 2002), yeast extract (Güntert et al., 1990; Münch and Schieberle, 1998; Werkhoff et al., 1996)	In air: 0.2–0.8 ppt (Ames and Mac Leod, 1985; Hofmann and Schieberle, 1995)	Burnt cereal/hamburger/vegetable/bread (Mottram and Madruga, 1995) Cooked meat (Mottram and Madruga, 1994; Wu and Cadwallader, 2002) Onion (Mottram and Madruga, 1994; Werkhoff et al., 1996) Roasted, meaty, fatty, durian, tropical fruit, blackcurrant (Werkhoff et al., 1996) Rotten (Ames and Mac Leod, 1985; Hofmann and Schieberle, 1995, 1997) Rubber, sour (Wu and Cadwallader, 2002) Sulfury (Ames and Mac Leod, 1985; Hofmann and Schieberle, 1995, 1997; Mottram and Madruga 1994, 1995; Schieberle and Hofmann, 1998; Werkhoff et al., 1996)

19	In beverages: Wine (Pripis-Nicolau et al., 1999) In cheeses (Werkhoff et al., 1996) In meats (Madruga and Mottram, 1998): Beef—55–73 ppb (Gasser and Grosch, 1990; Kerscher and Grosch, 1998; Münch and Schieberle, 1998; Werkhoff et al., 1996), beef liver (Werkhoff et al., 1996), ham (Carrapiso et al., 2002), lamb—30 ppb (Kerscher and Grosch, 1998), pork—66–117 ppb (Kerscher and Grosch, 1998) In poultry: Chicken—100 ppb (Gasser and Grosch, 1990b; Hofmann and Schieberle, 1995; Kerscher and Grosch, 1998; Madruga and Mottram, 1998; Münch and Schieberle, 1998; Werkhoff et al., 1996) In miscellaneous matrices: Yeast extract—0–170 ppb (Kerscher and Grosch, 1998; Münch and Schieberle, 1998; Münch et al., 1997)	In air: 0.045–0.18 ppt (Carrapiso et al., 2002; Gasser and Grosch, 1990a, 1990b) 0.05–0.2 ppt (Hofmann and Schieberle, 1995; Ames and Mac Leod, 1985) 0.15 ppt (Kerscher and Grosch, 1998) In water: 0.2 ppb (Wu and Cadwallader, 2002) 0.7 ppb (Kerscher and Grosch, 1998; Münch and Schieberle, 1998)	Catty (Ames and Mac Leod, 1985; Baek et al., 2001; Bel Rhlid et al., 2002a; Farmer et al., 1989; Hofmann and Schieberle, 1995, 1997; Kerscher and Grosch, 1998; Pripis-Nicolau et al., 1999; Schieberle and Hofmann, 1998; Wu and Cadwallader, 2002) . Garlic (Farmer et al., 1989) Ham, potato (Carrapiso et al., 2002) Hydrogen sulfide (Mottram and Madruga 1995) Meaty (Carrapiso et al., 2002; Werkhoff et al., 1996) Onion, liver, herbaceous, fruity, tropical fruit, passion fruit, grapefruit, buchu (Werkhoff et al., 1996) Spicy (Baek et al., 2001) Sulfury (Bel Rhlid et al., 2002a; Gasser and Grosch, 1990a, b; Hofmann and Schieberle, 1995, 1997; Kerscher and Grosch, 1998; Mottram and Madruga, 1995; Münch and Schieberle, 1998; Münch et al., 1997; Pripis-Nicolau et al., 1999; Schieberle and Hofmann, 1998; Werkhoff et al., 1996) Urine (Farmer et al., 1989; Wu and Cadwallader, 2002)
20	In meats: Beef liver (Werkhoff et al., 1996)	BE-GC-LOADS: 0.01 ng (Vermeulen et al., in press)	Meaty, roasted, lard, sulfury (Werkhoff et al., 1996; Güntert et al., 1992) Potato (Güntert et al., 1992; Werkhoff et al., 1996; Vermeulen et al., in press)

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Table 3
Continued

No.	Matrix–concentration	Perception threshold	Odor
21	In beverages: Beer (Polak et al., 1988; Schieberle, 1991a), tea (Kumazawa and Masuda, 1999, 2002), wine—4–400 ppt (Bouchilloux et al., 1996, 1998a, 1998b; Darriet et al., 1993, 1995, 2001a; Du Plessis and Augustyn, 1981; Dubourdieu, 1995; Dubourdieu and Darriet, 1993; Ferreira et al., 2001, 2002; Guth, 1997a, 1997b, 1998; Hatzimiditriou et al., 1996; Kotseridis and Baumes, 2000; Kotseridis et al., 2000; Kumazawa and Masuda, 1999; Lopez et al., 1999; Marais, 1994; Marais and Swart, 1999; Masneuf et al., 1999, 2002; Mestres et al., 2000; Murat et al., 2001c; Peyrot des Gachons et al., 1999, 2000, 20002a, 20002b; Spinnler and Bonnarme, 2002; Tominaga and Dubourdieu, 1997; Tominaga et al., 1995, 1996, 1998a, b, c, 2000a, b, 2003a, van de Waal et al., 2002) In cheeses (Polak et al., 1988) In dairies (Maga, 1976) In fruits (Maga, 1976): Blackcurrant (Kumazawa and Masuda, 1999), grapefruit—0.8 ppb (Bredie et al., 2002; Buettner and Schieberle, 1999, 2001; Lin et al., 2002) In meats (Maga, 1976; Polak et al., 1988; Spencer, 1969; Wasserman, 1972) In miscellaneous matrices: Buchu (Boelens and van Gemert, 1993), olive oil (Kumazawa and Masuda, 1999), yeast extract (Kotseridis and Baumes, 2000) In vegetables (Maga, 1976; Polak et al., 1988)	BE-GC-LOADS: 0.004 ng (Vermeulen et al., 2001, in press) In water: 0.066–0.165 ppt (Darriet et al., 1995) 0.1 ppt (Buettner and Schieberle, 2001; Kumazawa and Masuda, 1999; Marais, 1994; Tominaga and Dubourdieu, 1997; Tominaga et al., 1996, 2000a) In water + 10% ethanol: 0.6 ppt (Guth, 1997b; Mestres et al., 2000) 0.792–1.98 ppt (Darriet et al., 1995) In water + 12% ethanol: 0.8 ppt (Peyrot des Gachons et al., 1999; Peyrot des Gachons et al., 2002a; Tominaga et al., 1996, 1998a, 1998b, 2000a, 2003a) 0.99–1.18 ppt (Darriet et al., 1995) In wine: 0.8–3 ppt (Mestres et al., 2000) 3 ppt (Bouchilloux et al.,1996; Darriet et al., 1995) 3.3 ppt (Darriet et al., 1995)	Blackcurrant (Boelens and van Gemert, 1993; Bredie et al., 2002; Buettner and Schieberle, 1999, 2001; Guth, 1997a, 1997b; Hatzimiditriou et al.,1996; Kotseridis et al., 2000; Kumazawa and Masuda, 2002; Polak et al., 1988; Vermeulen et al., 2001, in press) Box tree (Aznar et al., 2001; Bouchilloux et al., 1996, 1998b; Darriet et al., 1993, 1995; Ferreira et al., 2001; Hatzimiditriou et al., 1996; Kotseridis and Baumes, 2000; Kotseridis et al., 2000; Marais and Swart, 1999; Masneuf et al., 2002; Mestres et al., 2000; Peyrot des Gachons et al., 1999, 2002a, 2002b; Spinnler and Bonnarme, 2002; Tominaga et al., 1998a, 1998b, 2000a, 2000b) Broom (Masneuf et al., 2002; Mestres et al., 2000; Peyrot des Gachons et al., 1999, 2002; Spinnler and Bonnarme, 2002; Tominaga et al., 1998, 2000; Vermeulen et al., in press) Catty (Buettner and Schieberle, 2001; Darriet et al., 1995; Farmer et al., 1989; Kotseridis et al., 2000; Marais and Swart, 1999; Marais, 1994; Mestres et al., 2000; Polak et al., 1988; Shankaranarayana et al., 1982; Spencer, 1969; Tominaga et al., 2003a; Vermeulen et al., 2001, in press; Wasserman, 1972) Conifer (Marais and Swart, 1999) Guava (Du Plessis and Augustyn, 1981; Marais, 1994; Marais and Swart, 1999; Mestres et al., 2000) Meaty (Kumazawa and Masuda, 1999, 2002) Passion fruit (Mestres et al., 2000) Patchouli, greenery, bitter (Lopez et al., 1999) Sulfury (Lin et al., 2002; Marais and Swart, 1999)
22	In fruits: Durian (Weenen et al., 1996)	BE-GC-LOADS: 0.03 ng (Vermeulen et al., 2001, in press)	Exotic fruit, sweet (Vermeulen et al., 2001, in press) Sulfury, cabbage (Weenen et al., 1996)

BE-GC-LOADS: Best Estimated-Gas Chromatography-Lowest Amount Detected by Sniffing.
ppb, μg/L; ppt, ng/L.

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Table 4
Beverage/food occurrence, perception threshold, and odor of mercapto-esters illustrated in Fig. 3

No.	Matrix-concentration	Perception threshold	Odor
23	In beverages: Wine—23–134 ppb (Bouchilloux et al., 1998a, 1998b; Lavigne et al., 1998; Mestres et al., 2000; Spinnler and Bonnarme, 2002; Tominaga et al., 1998a, 2000b, 2003a)	In a wine-model solution: 40 ppb (Blanchard et al., 1999) 65 ppb (Mestres et al., 2000; Lavigne et al., 1998)	Burnt wood, grilling (Lavigne et al., 1998) Roasted, roasted meat (Blanchard et al., 1999; Bouchilloux et al., 1998a, 1998b; Lavigne et al., 1998; Mestres et al., 2000; Spinnler and Bonnarme, 2002; Tominaga et al., 1998a, 2000b)
24	In beverages: Wine—0–3278 ppt (Aznar et al., 2001; Blanchard et al., 1999; Bouchilloux et al., 1998a, 1998b; Ferreira et al., 2001; Kotseridis and Baumes, 2000; Kotseridis et al., 2000; Lin et al., 2002; Marais and Swart, 1999; Masneuf et al., 1999; Mestres et al., 2000; Murat et al., 2001b, 2001d; Peyrot des Gachons et al., 1999; Spinnler and Bonnarme, 2002; Tominaga and Dubourdieu, 2000; Tominaga et al., 1996, 1998a, 1998b, 2000a, 2000b, 2003a; van de Waal et al., 2002) In fruits: Grapefruit (Lin et al., 2002), passion fruit—2 ppb (Bouchilloux et al., 1998a, 1998b; Engel and Tressl, 1991; Kotseridis et al., 2000; Lin et al., 2002; Tominaga and Dubourdieu, 2000; Tominaga et al., 1996, 1998b, 2000b; Weber et al., 1992, 1994, 1995; Werkhoff et al., 1998)	BE-GC-LOADS: 0.02 ng (Vermeulen and Collin, in press) In water: 2–3 ppt (Bouchilloux et al., 1998b) 2.3 ppt (Mestres et al., 2000; Tominaga et al., 1996, 2000a) In a water-ethanol mixture: 4.2 ppt (Murat et al., 2001b; Tominaga et al., 1996, 1998a, 2000a, 2003a) 60 ppt (Lin et al., 2002; Peyrot des Gachons et al., 1999) In water + 12% ethanol: 4 ppt (Mestres et al., 2000; Tominaga et al., 1998b) In a wine-model solution: 5 ppt (Blanchard et al., 1999)	Anise (Aznar et al., 2001) Banana (Kotseridis and Baumes, 2000) Box tree (Aznar et al., 2001; Blanchard et al., 1999; Bouchilloux et al., 1998b; Ferreira et al., 2001; Mestres et al., 2000; Murat et al., 2001b; Peyrot des Gachons et al., 1999; Spinnler and Bonnarme, 2002; Tominaga et al., 1996, 1998a, 1998b, 2000a); Broom (Bouchilloux et al., 1998b; Mestres et al., 2000) Candy, blackcurrant (Vermeulen and Collin, in press) Fruity (Engel and Tressl, 1991; Kotseridis et al., 2000; Tominaga et al., 1996) Grapefruit (Kotseridis and Baumes, 2000; Lin et al., 2002; Tominaga et al., 1996, 2000b; Werkhoff et al., 1998) Mango, guava, black-currant, buchu (Werkhoff et al., 1998) Passion fruit (Bouchilloux et al., 1998b; Engel and Tressl, 1991; Marais and Swart, 1999; Mestres et al., 2000; Murat et al., 2001b; Peyrot des Gachons et al., 1999; Spinnler and Bonnarme, 2002; Tominaga et al., 1996, 1998b, 2000a; Vermeulen and Collin, in press; Werkhoff et al., 1998;) Riesling wine (Engel and Tressl, 1991; Tominaga et al., 1996) (R): tropical fruit, passion fruit (Weber et al., 1992) (S): sulfury, cabbage (Weber et al., 1992)

(*continued*)

Table 4
Continued

No.	Matrix-concentration	Perception threshold	Odor
25	In fruits: Passion fruit—2 ppb (Engel and Tressl, 1991; Weber et al., 1992, 1994, 1995; Werkhoff et al., 1998)	—	Grapefruit, blackcurrant, buchu, tropical fruit, mango (Werkhoff et al., 1998) (R): tropical fruit, passion fruit (Weber et al., 1992) (S): sulfury, roasted, fruity (Weber et al., 1992)
26	In fruits: Passion fruit—1 ppb (Engel and Tressl, 1991; Weber et al., 1992, 1994, 1995; Werkhoff et al., 1998)	—	Grapefruit, guava, buchu, tropical fruit, passion fruit, blackcurrant (Werkhoff et al., 1998) (R): cabbage, sulfury (Weber et al., 1992) (S): sulfury (Weber et al., 1992)
27	In fruits: Passion fruit (Werkhoff et al., 1998)	In water: 10 ppb (Werkhoff et al., 1998)	Tropical fruit, passion fruit, buchu (Werkhoff et al., 1998)
28	In beverages: Wine—3–32 ppb (Bouchilloux et al., 1998a, 1998b; Lavigne et al., 1998; Mestres et al., 2000; Spinnler and Bonnarme, 2002; Tominaga et al., 1998a, 2000b, 2003a) In meats (Lavigne et al., 1998)	BE-GC-LOADS: 0.9 ng (Vermeulen and Collin, in press) In a wine-model solution: 35 ppb (Lavigne et al., 1998; Mestres et al., 2000)	Burnt wood, grilling (Lavigne et al., 1998; Vermeulen and Collin, in press) Roasted, roasted meat (Bouchilloux et al., 1998a, 1998b; Lavigne et al., 1998; Mestres et al., 2000; Spinnler and Bonnarme, 2002; Tominaga et al., 1998a, 2000b; Vermeulen and Collin, in press)
29	In fruits: Passion fruit (Tominaga and Dubourdieu, 2000)	BE-GC-LOADS: 2 ng (Vermeulen and Collin, in press)	Grapefruit peel (Tominaga and Dubourdieu, 2000) Roasted meat, onion, vinegar, fruity (Vermeulen and Collin, in press)

30	In beverages: Beer (Boelens and van Gemert, 1993; Gresser, 1997; Grosch, 1993; Schieberle, 1991a), coffee—4.3–115 ppb (Blank et al., 1992; Boelens and van Gemert, 1993; Bücking et al., 2002; Czerny et al., 1999; Grosch, 1993; Holscher et al., 1990, 1992; Masanetz et al., 1995; Sanz et al., 2002; Schieberle, 1991a; Semmelroch and Grosch, 1995, 1996; Semmelroch et al., 1995; van de Waal et al., 2002)	In air: 0.0002–0.0004 ppt (Blank et al., 1992; Boelens and van Gemert, 1993) 0.0003 ppt (Schieberle, 1991a) In water: 2–5 ppt (Boelens and van Gemert, 1993; Holscher et al., 1992; Masanetz et al., 1995) 3.5 ppt (Semmelroch et al., 1995) 5 ppt (Gresser, 1997)	Blackcurrant (Boelens and van Gemert, 1993; Buettner and Schieberle, 1999; Gresser, 1997; Holscher et al., 1990, 1992; Schieberle, 1991a) Catty (Blank et al., 1992; Boelens and van Gemert, 1993; Holscher et al., 1990, 1992; Masanetz et al., 1995; Schieberle, 1991a; Semmelroch and Grosch, 1995; Semmelroch et al., 1995) Fox (Bücking et al., 2002) Roasted (Blank et al., 1992; Masanetz et al., 1995; Sanz et al., 2002; Semmelroch and Grosch, 1995) Sweat, fruity (Holscher et al., 1992)
31	In beverages: Wine—40 ppt–12 ppb (Blanchard et al., 1999; Tominaga et al., 2003b) In fruits: Grape (Boelens and van Gemert, 1993; Kolor, 1983)	In water: 200 ppb (Boelens and van Gemert, 1993; Kolor, 1983) In a wine-model solution: 200 ppt (Tominaga et al., 2003b)	Animal (Kolor, 1983) Empyreumatic (Tominaga et al., 2003b) Fruity, grape, skunk, fox (Boelens and van Gemert, 1993; Kolor, 1983)
32	In beverages: Appel juice (Tominaga et al., 2003b), wine—50–800 ppt (Tominaga et al., 2003b) In fruits: Strawberry (Tominaga et al., 2003b)	In a wine-model solution: 500 ppt (Tominaga et al., 2003b)	Fruity (Tominaga et al., 2003b)

BE-GC-LOADS: Best Estimated-Gas Chromatography-Lowest Amount Detected by Sniffing.
ppb, μg/L; ppt, ng/L.

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Table 5
Beverage/food occurrence, perception threshold, and odor of mercapto-ethers illustrated in Fig. 4

No.	Matrix–quantity	Perception threshold	Odor
33	In miscellaneous matrices: Rue (van de Waal et al., 2002)	In air: 0.00082 ppt (van de Waal et al., 2002)	Onion, tropical fruit, sulfury (van de Waal et al., 2002)
34	In fruits: Tomato (van de Waal et al., 2002) In miscellaneous matrices: Mint (van de Waal et al., 2002), rue (van de Waal et al., 2002), sage (van de Waal et al., 2002)	In air: 0.00036 ppt (van de Waal et al., 2002) (R): 0.00109 ppt (van de Waal et al., 2002) (S): 0.00004 ppt (van de Waal et al., 2002)	Sulfury, herbaceous, green, pungent, repulsive, tropical fruit (van de Waal et al., 2002) (R): sulfury, onion, herbaceous (van de Waal et al., 2002) (S): herbaceous, sage, burnt sulfur, alliaceous, sweat (van de Waal et al., 2002)
35	In miscellaneous matrices: Rue (van de Waal et al., 2002)	In air: 0.043 ppt (van de Waal et al., 2002)	Tropical fruit, alliaceous, rubber (van de Waal et al., 2002)
36	In beverages: Tea (Kumazawa and Masuda, 1999; van de Waal et al., 2002), wine (Kumazawa and Masuda, 1999) In fruits: Blackcurrant (Boelens and van Gemert, 1993; Bouchilloux et al.,1996; Darriet et al., 1995; Kumazawa and Masuda, 1999; Le Quere and Latrasse, 1990; Polak et al., 1988; Reiners and Grosch, 1998, 1999; Rigaud et al.,1986; Tominaga and Dubourdieu, 1997; van de Waal et al., 2002) In miscellaneous matrices: Hop (Lermusieau et al., 2001), olive oil—0.1–4.3 ppb (Boelens and van Gemert, 1993; Grosch, 1993, 1994; Guth and Grosch, 1993; Kumazawa and Masuda, 1999; Reiners and Grosch, 1998, 1999; van de Waal et al., 2002), rue (van de Waal et al., 2002)	In air: 0.00008–0.00030 ppt (Boelens and van Gemert, 1993) In oil: 17–24 ppt (Reiners and Grosch, 1998) 30–60 ppt (Boelens and van Gemert, 1993) 45 ppt (Grosch, 1994; Guth and Grosch, 1993; Reiners and Grosch, 1999) In water: 0.1 ppt (Kumazawa and Masuda, 1999) 1 ppt (Rigaud et al.,1986)	Blackcurrant (Boelens and van Gemert, 1993; Buettner and Schieberle, 1999; Grosch, 1994; Guth and Grosch, 1993; Reiners and Grosch, 1998, 1999; Rigaud et al.,1986) Box tree (Darriet et al., 1993, 1995) Catty (Le Quere and Latrasse, 1990; Polak et al., 1988) Meaty (Kumazawa and Masuda, 1999)

ppt, ng/L.

Table 6
Beverage/food occurrence, perception threshold, and odor of aliphatic and aromatic mercaptans illustrated in Fig. 4

No.	Matrix–concentration	Perception threshold	Odor
37	In meats: Pork (Liu et al., 2001) In vegetables: Onion (Kuo and Ho, 1992), scallion (Kuo and Ho, 1992)	—	—
38	In beverages: Beer (Meilgaard, 1975) In fish and crustaceans: Oyster (Maga, 1976) In meats: Beef (Maga, 1976)	In beer: 0.6 ppb (Meilgaard, 1975; Boelens and van Gemert, 1993)	Putrefaction, onion, garlic, cheese, fish, egg (Meilgaard, 1975)
39	In beverages: Beer—0.1–8 ppb (Haboucha et al., 1982; Hill and Smith, 2000) In meats: Beef (Maga, 1976; Wilson et al., 1973)	In beer: 2–3 ppb (Haboucha et al., 1982)	—
40	In beverages: Beer (Meilgaard, 1975) In fish and crustaceans: Fish protein (Maga, 1976; Qvist and von Sydow, 1974), oyster (Maga, 1976) In meats: Beef (Shankaranarayana et al., 1982; Wilson et al., 1973)	BE-GC-LOADS: 0.2 ng (Gijs et al., 2000b) In air: 1 ppb (Qvist and von Sydow, 1974) In beer: 2.5 ppb (Meilgaard, 1975; Boelens and van Gemert, 1993)	Onion (Gijs et al., 2000b; Meilgaard, 1975) Putrefaction, garlic, egg (Meilgaard, 1975) Shallot (Gijs et al., 2000b)
41	In beverages: Beer (Meilgaard, 1975)	In beer: 0.07 ppt (Boelens and van Gemert, 1993) 0.08 ppb (Meilgaard, 1975) In water: 0.7 ppt (Gora and Brud, 1983)	Putrefaction, onion, garlic, egg (Meilgaard, 1975)
42	In beverages: Beer—2 ppb (Peppard and Laws, 1979; Polak et al., 1988; Shankaranarayana et al., 1982; Soltoft, 1988) In fish and crustaceans: Oyster (Maga, 1976) In meats: Beef (Shankaranarayana et al., 1982) In vegetables: Potato (Shankaranarayana et al., 1982)	In beer: 80 ppt (Boelens and van Gemert, 1993) 90–500 ppt (Soltoft, 1988)	Unpleasant (Soltoft, 1988)
43	In fruits: Passion fruit (Werkhoff et al., 1998)	—	—
44	In miscellaneous matrices: Roasted sesame—5–50 ppb (Buettner, 2002; Schieberle, 1996)	In oil: 50 ppt (Buettner, 2002) 50 ppm (Schieberle, 1996)	Sulfury, rubber (Buettner, 2002; Schieberle, 1996)
45	In fish and crustaceans: Fish protein (Maga, 1976; Qvist and von Sydow, 1974), oyster (Maga, 1976; Shankaranarayana et al., 1982) In meats: Beef (Edwards et al., 1987) In miscellaneous matrices: Casein (Qvist and von Sydow, 1974) In vegetables: Potato (Maga, 1976; Shankaranarayana et al., 1982), soy (Qvist and von Sydow, 1974)	In air: 0.45 ppb (Qvist and von Sydow, 1974)	—
46	In fish and crustaceans: Oyster (Maga, 1976) In meats: Beef (Maga, 1976)	—	—
47	In meats: Beef (Maga, 1976; Wilson et al., 1973)	In beer: 0.2 ppb (Boelens and van Gemert, 1993)	Repulsive (Maga, 1976)

(*continued*)

Table 6
Continued

No.	Matrix–concentration	Perception threshold	Odor
48	In beverages: Beer—<1 ppb (Blockmans et al., 1981; Boelens and van Gemert, 1993; Drost et al., 1990; Goldstein et al., 1993; Gunst and Verzele, 1978; Haboucha and Masschelein, 1979; Haboucha et al., 1982; Hill and Smith, 2000; Holscher et al., 1992; Hugues, 1998, 1999; Irwin et al., 1993; Kuroiwa et al., 1967; Maga, 1976; Mändli and Anderegg, 1991; Masuda et al., 2000; Polak et al., 1988; Sakuma et al., 1991; Seaton et al., 1981; Shankaranarayana et al., 1982; Soltoft, 1988; Walker, 1991, 1992; Wilson et al., 2001), coffee—8.2–8.3 ppb (Bücking et al., 2002; Blank et al., 1992; Czerny et al., 1999; Holscher et al., 1990, 1992; Semmelroch and Grosch, 1995, 1996), sake (Kuroiwa et al., 1967), wine (Maga, 1976)	In beer: 0.46–338 ppt (Burns et al., 2001) 1 ppt (Walker, 1992) 1–30 ppt (Hugues, 1998) 1.25–3200 ppt (Goldstein et al., 1993) 4.4–35 ppt (Irwin et al., 1993; Masuda et al., 2000) 7 ppt–1 ppb (Hill and Smith, 2000) <10 ppt (Wilson et al., 2001) <30 ppt (Boelens and van Gemert, 1993) In water: 0.2–0.3 ppt (Boelens and van Gemert, 1993; Masuda et al., 2000) 0.2–0.4 ppt (Holscher et al., 1992) 0.3 ppt (Semmelroch and Grosch, 1996) <1 ppt (Burns et al., 2001)	Amine (Blank et al., 1992) Fox (Bücking and Steinhart, 2002; Holscher et al., 1990, 1992; Semmelroch and Grosch, 1995; Soltoft, 1988) Leek (Maga, 1976; Holscher et al., 1992; Hugues, 1998) Onion (Maga, 1976) Pungent, animal (Holscher et al., 1990, 1992) Skunky (Burns et al., 2001; Holscher et al., 1990, 1992; Hugues, 1998; Irwin et al., 1993; Masuda et al., 2000; Semmelroch and Grosch, 1995; Shankaranarayana et al., 1982; Soltoft, 1988; Walker, 1992)
49	In beverages: Beer (Soltoft, 1988) In vegetables: Allium vegetable (Negishi et al., 2002), garlic (Mateo and Zumalacarregui, 1996), onion (Boelens et al., 1971; Maga, 1976; Shankaranarayana et al., 1982) In meats: Chorizo (Mateo and Zumalacarregui, 1996)	In air: 11–50 ppt (Maga, 1976)	Garlic (Maga, 1976; Soltoft, 1988)
50	In beverages: Wine—10–400 ppt (Tominaga et al., 2003a, 2003b) In dairies: Butter (Shankaranarayana et al., 1982), milk (Maga, 1976; Walker and Gray, 1970) In fish and crustaceans: Carp (Tominaga et al., 2003a) In meats: Beef (Gasser and Grosch, 1988; Shankaranarayana et al., 1982)	In air: 0.19–13 ppb (Maga, 1976) In milk: 1 ppb (Walker and Gray, 1970) In a wine-model solution: 0.3 ppt (Tominaga et al., 2003a, 2003b)	Cress (Walker and Gray, 1970) Repulsive, garlic (Maga, 1976) Smoky, empyreumatic, gun flint, cooked/smoked meat (Tominaga et al., 2003a, 2003b) Sulfury (Gasser and Grosch, 1988)

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51	In beverages: Beer (Meilgaard, 1975) In cheeses: Cheddar (Maga, 1976) In fish and crustaceans: Oyster (Maga, 1976; Shankaranarayana et al., 1982) In meats: Beef (Shankaranarayana et al., 1982) In miscellaneous matrices: Corn (Macku and Shibamoto, 1991) In poultry: Chicken (Maga, 1976; Wilson and Katz, 1972) In vegetables: Potato (Maga, 1976)	In air: 1.0–18 ppb (Maga, 1976) In beer: 0.7 ppb (Boelens and van Gemert, 1993; Meilgaard, 1975) In water: 6 ppb (Maga, 1976)	Putrefaction, garlic, onion, egg (Meilgaard, 1975)
52	In beverages: Beer—1.2–6.1 ppb (Haboucha et al., 1982; Hill and Smith, 2000; Meilgaard, 1975; Shankaranarayana et al., 1982; Soltoft, 1988; Walker, 1995), coffee (Maga, 1976; Shankaranarayana et al., 1982), tea (Maga, 1976), whiskey (Shankaranarayana et al., 1982), wine—0–11.1 ppm (Ferreira et al., 2003; Haye et al., 1977; Kataoka et al., 2000; Lavigne and Dubourdieu, 1996; Lavigne et al., 1993; Mestres et al., 1997, 1999, 2000; Nedjma and Maujean, 1995; Park et al., 2000; Rankine, 1968; Rauhut et al., 1996; Shankaranarayana et al., 1982) In cheeses: Cheddar (Cuer, 1982; Liebich et al., 1970; Maga, 1976) In dairies: Butter (Shankaranarayana et al., 1982) In fish and crustaceans: Fish protein (Maga, 1976; Qvist and von Sydow, 1974), haddock (Maga, 1976), oyster (Maga, 1976; Shankaranarayana et al., 1982), parsnip (Maga, 1976; Shankaranarayana et al., 1982) In fruits: Coconut (Maga, 1976), durian (Shankaranarayana et al., 1982; Weenen et al., 1996) In meats (Shankaranarayana et al., 1982): Beef—170–280 ppb (Maga, 1976) In miscellaneous matrices: Casein (Maga, 1976; Qvist and von Sydow, 1974), corn (Maga, 1976) In poultry: Chicken (Maga, 1976; Nonaka et al., 1967; Shankaranarayana et al., 1982; Wilson and Katz, 1972) In vegetables: Bean (Maga, 1976), Brussels sprout (Maga, 1976; Shankaranarayana et al., 1982), carrot—50 ppb (Maga, 1976; Shankaranarayana et al., 1982), cauliflower (Maga, 1976; Shankaranarayana et al., 1982), cooked lettuce (Maga, 1976), leek (Maga, 1976), onion (Maga, 1976; Shankaranarayana et al., 1982), pea (Maga, 1976; Shankaranarayana et al., 1982), potato—100–220 ppb (Maga, 1976; Shankaranarayana et al., 1982), soy (Qvist and von Sydow, 1974)	In air: 0.66 ppt–12 ppm (Maga, 1976) 1 ppb (Qvist and von Sydow, 1974) 46 ppb (Shankaranarayana et al., 1982) In beer: 0.25–10 ppb (Soltoft, 1988) 1–10 ppb (Mestres et al., 2000) 1.7 ppb (Meilgaard, 1975) 5–8 ppb (Haboucha et al., 1982) In water: 8 ppt (Mestres et al., 2000) 0.19 ppb–4.3 ppm (Shankaranarayana et al., 1982) 0.19 ppb–43 ppm (Maga, 1976) In wine: 1.1 ppb (Mestres et al., 2000; Nedjma and Maujean, 1995; Rauhut, 1993) In wine-model solution: 0.1 ppb (Lavigne et al., 1993; Mestres et al., 2000)	Fecal (Mestres et al., 2000) Onion (Lavigne et al., 1993; Mestres et al., 2000; Meilgaard, 1975; Rauhut, 1993; Soltoft, 1988) Putrefaction, garlic, leek, egg (Meilgaard, 1975; Mestres et al., 2000) Rubber (Mestres et al., 2000; Rauhut, 1993.)
53	In meats: Beef (Farmer et al., 1989; Shankaranarayana et al., 1982)	—	—
54	In meats: Beef (Shankaranarayana et al., 1982) In poultry: Chicken (Maga, 1976; Shankaranarayana et al., 1982; Wilson and Katz, 1972)	—	—

(*continued*)

Table 6
Continued

No.	Matrix–concentration	Perception threshold	Odor
55	In beverages: Beer—0–16 ppb (Blockmans et al., 1981; Burmeister et al., 1992; Haboucha and Masschelein, 1979; Haboucha et al., 1982; Hill and Smith, 2000; Hugues, 1998; Meilgaard, 1975; Olsen, 1988; Peppard and Laws, 1979; Shankaranarayana et al., 1982; Soltoft, 1988; Walker, 1991, 1992; Walker and Simpson, 1993), coffee—210–600 ppb (Bücking et al., 2002; Czerny et al., 1999; Holscher et al., 1990; Maga, 1976; Semmelroch and Grosch, 1995, 1996; Shankaranarayana et al., 1982), orange juice (Shaw et al., 1980), tea (Maga, 1976), wine—0–3.3 ppm (Ferreira et al., 2003; Kataoka et al., 2000; Lavigne and Dubourdieu, 1996; Lavigne et al., 1993; Mestres et al., 1997, 1999; Park et al., 2000; Rauhut, 1993; Rauhut et al., 1996) In cheeses (Kadota and Ishida, 1972; Maga, 1976): Camembert (Jaillais et al., 1999; Lecanu et al., 2002), cheddar—3–30 ppb (Chin et al., 1996; Cuer, 1982; Dias and Weimer, 1998; Lecanu et al., 2002; Maga, 1976; Manning and Price, 1977; Milo and Reineccius, 1997; Shankaranarayana et al., 1982), gouda—6 ppb (Maga, 1976), grana (Lecanu et al., 2002), oryzae—138 ppb (Maga, 1976), trappist (Lecanu et al., 2002) In dairies: Butter (Shankaranarayana et al., 1982), milk (Maga, 1976; Shankaranarayana et al., 1982) In fish and crustaceans: Codfish (Shankaranarayana et al., 1982; Wu and Cadwallader, 2002), fish protein (Maga, 1976; Qvist and von Sydow, 1974), herring (Maga, 1976; Shankaranarayana et al., 1982), mackerel (Maga, 1976; Shankaranarayana et al., 1982), oyster (Maga, 1976; Shankaranarayana et al., 1982), parsnip (Maga, 1976), salmon (Girard and Durance, 2000), tuna (Maga, 1976; Shankaranarayana et al., 1982) In fruits: Coconut (Maga, 1976), durian (Shankaranarayana et al., 1982), filbert (Maga, 1976; Shankaranarayana et al., 1982; Kinlin et al., 1972), strawberry (Kolor, 1983), tomato (Buttery et al., 1990; Landy et al., 2002) In meats (Shankaranarayana et al., 1982): Beef—1.1–4.5 ppm (Edwards et al., 1987; Guth and Grosch, 1994; Maga, 1976; Shankaranarayana et al., 1982; Shibamoto and Russell, 1976; Wilson et al., 1973; Wu and Cadwallader, 2002), ham (Carrapiso et al., 2002; Maga, 1976), pork (Elmore et al., 2000; Maga, 1976; Shankaranarayana et al., 1982), pork liver (Shankaranarayana et al., 1982) In miscellaneous matrices: Barley (Shankaranarayana et al., 1982), bread (Maga, 1976; Shankaranarayana et al., 1982), carob bean (MacLeod and Forcen, 1992), casein (Maga, 1976; Qvist and von Sydow, 1974), corn—35–70 ppb (Maga, 1976; Shankaranarayana et al., 1982), hop—0–75 ppb (Maga, 1976; Seaton et al., 1981), mushroom (Shankaranarayana et al., 1982), rape seed (Shankaranarayana et al., 1982), shiitake (Shankaranarayana et al., 1982), yeast extract (Ames and Mac Leod, 1985) In poultry: Chicken (Maga, 1976; Nonaka et al., 1967; Senter et al., 2000; Shankaranarayana et al., 1982; Wilson and Katz, 1972), turkey (Fan et al., 2002) In vegetables: Allium vegetable (Negishi et al., 2002), asparagus (Shankaranarayana et al., 1982), bean (Maga, 1976; Shankaranarayana et al., 1982), broccoli (Chin and Lindsay, 1994; Dan et al., 1997, 1999; Engel et al., 2002; Forney et al., 1991; Obenland and Aung, 1996; Tulio et al., 2002), Brussels sprout (Maga, 1976; Shankaranarayana et al., 1982), cabbage (Chin and Lindsay, 1994; Dan et al., 1999; Maga, 1976; Shankaranarayana et al., 1982), carrot (Maga, 1976; Shankaranarayana et al., 1982), cauliflower (Dan et al., 1999; Maga, 1976; Shankaranarayana et al., 1982), cooked lettuce (Maga, 1976), garlic (Maga, 1976; Shankaranarayana et al., 1982; Shibamoto and Russell, 1976), leek (Maga, 1976; Shankaranarayana et al., 1982; Shibamoto and Russell, 1976), onion (Boelens et al., 1971; Maga, 1976; Shankaranarayana et al., 1982; Shibamoto and Russell, 1976), pea (Maga, 1976; Shankaranarayana et al., 1982), potato—42–87 ppb (Maga, 1976; Shankaranarayana et al., 1982), rutabaga (Casey et al., 1965; Maga, 1976), sauerkraut (Maga, 1976), soy (Maga, 1976; Qvist and von Sydow, 1974; Shankaranarayana et al., 1982)	In air 0.2–41 ppb (Maga, 1976; Mestres et al., 2000) 2.1 ppb (Qvist and von Sydow, 1974) 41 ppb (Shankaranarayana et al., 1982) In beer: 2 ppb (Meilgaard, 1975) 2–4 ppb (Haboucha et al., 1982) 2–12 ppb (Rauhut, 1993; Soltoft, 1988) In water: 0.02 ppb (Engel et al., 2002; Fan et al., 2002; Forney et al., 1991; Landy et al., 2002) 0.02–2 ppb (Mestres et al., 2000; Rauhut, 1993; Shankaranarayana et al., 1982) 0.02–20 ppb (Maga, 1976) 0.2 ppb (Guth and Grosch, 1994) 0.2–25 ppb (Wu and Cadwallader, 2002) In wine-model solution: 0.3 ppb (Lavigne et al., 1993; Mestres et al., 2000)	Cabbage (Edwards et al., 1987; Guth and Grosch, 1994; Landy et al., 2002; Lecanu et al., 2002; Mestres et al., 2000; Meilgaard, 1975; Rauhut, 1993; Semmelroch and Grosch, 1995; Soltoft, 1988) Cheese (Carrapiso et al., 2002; Lecanu et al., 2002) Drains, estery (Meilgaard, 1975) Garbage (Wu and Cadwallader, 2002) Fecal (Engel et al., 2002; Forney et al., 1991) Fish, meaty (Carrapiso et al., 2002) Garlic (Lecanu et al., 2002) Putrid (Bücking et al., 2002; Edwards et al., 1987; Engel et al., 2002; Forney et al., 1991; Holscher et al., 1990; Lavigne et al., 1993; Lecanu et al., 2002; Mestres et al., 2000; Semmelroch and Grosch, 1995) Rotten, egg (Carrapiso et al., 2002; Forney et al., 1991; Meilgaard, 1975; Rauhut, 1993.; Wu and Cadwallader, 2002) Sulfury (Edwards et al., 1987; Guth and Grosch, 1994; Landy et al., 2002; Lecanu et al., 2002; Semmelroch and Grosch, 1995; Wu and Cadwallader, 2002)

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56	In meats: Beef (Maga, 1976; Shankaranarayana et al., 1982; Wilson et al., 1973)	—	Unpleasant (Maga, 1976)
57	In meats: Beef (Farmer et al., 1989)	—	—
58	In miscellaneous matrices: Corn (Macku and Shibamoto, 1991)	BE-GC-LOADS: 0.07 ng (Gijs et al., 2000b) In water: 0.8 ppb (Gijs et al., 2000b)	Painting, smoke, pharmacy (Gijs et al., 2000b)
59	In beverages: Beer—0.11 ppb (Meilgaard, 1975; Walker, 1991, 1992; Walker and Simpson, 1993), coffee (Maga, 1976; Shankaranarayana et al., 1982), tea (Maga, 1976) In fish and crustaceans: Oyster (Maga, 1976; Shankaranarayana et al., 1982), parsnip (Maga, 1976) In fruits: Coconut (Maga, 1976), durian (Shankaranarayana et al., 1982; Weenen et al., 1996) In meats: Beef (Maga, 1976) In miscellaneous matrices: Casein (Maga, 1976), corn (Shankaranarayana et al., 1982; Macku and Shibamoto, 1991) In poultry: Chicken (Maga, 1976; Shankaranarayana et al., 1982; Wilson and Katz, 1972) In vegetables: Allium vegetable (Negishi et al., 2002; Kubec et al., 1999), bean (Shankaranarayana et al., 1982), cauliflower (Maga, 1976), leek—6.02–10.99 ppm (Maga, 1976; Schulz et al., 1998; Shankaranarayana et al., 1982), onion—1.04–2.46 ppm (Boelens et al., 1971; Kuo and Ho, 1992; Maga, 1976; Schulz et al., 1998; Shankaranarayana et al., 1982), pea (Maga, 1976; Shankaranarayana et al., 1982), potato (Maga, 1976; Shankaranarayana et al., 1982), scallion (Kuo and Ho, 1992)	In air: 75 ppt–6 ppb (Maga, 1976) 6 ppb (Shankaranarayana et al., 1982) In beer: 0.15 ppb (Meilgaard, 1975)	Cabbage (Maga, 1976) Onion (Meilgaard, 1975; Weenen et al., 1996) Putrefaction, garlic, egg (Meilgaard, 1975)
60	In beverages: Beer (Meilgaard, 1975)	In beer: 0.2 ppb (Meilgaard, 1975)	Putrefaction, onion, garlic, egg (Meilgaard, 1975)
61	In meats: Beef (Shankaranarayana et al., 1982)	—	—
62	In beverages: Beer (Meilgaard, 1975) In meats: Beef (Shankaranarayana et al., 1982)	In beer: 0.00007 ppb (Meilgaard, 1975)	Putrefaction, guava, peach, fish, catty (Meilgaard, 1975)

BE-GC-LOADS, Best Estimated-Gas Chromatography-LOwest Amount Detected by Sniffing.
ppm, mg/L; ppb, μg/L; ppt, ng/L.

Table 7
Beverage/food occurrence, perception threshold, and odor of terpenic mercaptans illustrated in Fig. 5

No.	Matrix–concentration	Perception threshold	Odor
63	In fruits: Grapefruit—10 ppt (Boelens and van Gemert, 1993; Bouchilloux et al., 1998a; Buettner and Schieberle, 1999, 2001; Darriet et al., 1995; Demole et al., 1982; Lin et al., 2002; Polak et al., 1988)	In air: 0.001 ppt (Huber and Bergamin, 1993) In water: 0.1 ppt (Bouchilloux et al., 1998a; Buettner and Schieberle, 1999, 2001; Darriet et al., 1995; Demole et al., 1982) (+)–(R): 0.02 ppt (Boelens and van Gemert, 1993; Demole et al., 1982) (−)–(S): 0.08 ppt (Boelens and van Gemert, 1993; Demole et al., 1982)	Fruity (Demole et al., 1982) Grapefruit (Buettner and Schieberle, 1999, 2001; Demole et al., 1982; Lin et al., 2002) Green citrus (Polak et al., 1988) Sulfury (Buettner and Schieberle, 2001) (+)–(R): grapefruit (Boelens and van Gemert, 1993), fruity (Polak et al., 1988) (−)–(S): sulfury (Boelens and van Gemert, 1993; Polak et al., 1988)
64	In fruits: Blackcurrant (Gora and Brud, 1983; Maga, 1976; Rigaud et al.,1986) In miscellaneous matrices: Buchu (Boelens and van Gemert, 1993; Darriet et al., 1995; Gora and Brud, 1983; Kaiser et al., 1975; Lamparsky and Schudel, 1971a; Polak et al., 1988; Rigaud et al.,1986; Sundt et al., 1971)	—	Blackcurrant (Maga, 1976; Polak et al., 1988; Sundt et al., 1971) Box tree (Darriet et al., 1993, 1995) Buchu, fruity, minty (Polak et al., 1988) 1(R)–4(R): tropical fruit, onion, dirty (Boelens and van Gemert, 1993) 1(R)–4(S): rubber, thiol, isopugelone, sulfury, buchu (Boelens and van Gemert, 1993) 1(S)–4(R): fruity, blackcurrant, passion fruit, tropical fruit (Boelens and van Gemert, 1993) 1(S)–4(S): tropical fruit, sulfury, buchu (Boelens and van Gemert, 1993)
65	In beverages: Beer (Peppard and Laws, 1979)	—	Solvent, sulfury, rubber (Peppard and Laws, 1979)

ppt, ng/L.

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Table 8

Beverage/food occurrence, perception threshold, and odor of acyclic mercaptans containing another sulfur function illustrated in Fig. 5

No.	Matrix–concentration	Perception threshold	Odor
66	In meats: Beef (Drumm and Spanier, 1991), pork(Tai and Ho, 1997)	—	Sulfury, rubber, cheese, onion, meaty (Tai and Ho, 1997)
67	In meats: Beef (Shankaranarayana et al., 1982) In poultry: Chicken (Maga, 1976; Nonaka et al., 1967; Shankaranarayana et al., 1982; Wilson and Katz, 1972)	In air: 1.6–31 ppb (Maga, 1976)	—
68	In meats: Beef (Shankaranarayana et al., 1982)	—	—
69	In meats: Beef (Shankaranarayana et al., 1982)	—	—
70	In meats: Beef (Shankaranarayana et al., 1982)	—	—
71	In meats: Beef (Shankaranarayana et al., 1982)	—	—
72	In meats: Beef (Boelens et al., 1974; Brinkman et al., 1972; Maga, 1976; Schutte and Koenders, 1972; Schutte, 1971; Shankaranarayana et al., 1982; Werkhoff et al., 1989)	In water: 1–5 ppb (Brinkman et al., 1972)	Meaty (Brinkman et al., 1972; Drumm and Spanier, 1991) Onion (Boelens et al., 1974; Brinkman et al., 1972; Drumm and Spanier, 1991; Werkhoff et al., 1989, 1990)

ppb, μg/L.

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Table 9
Beverage/food occurrence, perception threshold, and odor of heterocyclic mercaptans illustrated in Fig. 5

No.	Matrix–concentration	Perception threshold	Odor
73	In meats: Beef (Gasser and Grosch, 1990) In poultry: Chicken (Gasser and Grosch, 1990; Huber and Bergamin, 1993)	In air: 0.0035–0.014 ppt (Gasser and Grosch, 1990)	Meaty (Gasser and Grosch, 1990)
74	In beverages: Coffee—19.1–2500 ppb (Ames et al., 2001; Blanchard et al., 2001; Bücking and Steinhart, 2002; Blank et al., 1992, 2002; Buettner, 2002; Boelens and van Gemert, 1993; Czerny et al., 1999; Farmer and Mottram, 1990; Gora and Brud, 1983; Grosch, 1993, 1994; Hofmann and Schieberle, 1995, 1998; Hofmann et al., 1996; Holscher et al., 1990; Kerscher and Grosch, 1998; Maga, 1976; Meynier and Mottram, 1995; Mussinan and Katz, 1973; Sanz et al., 2002; Schieberle, 1996; Semmelroch and Grosch, 1995, 1996; Semmelroch et al., 1995; Shankaranarayana et al., 1982; Shibamoto, 1977; Shibamoto and Russell, 1976; Tominaga et al., 2000a; Tressl and Silwar, 1981; Wu and Cadwallader, 2002), wine—2 ppt–5.5 ppb (Blanchard et al., 1999, 2001; Marchand et al., 2000; Spinnler and Bonnarme, 2002; Tominaga et al., 2000a, 2000b, 2003a, 2003b) In meats (Blanchard et al., 2001; Carrapiso et al., 2002; Gasser and Grosch, 1990a; Hofmann et al., 1996; Madruga and Mottram, 1995; Meynier and Mottram, 1995; Mottram and Madruga, 1994; Mottram et al., 1998; Tominaga et al., 2000b): Beef—1.5–42 ppb (Cerny and Grosch, 1992; Drumm and Spanier, 1991; Farmer and Mottram, 1990; Gasser and Grosch, 1990b; Grosch, 1993, 1994; Guth and Grosch, 1994; Hofmann and Schieberle, 1995, 1998; Kerscher and Grosch, 1998; Madruga and Mottram, 1998; Shankaranarayana et al., 1982; Wu and Cadwallader, 2002), ham (Carrapiso et al., 2002), lamb—9–14 ppb (Kerscher and Grosch, 1998), pork—8–10 ppb (Liu et al., 2001; Kerscher and Grosch, 1998; Madruga and Mottram, 1998; Mottram, 1985) In poultry: Chicken—2.4 ppb (Farkas et al., 1997; Farmer and Mottram, 1990; Gasser and Grosch, 1990b; Hofmann and Schieberle, 1995; Kerscher and Grosch, 1998; Madruga and Mottram, 1998; Wu and Cadwallader, 2002), hen (Farkas et al., 1997) In miscellaneous matrices: Bread (Blanchard et al., 2001; Hofmann et al., 1996; Kerscher and Grosch, 1998), popcorn (Ames et al., 2001; Blanchard et al., 2001; Buttery and Ling, 1998; Grosch, 1993, 1994; Hofmann and Schieberle, 1995, 1998; Kerscher and Grosch, 1998; Schieberle, 1991b, 1996), roasted sesame (Ames et al., 2001; Buettner, 2002; Grosch, 1994; Hofmann and Schieberle, 1995, 1998; Kerscher and Grosch, 1998; Schieberle, 1996), tortilla chip—<5 ppb (Buttery and Ling, 1998), wheat flour (Bredie et al., 2002), yeast extract—29–580 ppb (Ames and Mac Leod, 1985; Hofmann and Schieberle, 1998; Kerscher and Grosch, 1998; Münch and Schieberle, 1998; Münch et al., 1997; Wu and Cadwallader, 2002)	In air: 0.0025 ppt (Ames et al., 2001; Carrapiso et al., 2002; Hofmann and Schieberle, 1998) 0.0025–0.01 ppt (Hofmann and Schieberle, 1995) 0.0045–0.002 ppt (Gasser and Grosch, 1990a, 1990b) 0.01 ppt (Blank et al., 2002) 0.01–0.02 ppt (Blank et al., 1992; Bel Rhlid et al., 2002b) In oil: 400 ppm (Schieberle, 1996) In water: 2 ppt (Gora and Brud, 1983) 5 ppt (Boelens and van Gemert, 1993; Tressl and Silwar, 1981) 6 ppt (Buttery and Ling, 1998) 10 ppt (Bel Rhlid et al., 2002b; Blank et al., 2002; Buettner, 2002; Kerscher and Grosch, 1998; Münch and Schieberle, 1998; Semmelroch et al., 1995) 120 ppt (Guth and Grosch, 1994) In wine-model solution: 0.1 ppt (Blanchard et al., 1999) 0.4 ppt (Tominaga et al., 2000b, 2003a, 2003b) 1 ppt (Marchand et al., 2000)	Beef broth (Farmer et al., 1989) Burnt (Bredie et al., 2002; Marchand et al., 2000; Tominaga et al., 2003b) Caramel, sweet (Zhang and Ho, 1991) Coffee (Ames et al., 2001; Bel Rhlid et al., 2002b; Blanchard et al., 1999; Blank et al., 1992, 2002; Boelens and van Gemert, 1993; Bücking and Steinhart, 2002; Chen and Ho, 2002; Czerny et al., 1999; Farkas et al., 1997; Farmer et al., 1989; Gora and Brud, 1983; Hofmann and Schieberle, 1995, 1997; Holscher et al., 1990; Marchand et al., 2000; Mottram et al., 1998; Münch and Schieberle, 1998; Münch et al., 1997; Schieberle, 1991b, 1996; Schieberle and Hofmann, 1998; Shankaranarayana et al., 1982; Shibamoto, 1977; Spinnler and Bonnarme, 2002; Tominaga et al., 2000a, 2000b, 2003b; Tressl and Silwar, 1981; Wu and Cadwallader, 2002; Zhang and Ho, 1991) Cured ham, toasted, sewage, fatty, fruity (Carrapiso et al., 2002) Garlic (Drumm and Spanier, 1991; Farmer et al., 1989; Gora and Brud, 1983) Meaty (Buettner, 2002) Pungent (Drumm and Spanier, 1991; Farmer et al., 1989; Gora and Brud, 1983; Shankaranarayana et al., 1982) Roasted (Ames et al., 2001; Bel Rhlid et al., 2002b; Blank et al., 1992, 2002; Bücking and Strinhart, 2002; Chen and Ho, 2002; Czerny et al., 1999; Farkas et al., 1997; Gasser and Grosch, 1990a, 1990b; Hofmann and Schieberle, 1995, 1997; Holscher et al., 1990; Münch and Schieberle, 1998; Münch et al., 1997; Sanz et al., 2002; Schieberle, 1991b, 1996; Schieberle and Hofmann, 1998; Semmelroch and Grosch, 1995) Sulfury (Bel Rhlid et al., 2002b; Bredie et al., 2002; Czerny et al., 1999; Farmer et al., 1989; Tressl and Silwar, 1981; Wu and Cadwallader, 2002)

75	In beverages: Beer (Lermusieau et al., 2001), coffee (Blank et al., 1992; Bouchilloux et al., 1998a; Czerny et al., 1999; Hofmann and Schieberle, 1995; Hofmann and Schieberle, 1998; Hofmann et al., 1996; Holscher et al., 1990; Kerscher and Grosch, 1998; Münch and Schieberle, 1998; Semmelroch and Grosch, 1995; Wu and Cadwallader, 2002), grapefruit juice (Lin et al., 2002), orange juice (Bezman et al., 2001), wine (Aznar et al., 2001; Bezman et al., 2001; Blanchard et al., 1999; Bouchilloux et al., 1998a; Ferreira et al., 2001, 2002; Kotseridis and Baumes, 2000; Spinnler and Bonnarme, 2002; Tominaga et al., 2000b, 2003b) In fish and crustaceans: Tuna (Baek et al., 2001; Güntert et al., 1990; Hofmann and Schieberle, 1998; Huber and Bergamin, 1993; Kerscher and Grosch, 1998; Withycombe and Mussinan, 1988) In meats (Bouchilloux et al., 1998a; Gasser and Grosch, 1990a; Hofmann et al., 1996; Holscher et al., 1990; Madruga and Mottram, 1995, 1998; Meynier and Mottram, 1995; Mottram et al., 1998; Shankaranarayana et al., 1982): Beef—7–28ppb (Baek et al., 2001; Boelens and van Gemert, 1993; Cerny and Grosch, 1992; Gasser and Grosch, 1988, 1990b; Grosch, 1993; Güntert et al., 1990; Hofmann and Schieberle, 1995, 1998; Huber and Bergamin, 1993; Kerscher and Grosch, 1998; Mottram and Whitfield, 1994; Wu and Cadwallader, 2002), ham (Carrapiso et al., 2002), lamb—5–11 ppb (Kerscher and Grosch, 1998), pork—6–9 ppb (Kerscher and Grosch, 1998) In poultry: Chicken—4.5 ppb (Boelens and van Gemert, 1993; Farkas et al., 1997; Gasser and Grosch, 1990b; Hofmann and Schieberle, 1995; Huber and Bergamin, 1993; Kerscher and Grosch, 1998; Wu and Cadwallader, 2002), hen (Farkas et al., 1997) In miscellaneous matrices: Bread (Hofmann et al., 1996), rice (Jezussek et al., 2002), yeast extract—22–530 ppb (Ames and Mac Leod, 1985; Baek et al., 2001; Blanchard et al., 1999; Bouchilloux et al., 1998b; Ferreira et al., 2001; Gasser and Grosch, 1988; Güntert et al., 1990; Kerscher and Grosch, 1998; Kotseridis and Baumes, 2000; Münch and Schieberle, 1998; Werkhoff et al., 1989, 1990)	In air: 0.001–0.002 ppt (Blank et al., 1992) 0.0025 ppt (Carrapiso et al., 2002; Hofmann and Schieberle, 1998) 0.0025–0.01 ppt (Boelens and van Gemert, 1993; Chen and Ho, 2002; Gasser and Grosch, 1990a, 1990b; Hofmann and Schieberle, 1995; Huber and Bergamin, 1993) 0.005–0.01 ppt (Bel Rhlid et al., 2002b) In orange juice: 5 ppt (Bezman et al., 2001) In water: 0.4–1 ppt (Bouchilloux et al., 1998a) 0.5–7 ppt (Bezman et al., 2001) 0.005–0.01 ppb (Baek et al., 2001; Gasser and Grosch, 1988; Meynier and Mottram, 1995; Wu and Cadwallader, 2002) 7 ppt (Bel Rhlid et al., 2002b; Kerscher and Grosch, 1998; Münch and Schieberle, 1998) In wine-model solution: 2 ppt (Blanchard et al., 1999) 2–8 ppt (Bouchilloux et al., 1998a) 5 ppt (Ferreira et al., 2002)	Barbecue, smoke, empyreumatic (Ferreira et al., 2001; Spinnler and Bonnarme, 2002; Tominaga et al., 2000b) Coffee, acrid (Farmer et al., 1989) Cooked rice (Baek et al., 2001) Cured ham, toasted (Carrapiso et al., 2002) Hydrolyzed vegetal protein (Ames and Mac Leod, 1985; Hartman et al., 1984b) Meaty, beef broth, sweet (Ames and Mac Leod, 1985; Ames et al., 2001; Baek et al., 2001; Bel Rhlid et al., 2002a, 2002b; Bezman et al., 2001; Blank et al., 1992; Boelens and van Gemert, 1993; Bouchilloux et al., 1998a; Chen and Ho, 2002; Farkas et al., 1997; Farmer and Mottram, 1990; Farmer et al., 1989; Gasser and Grosch, 1988, 1990a, 1990b; Hartman et al., 1984b; Hofmann and Schieberle, 1995; Holscher et al., 1990; Jezussek et al., 2002; Jhoo et al., 2002; Kotseridis and Baumes, 2000; Lin et al., 2002; Maga, 1976; Meynier and Mottram, 1995; Mottram and Madruga, 1994; Mottram et al., 1998; Münch and Schieberle, 1998; Schieberle and Hofmann, 1998; Semmelroch and Grosch, 1995; Tominaga et al., 2003b; Werkhoff et al., 1989, 1990; Withycombe and Mussinan, 1988; Wu and Cadwallader, 2002; Zhang and Ho, 1991) Milk, sunflower seed (Kotseridis and Baumes, 2000) Onion, fatty (Aznar et al., 2001; Ferreira et al., 2001; Mottram and Madruga, 1994) Pungent, burnt, rubber (Farmer and Mottram, 1990; Meynier and Mottram, 1995) Roasted (Bel Rhlid et al., 2002a) Roasted nut (Bouchilloux et al., 1998a; Carrapiso et al., 2002; Kotseridis and Baumes, 2000;) Sulfury (Ames et al., 2001; Bel Rhlid et al., 2002b; Farmer and Mottram, 1990; Farmer et al., 1989; Gasser and Grosch, 1988; Hofmann and Schieberle, 1995; Jezussek et al., 2002) Vitamin (Baek et al., 2001; Bezman et al., 2001; Wu and Cadwallader, 2002)

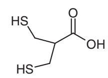
(*continued*)

Table 9
Continued

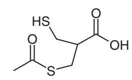
No.	Matrix–concentration	Perception threshold	Odor
76	In meats: Pork(Madruga and Mottram, 1998) In miscellaneous matrices: Yeast extract (Güntert et al., 1990)	In air: 0.0032–0.0128 ppt (Hofmann and Schieberle, 1995)	Metallic (Farmer et al., 1989; Werkhoff et al., 1990) PVC, coal (Farmer et al., 1989) Roasted meat (Chen and Ho, 2002; Farmer and Mottram, 1990; Farmer et al., 1989; Hofmann and Schieberle, 1995; Maga, 1976; van den Ouweland and Peer, 1975; Werkhoff et al., 1989, 1990) Rubber (Werkhoff et al., 1990) Sulfury (Chen and Ho, 2002; Hofmann and Schieberle, 1995; Werkhoff et al., 1990)
77	In miscellaneous matrices: Syrup (Maga, 1975)	—	Burnt, onion (Maga, 1975)
78	In beverages: Wine (Marchand et al., 2000) In meats: Pork—hypothesis (Madruga and Mottram, 1998) In miscellaneous matrices: Syrup (Maga, 1975)	In air: 0.003–0.012 ppt (Hofmann and Schieberle, 1995) In water: 0.8 ppb (Marchand et al., 2000)	Burnt, rubber (Marchand et al., 2000) Coffee (Marchand et al., 2000; Maga, 1975) Egg, onion, fatty, leek (Chen and Ho, 2002) Garlic, sulfury, pungent (Farmer et al., 1989) Meaty, vitamin (Wu and Cadwallader, 2002) Roasted (Hofmann and Schieberle, 1995) Unpleasant, burned caramel (Farmer et al., 1989; Maga, 1976)
79	In vegetables: Onion (Block, 1992; Kuo and Ho, 1992), scallion (Block, 1992; Kuo and Ho, 1992)	—	—
80	In meats: Pork (Bouchilloux et al., 1998a; Madruga and Mottram, 1998)	In water: 5–10 ppb (Bouchilloux et al., 1998a)	Meaty (Bouchilloux et al., 1998a; Güntert et al., 1990)
81	In beverages: Wine—hypothesis (Guedes de Pinho et al., 1997)	—	Strawberry, sulfury (Guedes de Pinho et al., 1997)
82	In beverages: Coffee (Boelens and van Gemert, 1993; Tressl and Silwar, 1981) In miscellaneous matrices: Yeast extract (Münch and Schieberle, 1998)	In air: 0.019 ppt (Hofmann and Schieberle, 1997) In water: 0.006 ppt (Hofmann and Schieberle, 1997) 0.05 ppb (Boelens and van Gemert, 1993; Tressl and Silwar, 1981)	Coffee (Hofmann and Schieberle, 1997; Schieberle and Hofmann, 1998) Meaty (Tressl and Silwar, 1981) Roasted (Hofmann and Schieberle, 1997; Schieberle, 1996; Schieberle and Hofmann, 1998) Sulfury (Boelens and van Gemert, 1993; Schieberle, 1996; Tressl and Silwar, 1981)

Ppb, μg/L; ppt, ng/L.

Mercapto-acids

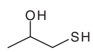


3,3'-Dimercaptoisobutyric acid
1

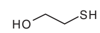


3-Thioacetoxy-3'-mercaptoisobutyric acid
2

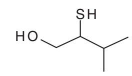
Mercapto-alcohols



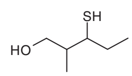
1-Mercapto-2-propanol
3



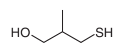
2-Mercapto-1-ethanol
4



2-Mercapto-3-methyl-1-butanol
5



3-Mercapto-2-methyl-1-pentanol
6



3-Mercapto-2-methyl-1-propanol
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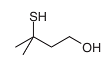
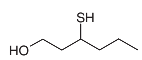
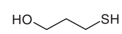


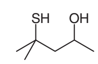
3-Mercapto-3-methyl-1-butanol
8



3-Mercapto-1-hexanol
9



3-Mercapto-1-propanol
10



4-Mercapto-4-methyl-2-pentanol
11

Figure 2. The structure of two mercapto-acids (Yanagawa et al., 1972) and nine mercapto-alcohols occurring in foods or beverages.

2001; Murat et al., 2001d; 2000b; Price and Menneer, 2000; Reiners and Grosch, 1999; Rigaud et al., 1986; Stoffelsma and Pijpker, 1973; Vermeulen and Collin, 2002a, b; Vermeulen et al., 2001; Tominaga et al., 2003a; Widder et al., 1999) (Table 10), and even in perfumes or cosmetics (Lamparsky and Schudel, 1971b; Lüntzel et al., 2000; Maga, 1976; Masuda et al., 1989, 1988; Stoffelsma and Pijpker, 1973; Thorne, 1966; Widder et al., 1999). Minimal moieties have more recently been proposed (Vermeulen and Collin, 2002a) for predicting whether mercapto-aldehydes, -ketones, or -alcohols will exhibit rhubarb/carrot, onion/sweat/pungent/leek, or potato odors. Roasted/coffee/toasted/meaty descriptors often characterize the heterocyclic mercaptans.

Although characterized by delicate pleasant odors at very low concentrations, most thiols become sharp, irritating, and repulsive when pure or highly concentrated (Boelens and van Gemert, 1993; Engel and Tressl, 1991; Gora and Brud, 1983; Marais, 1994; Mestres et al., 1999; Mottram and Whitfield, 1995c; Rigaud et al., 1986; Widder et al., 2000). Odor descriptors also depend on the accessibility of the sulfur-atom (Boelens and van Gemert, 1993; Madruga and Mottaram, 1998; Mottram and Madruga, 1994; Mottram and Whitfield, 1994), the chain length (Meilgaard, 1975; Node et al., 2001; Werkhoff et al., 1998), the chirality (Boelens and

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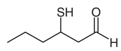
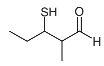
Mercapto-aldehydes

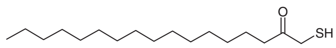


3-Mercaptohexanal
12

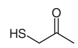


3-Mercapto-2-methylpentanal
13

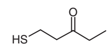
Mercapto-ketones



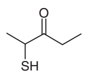
1-Mercapto-2-heptadecanone
14



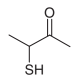
1-Mercapto-2-propanone
15



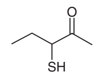
1-Mercapto-3-pentanone
16



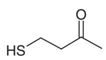
2-Mercapto-3-pentanone
17



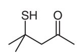
3-Mercapto-2-butanone
18



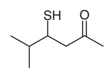
3-Mercapto-2-pentanone
19



4-Mercapto-2-butanone
20

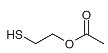


4-Mercapto-4-methyl-2-pentanone
21

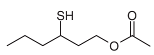


5-Methyl-4-mercapto-2-hexanone
22

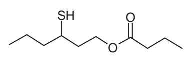
Mercapto-esters



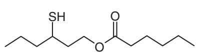
2-Mercaptoethyl-acetate
23



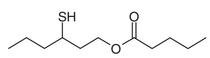
3-Mercaptohexyl-acetate
24



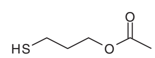
3-Mercaptohexyl-butanoate
25



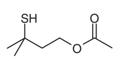
3-Mercaptohexyl-hexanoate
26



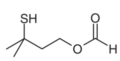
3-Mercaptohexyl-pentanoate
27



3-Mercaptopropyl-acetate
28



3-Methyl-3-mercaptobutyl-acetate
29



3-Methyl-3-mercaptobutyl-formate
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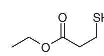
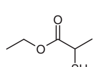


Ethy l-3-mercapto-propanoate
31



Ethy l-2-mercapto-propanoate
32

Figure 3. The structure of two mercapto-aldehydes, nine mercapto-ketones, and 10 mercapto-esters occurring in foods or beverages.

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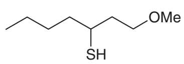
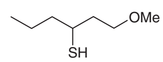
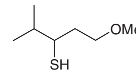
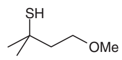
Mercapto-ethers

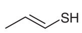

1-Methoxyheptane-3-thiol
33

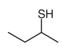

1-Methoxyhexane-3-thiol
34

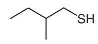

1-Methoxy-4-methylpentane-3-thiol
35

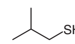

4-Methoxy-2-methylbutane-2-thiol
36

Aliphatic and aromatic mercaptans


1-Propene-1-thiol
37


2-Butanethiol
38


2-Methyl-1-butanethiol
39


2-Methyl-1-propanethiol
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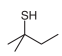
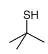

2-Methyl-2-butanethiol
41


2-Methyl-2-propanethiol
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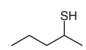
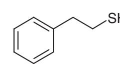
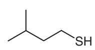
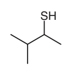
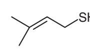

2-Pentanethiol
43

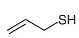

2-Phenylethanethiol
44

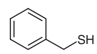

2-Propanethiol
45


3-Methyl-1-butanethiol
46


3-Methyl-2-butanethiol
47


3-Methyl-2-butene-1-thiol
48


Allylthiol
49


Benzylthiol
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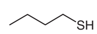
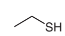
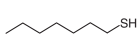
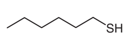
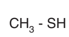

Butanethiol
51


Ethanethiol
52


Heptanethiol
53


Hexanethiol
54


Methanethiol
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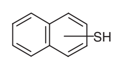
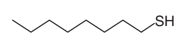
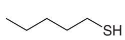
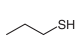
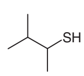
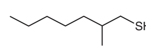

Naphtalene-thiol
56


Octanethiol
57


Pentanethiol
58


Propanethiol
59


s-Isoamylthiol
60


s-Octanethiol
61

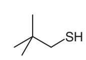

t-Pentanethiol
62

Figure 4. The structure of four mercapto-ethers and 26 aliphatic and aromatic mercaptans occurring in foods or beverages.

van Gemert, 1993; Bouchilloux et al., 2000; Lamparsky and Schudel, 1971a; Weber et al., 1995; Werkhoff et al., 1998), and the presence of other functional group(s) (Boelens and van Gemert, 1993; Polak et al., 1998). For example, tertiary thiols are often characterized by a catty smell (Polak et al., 1988), whereas the presence of a proton-attracting group such as C = O or C-O-C near the SH moiety seems to have

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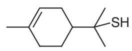
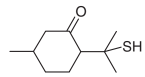
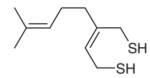
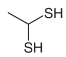
Terpenic mercaptans

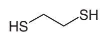

1-p-Menthene-8-thiol
63

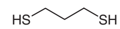

3-p-Menthanone-8-thiol
64

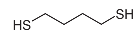

My rcenedithiol
65

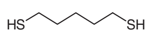
Acyclic mercaptans containing another sulfur function

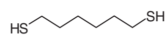

1,1-Ethanedithiol
66

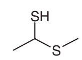

1,2-Ethanedithiol
67


1,3-Propanedithiol
68

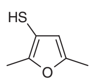

1,4-Butanedithiol
69

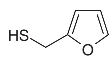

1,5-Pentanedithiol
70

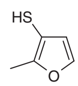

1,6-Hexanedithiol
71

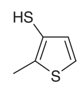

1-Methylthio-1-ethanethiol
72

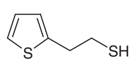
Heterocyclic mercaptans

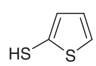

2,5-Dimethyl-3-furanthiol
73

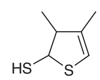

2-Furfurylthiol
74

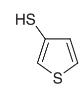

2-Methyl-3-furanthiol
75

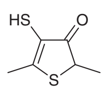

2-Methyl-3-thiophenethiol
76


2-(Thiophene-2)-ethanethiol
77


2-Thiophenethiol
78


3,4-Dimethyl-2,3-dih
thiophene-2-thiol
79


d 3-Thiophenethiol ro-
80


4-Mercapto-2,5-
dimethylthiophene-3-one
81

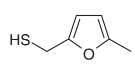

5-Methyl-2-furfurylthiol
82

Figure 5. The structure of three terpenic mercaptans, seven acyclic mercaptans containing another sulfur function, and 10 heterocyclic mercaptans occurring in foods or beverages.

an influence on the sweetness of these organic compounds (Boelens and van Gemert, 1993). For their part, Vermeulen et al. emphasized that the descriptor ‘‘cheese’’ commonly associated with mercaptoaldehydes and thioesters is rarely used to qualify the odor of mercaptoalcohols or mercaptoketones. They also prove that most of the primary mercaptoalcohols containing at least six carbon atoms emerged as more delicate (rhubarb, carrot, greenery smell) than those with an intermediate size and branching, which are generally described as onion, plastic, or pungent (Vermeulen and Collin, 2002b).

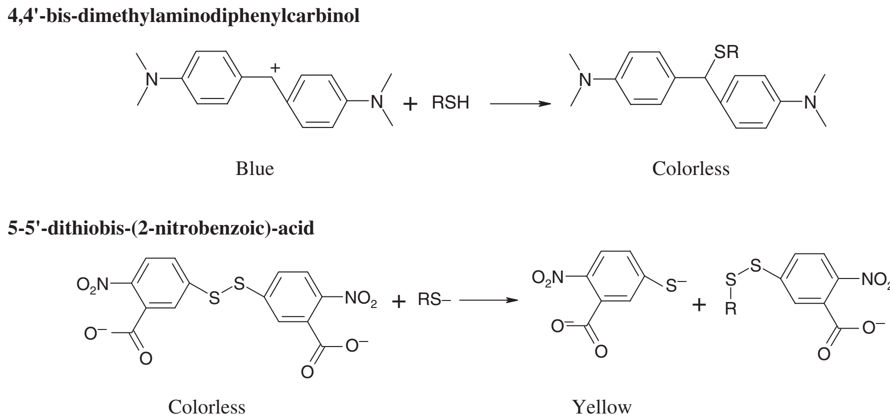


Figure 6. Reactivity between thiols and either 4,4′-*bis*-dimethylaminodiphenylcarbinol or 5-5′-dithiobis-(2-nitrobenzoic)-acid.

Chemical and Biological Synthetic Pathways

Thiols Issued from Secondary Metabolism of Microorganisms or Plants

The volatile thiols responsible for the box tree, grapefruit, and passion fruit nuances of Sauvignon wines are released by yeast from cysteinylated precursors: *S*-4-(4-methyl-2-pentanone)-L-cysteine, *S*-3-(1-hexanol)-L-cysteine, and *S*-4-(4-methyl-2-pentanol)-L-cysteine (Bouchilloux et al., 1998b, 1999; Darriet et al., 1993; Hatzimiditriou et al., 1996; Kotseridis and Baumes, 2000; Masneuf et al., 2002; Marchand et al., 2000; Marais and Swart, 1999; Murat et al., 20001b, 2001c, 2001d; Tominaga et al., 2000a). The mechanisms by which these odorless precursors found in grape skins are converted during fermentation into aromas have not yet been fully elucidated (Murat et al., 2001a). Nevertheless, β-lyase activities found in several microorganisms or plants (Fig. 7) may explain this phenomenon (Chin and Lindsay, 1994; Dubourdieu and Lees arômes, 1995; Guth, 1998; Murat et al., 20001c; Obenland and Aung, 1996; Peyrot des Gachons et al., 1999, 2002a; Tominaga et al., 1995). Similar pathways are suspected in passion fruits (Tominaga and Dubourdieu, 2000) and broccoli (Chin and Lindsay, 1994; Obenland and Aung, 1996). As for the corresponding D,L-homocysteine, glutathione, or sulfoxide conjugates, they hardly release free thiols (Gardner and Dauterman, 1992; Tominaga et al., 1995, 1998c). However, Peyrot des Gachons et al. suggested that *S*-3-(1-hexanol)-L-cysteine adducts might be issued from the catabolism of *S*-3-(1-hexanol)-glutathione (Peyrot des Gachons et al., 2002b). According to these scientists, quantification of such precursors in grapes or musts could allow assessment of the aromatic potential of Sauvignon blanc must (Peyrot des Gachons et al., 2000).

Moreover, Bel Rhlid et al. (2002a) showed that 2-methyl-3-furanthiol and 2-furfurylthiol can also be generated from their corresponding thioacetates during fermentation without any heat treatment. Such bioconversion could be exploited in the future to produce natural-labeled aromas (Bel Rhlid et al., 1998, 2001, 2002b; Bel Rhlid and Matthey-Doret, 1998; Kerkenaar et al., 1996a, 1996b; Huynh-Ba et al., 1997; Tominaga et al., 1995).

Table 10
Relevance of thiols in foods

Matrix	Thiol	Reference
Beer	3-Methyl-3-mercaptobutylformate	(Schieberle, 1991a)
	4-Mercapto-4-methyl-2-pentanone	(Schieberle, 1991a)
Blackcurrant liquor	4-Methoxy-2-methyl-2-butanethiol	(Rigaud et al.,1986; Reiners and Grosch, 1999)
Butter	Methanethiol	(Shankaranarayana et al., 1982)
Cheddar	Methanethiol	(Dias and Weimer, 1998; Lecanu et al., 2002; Manning and Price, 1977; Milo and Reineccius, 1997)
Coffee	2-Furfurylthiol	(Blank et al., 1992; Czerny et al., 1999; Holscher et al., 1990; Semmelroch and Grosch, 1996)
	2-Methyl-3-furanthiol	(Blank et al., 1992; Semmelroch and Grosch, 1995)
	3-Mercapto-3-methylbutylformate	(Blank et al., 1992; Semmelroch and Grosch, 1996)
Grapefruit juice	1-*p*-Menthene-8-thiol	(Buettner and Schieberle, 2001; Demole et al., 1982; Lin et al., 2002)
	3-Mercaptohexanol	(Lin et al., 2002)
	3-Mercaptohexyl acetate	(Lin et al., 2002)
	4-Mercapto-4methyl-2-pentanol	(Lin et al., 2002)
	4-Mercapto-4-methyl-2-pentanone	(Buettner and Schieberle, 2001; Lin et al., 2002)
Olive oil	4-Mercapto-4-methyl-2-pentanone	(Reiners and Grosch, 1998)
Tea	4-Mercapto-4-methyl-2-pentanone	(Kumazawa and Masuda, 1999)
Wine	2-Methyl-3-furanthiol	(Bouchilloux et al., 1998a)
	3-Mercapto-2-methylpropanol	(Bouchilloux et al., 2000)
	3-Mercaptohexanol	(Murat et al., 2001b; Tominaga et al., 1998b)
	3-Mercaptohexyl-acetate	(Tominaga et al., 1998b)
	4-Mercapto-4-methyl-2-pentanol	(Tominaga et al., 1998b)
	4-Mercapto-4-methyl-2-pentanone	(Bouchilloux et al.,1996; Guth, 1997b, 1998; Marais and Swart, 1999; Marais, 1994; Tominaga et al., 1998a, 1998b)
	Ethyl 3-mercaptopropionate	(Kolor, 1983)

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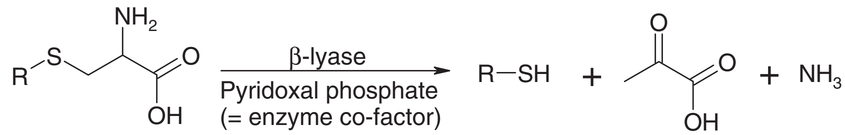

Figure 7. The ability of β-lyase to release thiols from cysteinylated precursors.

As reported in Table 11, some polyfunctional thiols might also be synthesized by H_2S nucleophilic reaction on carbonyl compounds (Blanchard et al., 2001; Boelens et al., 1974; Brinkman et al., 1972; Hofmann and Schieberle, 1998; Kleipool et al., 1976; Madruga and Mottram, 1995, 1998; Maujean, 2001; Mottram and Nobrega, 2002; Mottram and Whitfield, 1994; Scanlan et al., 1973; Shankaranarayana et al., 1982; Spencer, 1969; Thiel et al., 1958; Tominaga et al., 2003a, 2003b; Wasserman, 1972; Werkhoff et al., 1989, 1996; Whitfield and Mottram, 1999; Whitfield et al., 1988; Zheng et al., 1997). Hydrogen sufide is produced by yeast (Fig. 8), and its occurrence is highly regulated (Table 12) (Beloqui and Bertrand, 1995b; Breton and Surdin-Kerjan, 1977; Cherest and Surdin-Kerjan, 1992; Dott and Trüper, 1978; Elskens et al., 1991; Gijs et al., 2003; Giudici and Kunkee, 1994; Hansen and Kielland-Brandt, 1996; Heinzel and Trüper, 1978; Henschke and Jiranek, 1991; Jangaard et al., 1974; Jiranek et al., 1995; Mestres et al., 2000; Nagami et al., 1980; Ono et al., 1994, 1996; Peppard and Laws, 1979; Rankine, 1963; Smith et al., 1995; Stratford and Rose, 1985; Spiropoulos and Bisson, 2000; Thomas et al., 1990, 1992; Vermeulen and Collin, 2002b; Wainwright, 1970, 1971; Walker, 1995). Various α,β-unsaturated ketones or aldehydes are often found in worts, most of them coming from oxidation of unsaturated fatty acids. They may react with H_2S to form addition products such as mercapto-ketones or -aldehydes, which could be further reduced to the corresponding alcohols by yeast reductases or dehydrogenases. Esterification or methylation would then occur, leading to mercapto-esters (Murat et al., 2001b; Peyrot des Gachons et al., 1999; Tominaga et al., 1996; Vermeulen and Collin, 2003b) or methoxy-alkylthiols. Such pathways have been chemically mimicked to synthesize thiol libraries by combinatorial chemistry (Vermeulen and Collin, 2002b, in press; Vermeulen et al., 2001, 2003a, 2003b).

Thiols Issued from Radical Reactions Induced by Light

Many thiols result from photodegradation reactions. Methional is thus known to impart off-flavors to ice creams, beer, and other foods after releasing methanethiol (Gijs et al., 2000a; Haboucha and Masschelein, 1979; Hugues, 1998; Kattein et al., 1988; Sakuma et al., 1991), which is further transformed to dimethyltrisulfide (onion-like defect).

In the presence of light (350–500 nm) and riboflavin (photosensitiser), hop bitter iso-α-acids and cysteine yield in beer the well-known beer skunky flavor: 3-methyl-2-butene-1-thiol (Fig. 9) (Chen and Ho, 2002; Drost et al., 1990; Duyvis et al., 2002; Gunst and Verzele, 1978; Haboucha and Masschelein, 1979; Hashimoto and Eshima, 1979; Hugues, 1998, 1999; Irwin et al., 1993; Kattein et al., 1988; Masuda et al., 2000; Olsen, 1988; Sakuma et al., 1991; Shankaranarayana et al., 1982; Wilson et al., 2001). To prevent the occurrence of 3-methyl-2-butene-1-thiol, brewers use

Table 11
Thiols related to H_2S and carbonyl compounds reaction

Identified thiol	Odor	Identified thiol	Odor
1,1-Propanedithiol	Onion (Boelens et al., 1974)	3-Mercaptobutanal (Badings et al., 1976; Kleipool et al., 1976; Vermeulen and Collin, 2002b)	Omelet, broth, cheese, pungent (Badings et al., 1976; Vermeulen and Collin, 2002b)
1-Ethylthio-1-ethanethiol (Boelens et al., 1974)	Onion, leek, blackcurrant (Boelens et al., 1974)	3-Mercaptoheptanal (Vermeulen and Collin, 2002b)	Flowery, citrus fruit peel (Vermeulen and Collin, 2002b)
1-Mercapto-3-butanone (Vermeulen et al., in press)	Potato (Vermeulen et al., in press)	3-Mercaptohexanal (Kleipool et al., 1976; Vermeulen and Collin, 2002b)	**12** (Table 2)
1-Mercapto-3-pentanone (Vermeulen et al., in press)	Cheese, solvent, pungent, skunky (Vermeulen et al., in press)	3-Mercaptononanal (Kleipool et al., 1976; Vermeulen and Collin, 2002b)	Stale odor, greenery (Vermeulen and Collin, 2002b)
1-Methylthio-1-ethanethiol (Boelens et al., 1974; Brinkman et al., 1972; Schutte and Koenders, 1972; Shankaranarayana et al., 1982)	**72** (Table 8)	3-Mercaptooctanal (Vermeulen and Collin, 2002b)	Citrus fruit peel, grapefruit, greenery, fresh (Vermeulen and Collin, 2002b)
1-Methylthio-1-hexanethiol (Boelens et al., 1974)	Onion, blackcurrant, rhubarb, green bell-pepper (Boelens et al., 1974)	3-Mercaptopentanal (Vermeulen and Collin, 2002b)	Broth, raw onion, flowery (Vermeulen and Collin, 2002b)
1-Methylthio-1-propanethiol (Boelens et al., 1974)	Onion, meaty (Boelens et al., 1974)	3-Mercaptopropanal (Vermeulen and Collin, 2002b)	Rotten potato, broth (Vermeulen and Collin, 2002b)
1-Propylthio-1-propanethiol (Boelens et al., 1974)	Onion, blackcurrant (Boelens et al., 1974)	4-Mercapto-2-nonanone (Vermeulen et al., in press)	Rhubarb, lemon, cannabis, spicy (Vermeulen et al., in press)

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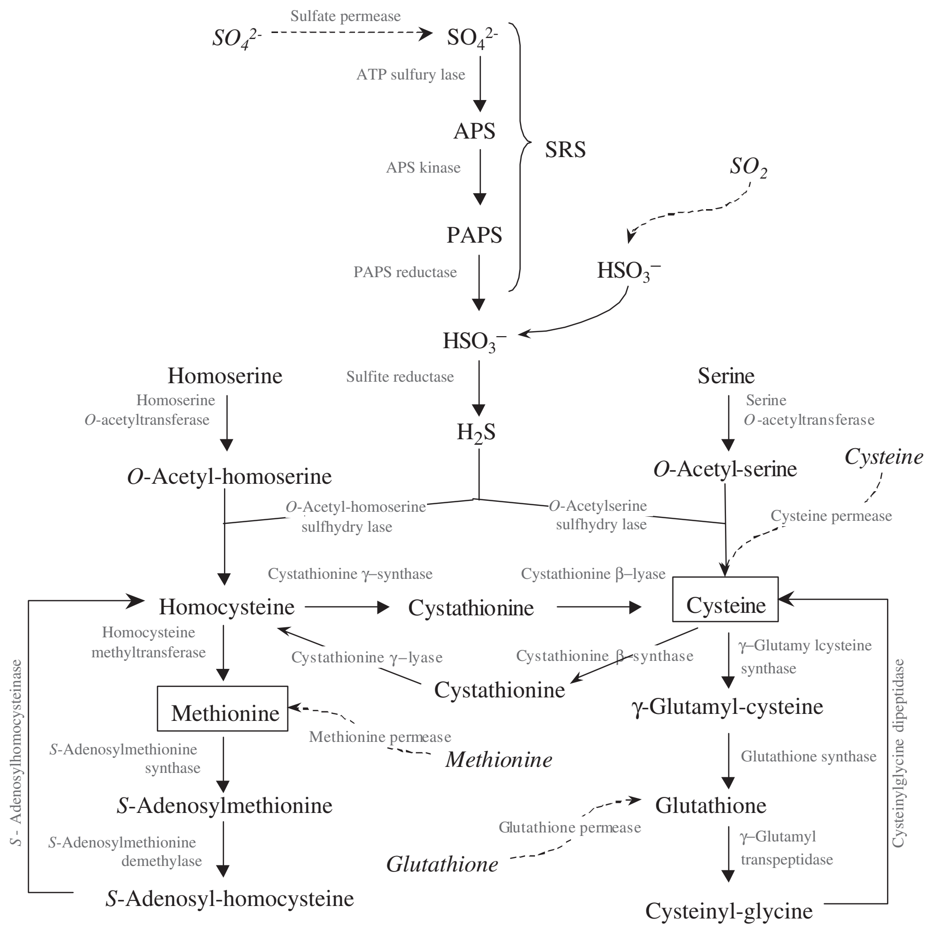
2-Furfurylthiol (Ames et al., 2001; Blanchard et al., 2001; Chen and Ho, 2002; Farmer et al., 1989; Holscher et al., 1990; Madruga and Mottram, 1995; Meynier and Mottram, 1995; Münch et al., 1997)	**74** (Table 9)	4-Mercapto-2-pentanone (Vermeulen et al., 2001, in press)	Greenery, potato, blackcurrant (Vermeulen et al., 2001, in press)
2-Mercapto-3-pentanone (Mottram and Madruga 1994, 1995; Pripis-Nicolau et al., 1999)	**17** (Table 3)	4-Mercapto-3-methyl-2-pentanone (Vermeulen et al., 2001, in press)	Sweat, cooked milk (Vermeulen et al., 2001, in press)
3-Mercapto-2-butanone (Ames et al., 2001; Mottram and Madruga 1994, 1995)	**18** (Table 3)	4-Methyl-4-mercapto-2-pentanone (Vermeulen et al., 2001, in press; Shankaranarayana et al., 1982; Spencer, 1969)	**21** (Table 3)
3-Mercapto-2-butylpropanal (Vermeulen and Collin, 2002b)	Plastic, rhubarb, pungent (Vermeulen and Collin, 2002b)	5-Mercapto-3-hexanone (Vermeulen et al., 2001, in press)	Box tree, fresh, empyreumatic (Vermeulen et al., 2001, in press)
3-Mercapto-2-ethylpropanal (Vermeulen and Collin, 2002b)	Broth, rotten potato, plastic, groundnut (Vermeulen and Collin, 2002b)	5-Methyl-4-mercapto-2-hexanone (Vermeulen et al., 2001, in press)	Exotic fruit, sweet, sulfury (Vermeulen et al., 2001, in press)
3-Mercapto-2-methylbutanal (Vermeulen and Collin, 2002b)	Broth, onion, meaty, cheese (Vermeulen and Collin, 2002b)	Bis-(1-mercaptoethyl)-sulfide (Boelens et al., 1974)	Onion, chive, meaty (Boelens et al., 1974)
3-Mercapto-2-methylpentanal (Vermeulen and Collin, 2002b; Widder et al., 2000)	**13** (Table 2)	Bis-(1-mercaptohexyl)-sulfide (Boelens et al., 1974)	Onion, green, fatty (Boelens et al., 1974)
3-Mercapto-2-methylpropanal (Vermeulen and Collin, 2002b)	Meat, broth, raw bread paste (Vermeulen and Collin, 2002b)	Bis-(1-mercaptoisobutyl)-sulfide (Boelens et al., 1974)	Onion, mushroom, soup (Boelens et al., 1974)

(*continued*)

Table 11
Continued

Identified Thiol	Odor	Identified Thiol	Odor
3-Mercapto-2-pentanone (Ames et al., 2001; Mottram and Madruga 1994, 1995; Pripis-Nicolau et al., 1999)	**19** (Table 3)	Bis-(1-mercaptopropyl)-sulfide (Boelens et al., 1974)	Green, fruity, onion, garlic (Boelens et al., 1974)
3-Mercapto-3-methylbutanal (Vermeulen and Collin, 2002b)	Broth, cheese, pungent (Vermeulen and Collin, 2002b)	Ethanethiol (Rauhut, 1993; Rankine, 1968)	**52** (Table 6)



APS = Adenosine-5′-phosphosulfate
PAPS =3′ Phosphoadenosine-5′-phosphosulfate
SRS = Sulfate Reducing Sequence

Figure 8. *S. cerevisiae* sulfur metabolism.

lightproof containers (dark glass or cans) or reduced iso-α-acids (Burns et al., 2001; Drost et al., 1990; Wilson et al., 2001, 2002).

Thiols Issued from Thermal Reactions

Maillard reactions most probably produce thiols efficiently in cooked meat and roasted or baked foods (Ames et al., 2001; Bouchilloux et al., 1998a; Elmore et al., 2002; Farmer and Mottram, 1990; Farmer et al., 1989; Hofmann and Schieberle, 1998; Holscher et al., 1990; Huber and Bergamin, 1993; Marchand et al., 2000; Mottram and Edwards, 1983; Mottram and Madruga, 1994; Mottram and Nobrega, 2002; Mulders, 1973; Münch and Schieberle, 1998; Münch et al., 1997; Schieberle, 1991b; Schieberle and Hofmann, 1998; Tai and Ho, 1997; Tominaga et al., 2000b; van Seeventer et al., 2001; Whitfield and Mottram, 1999; Whitfield et al., 1988;

Table 12
Many molecules can regulate the H_2S production by yeast

H_2S Production is promoted by	Explanation
ATP, NADPH	They act as enzymatic cofactors in the sulfate-reducing sequence.
Cysteine	It can give H_2S by decomposition.
Threonine	It decreases the homoserine occurrence, which is precursor of methionine (see below).
$[\text{Glutathione}]_{cell}$	It is a sulfur reserve for yeast.
$[\text{Sulfate, sulfite, thiosulfate, sulfur, sulfur-containing pesticides}]_{medium}$	They are all potential sources of sulfur.
H_2S production is inhibited by	
Pantothenate (vitamin B_5)	It is a co-factor in the synthesis of *O*-acetylserine and *O*-acetylhomoserine sulfhydrylase, which are the enzymes involved in the H_2S incorporation in organic molecules. It is also a sulfate reductase inhibitor.
Sérine, glutamine, aspartate, arginine, asparagine	They are considered as good sources of nitrogen. The serine and aspartate are even indirect precursors of cysteine and methionine, respectively (see below).
Glycine, tryptophane, valine, lysine, histidine	They are considered as partial nitrogen sources (see below).
$[\text{Sulfate, APS, PAPS, sulfite, sulfide}]_{cell}$	Probably to spare energy, they are responsible of retroinhibitions. They act in the sulfate assimilation pathway just before enzymes requiring ATP.
Methionine and its derivated molecules	They stop the activity of sulfate permease, ATP sulfurylase, and sulfite reductase. They also inactivate a lot of enzymes implicated in sulfur amino acid synthesis.
NH_4^+ (ammonium ion) or yeast nitrogen sources	They favor the production of amino acids, methionine and cysteine included—inhibitors in the H_2S biosynthesis. Moreover, in the presence of nitrogen, H_2S is "overconsumed" for the biosynthesis of sulfur amino acids. It is, however, not the case at the end of fermentation when the yeast is no more able to assimilate ammonium.

ATP, adenosine triphosphate.
NADPH, nicotinamide adenine dinucleotide phosphate.
APS, adenosine 5′-phosphosulfate.
PAPS, 3′-phosphoadenosine 5′-phosphosulfate.

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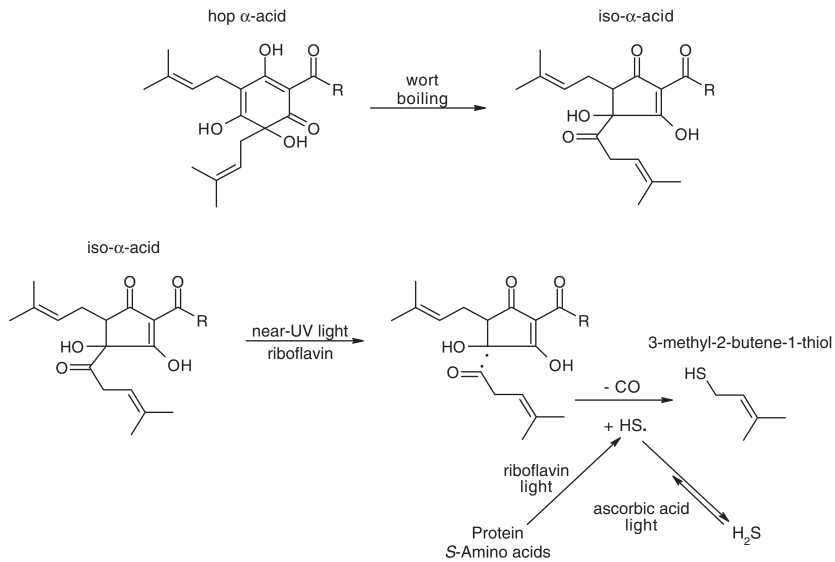

Figure 9. The formation of 3-methyl-2-butene-1-thiol from hop α-acids, sulfur products, riboflavin, and light.

Zhang and Ho, 1991), especially under acidic conditions (Ames et al., 2001; Madruga and Mottram, 1995, 1998; Meynier and Mottram, 1995; Mottram and Madruga, 1994; Whitfield and Mottram, 2001). Table 13 summarizes most structures known to be produced in this way.

Some thiols can also be produced by thermal degradation of thiamine (Table 14). The extent of this degradation and the nature of the products formed appear to be determined by the pH (*122*): alkaline conditions lead to the formation of H_2S and 3-mercapto-5-hydroxy-2-pentanone, which are excellent precursors of thiols (Fig. 10).

Other Formation Pathways Potentially Leading to Thiols

Some examples of other potential formation pathways mentioned in the literature include

- Cysteine (Beloqui and Bertrand, 1995a; Chen and Ho, 2002; Ferreira et al., 2003; Güntert et al., 1990; Madruga and Mottram, 1998; Mestres et al., 2000; Shu et al., 1985a; Yeo and Shibamoto, 1991), methionine (Cuer, 1982; Dias and Weimer, 1998; Rauhut, 1993; Segal and Starkey, 1969; Shankaranarayana et al., 1982), or glutathione degradation (Zheng and Ho, 1994), leading to small thiols like H_2S and methanethiol.
- Alcohol nucleophilic substitution to thiol (Holscher et al., 1992; Madruga and Mottram, 1995; Macku and Shibamoto, 1991; Maujean, 2001; Nedjma and Maujean, 1995; Spinnler and Bonnarme, 2002; Werkhoff et al., 1996).
- Retro Michael-type reaction, breaking, for instance, methional into methanethiol (Maujean, 2001; Tressl et al., 1994).

Table 13
Thiols produced in Maillard conditions

Identified thiol	Odor	Identified thiol	Odor
?-Ethyl-3-furanthiol (Farmer et al., 1989)	—	2-Methyl-4-thiophenethiol (van den Ouweland and Peer, 1975)	Rubber (van den Ouweland and Peer, 1975)
1,2-Ethanedithiol (Engel and Schieberle, 2002a)	Cabbage (Engel and Schieberle, 2002a)	2-Methyl-tetrahydro-3-furanthiol (Mottram and Whitfield, 1994; Whitfield and Mottram, 1999)	—
1,2-Ethenyldithiol (Umano et al., 1995)	—	2-Methyl-tetrahydro-3-thiophenethiol (Mottram and Whitfield, 1994; Whitfield and Mottram, 1999)	—
1-Heptanethiol (Farmer and Mottram, 1990; Farmer et al., 1989)	—	2-Propanethiol (Mulders et al., 1973)	—
1-Mercapto-2-butanone (Whitfield and Mottram, 1999)	—	2-Thiophenemethanethiol (Madruga and Mottram, 1998; Mottram and Nobrega, 2002)	—
1-Mercapto-2-propanone (Hofmann and Schieberle, 1995; Madruga and Mottram, 1998; Shu et al., 1985b; Zhang and Ho, 1991)	**15** (Table 3)	2-Thiophenethiol (Ames et al., 2001; Farmer and Mottram, 1990; Farmer et al., 1989; Hofmann and Schieberle, 1995, 1997; Madruga and Mottram, 1998; Meynier and Mottram, 1995; Mottram and Whitfield, 1994, 1995a; Scanlan et al., 1973; Shu et al., 1986; Whitfield et al., 1988; Wu and Cadwallader, 2002; Yeo and Shibamoto, 1991)	**78** (Table 9)

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1-Mercapto-3-pentanone (Farmer et al., 1989; Madruga and Mottram, 1998)	**16** (Table 3)	3-Mercapto-2-butanone (Ames et al., 2001; Farmer and Mottram, 1990; Güntert et al., 1990; Hofmann and Schieberle, 1995, 1997; Madruga and Mottram, 1998; Mottram and Nobrega, 2002; Mottram and Whitfield, 1994; Münch and Schieberle, 1998; Schieberle and Hofmann, 1998; van Seeventer et al., 2001; Whitfield and Mottram, 1999, 2001; Zhang and Ho, 1991)	**18** (Table 3)
1-Octanethiol (Farmer and Mottram, 1990; Farmer et al., 1989)	—	3-Mercapto-2-pentanone (Ames et al., 2001; Farmer and Mottram, 1990; Farmer et al., 1989; Güntert et al., 1990; Hofmann and Schieberle, 1995, 1997; Madruga and Mottram, 1998; Meynier and Mottram, 1995; Mottram and Nobrega, 2002; Mottram and Whitfield, 1994; Münch and Schieberle, 1998; Schieberle and Hofmann, 1998; Shu et al., 1985b; van Seeventer et al., 2001; Whitfield and Mottram, 1999, 2001; Wu and Cadwallader, 2002)	**19** (Table 3)
1-Pentanethiol (Ames et al., 2001; Mulders, 1973)	**58** (Table 6)	3-Mercaptopropanoic acid (Hofmann and Schieberle, 1995, 1997)	Sulfury, seasoning-like (Hofmann and Schieberle, 1997)
1-Propanethiol (Zhang and Ho, 1991; Mulders , 1973)	**59** (Table 6)	3-Methyl-2-butanethiol (Zheng et al., 1997)	**47** (Table 6)

(*continued*)

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Table 13
Continued

Identified thiol	Odor	Identified thiol	Odor
2-(1-Mercaptoethyl)-furan (Güntert et al., 1990; Hofmann and Schieberle, 1997; Schieberle and Hofmann, 1998)	Burnt, sulfury (Hofmann and Schieberle, 1997)	3-Oxo-tetrahydro-4-furanthiol (van den Ouweland and Peer, 1975)	Green, meaty, vegetable, meat extract (van den Ouweland and Peer, 1975)
2-(1-Mercaptoethyl)-thiophene (Hofmann and Schieberle, 1997)	—	3-Thiophenethiol (Ames et al., 2001; Elmore et al., 2002; Farmer and Mottram, 1990; Güntert et al., 1990; Hofmann and Schieberle, 1997; Madruga and Mottram, 1998; Mottram and Nobrega, 2002; Mottram and Whitfield, 1995a; Whitfield and Mottram, 1999; Whitfield et al., 1988)	**80** (Table 9)
2-(Mercaptomethyl)-4-methyl-1,3-dioxo-lane (Güntert et al., 1990)	—	4-Mercapto-2,5-dimethyl-3-thiophenone (Guedes de Pinho et al., 1997)	**81** (Table 9)
2-Mercapto-3-butanone (Zheng et al., 1997)	—	4-Methyl-4-mercapto-2-pentanone (Farmer et al., 1989)	**21** (Table 3)
2-Mercapto-3-pentanone (Ames et al., 2001; Engel and Schieberle, 2002a; Farmer and Mottram, 1990; Madruga and Mottram, 1998; Mottram and Nobrega, 2002; Mottram and Whitfield, 1994; Whitfield and Mottram, 1999; Zheng et al., 1997)	**17** (Table 3)	5-Hydroxy-3-mercapto-2-pentanone (Mottram and Whitfield, 1994)	—
2-Mercaptopropanoic acid (Hofmann and Schieberle, 1995, 1997)	Sulfury, seasoning-like (Hofmann and Schieberle, 1997)	5-Mercapto-2-hexanone (Whitfield and Mottram, 1999)	—

2-Methyl-2,3-dihydro-3-thiophenethiol (van den Ouweland and Peer, 1975)	Sweet, roasted meat (van den Ouweland and Peer, 1975)	5-Methyl-2-furfurylthiol (Chen and Ho, 2002; Hofmann and Schieberle, 1997; Münch and Schieberle, 1998; Schieberle and Hofmann, 1998; Umano et al., 1995)	**82** (Table 9)
2-Methyl-2,3-dihydro-4-hydroxy-3-thiophenethiol (van den Ouweland and Peer, 1975)	Meaty, savory (van den Ouweland and Peer, 1975)	5-Methyl-2-thenylthiol (Hofmann and Schieberle, 1997)	—
2-Methyl-2,3-dihydro-4-thiophenethiol (van den Ouweland and Peer, 1975)	Rubber, meaty (van den Ouweland and Peer, 1975)	5-Methyl-3-oxo-tetrahydro-4-furanthiol (van den Ouweland and Peer, 1975)	Meaty, vegetable, meat extract (van den Ouweland and Peer, 1975)
2-Methyl-2-pentanethiol (Zheng et al., 1997)	—	Cyclopentanethiol (Mussinan and Katz, 1973)	—
2-Methyl-3-furanthiol (Ames et al., 2001; Bouchilloux et al., 1998a; Chen and Ho, 2002; Elmore et al., 2002; Engel and Schieberle, 2002a; Farmer and Mottram, 1990; Farmer et al., 1989; Gasser and Grosch, 1988; Hofmann and Schieberle, 1995, 1997, 1998; Huber and Bergamin, 1993; Madruga and Mottram, 1995, 1998; Meynier and Mottram, 1995; Mottram and Madruga, 1994; Mottram and Nobrega, 2002; Mottram and Whitfield, 1994, 1995a; Mottram et al., 1998; Münch and Schieberle, 1998; Schieberle and Hofmann, 1998; Tominaga et al., 2003b; van Seeventer et al., 2001; Whitfield and Mottram, 1999; Whitfield et al., 1988; Wu and Cadwallader, 2002; Zhang and Ho, 1991)	**75** (Table 9)	Ethanethiol (Hofmann and Schieberle, 1995; Mulders et al., 1973; Umano et al., 1995; Wu and Cadwallader, 2002)	**52** (Table 6)

(*continued*)

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Table 13
Continued

Identified Thiol	Odor	Identified Thiol	Odor
2-Methyl-3-thiophenethiol (Ames et al., 2001; Chen and Ho, 2002; Elmore et al., 2002; Farmer and Mottram, 1990; Farmer et al., 1989; Güntert et al., 1990; Hofmann and Schieberle, 1995; Madruga and Mottram, 1998; Mottram and Nobrega, 2002; Mottram and Whitfield, 1994, 1995a; van den Ouweland and Peer, 1975; Werkhoff et al., 1989; Whitfield and Mottram, 1999)	**76** (Table 9)	Ethyl-2-mercaptopropionate (Hofmann and Schieberle, 1997)	—
2-Methyl-4,5-dihydro-3-furanthiol (Güntert et al., 1990; Madruga and Mottram, 1998; van den Ouweland and Peer, 1975; Whitfield and Mottram, 1999)	—	2-Furfurylthiol (Ames and Mac Leod, 1985; Ames et al., 2001; Chen and Ho, 2002; Elmore et al., 2002; Engel and Schieberle, 2002a; Farmer and Mottram, 1990; Farmer et al., 1989; Güntert et al., 1990; Hofmann and Schieberle, 1995, 1997, 1998; Madruga and Mottram, 1998; Marchand et al., 2000; Meynier and Mottram, 1995; Mottram and Nobrega, 2002; Mottram and Whitfield, 1994; Mottram et al., 1998; Mussinan and Katz, 1973; Schieberle and Hofmann, 1998; Schieberle, 1991b; Tominaga et al., 2000b, 2003b; Tressl et al., 1994; van Seeventer et al., 2001; Whitfield et al., 1988; Wu and Cadwallader, 2002; Zhang and Ho, 1991)	**74** (Table 9)

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2-Methyl-4,5-dihydro-3-thiophenethiol (Mottram and Whitfield, 1994; van den Ouweland and Peer, 1975; Whitfield and Mottram, 1999)	Meaty (van den Ouweland and Peer, 1975)	Methanethiol (Meynier and Mottram, 1995; Mulders, 1973; Pripis-Nicolau et al., 2000; Umano et al., 1995)	**55** (Table 6)
2-Methyl-4,5-dihydro-4-thiophenethiol (van den Ouweland and Peer, 1975)	Roasted meat (van den Ouweland and Peer, 1975)	*N*-(2-Mercaptoethyl)-1,3-thiazoline (Engel and Schieberle, 2002a, 2002b)	Roasty, popcorn (Engel and Schieberle, 2002a, 2002b)
2-Methyl-4-furanthiol (van den Ouweland and Peer, 1975)	Green, meaty (van den Ouweland and Peer, 1975)	*N*-(2-Mercaptoethyl)-pyrrole (Engel and Schieberle, 2002a)	Roasty, burnt (Engel and Schieberle, 2002a)

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Table 14
Thiols related to thiamine degradation

Identified thiol	Odor	Identified thiol	Odor
1-(2-Methyl-3-furylthio)-ethanethiol (Werkhoff et al., 1989, 1990)	Roasted, brothy, spicy, onion, garlic, vegetable, meaty, gravy (Werkhoff et al., 1989, 1990)	2-Methyl-4,5-dihydro-3-furanthiol (Güntert et al., 1990, 1992; Hartman et al., 1984a; Mottram and Whitfield, 1994; Werkhoff et al., 1990)	Roasted meat (Güntert et al., 1990)
1-(2-Methyl-3-thienylthio)-ethanethiol (Werkhoff et al., 1989, 1990)	Sulfury, carrot, leek, meaty, yeast, onion (Werkhoff et al., 1989, 1990)	2-Methyl-4,5-dihydro-3-thiophenethiol (Werkhoff et al., 1990)	Meaty (van den Ouweland and Peer, 1975)
1,1-Ethanedithiol (Güntert et al., 1992)	**66** (Table 8)	2-Tetrahydrothiophenethiol (Güntert et al., 1990)	Onion, roasty, tropical fruit, meaty, sulfury (Güntert et al., 1990)
1,4-Dimercapto-3-pentanone (Güntert et al., 1990)	—	2-Thiophenethiol (Hofmann and Schieberle, 1995)	**78** (Table 9)
1-Hydroxy-4-mercapto-3-pentanone (Güntert et al., 1990)	—	3,5-Dimercapto-2-pentanone (Güntert et al., 1990; Werkhoff et al., 1990)	—
1-Mercapto-3-pentanone (Güntert et al., 1992)	**16** (Table 3)	3-Hydroxy-5-mercapto-2-pentanone (Güntert et al., 1990)	—
1-Mercapto-4-hydroxy-3-pentanone (Güntert et al., 1990)	—	3-Mercapto-2-butanone (Güntert et al., 1990, 1992)	**18** (Table 3)
1-Methylthio-ethanethiol (Güntert et al., 1992; Werkhoff et al., 1989, 1990)	**72** (Table 8)	3-Mercapto-2-pentanone (Güntert et al., 1990, 1992; Hartman et al., 1984a; Hofmann and Schieberle, 1995)	**19** (Table 3)
1-Methylthio-methanethiol (Güntert et al., 1992; Werkhoff et al., 1989, 1990)	—	3-Mercapto-5-hydroxy-2-pentanone (Güntert et al., 1990; Hartman et al., 1984a; Jhoo et al., 2002; Mottram and Whitfield, 1994; Werkhoff et al., 1990)	—

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2-(1-Mercaptoethyl)-furan (Güntert et al., 1990)	Mocha, roasty, elderberry (Güntert et al., 1990)	3-Mercaptopropanol (Güntert et al., 1990; Jhoo et al., 2002)	**10** (Table 2)
2,5-Dimethyl-3-furanthiol (Hartman et al., 1984a)	**73** (Table 9)	3-Mercaptopropyl-acetate (Güntert et al., 1990, 1992)	**28** (Table 4)
2-Mercapto-3-pentanone (Güntert et al., 1992)	**17** (Table 3)	3-Thiophenethiol (Güntert et al., 1990)	**80** (Table 9)
2-Methyl-2-tetrahydrothiophenethiol (Güntert et al., 1990, 1992)	Tropical fruit, sulfury, buchu, meaty, blackcurrant (Güntert et al., 1990)	4-Mercapto-2-butanone (Güntert et al., 1992)	**20** (Table 3)
2-Methyl-3-furanthiol (Ames and Mac Leod, 1985; Baek et al., 2001; Bezman et al., 2001; Bouchilloux et al., 1998b; Carrapiso et al., 2002; Gasser and Grosch, 1988; Güntert et al., 1990, 1992; Hartman et al., 1984a,1984b; Huber and Bergamin, 1993; Jhoo et al., 2002; Mottram and Madruga, 1994; Mottram and Whitfield, 1994; Mottram et al., 1998; Werkhoff et al., 1990)	**75** (Table 9)	5-(2-Mercaptoethyl)-4-methylthiazole (Güntert et al., 1992)	Tuna, metallic, sulfury, tropical fruit (Güntert et al., 1992)
2-Methyl-3-tetrahydrofuranthiol (Mottram and Whitfield, 1994)	—	5-Mercapto-2-pentanone (Güntert et al., 1992)	—
2-Methyl-3-tetrahydrothiophenethiol (Güntert et al., 1992)	—	Furfurylthiol (Mottram et al., 1998; Güntert et al., 1990)	**74** (Table 9)
2-Methyl-3-thiophenethiol (Güntert et al., 1990, 1992; Werkhoff et al., 1990)	**76** (Table 9)	Mercaptopropanone (Güntert et al., 1990, 1992)	**15** (Table 3)

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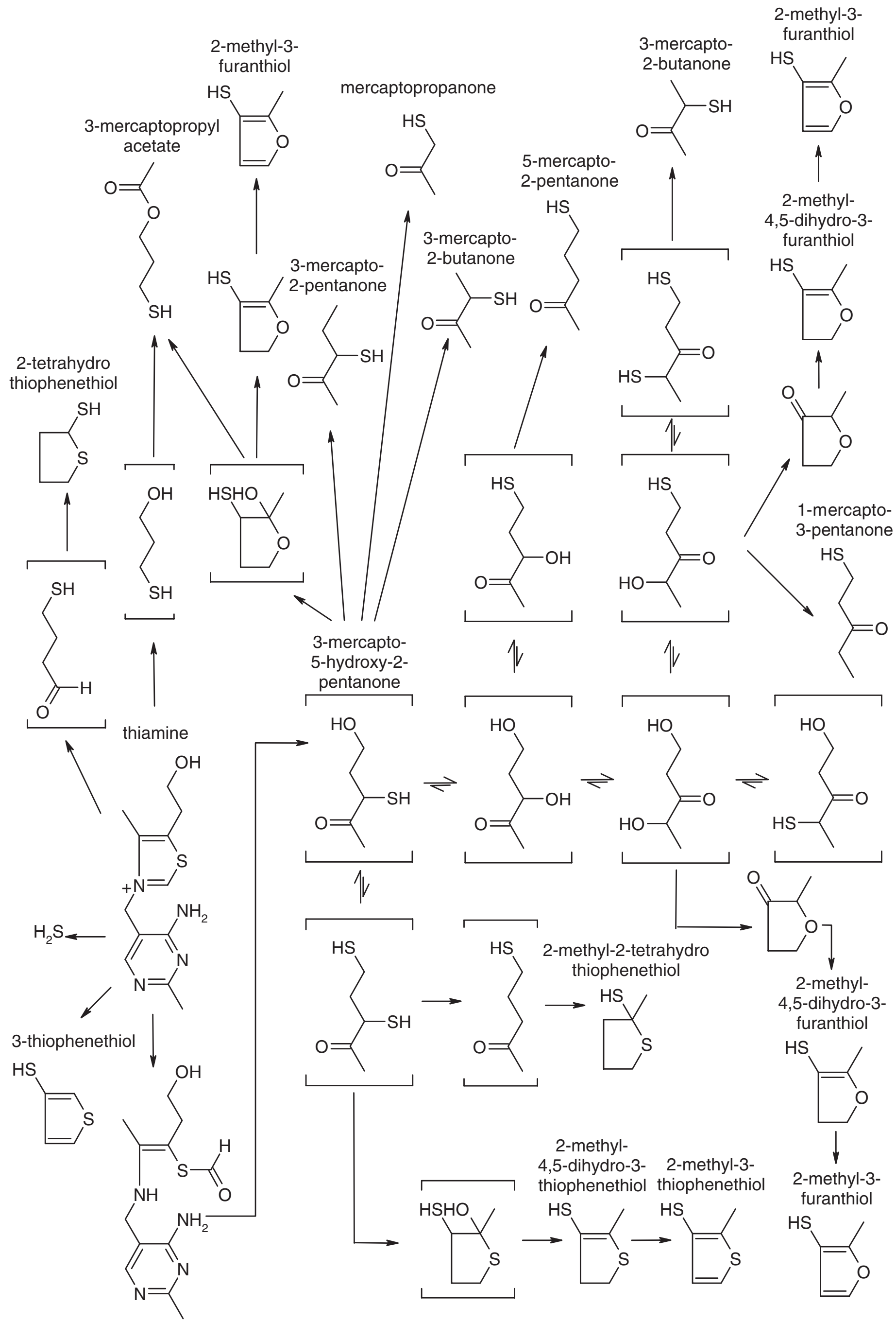

Figure 10. Some thiol formation pathways associated with the thermal degradation of thiamine.

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- Ionizing γ radiation, a method for pathogen inactivation in various foods increasing H_2S and methanethiol concentrations (Fan et al., 2002),
  - Cow metabolism, leading to a benzylthiol precursor in milk (Walker and Gray, 1970).

Conclusion

Because of their extremely low odor threshold, thiols are surely the most powerful odorants in many vegetables and fruits, fermented foods, and beverages. Although pungent at high concentrations, they prove highly desirable to consumers in many cases. Many chemical and biochemical pathways can explain their occurrence, but for most matrixes, accurate mechanisms are not yet well understood. More sensitive analytical methods are now required to more easily identify the thiol odorants detected by GC olfactometry or with sulfur-specific detectors.

References

Acuna, G., Gautschi, M., Kumli, F., Schmid, J., Zsindely, J. (2000). *Mercapto Alcohols as Flavouring Compounds*. Switzerland, Patent EP1055667.

Adams, R. L., Mottram, D. S., Parker, J. K., Brown, H. M. (2001). Flavor-protein binding: disulfide interchange reaction between ovalbumin and volatile disulfides. *J. Agric. Food Chem.* 49:4333–4336.

Ames, J. M., Guy, R. C. E., Kipping, G. J. (2001). Effect of pH and temperature on the formation of volatile compounds in cysteine/reducing sugar/starch mixtures during extrusion cooking. *J. Agric. Food Chem.* 49:1885–1894.

Ames, J. M., Mac Leod, G. (1985). Volatile components of a yeast extract composition. *J. Food Sci.* 50:125–131.

Axelsson, K., Mannervik, B. (1975). Synthesis of a mixed disulfide of egg white lysozyme and glutathione—a model substrate for enzymatic reduction of protein mixed disulfides. *FEBS Lett.* 53:40–43.

Aznar, M., Lopez, R., Cacho, J. F., Ferreira, V. (2001). Identification and quantification of impact odorants of aged red wines from Rioja. GC-olfactometry, quantitative GC-MS, and odor evaluation of HPLC fractions. *J. Agric. Food Chem.* 49:2924–2929.

Badings, H. T., Maarse, H., Kleipool, R. J. C., Tas, A. C., Neeter, R., ten Noever de Brauw, M. C. (1976). Formation of odorous compounds from hydrogen sulphide and 2-butanal. *Z. Lebensm. Unters. Forsch.* 161:53–59.

Baek, H. H., Kim, C. J., Ahn, B. H., Nam, H. S., Cadwallader, K. R. (2001). Aroma extract dilution analysis of a beef-like process flavor from extruded enzyme-hydrolyzed soybean protein. *J. Agric. Food Chem.* 49:790–793.

Bandaranayake, W. M., Wickramasinghe, W. A. (1996). Benzylmercaptan (benzylthiol) and dibenzyldisulfide from the marine sponge Crella spinulata (Hentschel) (Poecilosclerida: Crellidae). *Comp. Biochem. Physiol.* 113:499–502.

Bel Rhlid, R., Matthey-Doret, W. (1998). Biogeneration of thiols relevant to roasty notes. *Toegepaste Biol. Wet.* 63:1377–1380.

Marcel Dekker, Inc.
270 Madison Avenue, New York, New York 10016

Bel Rhlid, R., Blank, I., Cerny, C. (1999a). *Process for the Preparation of Flavouring Compositions and Use of These Compositions in Foodstuffs*. Switzerland, Patent WO9933359.

Bel Rhlid, R., Chaintreau, A., Pollien, P. (1999b). *Thiol-Forming Aroma Precursor Mixtures*. Switzerland Patent EP963706.

Bel Rhlid, R., Blank, I., Fay, L. B., Juillerat, M. A., Matthey-Doret, W. (2001). *Preparation of Thiols and Derivatives by Bio-Conversion*. Switzerland.

Bel Rhlid, R., Fleury, Y., Blank, I., Fay, L. B., Welti, D. H., Vera, F. A., Juillerat, M. A. (2002a). Generation of roasted notes based on 2-acetyl-2-thiazoline and its precursor, 2-(1-hydroxyethyl)-4,5-dihydrothiazole, by combined bio and thermal approaches. *J. Agric. Food Chem.* 50:2350–2355.

Bel Rhlid, R., Matthey-Doret, W., Blank, I., Fay, L. B., Juillerat, M. A. (2002b). Lipase-assisted generation of 2-methyl-3-furanthiol and 2-furfurylthiol from thioacetates. *J. Agric. Food Chem.* 50:4087–4090.

Beloqui, A. A., Bertrand, A. (1995a). Etudes des composés soufrés ''lourds'' dans le vin. In: 5 Symposium International d'Oenologie, Bordeaux, Editions Tec & Doc, Paris.

Beloqui, A. A., Bertrand, A. (1995b). Study on sulfur compounds in wine: preliminary results. *Italian J. Food Sci.* 7:279–289.

Bezman, Y., Rouseff, R. L., Naim, M. (2001). 2-Methyl-3-furanthiol and methional are possible off-flavors in stored orange juice: aroma-similarity, NIF/SNIF GC-O, and GC analyses. *J. Agric. Food Chem.* 49:5425–5432.

Blanchard, L. (2000). Recherche sur la contribution de certains thiols volatils à l'arôme des vins rouges. Etude de leur genèse et de leur stabilité. *Faculté d'Oenologie*. Bordeaux: Université Victor Segalen Bordeaux 2.

Blanchard, L., Bouchilloux, P., Darriet, P., Tominaga, T., Dubourdieu, D. (1999). Caractérisation de la fraction volatile de nature soufrée dans les vins de cabernet et merlot. Etude de son évolution au cours de l'élevage en barriques. In: 6° Symposium International d'Oenologie, Bordeaux, Editions Tec & Doc, Paris.

Blanchard, L., Tominaga, T., Dubourdieu, D. (2001). Formation of furfurylthiol exhibiting a strong coffee aroma during oak barrel fermentation from furfural released by toasted staves. *J. Agric. Food Chem.* 49:4833–4835.

Blank, I., Sen, A., Grosch, W. (1992). Potent odorants of the roasted powder and brew of Arabica coffee. *Z. Lebensm. Unters. Forsch.* 195:239–245.

Blank, I., Pascual, E. C., Devaud, S., Fay, L. B., Stadler, R. H., Yeretzian, C., Goodman, B. A. (2002). Degradation of the coffee flavor compound furfuryl mercaptan in model Fenton-type reaction. *J. Agric. Food Chem.* 50:2356–2364.

Block, E. (1992). The organosulfur chemistry of the genus *Allium*—implications for the organic chemistry of sulfur. *Angew. Chem. Int. Ed. Engl.* 31:1135–1178.

Blockmans, C., van der Meerssche, J., Masschelein, C. A., Devreux, A. (1981). Photodegradation and formation of carbonyl- and sulphur compounds in beer. In: EBC Congress, 347–357, Copenhagen.

Boelens, M. H., van Gemert, L. J. (1993). Volatile character-impact sulfur compounds and their sensory properties. *Perfumer & Flavorist* 18:29–39.

Boelens, M., De Valois, P. J., Wobben, H. J., Van der Gen, A. (1971). Volatile flavor compounds from onion. *J. Agric. Food Chem.* 19:984–991.

Boelens, M., van der Linde, L. M., de Valois, P. J., van Dort, H. M., Takken, H. J. (1974). Organic sulfur compounds from fatty aldehydes, hydrogen sulfide, thiols and ammonia as flavor constituents. *J. Agric. Food Chem.* 22:1071–1076.

Bouchilloux, P., Darriet, P., Dubourdieu, D. (1996). Mise au point d'une méthode de dosage de la 4-mercapto-4-méthylpentan-2-one dans les vins de Sauvignon. *J. Int. Sci. Vigne Vin.* 30:23–29.

Bouchilloux, P., Darriet, P., Dubourdieu, D. (1998a). Identification of a very odoriferous thiol, 2-methyl-3-furanthiol, in wines. *Vitis* 37:177–180.

Bouchilloux, P., Darriet, P., Henry, R., Lavigne-Cruège, V., Dubourdieu, D. (1998b). Identification of volatile and powerful odorous thiols in Bordeaux red wine varieties. *J. Agric. Food Chem.* 46:3095–3099.

Bouchilloux, P., Darriet, P., Bugaret, Y., Clerjeau, M., Dubourdieu, D. (1999). Incidences des stratégies de traitements phytosanitaires sur l'arôme des vins de merlot et de cabernet-sauvignon. In: 6° Symposium International d'Oenologie, Bordeaux, Editions Tec & Doc, Paris.

Bouchilloux, P., Darriet, P., Dubourdieu, D., Henry, R., Reichert, S., Mosandl, A. (2000). Stereodifferentiation of 3-mercapto-2-methylpropanol in wine. *Eur. Food Res. Technol.* 210:349–352.

Bredie, W. L. P., Mottram, D. S., Guy, R. C. E. (2002). Effect of temperature and pH on the generation of flavor volatiles in extrusion cooking of wheat flour. *J. Agric. Food Chem.* 50:1118–1125.

Breton, A., Surdin-Kerjan, Y. (1977). Sulfate uptake in *Saccharomyces cerevisiae*: biochemical and genetic study. *J. Bacteriol.* 132:224–232.

Brinkman, H. W., Copier, H., de Leuw, J. J. M., Tjan, S. B. (1972). Components contributing to beef flavor: analysis of the headspace volatiles of beef broth. *J. Agric. Food Chem.* 20:177–181.

Bücking, M., Steinhart, H. (2002). Headspace GC and sensory analysis characterization of the influence of different milk additives on the flavor release of coffee beverages. *J. Agric. Food Chem.* 50:1529–1534.

Buettner, A. (2002). Influence of salivary enzymes on odorant concentration changes occuring in vivo. I. Esters and thiols. *J. Agric. Food Chem.* 50:3283–3289.

Buettner, A., Schieberle, P. (1999). Characterization of the most odor-active volatiles in fresh, hand-squeezed juice of grapefruit (*Citrus paradisi* Macfayden). *J. Agric. Food Chem.* 47:5189–5193.

Buettner, A., Schieberle, P. (2001). Evaluation of key aroma compounds in hand-squeezed grapefruit juice (*Citrus paradisi* Macfayden) by quantification and flavor reconstitution experiments. *J. Agric. Food Chem.* 49:1358–1363.

Burmeister, M. S., Drummond, C. J., Pfisterer, E. A., Hysert, D. W. (1992). Measurement of volatile sulfur compounds in beer using gas chromatography with a sulfur chemiluminescence detector. *J. ASBC* 50:53–58.

Burns, C. S., Heyerick, A., De Keukeleire, D., Forbes, M. D. E. (2001). Mechanism for formation of the lightstruck flavor in beer revealed by time-resolved electron paramagnetic resonance. *Chem. Eur. J.* 7:4554–4561.

Buttery, R. G., Ling, L. C. (1998). Additional studies on flavor components of corn tortilla chips. *J. Agric. Food Chem.* 46:2764–2769.

Buttery, R. G., Teranishi, R., Flath, R. A., Ling, L. C. (1990). Identification of additional tomato paste volatiles. *J. Agric. Food Chem.* 38:792–795.

Marcel Dekker, Inc.
270 Madison Avenue, New York, New York 10016

Carrapiso, A. I., Ventanas, J., Garcia, C. (2002). Characterization of the most odor-active compounds of Iberian ham headspace. *J. Agric. Food Chem.* 50:1996–2000.

Casey, J. C., Self, R., Swain, T. (1965). Factors influencing the production of low-boiling volatiles from foods. *Res. Note*. 30:33–34.

Cerny, C., Grosch, W. (1992). Evaluation of potent odorants in roasted beef by aroma extract dilution analysis. *Z. Lebensm. Unters. Forsch.* 194:322–325.

Chen, X., Schofield, J. D. (1995). Determination of protein-gluthione mixed disulfides in wheat flour. *J. Agric. Food Chem.* 43:2362–2368.

Chen, Y., Ho, C.-T. (2002). Effects of Carnosine on volatile generation from Maillard reaction of ribose and cysteine. *J. Agric. Food Chem.* 50:2372–2376.

Cherest, H., Surdin-Kerjan, Y. (1992). Genetic analysis of a new mutation conferring cysteine auxotrophy in *Saccharomyces cerevisiae*: updating of the sulfur metabolism pathway. *Genetics* 130:51–58.

Chin, H. W., Lindsay, R. C. (1994). Mechanisms of formation of volatile sulfur compounds following the action of cysteine sulfoxide lyases. *J. Agric. Food Chem.* 42:1529–1536.

Chin, H. W., Bernhard, R. A., Rosenberg, M. (1996). Solid phase microextraction for cheese volatile compound analysis. *J. Food Sci.* 61:1118–1122.

Cuer, A. (1982). Les arômes de fromage. *Parf. Cosm. Arômes*. 44:88–92.

Czerny, M., Mayer, F., Grosch, W. (1999). Sensory study on the character impact odorants of roasted Arabica coffee. *J. Agric. Food Chem.* 47:695–699.

Dan, K., Nagata, M., Yamashita, I. (1997). Methanethiol formation in disrupted tissue solution of fresh broccoli. *J. Japan Soc. Hort. Sci.* 66:621–627.

Dan, K., Nagata, M., Yamashita, I. (1999). Mechanism of off-flavor production in Brassica vegetables under anaerobic conditions. *J. A. R. Q.* 33:109–114.

Darriet, P., Tominaga, T., Demole, E., Dubourdieu, D. (1993). Mise en évidence dans le raisin de *Vitis vinifera* var Sauvignon d'un précurseur de la 4-mercapto-4-méthylpentan-2-one. *C. R. Acad. Sci. Paris (Life Science)* 316:1332–1335.

Darriet, P., Tominaga, T., Lavigne, V., Boidron, J.-N., Dubourdieu, D. (1995). Identification of a powerful aromatic component of *Vitis vinifera* L. Sauvignon wines: 4-mercapto-4-methylpentan-2-one. *Flavour Fragr. J.* 10:385–392.

Darriet, P., Bouchilloux, P., Poupot, C., Bugaret, Y., Clerjeau, M., Sauris, P., Medina, B., Dubourdieu, D. (2001a). Effects of copper fungicide spraying on volatile thiols of varietal aroma Sauvignon blanc, Cabernet Sauvignon and Merlot wines. *Vitis* 40:93–99.

Darriet, P., Poupot, C., Armand, J.-M., Duourdieu, D., Clerjeau, M., Glories, Y., Bordeu, E., Pszczolkowski, P., Bugaret, Y. (2001b). Incidence of vine sprayings with downy mildew fungicides, without parasitic fungi, on Cabernet Sauvignon grapes and wine composition. *J. Int. Sci. Vigne Vin.* 35:23–29.

Demole, E., Enggist, P., Ohloff, G. (1982). 1-*p*-Menthene-8-thiol: a powerful flavor impact constituent of grapefruit juice (*Citrus paradisi* MacFayden). *Helv. Chim. Acta* 65:1785–1794.

Dias, B., Weimer, B. (1998). Conversion of methionine to thiols by Lactococci, Lactobacilli, and Brevibacteria. *Appl. Environ. Microbiol.* 64:3320–3326.

Dott, W., Trüper, H. G. (1978). Sulfite formation by wine yeasts. *Arch. Microbiol.* 118:249–251.

Drost, B. W., van den Berg, R., Freijiee, F. J. M., van der Velde, E. G., Hollemans, M. (1990). Flavor stability. *Am. Soc. Brew. Chem.* 48:124–131.

Drumm, T. D., Spanier, A. M. (1991). Changes in the content of lipid autoxidation and sulfur-containing compounds in cooked beef during storage. *J. Agric. Food Chem.* 39:336–343.

Du Plessis, C. S., Augustyn, O. P. H. (1981). Initial study on the guava aroma of Chenin blanc and Colombar wines. *Am. J. Enol. Viticult.* 2:101–103.

Dubourdieu, D. (1995). Les arômes: facteurs de qualité. Les arômes du Sauvignon, valorisation par la vinification. *9ème Colloque Viticole et Oenologique Euroviti,* Bordeaux, Editions Tec & Doc, Paris.

Dubourdieu, D., Darriet, P. (1993). Ricerche sull'aroma varietale del Sauvignon. *Vignevini* 20:38–41.

Duyvis, M. G., Hilhorst, R., Laane, C., Evans, D. J., Schmedding, D. J. M. (2002). Role of riboflavin in beer flavor instability: determination of levels of riboflavin and its origin in beer by fluorometric apoprotein titration. *J. Agric. Food Chem.* 50:1548–1552.

Edwards, A. S., Wedzicha, B. L. (1997). Uptake of thiol anti-browning agents by cabbage on blanching and reactivity during dehydration. *Food Chem.* 59:453–457.

Edwards, R. A., Dainty, R. H., Hibbard, C. M. (1987). Volatile compounds produced by meat pseudomonas and relate reference strains during growth on beef stored in air at chill temperatures. *J. Appl. Bacteriol.* 62:403–412.

Elmore, J. S., Mottram, D. S., Hierro, E. (2000). Two-fibre solid phase microextraction combined with gas chromatography–mass spectrometry for the analysis of volatile aroma compounds in cooked pork. *J. Chromatogr.* A 905:233–240.

Elmore, J. S., Campo, M. M., Enser, M., Mottram, D. S. (2002). Effect of lipid composition on meat-like model systems containing cysteine, ribose, and polyunsaturated fatty acids. *J. Agric. Food Chem.* 50:1126–1132.

Elskens, M. T., Jaspers, C. J., Penninckx, M. J. (1991). Glutathione as an endogenous sulphur source in the yeast *Saccharomyces cerevisiae*. *J. Gen. Microbiol.* 137:637–644.

Engel, K.-H., Tressl, R. (1991). Identification of new sulfur-containing volatiles in yellow passion fruits (*Passiflora edulis* f. flavicarpa). *J. Agric. Food Chem.* 39:2249–2252.

Engel, W., Schieberle, P. (2002a). Identification and quantification of key aroma compounds formed in Maillard-type reactions of fructose with cysteamine or isothiaproline (1,3-thiazolidine-2-carboxylic acid). *J. Agric. Food Chem.* 50:5394–5399.

Engel, W., Schieberle, P. (2002b). Structural determination and odor characterization of N-(2-mercaptoethyl)-1,3-thiazolidine, a new intense popcorn-like-smelling odorant. *J. Agric. Food Chem.* 50:5391–5393.

Engel, E., Baty, C., Le Corre, D., Souchon, I., Martin, N. (2002). Flavor-active compounds potentially implicated in cooked cauliflower acceptance. *J. Agric. Food Chem.* 50:6459–6467.

Fan, X., Sommers, C. H., Thayer, D. W., Lehotay, S. J. (2002). Volatile sulfur compounds in irridiated precooled turkey breast analyzed with pulsed flame photometric detection. *J. Agric. Food Chem.* 50:4257–4261.

Marcel Dekker, Inc.
270 Madison Avenue, New York, New York 10016

Farkas, P., Sadecka, J., Kovac, M., Siegmund, B., Leitner, E., Pfannhauser, W. (1997). Key odourants of pressure-cooked hen meat. *Food Chem*. 60:617–621.

Farmer, L. J., Mottram, D. S. (1990). Interaction of lipid in Maillard reaction between cysteine and ribose: the effect of a triglyceride and three phospholipids on the volatile products. *J. Sci. Food Agric*. 53:505–525.

Ferreira, V., Aznar, M., Lopez, R., Cacho, J. (2001). Quantitative gas chromatography—olfactometry carried out at different dilutions of an extract. Key differences in the odor profiles of four high-quality Spanish aged red wines. *J. Agric. Food Chem*. 49:4818–4824.

Ferreira, V., Ortin, N., Escudero, A., Lopez, R., Cacho, J. (2002). Chemical characterization of the aroma of grenache rosé wines: aroma extract dilution analysis, quantitative determination, and sensory reconstitution studies. *J. Agric. Food Chem*. 50:4048–4054.

Ferreira, A. C. S., Rodrigues, P., Hogg, T., Guedes de Pinho, P. (2003). Influence of some technological parameters on the formation of dimethyl sulfide, 2-mercaptoethanol, methanol, and dimethyl sulfone in Port wines. *J. Agric. Food Chem*. 51:727–732.

Fitz, W., Van Delft, A., Kerler, J., Hesp, T. G. M., Apeldoorn, W., Altena, G. H. (2001). *Savoury Flavour Comprising 2-Methyl-Furan-3-Thiol and/or a Derivative and Methylenedithiol and/or a Derivative*. Netherlands, Patent EP1090557.

Forney, C. F., Mattheis, J. P., Austin, R. K. (1991). Volatile compounds produced by broccoli under anaerobic conditions. *J. Agric. Food Chem*. 39:2257–2259.

Friedman, M. (1994). Mechanisms of beneficial effects of sulfur amino acids. *A. C. S. Symp. Ser*. 564:258–277.

Gardner, S. C. M., Dauterman, W. C. (1992). Studies on cysteine conjugate β-lyase and thiol S-methyltransferase in insects. *Insect Biochem. Molec. Biol*. 22:181–184.

Gasser, U., Grosch, W. (1988). Identification of volatile flavour compounds with high aroma values from cooked beef. *Z. Lebensm. Unters. Forsch*. 186:489–494.

Gasser, U., Grosch, W. (1990a). Aromaextraktverdünnungsanalyse handelsüblicher fleischaromen. *Z. Lebensm. Unters. Forsch*. 190:511–515.

Gasser, U., Grosch, W. (1990b). Primary odorants of chicken broth. A comparative study with meat broths from cow and ox.. *Z. Lebensm. Unters. Forsch*. 190:3–8.

Gijs, L., Perpète, P., Timmermans, A., Collin, S. (2000a). 3-Methylthiopropionaldehyde as precursor of dimethyl trisulfide in aged beers. *J. Agric. Food Chem*. 48:6196–6199.

Gijs, L., Piraprez, G., Perpète, P., Spinnler, E., Collin, S. (2000b). Retention of sulfur flavours by food matrix and determination of sensorial data independent of the medium composition. *Food Chem*. 69:319–330.

Gijs, L., Vermeulen, C., Collin, S. (2003). Review—occurrence et voies de formation des arômes soufrés dans la bière. 1. Les sulfures et les polysulfures. *Cerevisia* 28:37–46.

Girard, B., Durance, T. (2000). Headspace volatiles of sockeye and pink salmon as affected by retort process. *J. Food Sci*. 65:34–39.

Giudici, P., Kunkee, R. E. (1994). The effect of nitrogen deficiency and sulfur-containing amino acids on the reduction of sulfate to hydrogen sulfide by wine yeasts. *Am. J. Enol. Viticuit*. 45:107–112.

Marcel Dekker, Inc.
270 Madison Avenue, New York, New York 10016

Goldstein, H., Rader, S., Murakami, A. A. (1993). Determination of 3-methyl-2-butene-1-thiol in beer. *Am. Soc. Brew. Chem.* 51:70–74.

Gora, J., Brud, W. (1983). Progress in synthesis of sensory important trace components of essential oils and natural flavours. *Nahrung*. 27:413–428.

Gresser, A. (1997). La stabilita della birra e la sua influenzabilita tecnologica. *Birra e Malto*. 67:25–80.

Grosch, W. (1993). Detection of potent odorants in foods by aroma extract dilution analysis. *Trends Food Sci. Technol.* 4:68–73.

Grosch, W. (1994). Determination of potent odourants in foods by aroma extract dilution analysis (AEDA) and calculation of odour activity values (OAVs). *Flavour Fragr. J.* 9:147–158.

Guedes de Pinho, P., Bertrand, A. (1995). L'odeur caractéristique des vins issus de cépages blancs non vitis vinefera. In: 5 Symposium International d'Oenologie, Bordeaux Editions Tec & Doc, Paris.

Guedes de Pinho, P., Beloqui, A. A., Bertrand, A. (1997). Detection of a sulfur compound responsible for the typical aroma of some non *Vitis vinifera* wines. *Sci. Aliments* 17:341–348.

Gunst, F., Verzele, M. (1978). On the sunstruck flavour of beer. *J. Inst. Brew.* 84:291–292.

Güntert, M., Brüning, J., Emberger, R., Köpsel, M., Kuhn, W., Thielmann, T., Werkhoff, P. (1990). Identification and formation of some selected sulfur-containing flavor compounds in various meat model systems. *J. Agric. Food Chem.* 38:2027–2041.

Güntert, M., Bruening, J., Emberger, R., Hopp, R., Koepsel, M., Surburg, H., Werkhoff, P. (1992). Thermally degraded thiamin. A potent source of interesting flavor compounds. *A. C. S. Symp. Ser.* 490:140–163.

Guth, H. (1997a). Identification of character impact odorants of different white wine varieties. *J. Agric. Food Chem.* 45:3022–3026.

Guth, H. (1997b). Quantification and sensory studies of character impact odorants of different white wine varieties. *J. Agric. Food Chem.* 45:3027–3032.

Guth, H. (1998). Comparison of different white wine varieties in odor profiles by instrumental analysis and sensory studies. *A. C. S. Symp. Ser.* 714:39–52.

Guth, H., Grosch, W. (1993). Quantitation of potent odorants of virgin olive oil by stable-isotope dilution assays. *J. Am. Oil Chem. Soc.* 70:513–518.

Guth, H., Grosch, W. (1994). Identification of the character impact odorants of stewed beef juice by instrumental analyses and sensory studies. *J. Agric. Food Chem.* 42:2862–2866.

Guth, H., Hofmann, T., Schieberle, P., Grosch, W. (1995). Model reactions on the stability of disulfides in heated foods. *J. Agric. Food Chem.* 43:2199–2203.

Haboucha, J., Masschelein, C. A. (1979). Formation de methane thiol et sensibilité de la bière à la lumière. *Cerevisiae* 3:97–102.

Haboucha, J., Devreux, A., Masschelein, C. A. (1982). Influence des paramètres de fabrication sur la teneur en composés soufrés volatils de la bière. *Cerevisia* 3:143–150.

Hansen, J., Kielland-Brandt, M. C. (1996). Modification of biochemical pathways in industrial yeasts. *J. Biotechnol.* 49:1–12.

Hartman, G. J., Carlin, J. T., Scheide, J. D., Ho, C.-H. (1984a). Volatile products formed from the thermal degradation of thiamin at high and low moisture levels. *J. Agric. Food Chem.* 32:1015–1018.

Hartman, G. J., Scheide, J. D., Ho, C.-H. (1984b). Effect of water activity on the major volatiles produced in a model system approximating cooked meat. *J. Food Sci.* 49:607–613.

Hashimoto, N., Eshima, T. (1979). Oxidative degradation of isohumulones in relation to flavour stability of beer. *J. Inst. Brew.* 85:136–140.

Hatzimiditriou, E., Bouchilloux, P., Darriet, P., Bugaret, Y., Clerjeau, M., Poupot, C., Medina, B., Dubourdieu, D. (1996). Incidence of vine protection using a commercial formula of Bordeaux mixture of the Sauvignon grapes maturity and the wines varietal aroma. *J. Int. Sci. Vigne Vin.* 30:133–150.

Haye, B., Maujean, A., Jacquemin, C., Feuillat, M. (1977). Contribution à l'étude des ''goûts de lumière'' dans le vin de Champagne. *Connaissance Vigne Vin.* 11:243–254.

Heinzel, M. A., Trüper, H. G. (1978). Sulfite formation by wine yeasts. Regulation of biosynthesis of ATP- and ADP-sulfurylase by sulfur- and selenium-compounds. *Arch. Microbiol.* 118:243–247.

Helmlinger, D., Lamparsky, D., Schudel, P., Wild, J., Sigg-Grutter, T. (1976). *Flavoring with 3,7-Dimethyl-Octa-2,6-Dienyl-Mercaptan*. USA.

Henschke, P. A., Jiranek, V. (1991). Hydrogen sulfide formation during fermentation: effect of nitrogen composition in model grape must. In: International Symposium on Nitrogen in Grapes and Wine. Seattle.

Heusinger, G., Mosandl, A. (1984). Chirale, schwefelhaltige aromastoffe der gelben passionsfrucht (*Passiflora edulis* F. flavicarpa) darstellung der enantiomeren und absolute konfiguration. *Tetrahedron Lett.* 25:507–510.

Hill, P. G., Smith, R. M. (2000). Determination of sulphur compounds in beer using headspace solid-phase microextraction and gas chromatographic analysis with pulsed flame photometric detection. *J. Chromatogr.* A 872:203–213.

Hofmann, T., Schieberle, P. (1995). Evaluation of the key odorants in a thermally treated solution of ribose and cysteine by aroma extract dilution techniques. *J. Agric. Food Chem.* 43:2187–2194.

Hofmann, T., Schieberle, P. (1997). Identification of potent aroma compounds in thermally treated mixtures of glucose/cysteine and rhamnose/cysteine using aroma extract dilution techniques. *J. Agric. Food Chem.* 45:898–906.

Hofmann, T., Schieberle, P. (1998). Quantitative model studies on the effectiveness of different precursor systems in the formation of the intense food odorants 2-furfurylthiol and 2-methyl-3-furanthiol. *J. Agric. Food Chem.* 46:235–241.

Hofmann, T., Schieberle, P. (2002). Chemical interactions between odor-active thiols and melanoidins involved in the aroma staling of coffee beverages. *J. Agric. Food Chem.* 50:319–326.

Hofmann, T., Schieberle, P., Grosch, W. (1996). Model studies on the oxidative stability of odor-active thiols occurring in food flavors. *J. Agric. Food Chem.* 44:251–255.

Hofmann, T., Czerny, M., Calligaris, S., Schieberle, P. (2001). Model studies on the influence of coffee melanoidins on flavor volatiles of coffee beverages. *J. Agric. Food Chem.* 49:2382–2386.

Holscher, W., Vitzthum, O. G., Steinhart, H. (1990). Identification and sensorial evaluation of aroma-impact-compounds in roasted Colombian coffee. *Café Cacao Thé* 34:205–212.

Holscher, W., Vitzthum, O. G., Steinhart, H. (1992). Prenyl alcohol—source for odorants in roasted coffee. *J. Agric. Food Chem.* 40:655–658.

Marcel Dekker, Inc.
270 Madison Avenue, New York, New York 10016

Huber, U. A., Bergamin, D. (1993). Novel access to furan-3-thiols and derivatives, impact meat-flavor compounds. *Helv. Chim. Acta* 76:2528–2536.

Hugues, P. (1998). The lightstruck flavour problem. In: Chair De Clerck VIII. Leuven.

Hugues, P. S. (1999). Theoretical approaches to understanding the mechanism of lightstruck flavour formation. In: EBC Congress. Cannes.

Huynh-Ba, T., Jaeger, D., Matthey-Doret, W. (1997). *Production of Aroma-Enhancing Thiols*. Switzerland, Patent EP770686.

Irwin, A. J., Bordeleau, L., Barker, R. L. (1993). Model studies and flavor threshold determination of 3-methyl-2-butene-1-thiol in beer. *Am. Soc. Brew. Chem.* 51:1–3.

Jaillais, B., Bertrand, V., Auger, J. (1999). Cryo-trapping/SPME/GC analysis of cheese aroma. *Talanta* 48:747–753.

Jangaard, N. O., Gress, H. S., Coe, R. W. (1974). The effect of some wort constituents on hydrogen sulfide production by *Saccharomyces carlsbergensis*. In: American Society of Brewing Chemists.

Jezussek, M., Juliano, B. O., Schieberle, P. (2002). Comparison of key aroma compounds in cooked brown rice varieties based on aroma extract dilution analyses. *J. Agric. Food Chem.* 50:1101–1105.

Jhoo, J.-W., Lin, M.-C., Sang, S., Cheng, X., Zhu, N., Stark, R. E., Ho, C.-T. (2002). Characterization of 2-methyl-4-amino-5-(2-methyl-3-furylthiomethyl)-pyrimidine from thermeal degradation of thiamin. *J. Agric. Food Chem.* 50:4055–4058.

Jiranek, V., Langridge, P., Henschke, P. A. (1995). Regulation of hydrogen sulfide liberation in wine-producing *Saccharomyces cerevisiae* strains by assimilable nitrogen. *Appl. Environ. Microbiol.* 61:461–467.

Kadota, H., Ishida, Y. (1972). Production of volatile sulfur compounds by microorganisms. *Ann. Rev. Microbiol.* 26:127–138.

Kaiser, R., Lamparsky, D., Schudel, P. (1975). Analysis of buchu leaf oil. *J. Agric. Food Chem.* 23:943–950.

Kataoka, H., Lord, H. L., Pawliszyn, J. (2000). Applications of solid–phase microextraction in food analysis. *J. Chromatogr.* A 880:35–62.

Kattein, U., Miedaner, H., Narzib, L. (1988). Zur problematik des lichtgesmacks im bier. *Monatsschrift für Brauwissenschaft* 5:205–208.

Kerkenaar, A., Schmedding, D. J. M., Berg, J. (1996a). *Method for Preparing Thiol Compounds with Bacterial β-Lyase*. Netherlands, Patent US5578470.

Kerkenaar, A., Schmedding, D. J. M., Berg, J. (1996b). *Preparation of Thiol Compounds with β-Lyase-Producing Microorganisms*. Netherlands, Patent US5578470.

Kerscher, R., Grosch, W. (1998). Quantification of 2-methyl-3-furanthiol, 2-furfurylthiol, 3-mercapto-2-pentanone, and 2-mercapto-3-pentanone in heated meat. *J. Agric. Food Chem.* 46:1954–1958.

Kinlin, T. E., Muralidhara, R., Pittet, A. O., Sanderson, A., Walradt, J. P. (1972). Volatile components of the roasted filberts. *J. Agric. Food Chem.* 20:1021–1028.

Kleipool, R. J. C., Tas, A. C., Maarse, H., Neeter, R., Badings, H. T. (1976). Reaction of hydrogen sulphide with 2-alkenals. *Z. Lebensm. Unters. Forsch.* 161:231–238.

Marcel Dekker, Inc.
270 Madison Avenue, New York, New York 10016

Kolor, M. G. (1983). Identification of an important new flavor compound in Concord grape: ethyl-3-mercaptopropionate. *J. Agric. Food Chem.* 31:1125–1127.

Kotseridis, Y., Baumes, R. (2000). Identification of impact odorants in Bordeaux red grape juice, in the commercial yeast used for its fermentation, and in the produced wine. *J. Agric. Food Chem.* 48:400–406.

Kotseridis, Y., Ray, J.-L., Augier, C., Baumes, R. (2000). Quantitative determination of sulfur containing wine odorants at sub-ppb levels. 1. Synthesis of the deuterated analogues. *J. Agric. Food Chem.* 48:5819–5823.

Kubec, R., Drhova, V., Velisek, J. (1999). Volatile compounds thermally generated from *S*-propylcysteine and *S*-propylcysteine sulfoxide—aroma precursors of *Allium* vegetables. *J. Agric. Food Chem.* 47:1132–1138.

Kumazawa, K., Masuda, H. (1999). Identification of potent odorants in Japanese green tea (Sen-cha). *J. Agric. Food Chem.* 47:5169–5172.

Kumazawa, K., Masuda, H. (2002). Identification of potent odorants in different green tea varieties using flavor dilution technique. *J. Agric. Food Chem.* 50:5660–5663.

Kumazawa, K., Harada, Y., Masuda, H., Kato, T. (2000a). *Butanethiol Derivative as Additive to Tea Beverage*. Japan, Patent JP3026436.

Kumazawa, K., Harada, Y., Masuda, H., Kato, T. (2000b). *Mercapto-Pentanone Derivative as Additive to Tea Beverage*. Japan, Patent JP3023437.

Kuo, M.-C., Ho, C.-T. (1992). Volatile constituents of the distilled oils of Welsh onions (*Allium fistulosum* L. variety maichuon) and scallions (*Allium fistulosum* L. variety caespitosum). *J. Agric. Food Chem.* 40:111–117.

Kuroiwa, Y., Hashimoto, N., Hashimoto, H., Kokubo, E., Nakagawa, K. (1967). Factors essential for the evolution of sunstruck flavor. In: American Society of Brewing Chemists.

Lamparsky, D., Schudel, P. (1971a). *p*-Menthane-8-thiol-3-one, a new component of buchu leaf oil. *Tetrahedron Lett.* 36:3323–3326.

Lamparsky, D., Schudel, P. (1971b). *p-Menthane-8-Thiol-3-One*. Switzerland, Patent DE2043341.

Landy, P., Boucon, C., Kooyman, G. M., Musters, P. A. D., Rosing, E. A. E., de Joode, T., Laan, J., Haring, P. G. M. (2002). Sensory and chemical changes in tomato sauces during storage. *J. Agric. Food Chem.* 50:3262–3271.

Lavigne, V., Dubourdieu, D. (1996). Mise en évidence et interprétation de l'aptitude des lies à éliminer certains thiols volatils du vin. *J. Int. Sci. Vigne Vin.* 30:201–204.

Lavigne, V., Boidron, J. N., Dubourdieu, D. (1993). Dosage des composés soufrés volatils légers dans les vins par chromatographie en phase gazeuse et photométrie de flamme. *J. Int. Sci. Vigne Vin.* 27:1–12.

Lavigne, V., Henry, R., Dubourdieu, D. (1998). Identification et dosage de composés soufrés intervenant dans l'arôme ''grille'' des vins. *Sci. Aliments* 18:175–191.

Le Quere, J.-L., Latrasse, A. (1990). Composition of the essential oils of blackcurrant buds (*Ribes nigrum* L.). *J. Agric. Food Chem.* 38:3–10.

Lecanu, L., Ducruet, V., Jouquant, C., Gratadoux, J.-J., Feigenbaum, A. (2002). Optimization of headspace solid-phase microextraction (SPME) for the odor analysis of surface-ripened cheese. *J. Agric. Food Chem.* 50:3810–3817.

Lermusieau, G., Bulens, M., Collin, S. (2001). Use of GC-olfactometry to identify the hop aromatic compounds in beer. *J. Agric. Food Chem.* 49:3867–3874.

Liebich, H. M., Douglas, D. R., Bayer, E., Zlatkis, A. (1970). The volatile flavor components of cheddar cheese. *J. Chromatogr. Sci.* 8:355–359.

Lin, J., Rouseff, R. L., Barros, S., Naim, M. (2002). Aroma composition changes in early season grapefruit juice produced from thermal concentration. *J. Agric. Food Chem.* 50:813–819.

Liu, T.-T., Yang, T.-S., Wu, C.-M. (2001). Changes of volatiles in soy sauce-stewed pork during cold storage and reheating. *J. Sci. Food Agric.* 81:1547–1552.

Lopez, R., Ferreira, V., Hernandez, P., Cacho, J. F. (1999). Identification of impact odorants of young red wines made with Merlot, Cabernet Sauvignon and Grenache grape varieties: a comparative study. *J. Sci. Food Agric.* 79:1461–1467.

Lüntzel, C. S., Widder, S., Pickenhagen, W. (2000a). *Preparation of Mercaptoalkanals and Acetals Thereof as Parfuming and Flavoring Agents*. Germany, Patent EP982296.

Lüntzel, C. S., Widder, S., Pickenhagen, W., Vossing, T. (2000b). *Reductive Preparation of 2-Mercapto-2-Methyl-1-Pentanol and its Use as Perfuming or Flavoring Agent*. Germany, Patent EP982294.

Lüntzel, C. S., Widder, S., Vössing, T., Pickenhagen, W. (2000c). Enantioselective syntheses and sensory properties of the 3-mercapto-2-methylpentanols. *J. Agric. Food Chem.* 48:424–427.

Macku, C., Shibamoto, T. (1991). Volatile sulfur-containing compounds generated from the thermal interaction of corn oil and cysteine. *J. Agric. Food Chem.* 39:1987–1989.

MacLeod, G., Forcen, M. (1992). Analysis of volatile components derived from the carob bean Ceratonia siliqua. *Phytochemistry* 31:3113–3119.

Madruga, M. S., Mottram, D. S. (1995). The effect of pH on the formation of Maillard-derived aroma volatiles using cooked meat system. *J. Sci. Food Agric.* 68:305–310.

Madruga, M. S., Mottram, D. S. (1998). The effect of pH on the formation of volatile compounds produced by heating a model system containing 5′-Imp and cysteine. *J. Braz. Chem. Soc.* 9:261–271.

Maga, J. A. (1975). The role of sulfur compounds in food flavor. Part II: thiophenes. *Crit. Rev. Food Sci. Nutr.*, 6:241–270.

Maga, J. A. (1976). The role of sulfur compounds in food flavor. Part III: thiols. *Crit. Rev. Food Sci. Nutr.*, 7:147–192.

Mändli, H., Anderegg, P. (1991). Zur lichtstabilität von bier. In: EBC Congress. Lisbon.

Manning, D. J., Price, J. C. (1977). Cheddar cheese aroma—the effect of selectively removing specific classes of compounds from cheese headspace. *J. Dairy Res.* 44:357–361.

Marais, J. (1994). Sauvignon blanc cultivar aroma—a review. *S. Afr. Enol. Vitic.* 15:41–45.

Marais, J., Swart, E. (1999). Sensory impact of 2-methoxy-3-isobutylpyrazine and 4-mercapto-4-methylpentan-2-one added to a neutral Sauvignon blanc wine. *S. Afr. J. Enol. Vitic.* 20:77–79.

Marchand, S., de Revel, G., Bertrand, A. (2000). Approaches to wine aroma: release of aroma compounds from reactions between cysteine and carbonyl compounds in wine. *J. Agric. Food Chem.* 48:4890–4895.

Masanetz, C., Blank, I., Grosch, W. (1995). Synthesis of [2H6]-3-mercapto-3-methylbutyl formate to be used as internal standard in quantification assays. *Flavour Fragr. J.* 10:9–14.

Masneuf, I., Naumov, G. I., Murat, M.-L., Glumineau, N., Dubourdieu, D. (1999). Des hybrides saccharomyces cerevisiae/saccharomyces bayanus pour la vinification des vins de sauvignon. In: 6° Symposium International d'Oenologie.

Masneuf, I., Murat, M.-L., Naumov, G. I., Tominaga, T., Dubourdieu, D. (2002). Hybrids *Saccharomyces cerevisiae* x *Saccharomyces bayanus* var. *uvarum* having a high liberating abibilty of some sulfur varietal aromas of *Vitis vinifera* Sauvignon blanc wines. *J. Int. Sci. Vigne Vin.* 36:205–212.

Masuda, H., Kikuiri, H., Mihara, S. (1988). *Preparation of 1-p-Menthene-8-Thiol as Flavor Component*. Japan, Patent JP63201162.

Masuda, H., Kikuiri, H., Shishido, Y., Mihara, S. (1989). *Perfume Compositions Containing 4-Mercapto-4-Methylpentan-2-One*. Japan, Patent JP01102019.

Masuda, S., Kikuchi, K., Harayama, K. (2000). Determination of lightstruck character in beer by gas chromatography–mass spectrometry. *Am. Soc. Brew. Chem.* 58:152–154.

Mateo, J., Zumalacarregui, J. M. (1996). Volatile compounds in Chorizo and their changes during ripening. *Meat Science* 44:255–273.

Maujean, A. (2001). The chemistry of sulphur in musts and wines. *J. Int. Sci. Vigne Vin.* 35:171–194.

Meilgaard, M. C. (1975). Flavor chemistry of beer. Part II: flavor and threshold of 239 aroma volatiles. *MBAA Tech. Quat.* 12:151–168.

Menneer, I., Molzahn, S. W., Quain, D. E. (2001). *Development of Light-Struck Flavor in Beer*. Luxembourg, Patent WO2001092459.

Mestres, M., Busto, O., Guasch, J. (1997). Chromatographic analysis of volatile sulphur compounds in wines using the static headspace technique with flame photometric detection. *J. Chromatgra. A* 773:261–269.

Mestres, M., Marti, M. P., Busto, O., Guasch, J. (1999). Simultaneous analysis of thiols, sulphides and disulphides in wine aroma by headspace solid-phase microextraction-gas chromatography. *J. Chromatogr. A* 849:293–297.

Mestres, M., Busto, O., Guasch, J. (2000). Analysis of organic sulfur compounds in wine aroma. *J. Chromatogr. A.* 881:569–581.

Mestres, M., Busto, O., Guasch, J. (2002). Application of headspace solid-phase microextraction to the determination of sulphur compounds with low volatility in wines. *J. Chromatogr. A* 945:211–219.

Meynier, A., Mottram, D. S. (1995). The effect of pH on the formation of volatile compounds in meat-related model systems. *Food Chem.* 52:361–366.

Milo, C., Reineccius, G. A. (1997). Identification and quantification of potent odorants in regular-fat and low-fat mild cheddar cheese. *J. Agric. Food Chem.* 45:3590–3594.

Morel, M. H., Bonicel, J., Micard, V., Guilbert, S. (2000). Protein insolubilization and thiol oxidation in sulfite-treated wheat gluten films during aging at various temperatures and relative humidities. *J. Agric. Food Chem.* 48:186–192.

Mottram, D. S. (1985). The effect of cooking conditions on the formation of volatile heterocyclic compounds in pork. *J. Sci. Food Agric.* 36:377–382.

Mottram, D. S., Edwards, R. A. (1983). The role of triglycerides and phospholipids in the aroma of cooked beef. *J. Sci. Food Agric.* 34:517–522.

Mottram, D. S., Madruga, M. S. (1994). Important sulfur-containing aroma volatiles in meat. *A. C. S. Symp. Ser.* 564:180–187.
Mottram, D. S., Whitfield, F. B. (1994). Aroma volatiles from meatlike Maillard systems. *A. C. S. Symp. Ser.* 543:180–191.
Mottram, D. S., Madruga, M. S. (1995). Some novel meatlike aroma compounds from the reactions of alkanediones with hydrogen sulfide and furanthiols. *J. Agric. Food Chem.* 43:189–193.
Mottram, D. S., Whitfield, F. B. (1995a). Maillard–lipid interactions in nonaqueous systems: volatiles from the reaction of cysteine and ribose with phosphatidylcholine. *J. Agric. Food Chem.* 43:1302–1306.
Mottram, D. S., Whitfield, F. B. (1995b). Volatile compounds from the reaction of cysteine, ribose, and phospholipid in low-moisture systems. *J. Agric. Food Chem.* 43:984–988.
Mottram, D. S., Nobrega, I. C. C. (2002). Formation of sulfur aroma compounds in reaction mixtures containing cysteine and three different forms of ribose. *J. Agric. Food Chem.* 50:4080–4086.
Mottram, D. S., SzaumanSzumski, C., Dodson, A. (1996). Interaction of thiol and disulfide flavor compounds with food components. *J. Agric. Food Chem.* 44:2349–2351.
Mottram, D. S., Nobrega, I. C. C., Dodson, A. T. (1998). Extraction of thiol and disulfide aroma compounds from food systems. *A. C. S. Symp. Ser.* 705:78–84.
Mulders, E. J. (1973). Volatile components from the non-enzymic browning reaction of the cysteine/cystine-ribose-system. *Z. Lebensm. Unters. Forsch.* 152:193–201.
Münch, P., Schieberle, P. (1998). Quantitative studies on the formation of key odorants in thermally treated yeast extracts using stable isotope dilution assays. *J. Agric. Food Chem.* 46:4695–4701.
Münch, P., Hofmann, T., Schieberle, P. (1997). Comparison of key odorants generated by thermal treatment of commercial and self-prepared yeast extracts: influence of the amino acid composition on odorant formation. *J. Agric. Food Chem.* 45:1338–1344.
Murat, M.-L., Tominaga, T., Dubourdieu, D. (2001a). Assessing the aromatic potential of Cabernet Sauvignon and Merlot musts used to produce rose wine by assaying the cysteinylated precursor of 3-mercaptohexan-1-ol. *J. Agric. Food Chem.* 49:5412–5417.
Murat, M.-L., Tominaga, T., Dubourdieu, D. (2001d). Impact of some components on Bordeaux roses and Clairets aroma. *J. Int. Sci. Vigne Vin.* 35:99–105.
Murat, M.-L., Masneuf, I., Darriet, P., Lavigne, V., Tominaga, T., Dubourdieu, D. (2001c). Effects of *Saccharomyces cerevisiae* yeast strains on the liberation of volatile thiols in Sauvignon blanc wine. *Am. J. Enol. Viticult.* 52:136–139.
Murat, M.-L., Tominaga, T., Dubourdieu, D. (2001b). Mise en évidence de composés clefs dans l'arôme des vins rosés et clairets de Bordeaux. *J. Int. Sci. Vigne Vin.* 35:99–105.
Mussinan, C. J., Katz, I. (1973). Isolation and identification of some sulphur chemicals present in two model systems approximating cooked meat. *J. Agric. Food Chem.* 21:43–45.
Nagami, K., Takahashi, T., Nakatani, K., Kumada, J. (1980). Hydrogen sulfide in brewing. *MBAA Tech. Quart.* 17:64–68.
Naim, M., Wainish, S., Zehavi, U., Peleg, H., Rouseff, R. L., Nagy, S. (1993). Inhibition by thiol compounds of off-flavor formation in stored orange juice 1.

Effect of L-cysteine and *N*-acetyl-L-cysteine on 2,5-dimethyl-4-hydroxy-3(2H)-furanone formation. *J. Agric. Food Chem.* 41:1355–1358.

Naim, M., Zehavi, U., Zuker, I., Rouseff, R. L., Nagy, S. (1994). Effect of L-cysteine and *N*-acetyl-L-cysteine on off-flavor formation in stored citrus products. *A.C.S. Symp. Ser.* 564:80–89.

Naim, M., Schutz, O., Zehavi, U., Rouseff, R. L., Haleva-Toledo, E. (1997). Effects of orange juice fortification with thiols on *p*-vinylguaiacol formation, ascorbic-acid degradation, browning, and acceptance during pasteurization and storage under moderate conditions. *J. Agric. Food Chem.* 45:1861–1867.

Naim, M., Rouseff, R. L., Zehavi, U., Schutz, O., Halvera-Toledo, E. (1998). Chemical and sensory analysis of off-flavors in citrus products. *A. C. S. Symp. Ser.* 705:303–319.

Nedjma, M. (1997). Influence of complex media composition, Cognac's brandy, or Cognac, on the gas chromatography analysis of volatile sulfur compounds—preliminary results of the matrix effect. *Am. J. Enol. Viticult.* 48:333–338.

Nedjma, M., Maujean, A. (1995). Comportement chimique du sulfure d'hydrogène dans les vins et les spiritueux en relation avec l'effet de matrice observé par chromatographie en phase gazeuse. In: 5° Symposium International d'Oenologie, Bordeaux, Editions Tec & Doc, Paris.

Negishi, O., Ozawa, T. (2000). Inhibition of enzymatic browning and protection of sulfhydryl enzymes by thiol compounds. *Phytochemistry* 54:481–487.

Negishi, O., Negishi, Y., Ozawa, T. (2002). Effects of food materials on removal of *Allium*-specific volatile sulfur compounds. *J. Agric. Food Chem.* 50:3856–3861.

Node, M., Kumar, K., Nishide, K., Ohsugi, S.-I., Miyamoto, T. (2001). Odorless substitutes for foul-smelling thiols: syntheses and applications. *Tetrahedron Lett.* 42:9207–9210.

Nonaka, M., Black, D. R., Pippen, E. L. (1967). Gas chromatographic and mass spectral analyses of cooked chicken meat volatiles. *J. Agric. Food Chem.* 15:713–717.

Obenland, D. M., Aung, L. H. (1996). Cystine lyase activity and anaerobically-induced sulfur gas emission from broccoli florets. *Phyton* 58:147–156.

Olsen, A. (1988). Onion-like off-flavour in beer: isolation and identification of the culprits. *Carlsberg Res. Commun.* 53:1–9.

Ono, B.-I., Kijima, K., Inoue, T., Miyoshi, S.-I., Matsuda, A., Shinoda, S. (1994). Purification and properties of *Saccharomyces cerevisiae* cystathionine β-synthase. *Yeast* 10:333–339.

Ono, B.-I., Kijima, K., Ishii, N., Kawato, T., Matsuda, A., Paszewski, A., Shinoda, S. (1996). Regulation of sulphate assimilation in *Saccharomyces cerevisiae*. *Yeast* 12:1153–1162.

Park, S. K., Boulton, R. B., Noble, A. C. (2000). Automated HPLC analysis of glutathione and thiol-containing compounds in grape juice and wine using pre-column derivatization with fluorescence detection. *Food Chem.* 68:475–480.

Peppard, T. I., Laws, D. R. J. (1979). Hop derived sulphur compounds and their effect on beer flavour. In: EBC Congress. West Berlin.

Peyrot des Gachons, C., Tominaga, T., Dubourdieu, D. (1999). Acquisition récentes sur les arômes et les précurseurs d'arômes du sauvignon. In: 6 Symposium International d'Oenologie, Bordeaux, Editions Tec & Doc, Paris.

Peyrot des Gachons, C., Tominaga, T., Dubourdieu, D. (2000). Measuring the aromatic potential of *Vitis vinifera* L. cv. Sauvignon blanc grapes by assaying

S-cysteine conjugates, precursors of the volatile thiols responsible for their varietal aroma. *J. Agric. Food Chem.* 48:3387–3391.

Peyrot des Gachons, C., Tominaga, T., Dubourdieu, D. (2002a). Localisation of *S*-cysteine conjugates in the berry: effect of skin contact on aromatic potential of *Vitis vinifera* L. cv. Sauvignon blanc must. *Am. J. Enol. Viticult.* 53:144–146.

Peyrot des Gachons, C., Tominaga, T., Dubourdieu, D. (2002b). Sulfur aroma precursor present in S-glutathione conjuguate form: identification of *S*-3-(hexan-1-ol)-glutathione in must from *Vitis vinifera* L. cv. Sauvignon Blanc. *J. Agric. Food Chem.* 50:4076–4079.

Polak, E., Fetison, G., Fombon, A.-M., Skalli, A. (1988). Structure–odor relationships for ''catty''-smelling mercapto compounds in humans. *J. Agric. Food Chem.* 36:355–359.

Price, S. G., Menneer, I. (2000). *An Alcoholic Beverage Dispensing Apparatus with Addition of Flavoring or Other Property Modifier Using a Gas*. United Kingdom, Patent GB2340415.

Pripis-Nicolau, L., de Revel, G., Bertrand, A. (1999). Les composés dicarbonylés et carbonylés du vin: précurseurs possibles d'arômes. In: 6° Symposium International d'Oenologie, Bordeaux, Editions Tec & Doc, Paris.

Pripis-Nicolau, L., de Revel, G., Bertrand, A., Maujean, A. (2000). Formation of flavor components by the reaction of amino acid and carbonyl compounds in mild conditions. *J. Agric. Food Chem.* 48:3761–3766.

Qvist, I. H., von Sydow, E. C. F. (1974). Unconventional proteins as aroma precursors. Chemical analysis of the volatile compounds in heated soy, casein, and fish protein model systems. *J. Agric. Food Chem.* 22:1077–1084.

Rankine, B. C. (1963). Nature, origin and prevention of hydrogen sulphide aroma in wines. *J. Sci. Food Agric.* 14:79–91.

Rankine, B. C. (1968). The importance of yeast in determining the composition and quality of wines. *Vitis* 7:22–49.

Rauhut, D. (1993). Wine microbiology and biotechnology. Yeasts-production of sulfur compounds. In: Graham, F., Harwood, H. S. C., eds.

Rauhut, D., Kürbel, H., Dittrich, H. H., Grossman, M. (1996). Properties and differences of commercial yeast strains with respect to their formation of sulfur compounds. *Vitic. Enol. Sci.* 51:187–192.

Reiners, J., Grosch, W. (1998). Odorants of virgin olive oils with different flavor profiles. *J. Agric. Food Chem.* 46:2754–2763.

Reiners, J., Grosch, W. (1999). Concentration of 4-methoxy-2-methyl-2-butanethiol in Spanish virgin olive oils. *Food Chem.* 64:45–47.

Rigaud, J., Etiévant, P., Henry, R., Latrasse, A. (1986). Le méthoxy-4 méthyl-2 butanethiol-2, un constituant majeur de l'arôme du bourgeon de cassis (*Ribes nigrum* L.). *Sci. Aliments* 6:213–220.

Rohrbach, M. S., Humphries, B. A., Yost, F. J., Rhodes, W. G., Boatman, S., Hiskey, R. G., Harrison, J. H. (1973). The reaction of 4,4′-bis-dimethylaminodiphenylcarbinol with the sulfhydryl group. *Ann. Biochem.* 52:127–142.

Sakuma, S., Rikimaru, Y., Kobayashi, K., Kowaka, M. (1991). Sunstruck flavor formation in beer. *Am. Soc. Brew. Chem.* 49:142–145.

Sanz, C., Maeztu, L., Zapelena, M. J., Bello, J., Cid, C. (2002). Profiles of volatile compounds and sensory analysis of three blends of coffee: influence of different proportions of Arabica and Robusta and influence of roasting coffee with sugar. *J. Sci. Food Agric.* 82:840–847.

Scanlan, R. A., Kayser, S. G., Libbey, L. M., Morgan, M. E. (1973). Identification of volatile compounds from heated L-cysteine-hydrochloride/D-glucose. *J. Agric. Food Chem.* 21:673–675.

Schieberle, P. (1991a). Primary odorants in popcorn. *J. Agric. Food Chem.* 39:1141–1144.

Schieberle, P. (1991b). Primary odorants of pale lager beer. Differences to other beers and changes during storage. *Z. Lebensm. Unters. Forsch.* 193:558–565.

Schieberle, P. (1996). Odour-active compounds in moderately roasted sesame. *Food Chem.* 55:145–152.

Schieberle, P., Hofmann, T. (1998). Characterization of key odorants in dry-heated cysteine-carbohydrate mixtures: comparison with aqueous reaction systems. *A.C.S. Symp. Ser.* 705:320–330.

Schulz, H., Krüger, H., Liebmann, J., Peterka, H. (1998). Distribution of volatile sulfur compounds in an interspecific hybrid between onion (*Allium* cepa L.) and leek (*Allium porrum* L.). *J. Agric. Food Chem.* 46:5220–5224.

Schutte, L. (1971). One-step synthesis of dithiohemiacetals, a new class of compounds. *Tetrahedron Lett.* 25:2321–2322.

Schutte, L., Koenders, E. B. (1972). Components contributing to beef flavor. Natural precursors of 1-methylthio-ethanethiol. *J. Agric. Food Chem.* 20:181–184.

Seaton, J. C., Suggett, A., Moir, M. (1981). The role of sulphur compounds in beer flavour. In: EBC Congress. Copenhagen.

Segal, W., Starkey, R. L. (1969). Microbial decomposition of methionine and identity of the resulting sulfur products. *J. Bacteriol.* 98:908–913.

Semmelroch, P., Grosch, W. (1995). Analysis of roasted coffee powders and brews by gas chromatography-olfactometry of headspace samples. *Lebensm.-Wiss. u.-Technol.* 28:310–313.

Semmelroch, P., Grosch, W. (1996). Studies on character impact odorants of coffee brews. *J. Agric. Food Chem.* 44:537–543.

Semmelroch, P., Laskawy, G., Blank, I., Grosch, W. (1995). Determination of potent odourants in roasted coffee by stable isotope dilution assays. *Flavour Fragr. J.* 10:1–7.

Senter, S. D., Arnold, J. W., Chew, V. (2000). APC values and volatile compounds formed in commercially processed, raw chicken parts during storage at 4 and 13°C and under simulated temperature abuse conditions. *J. Sci. Food Agric.* 80:1559–1564.

Shankaranarayana, M. L., Raghavan, B., Abraham, K. O., Natarajan, C. P. (1982). *Food Flavours. Sulphur Compounds in Flavours.* Oxford: Elsevier Scientific.

Shaw, P. E., Ammons, J. M., Braman, R. S. (1980). Volatile sulfur compounds in fresh orange and grapefruit juices: identification, quantification, and possible importance to juice flavor. *J. Agric. Food Chem.* 28:778–781.

Shibamoto, T. (1977). Formation of sulfur- and nitrogen-containing compounds from the reaction of furfural with hydrogen sulfide and ammonia. *J. Agric. Food Chem.* 25:206–208.

Shibamoto, T., Russell, G. F. (1976). Study of meat volatiles associated with aroma generated in a D-glucose-hydrogen sulfide-ammonia model system. *J. Agric. Food Chem.* 24:843–846.

Shu, C.-K., Hagedorn, M. L., Mookherjee, B. D., Ho, C.-T. (1985a). pH effect on the volatile components in the thermal degradation of cysteine. *J. Agric. Food Chem.* 33:442–446.

Shu, C.-K., Hagedorn, M. L., Mookherjee, B. D., Ho, C.-T. (1985b). Two novel 2-hydroxy-3(2H)-thiophenones from the reaction between cysteine and 2,5-dimethyl-4-hydroxy-3(2H)-furanone. *J. Agric. Food Chem.* 33:638–641.

Shu, C.-K., Hagedorn, M. L., Ho, C.-T. (1986). Two novel thiophenes identified from the reaction between cysteine and 2,5-dimethyl-4-hydroxy-3(2H)-furanone. *J. Agric. Food Chem.* 34:344–346.

Smith, F. W., Hawkesford, M. J., Prosser, I. M., Clarkson, D. T. (1995). Isolation of cDNA from *Saccharomyces cerevisiae* that encodes a high affinity sulphate transporter at the plasma membrane. *Mol. Gen. Genet.* 247:709–715.

Soltoft, M. (1988). Flavour active sulphur compounds in beer. *Brygmesteren* 2:18–24.

Spencer, R. (1969). Catty taints in foods. *Food Technol.* 23:1372–1373.

Spinnler, H. E., Bonnarme, P. (2002). Biochemical routes used by micro-organisms to produce sulfur flavour compounds. In: Weurman Flavour Research Symposium. Beaunes.

Spiropoulos, A., Bisson, L. F. (2000). MET17 and hydrogen sulfide formation in *Saccharomyces cerevisiae*. *Appl. Environ. Microbiol.* 66:4421–4426.

Stoffelsma, J., Pijpker, J. (1973). *Odorous Mercaptoalcohols and Their Esters*. Germany, Patent US3970689.

Stratford, M., Rose, A. H. (1985). Hydrogen sulphide production from sulphite by *Saccharomyces cerevisiae*. *J. Gen. Microbiol.* 131:1417–1424.

Sundt, F., Willhalm, B., Chappaz, R., Ohloff, G. (1971). Das organoleptische prinzip von cassis-—flavor in buccublätteröl. *Helv. Chim. Acta* 54:1801–1805.

Tai, C.-Y., Ho, C.-T. (1997). Influence of cysteine oxidation on thermal formation of Maillard aromas. *J. Agric. Food Chem.* 45:3586–3589.

Takabe, K., Katagiri, T., Tanaka, J. (1970). Photodimerization of prenyl mercaptan. *Tetrahedron Lett.* 55:4805–4806.

Thiel, M., Asinger, F., Trümpler, G. (1958). Die synthese von dihydro-metathiazinen-Δ^3-durch einwirkung von gasförmigem ammoniak und oxogruppen enthaltenden verbindungen auf β-mercaptoketones II. *Liebigs Ann. Chem.* 619:137–141.

Thomas, D., Barbey, R., Henry, D., Surdin-Kerjan, Y. (1992). Physiological analysis of mutants of *Saccharomyces cerevisiae* impaired in sulphate assimilation. *J. Gen. Microbiol.* 138:2021–2028.

Thomas, D., Barbey, R., Surdin-Kerjan, Y. (1990). Gene–enzyme relationship in the sulfate assimilation pathway of *Saccharomyces cerevisiae*. *J. Biol. Chem.* 265:15518–15524.

Thorne, R. S. W. (1966). The contribution of yeast to beer flavor. *MBAA Tech. Quat.* 3:160–168.

Tominaga, T. (1998). Recherches sur l'arôme variétal des vins de *Vitis vinifera* L. cv. sauvignon blanc et sa genèse à partir de précurseurs inodores du raisin. *Faculté D'oenologie*. Bordeaux: Université Victor Segalen Bordeaux 2.

Tominaga, T., Dubourdieu, D. (1997). Identification of 4-mercapto-4-methylpentan-2-one from box tree (*Buxus sempervirens* L.) and broom (*Sarothamnus scoparius* (L.) Koch.). *Flavour Fragr. J.* 12:373–376.

Tominaga, T., Dubourdieu, D. (2000). Identification of cysteinylated aroma precursors of certain volatile thiols in passion fruit juice. *J. Agric. Food Chem.* 48:2874–2876.

Tominaga, T., Masneuf, I., Dubourdieu, D. (1995). A S-cysteine conjugate, precursor of aroma of white Sauvignon. *J. Int. Sci. Vigne Vin.* 29:227–232.

Tominaga, T., Darriet, P., Dubourdieu, D. (1996). Identification of 3-mercaptohexyl acetate in Sauvignon wine, a powerful aromatic compound exhibiting box-tree odor. *Vitis* 35:207–210.

Tominaga, T., Furrer, A., Henry, R., Dubourdieu, D. (1998a). Identification of new volatile thiols in the aroma of *Vitis vinifera* L. var. Sauvignon blanc wines. *Flavour Fragr. J.* 13:159–162.

Tominaga, T., Murat, M.-L., Dubourdieu, D. (1998b). Development of a method for analysing the volatile thiols involved in the characteristic aroma of wines made from *Vitis vinifera* L. cv. Sauvignon blanc. *J. Agric. Food Chem.* 46:1044–1048.

Tominaga, T., Peyrot des Gachons, C., Dubourdieu, D. (1998c). A new type of flavor precursors in *Vitis vinifera* L. cv. Sauvignon blanc: *S*-cysteine conjugates. *J. Agric. Food Chem.* 46:5215–5219.

Tominaga, T., Baltenweck-Guyot, R., Peyrot des Gachons, C., Dubourdieu, D. (2000a). Contribution of volatile thiols to the aromas of white wines made from several *Vitis vinifera* grape varieties. *Am. J. Enol. Viticult.* 51:178–181.

Tominaga, T., Blanchard, L., Darriet, P., Dubourdieu, D. (2000b). A powerful aromatic volatile thiol, 2-furanmethanethiol, exhibiting roast coffee aroma in wines made from several *Vitis vinifera* grape varieties. *J. Agric. Food Chem.* 48:1799–1802.

Tominaga, T., Guimbertau, G., Dubourdieu, D. (2003a). Contribution of benzenemethanethiol to smoky aroma of certain *Vitis vinifera* L. wines. *J. Agric. Food Chem.* 51:1373–1376.

Tominaga, T., Guimbertau, G., Dubourdieu, D. (2003b). Role of certain volatile thiols in the bouquet of aged Champagne wines. *J. Agric. Food Chem.* 51:1016–1020.

Tressl, R., Silwar, R. (1981). Investigation of sulfur-containing components in roasted coffee. *J. Agric. Food Chem.* 29:1078–1082.

Tressl, R., Kersten, E., Nittka, C., Rewicki, D. (1994). Formation of sulfur-containing flavor compounds from [^{13}C]-labeled sugars, cysteine, and methionine. *A. C. S. Symp. Ser.* 564:224–235.

Tulio, A. Z., Yamanaka, H., Ueda, Y., Imahori, Y. (2002). Formation of methanethiol and dimethyl disulfide in crushed tissues of broccoli florets and their inhibition by freeze-thawing. *J. Agric. Food Chem.* 50:1502–1507.

Umano, K., Hagi, Y., Nakahara, K., Shyoji, A., Shibamoto, T. (1995). Volatile chemicals formed in the headspace of a heated D-glucose/L-cysteine Maillard model system. *J. Agric. Food Chem.* 43:2212–2218.

van de Waal, M., Niclass, Y., Snowden, R. L., Bernardinelli, G., Escher, S. (2002). 1-Methoxyhexane-3-thiol, a powerful odorant of clary sage (*Salvia sclarea* L.). *Helv. Chim. Acta* 85:1246–1260.

van den Ouweland, G. A. M., Peer, H. G. (1975). Components contributing to beef flavor. Volatile compounds produced by the reaction of 4-hydroxy-5-methyl-3(2H)-furanone and its thio analog with hydrogen sulfide. *J. Agric. Food Chem.* 23:501–505.

van Seeventer, P. B., Weenen, H., Winkel, C., Kerler, J. (2001). Stability of thiols in an aqueous process flavoring. *J. Agric. Food Chem.* 49:4292–4295.

Vermeulen, C., Collin, S. (2002a). Sulphur compounds: synthesis and detection. In: J. De Clerck Chair X. Leuven.

Vermeulen, C., Collin, S. (2002b). Synthesis and sensorial properties of mercaptoaldehydes. *J. Agric. Food Chem.* 50:5654–5659.

Vermeulen, C., Collin, S. (2003a). Combinatorial synthesis and sensorial properties of 21 mercapto esters. *J. Agric. Food Chem* 51:3618–3622.

Vermeulen, C., Pellaud, J., Gijs, L., Collin, S. (2001). Combinatorial synthesis and sensorial properties of polyfunctional thiols. *J. Agric. Food Chem.* 49:5445–5449.

Vermeulen, C., Guyot-Declerck, C., Collin, S. (2003b). Combinatorial synthesis and sensorial properties of mercapto primary alcohols and analogues. *J. Agric. Food Chem.* 51:3623–3628.

Voldrich, M., Dupont, D., Dobias, J., Philippon, J. (1995). HPLC determination of thiol-containing anti-browning additives in fruit and vegetable products. *Lebensm.-Wiss. u.-Technol.* 28:213–217.

Wainwright, T. (1970). Hydrogen sulfide production by yeast under conditions of methionine, pantothenate, or vitamin B_6 deficiency. *J. Gen. Microbiol.* 61:107–119.

Wainwright, T. (1971). Origin and control of undesirable sulphur compounds in beer. In: EBC Congress. Estoril.

Walker, M. D. (1991). Formation and fate of sulphur volatiles in brewing. In: EBC Congress. Lisbon.

Walker, M. D. (1992). Estimation of volatile sulphur compounds in beer. *J. Inst. Brew.* 98:283–287.

Walker, M. D. (1995). The influence of metal ions on concentrations of flavour-active sulphur compounds measured in beer using dynamic headspace sampling. *J. Sci. Food Agric.* 67:25–28.

Walker, N. J., Gray, I. K. (1970). The glucosinolate of land cress (*Coronopus didymus*) and its enzymatic degradation products as precursors of off-flavor in milk—a review. *J. Agric. Food Chem.* 18:346–352.

Walker, M. D., Simpson, W. J. (1993). Production of volatile sulphur compounds by ale and lager brewing strains of *Saccharomyces cerevisiae*. *Lett. Appl. Microbiol.* 16:40–43.

Wasserman, A. E. (1972). Thermally produced flavor components in the aroma of meat and poultry. *J. Agric. Food Chem.* 20:737–741.

Weber, B., Haag, H.-P., Mosandl, A. (1992). Stereoisomere aromastoffe. LIX. 3-Mercaptohexyl und 3-methylthiohexylalkanoate—struktur und eigenschaften der enantiomeren. *Z. Lebensm. Unters. Forsch.* 195:426–428.

Weber, B., Dietrich, A., Maas, B., Marx, A., Olk, J., Mosandl, A. (1994). Stereoisomeric flavour compounds. LXVI. Enantiomeric distribution of the chiral sulphur-containing alcohols in yellow and purple passion fruits. *Z. Lebensm. Unters. Forsch.* 199:48–50.

Weber, B., Mass, B., Mosandl, A. (1995). Stereoisomeric flavor compounds. 72. Stereoisomeric distribution of some chiral sulfur-containing trace components of yellow passion fruits. *J. Agric. Food Chem.* 43:2438–2441.

Weenen, H., Koolhaas, W. E., Apriyantono, A. (1996). Sulfur-containing volatiles of durian fruits (*Durio zibethinus* Murr.). *J. Agric. Food Chem.* 44:3291–3293.

Werkhoff, P., Emberger, R., Güntert, M., Köpsel, M. (1989). Isolation and characterization of volatile sulfur-containing meat flavor components in model systems. *A. C. S. Symp. Ser.* 409:460–478.
Werkhoff, P., Brüning, J., Emberger, R., Güntert, M., Köpsel, M., Kuhn, W., Surburg, H. (1990). Isolation and characterization of volatile sulfur-containing meat flavor components in model systems. *J. Agric. Food Chem.* 38:777–791.
Werkhoff, P., Brüning, J., Güntert, M., Kaulen, J., Krammer, G., Sommer, H. (1996). Potent mercapto/methylthio-substituted aldehydes and ketones in cooked beef liver. *Adv. Food Sci.* 18:19–27.
Werkhoff, P., Güntert, M., Krammer, G., Sommer, H., Kaulen, J. (1998). Vacuum headspace method in aroma research: flavor chemistry of yellow passion fruits. *J. Agric. Food Chem.* 46:1076–1093.
Whitfield, F. B., Mottram, D. S. (1999). Investigation of the reaction between 4-hydroxy-5-methyl-3(2H)-furanone and cysteine or hydrogen sulfide at pH 4.5. *J. Agric. Food Chem.* 47:1626–1634.
Whitfield, F. B., Mottram, D. S. (2001). Heterocyclic volatiles formed by heating cysteine or hydrogen sufide with 4-hydroxy-5-methyl-3(2H)-furanone at pH 6.5. *J. Agric. Food Chem.* 49:816–822.
Whitfield, F. B., Mottram, D. S., Brock, S., Puckey, J. D., Salter, L. J. (1988). Effect of phospholipid on the formation of volatile heterocyclic compounds in heated aqueous solutions of amino acids and ribose. *J. Sci. Food Agric.* 42:261–272.
Widder, S., Dittner, T., Sabater-Lüntzel, C., Pickenhagen, W., Vollhardt, J. (1999). *3-Mercapto-2-alkyl-alkan-1-ols and their Use as Perfuming and Flavoring Agents*. Germany, Patent EP924198.
Widder, S., Lüntzel, C. S., Dittner, T., Pickenhagen, W. (2000). 3-Mercapto-2-methylpentan-1-ol, a new powerful aroma compound. *J. Agric. Food Chem.* 48:418–423.
Wilson, R. A., Katz, I. (1972). Review of literature on chicken flavor and report of isolation of several new chicken flavor components from aqueous cooked chicken broth. *J. Agric. Food Chem.* 20:741–747.
Wilson, R. A., Mussinan, C. J., Katz, I., Sanderson, A. (1973). Isolation and identification of some sulfur chemicals present in pressure-cooked beef. *J. Agric. Food Chem.* 21:873–876.
Wilson, R. J. H., Roberts, T., Smith, R. J., Biendl, M. (2001). Improving hop utilization and flavor control through the use of pre-isomerized products in the brewery kettle. *MBAA Tech. Quat.* 38:11–21.
Wilson, R. J. H., Gimbel, A. M., Roberts, T. R., Smith, R. J. (2002). *Rho-Iso-Alpha Acid Hop Products and Applications in Brewing*. Patent WO2002002497.
Withycombe, D. A., Mussinan, C. J. (1988). Identification of 2-methyl-3-furanthiol in the steam distillate from canned tuna fish. *J. Food Sci.* 53:658.
Wu, Y.-F. G., Cadwallader, K. R. (2002). Characterization of the aroma of a meat like process flavoring from soybean-based enzyme-hydrolyzed vegetable protein. *J. Agric. Food Chem.* 50:2900–2907.
Yanagawa, H., Kato, T., Kitahara, Y. (1972). Asparagusic acid, dihydroasparagusic acid and *S*-acetyldihydroasparagusic acid, a new plant growth inhibitor in etiolated young *Asparagus officinalis*. *Tetrahedron Lett.* 25:2549–2552.

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Yeo, H., Shibamoto, T. (1991). Effects of moisture content on the Maillard browning model system upon microwave irridiation. *J. Agric. Food Chem.* 39:1860–1862.

Zhang, Y., Ho, C.-T. (1991). Formation of meatlike aroma compounds from thermal reaction of inosine 5′-monophosphate with cysteine and glutathione. *J. Agric. Food Chem.* 39:1145–1148.

Zheng, Y., Ho, C.-T. (1994). Kinetics of the release of hydrogen sulfide from cystein and glutathione during thermal treatment. *A.C.S. Symp. Ser.* 564:138–146.

Zheng, Y., Brown, S., Ledig, W. O., Mussinan, C., Ho, C.-T. (1997). Formation of sulfur-containing flavor compounds from reactions of furaneol and cysteine, glutathione, hydrogen sulfide and alanine/hydrogen sulfide. *J. Agric. Food Chem.* 45:894–897.