Thermally Induced Flavor Compounds

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Given the number of recent reviews on flavor chemistry (Acker et al., 1990; Berger, 1995; Mathlouthi et al., 1993; Schab and Crowder, 1995; Shallenberger, 1993; Spielman and Brand, 1995), especially relative to thermally generated volatiles such as those produced via the Maillard reaction (For, 1983; Ikan, 1996; Mottram, 1994; Parliment et al., 1994; Whitfield, 1992), we have confined our review to a critique of chemical components and reactions modulating flavor, touching upon how thermally derived flavors overlap into the sphere of horticulture. Why would horticulturists be even remotely interested from a professional standpoint in the flavor of cooked products? Isn't this really the realm of food scientists or food chemists, i.e., changes in food products during or after cellular death?

Thermally generated flavors are in fact a relevant horticultural topic. First, flavors of most horticultural food products are largely generated during cooking. Vegetable crops, for example, are usually cooked before they are eaten [e.g., 370 of 390 commercially cultivated vegetable crops from around the world are routinely to intermittently

cooked (Kays and Silva Dias, 1996)], and cooking significantly alters their flavor. In addition, although fruits tend to be thought of as eaten raw, a major portion of the total production is processed (Table 1). In many cases, processing involves a thermal treatment, which alters the flavor of the final product. Therefore, a major portion of horticultural food crops are cooked and much of their final flavor is the result of cooking.

Second, the eventual cooked flavor of such products varies with the chemistry of the product and how it is handled prior to cooking. There are many examples of differences in flavor among cultivars of a particular fruit or vegetable. The basic chemistry of the fruit or

Table 1. Total U.S. production of several fruits in 1995 and their use.^z

Crop	Total production (kt)	Used fresh (%)	Processed ^y (%)
Apple (<i>Malus ×domestica</i> Borkh.)	5665.5	56.2	43.8
Cherry (sour) (<i>Prunus cerasus</i> L.)	150	0.9	99.1
Peach [<i>Prunus persica</i> (L.) Batsch.]	1119	50.9	49.1
Pear (<i>Pyrus communis</i> L.)	943.5	58.6	41.4

^z1994 data (U.S. Dept. of Agriculture, 1997).

^yCanned, dried, frozen, juiced—processes generally involving thermal treatments.

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vegetable as it arrives from the field largely dictates the subsequent flavor potential of the product. Thus, alteration of the basic flavor of a product is a plant breeding problem in that food scientists can only optimize the existing flavor potential.

Flavor perception. The sensory characteristics of foods can be loosely grouped into three categories: flavor, texture, and appearance. Flavor, in particular, plays a major role in both our selection and enjoyment of foods, and is generally considered to be the combination of taste and odor. Flavor perception can also be significantly influenced by heat, pain, and tactile sensations.

The flavor of an individual food product is derived from the collective mosaic of numerous compounds that impact odor and taste. It is important to note that a taste or odor is not an inherent property of a specific compound but is the physiological and psychological assessment of the individual sensing it. Therefore, the same compound can be perceived differently by different individuals or by the same individual at different times. Interactions among stimuli may occur at the taste bud/olfactory level or at signal processing in the brain (Thomson, 1986).

The flavor quality of food, therefore, is more than just odor and taste; it is a complex pattern that has different critical characteristics depending upon the food (Thomson, 1986). In contrast to visual or auditory sensations, flavor has a complex sensory basis involving receptors in both the oral and nasal cavities. These receptors include cells sensitive not only to taste and odor but also to pressure, touch, stretch, temperature, and pain (Moulton, 1982). Although odor and taste are well integrated in their contribution to the overall flavor, odor is often considered to play a dominant role in flavor delineation. This is, in part, due to the number of odor receptors and their ability to discriminate among odors. For example, the ability to identify the flavors of molasses, whiskey, salt, and sugar are superior with odor cues than without (Mozell et al., 1969). Thus, the uniqueness of many flavor substances appears to rely upon their ability to stimulate the olfactory organ. Because of the distinct differences between taste and odor, this review is separated into sections on taste and odor, followed by an overview of how flavor chemistry can be modified through plant breeding.

Taste. Taste is a sensation assessed through the contact of water-soluble compounds with the mouth and tongue. Four primary taste sensations are widely accepted: sweet, sour, salt, and bitter, though alkaline and metallic are considered by some as important in taste responses (Moncrieff, 1967). The sensation of taste is achieved through taste buds, which are distributed over the tongue and in certain areas of the buccal cavity. The number of taste buds in humans is estimated to be ≈ 4500 (Miller et al., 1990), with individual buds consisting of ≈ 15 to 18 receptor cells. The taste buds are located within specialized structures called papillae, found mainly on the tip, sides, and rear of the upper surface of the tongue (Thomson, 1986).

Of the primary taste sensations, the taste threshold concentration on a molar basis varies considerably (Table 2). When ranked, giving sucrose a value of 1.0, perception sensitivity proceeds from bitter > sour > sweet > salty (Pfaffmann et al., 1971). For example, quinine sulfate (bitter) can be perceived at 8×10^{-6} M while potassium chloride (salty) requires 1.7×10^{-2} M. Within categories, the threshold concentration varies among compounds (Table 2). In addition, a single

compound can elicit more than one taste sensation. Sodium chloride is sweet at low (e.g., 0.020 M), but salty at higher (0.050 M) concentrations. Such interactions can greatly complicate the quantification of taste.

Taste is dominated by sugars, acids, several amino acids, and nucleotides, salts, and a number of bitter compounds (Maga, 1990). Often these are present prior to cooking. There are, however, cases where distinct taste compounds are formed during cooking. For example, some of the Maillard reaction products impact taste. Perhaps a classic example of the synthesis of taste components upon cooking is the sweetpotato [*Ipomoea batatas* (L.) Lam.], in which a major portion of the final sugar concentration develops during exposure to high temperatures (Sun et al., 1994).

a. Sweetness. Sugars are the most widespread form of sweet compounds found in plant products, and in recent history man has selected certain species that have the ability to synthesize and store large quantities; e.g., sugar cane (*Saccharum officinarum* L.) and sugar beet (*Beta vulgaris* L. Vulgaris Group). A relatively wide range of sugars is present in plants, and the individual sugars vary substantially in both concentration and relative sweetness. The common sugars (L-form) are ranked in the following order of sweetness: fructose (1.2) > sucrose (1.0) > glucose (0.64) > galactose (0.5) > maltose (0.43) > lactose (0.33) (Shallenberger, 1993). A number of the amino acids [i.e., L forms of alanine, isoleucine, leucine, valine, serine, threonine, asparagine, glutamine, arginine, lysine, cysteine, methionine, phenylalanine, glycine (D-, L-form), tryptophan, and histidine] are also sweet (Haefeli and Glaser, 1990), the latter two in particular. Most of the D-amino acids are not sweet and, in the case of tryptophan and histidine, the taste shifts from very sweet (L-form) to bitter (D-form). Generally, the concentration of free amino acids in plants is too low to significantly impact sweetness.

In addition to sugars and amino acids, a wide range of other natural and synthetic compounds are sweet (Sardesai and Waldshan, 1991). These are typically found in either small quantities or in obscure plant species and, as a consequence, do not significantly impact the sweetness of horticultural products. The range of types of compounds that exhibit sweetness is impressive: peptides, proteins, flavanones, flavonols, dihydrochalcones, isovanillyl, sesquiterpenes, urea compounds, sulfones, and others.

The methyl ester of L-aspartyl-L-phenylalanine (aspartame) is very sweet (Mazur et al., 1969). Other synthetic peptides such as alitame [L- α -aspartyl-N-(2,2,4,4-tetramethyl-3-thietanyl)-D-alaninamid] is exceptionally sweet (i.e., 2000 times sweeter than aspartame) (Glowaky et al., 1991). The discovery of aspartame led to a greatly expanded research effort on artificial sweeteners and has resulted in several commercial products (e.g., Nutrasweet®, Sucralose®) that allow a reduction in calories while maintaining sweetness in processed foods.

Sweet compounds or compounds modulating sweetness have been isolated in a number of obscure plant species. For example, miraculin, a protein found in the berries of *Synsepalum dulcificum* (Schumacher & Thonn.) Daniell, has the unique property of being able to convert the sour taste of acids into the sensation of sweetness (Inglett, 1971; Kurihara 1971). The protein reacts with the taste buds, and at very low concentrations (i.e., 7×10^{-7} M), can render 0.02 M citric acid as sweet as 0.4 M (14%) sucrose. The duration of the effect is concentration-dependent, lasting from ≈ 20 min at low concentrations of the protein to as long as 3 h at high concentrations. Another sweet protein, monellin, found in the berries of *Dioscoreophyllum cumminsii* (Stapf.) Diels, is ≈ 1000 to 2250 times as sweet as sucrose on a weight basis (Inglett and May, 1968, 1969) or $\approx 100,000$ to 130,000 times as sweet on a molar basis (Ariyoshi et al., 1991; Kim et al., 1991). Thaumatin, a protein from the fruit of *Thaumatococcus daniellii* Benth. (van der Wel and Loeve, 1972) is $\approx 100,000$ times as sweet as sucrose on a molar basis. Phyllostulcin, an isocoumarin from the leaves of *Hydrangea macrophylla* (Thunb.) Ser., is ≈ 400 times as sweet as 3% sucrose (Yamato and Hashigaki, 1979). Several flavanones and flavonols are also sweet. For example, (+)-dihydroquercetin-3-acetate from *Tessaria dodoneifolia* (Hook. & Arn.) Cabrera. (Kingham and Soejarto, 1991) is ≈ 80 times as sweet as sucrose, and (+)-dihydroquercetin-3- α -L-rhamnosyl from *Engelhardtia chrysolepis* Hance is likewise sweet (Dick, 1981). However, in virtually all instances, sweet compounds

Table 2. Molar recognition thresholds of individual compounds and relative activity ranking of taste sensations.²

Taste	Compound	Median taste threshold (mM)	Relative activity ³
Sweet	Sucrose	17	1.0
	Sodium chloride	20	
Salty	Sodium chloride	30	0.6
	Potassium chloride	17	
Sour	Hydrochloric acid	0.09	18.8
	Acetic acid	1.8	
Bitter	Quinine sulfate	0.008	24.3
	Caffeine	0.7	

²After Pfaffmann et al. (1971).

³Activity relative to sucrose.

other than sugars are either not present or are found in sufficiently low concentrations in horticultural products to be of little importance in the overall contribution to sweetness.

Some loss in sweetness can occur as a result of thermal reactions. For example, sugars represent an essential substrate for the Maillard reaction (see below); thus, losses can occur via this mechanism. This reaction, however, occurs predominately in areas that have been largely dehydrated, such as the surface of a product. As a consequence, losses are localized and typically represent only a fraction of the total sugars present. Losses of sweetness can also occur due to leaching when the product is heated in an aqueous solution. The surface-to-volume ratio of the product, solvent volume, length of cooking, and other factors can affect losses.

In a few instances, perhaps best exemplified by the sweetpotato, a pronounced increase in sugar concentration occurs with exposure to high temperature. Starch present in the storage root is rapidly hydrolyzed during cooking by the amylase system, resulting in the formation of maltose. The reaction involves two enzymes, α -amylase [(E.C. 3.2.1.1) 1,4- α -D-glucan glucohydrolase] and β -amylase [(E.C. 3.2.1.2) 1,4- α -D-glucan maltohydrolase]. Alpha-amylase cleaves the α -(1,4)-glucosidic linkages between internal glucose molecules within amylose and amylopectin (Myrback and Neumuller, 1950), yielding dextrans and small amounts of reducing sugars, chiefly maltose. β -Amylase attacks the nonreducing end of the incompletely hydrolyzed dextrans, producing maltose and low molecular weight "limit dextrans" containing α -(1,6)-glucosidic branch points that neither enzyme can attack. Hydrolysis is extremely rapid (i.e., 10^{10} to 10^{12} times faster than hydrolysis by proton catalysis with acids) (Laszlo et al., 1978), such that one β -amylase molecule can hydrolyze 250,000 glucosidic linkages per minute (Englard and Singer, 1950; Englard et al., 1951).

The final sweetness perceived is a collective function of the amounts and types of sugars present in the raw root and the concentration of maltose formed through starch hydrolysis during cooking (Morrison et al., 1993). While maltose is distinctly less sweet than the endogenous sugars present, the volume formed results in the dominant sweet taste of the cooked product. Interestingly, maltose is the sugar form in sweetpotatoes preferred by sensory panels (Koehler and Kays, 1991).

The amount of maltose formed in sweetpotatoes during cooking is temperature-dependent. The temperature optimum is 70 to 75 °C for α -amylase (Ikemiya and Deobald, 1966) and 50 to 55 °C for β -amylase, well above the deactivation temperature for most plant enzymes. During cooking, the final sugar content increases until oven temperatures above 80 °C are reached (Sun et al., 1994) (Fig. 1A). The higher temperature optimum for the intact product reflects the rate at which the final temperature is reached. During baking, the temperature is not uniform throughout the root but progressively increases, starting at the exterior and moving inward. Thus, hydrolysis and deactivation zones shift toward the center of the organ with time. The extent of hydrolysis, hence the final intensity of sweetness, is temperature- and time-dependent. The final maltose concentration is higher if the roots are placed in a cold oven and then heated rather than being placed directly into a hot oven. In the latter scenario, the time available for hydrolysis in the reaction zone is shorter, reducing the extent of hydrolysis. A similar situation occurs when microwaves are used as the heat source. Heating occurs rapidly and throughout the root rather than progressing from the exterior to the interior (Sun et al., 1994). The final result is a much lower level of maltose in the cooked product (Fig. 1B).

Sugar formation in the sweetpotato during baking is highly cultivar-dependent, and certain sweetpotato lines have very low β -amylase activity (Morrison et al., 1993). As a consequence, sweetpotato germplasm can be separated into four general classes based upon initial sugar concentration and changes during cooking: 1) low sugars/low starch hydrolysis; 2) low sugars/high starch hydrolysis; 3) high sugars/low starch hydrolysis; and 4) high sugars/high starch hydrolysis.

b. Sourness. Organic acids are primary contributors to the sour/tart taste in fruits and, to a lesser extent, some vegetables. Organic acids commonly found in fruit are *cis*-aconitic, caffeic, chlorogenic, citramalic, citric, *p*-coumarylquinic, fumaric, galacturonic, glu-

Fig. 1. Effect of temperature on changes in levels of individual sugars in 'Jewel' sweetpotatoes (A) during baking and (B) during baking after a 2-min microwave pretreatment. (After Sun et al., 1994.)

ronic, glyceric, glycolic, glyoxylic, isocitric, lactic, malic, oxalic, oxaloacetic, α -oxoglutaric, pyruvic, quinic, shikimic, succinic, and tartaric (Ulrich, 1970). The presence or absence of a specific acid and the relative concentration when present vary widely among individual crops and cultivars within a crop. Organic acids are also significant components in vegetables and, while they generally occur in lower concentrations, may be of equal importance in flavor.

The degree of sourness of organic acids in solution is related to the hydrogen ion concentration, although sourness is not necessarily dependent upon dissociation (Beets, 1978). Sausville (1974) ranked selected organic acids relative to citric for sourness in the following order: adipic (1.10–1.15) > citric (1.0) > malic (0.89–0.94) > tartaric (0.80–0.85) > fumaric (0.67–0.72).

In addition to the organic acids, other plant constituents can contribute to the sensation of sourness. The amino acids aspartic and glutamic are sour (Haefeli and Glaser, 1990; Schiffman et al., 1981), a sensation that is transferred to peptides in which they are components. For example, leucyl-dipeptides, which are typically bitter, are sour when aspartic or glutamic acid is substituted (Ishibashi et al., 1987).

The organic acid concentration in sweetpotato remains essentially unchanged during baking, indicating that the participation of organic acids in thermally induced reactions is not quantitatively significant (Wang and Kays, personal communication). However, since organic acids are water-soluble, the method of cooking can have an effect on the final concentration because losses may occur due to leaching during boiling. Minor losses can also occur through volatilization.

c. Saltiness. Substances that taste salty, e.g., sodium and potassium chlorides, typically dissociate in solution. A salty taste is a common denominator among the halide (Cl^- , Br^- , I^-) salts of sodium. Saltiness is also conferred by the metal salts of organic acids, the most common

being acetic, citric, malic, and tartaric. Interestingly, dilute solutions of Na and K chloride taste sweet. Sodium chloride first tastes slightly sweet at a concentration of 0.01 M and progresses to strongly sweet at 0.03 M, making the transition to salty-sweet at 0.04 M, with higher concentrations being salty (Skramlik, 1926). Several synthetic peptides are also salty (Tada et al., 1984).

In general, saltiness is conferred by sodium and potassium chloride, which have recognition thresholds of 0.03 and 0.017 M, respectively (Table 2). Certain vegetable crops, especially breeding lines, can be salty. For example, several sweetpotato lines were characterized as salty (McLaurin and Kays, 1992). Sodium replacement for potassium fertilization in some crops has been advocated; however, carryover effects on saltiness have not been widely studied. For example, when 75% or 100% of the KCl used for cassava (*Manihot esculenta* Crantz) was replaced with NaCl, the cooked product had higher sweetness scores; however, alterations in saltiness were not indicated (Sudharmai Devi and Padmaja, 1996).

Thermal reactions occurring during processing or cooking have little impact on salts present within the tissue, unless cooking occurs in an aqueous medium that allows leaching of salts. Typically, however, salt is added to most vegetables during and/or after cooking, indicating that excessive saltiness is seldom a problem.

d. Bitterness. Bitter compounds are present in many horticultural crops (Rouseff, 1990a). Generally, they are considered undesirable in a food product, often indicating toxicity. Some exceptions are radicchio (*Cichorium intybus* L.) and the bitter melon (*Momordica charantia* L.), in which bitterness is considered desirable (Kays and Hayes, 1978). Bitter compounds may be present in both the raw material and in the final product. Some initially nonbitter products become bitter with processing, while some bitter products become less bitter with aging (Fenwick et al., 1990; Herrmann, 1972a, 1972b; Oberdieck, 1977; Rouseff, 1990b). In some instances, thermal reactions induce the formation or modulate the concentration of bitter compounds.

Bitterness is detected on the back of the tongue and palate and in the pharynx (Henkin and Christiansen, 1967); consequently, many foods do not taste bitter until swallowed and the intensity is frequently strongest as an aftertaste. Humans are very sensitive to low levels (i.e., a few parts per million) of certain bitter compounds, with the lower detection limits varying with the compound and the individual.

A wide range of naturally occurring bitter compounds are found in plants, and these compounds vary widely in molecular size, functional groups present, and manner of expression of bitterness. Examples are: the cucurbitacins (oxygenated tetracyclic triterpenes), of which ≈ 20 have been identified in the Cucurbitaceae (Guha and Sen, 1975; Hutt and Herrington, 1985); polyphenols, alkaloids, saponins, and furanoid norditerpenes in the Dioscoreaceae (Crockill, 1948; Ida et al., 1978; Kawasaki et al., 1968; Martin and Ruberte, 1975; Webster et al., 1984); glycoalkaloids such as α -solanine, α -chaconine (Zitnak and Filadelfi, 1985), and tomatine (Pribela and Danisova-Pikulikova, 1973; Pribela and Pikulikova, 1971) in the Solanaceae; 6-methoxymellein (Sondheimer, 1957) and 6-methoxymellein-8-O-glucoside (Carlton et al., 1961; Chalutz et al., 1969) in carrots (*Daucus carota* L.); sesquiterpene lactones, lactucin, and lactucopicrin in lettuce (*Lactuca sativa* L.) (Bachelor and Ito, 1973; Barton and Narayanan, 1958; Michl and Hogenauer, 1960) and chicory (*Cichorium intybus* L.), with the coumarins aesculetin, aesculin, and cichoriin also contributing to the bitterness in the latter (Head and Robertson, 1939; Leclercq, 1984); asparagospinin I in asparagus (*Asparagus officinalis* L.) (Kawano et al., 1977); and ipomeamarone in the sweetpotato (Uritani et al., 1980).

As mentioned above, bitterness can be induced via thermal reactions (Maga, 1990). Processing can result in the synthesis of 1,2,4-trihydroxy-*n*-heptadeca-16-ene and 1-acetoxy-2,4-dihydroxy-*n*-heptadeca-16-ene in avocado (*Persea americana* Miller) (Ben-Et et al., 1973) and 2-pyrrolidone-5-carboxylic acid in beetroot (*Beta vulgaris* L.) and several other vegetables (Lee et al., 1971; Mahdi et al., 1961). In citrus juice, bitterness is the result of thermally accelerated closure of lactone rings.

Proteins can be converted to bitter compounds upon heating. The taste threshold for bitterness varies from 0.005 g·L⁻¹ for heated gluten to 5 g·L⁻¹ for gelatin (Jugel et al., 1976). A number of Maillard reaction

products, e.g., 2-furfuryl, 2-furaldehyde, 5-hydroxymethyl-2-furaldehyde, are also bitter (For, 1983; Shibamoto, 1983). If proline is one of the reactants in the Maillard reaction, the chances of a bitter compound being formed is substantially increased (Shigematsu et al., 1975). Tressl et al. (1985) list a wide assortment of bitter flavors formed through reaction of proline with Maillard reaction products.

Given the wide range of bitter compounds formed via thermal reactions, preharvest and processing factors collectively must be monitored to assure a high-quality end product.

Odor. Volatile compounds are the second important component of flavor. Volatiles, which make up the aroma of foods, are extremely important in what is perceived as flavor, lending to the tremendous diversity in flavors that can be achieved. Cooking generally substantially alters the characteristic aroma from that of the raw product. The degree of alteration is a function of variables related to heating (e.g., intensity, duration, method) and the initial chemical composition of the product. Cooking causes a dramatic and extremely complex series of reactions, resulting in a myriad of new volatiles, many of which have a direct impact on the product's aroma.

In contrast to the four basic taste sensations, our level of sensitivity to odors is remarkable. Humans can discriminate over 10,000 distinct odors. In addition, human olfaction is exceptionally sensitive, capable of detecting very low concentrations of odorants. For example, a single molecule of butane-1-thiol may stimulate a single olfactory receptor in humans (De Vries and Stuver, 1960). Human odor thresholds for anethol, citral, methyl salicylate, and safrol are markedly lower than those of a gas chromatograph (Kendall and Nielson, 1964). The differential in sensitivity between taste and odor is illustrated by ethyl alcohol, for which the taste threshold is 130 mg·L⁻¹ of water vs. an odor threshold of only 4 mg·L⁻¹ of air (Margalith, 1981).

The odor of a compound perceived can vary, not only between individuals, but with the same individual over time, the hormonal and nutritional status of the individual, and his/her degree of hunger. For example, an orange [*Citrus sinensis* (L.) Osbeck] may be perceived as having a pleasant odor; however, within an hour of ingesting 100 g of glucose in water, the same odor was considered unpleasant (Cabanac, 1971).

a. Sources of thermally induced volatiles. There are three primary sources of thermally induced aroma compounds: 1) volatilization of endogenous pools of flavor components found in the raw product; 2) volatile compounds synthesized directly in response to high temperatures; and 3) compounds requiring enzymatic and thermal components for their synthesis. In the first case, the aroma perceived upon heating typically is significantly shifted because of high temperature volatilization of compounds of low volatility at room temperature. Thus, changes in the volatile profile do not necessarily require de novo synthesis, and these compounds can significantly alter the final volatile profile. The latter two sources of thermally induced volatiles will be the focus of the remainder of this section.

During cooking and processing, the Maillard reaction between reducing sugars and amino acids (or another source of an amino group) is a primary pathway involved in the formation of flavor volatiles. The Maillard reaction does not require high temperatures. For example, Maillard reaction products have been found in seeds of radish (*Raphanus sativum* L.) and barley (*Hordeum* sp.) ≈ 1500 years old (Evershed et al., 1997). The reaction rate, however, increases markedly with the high temperatures associated with cooking, and the nature of the volatiles formed is temperature-dependent. In addition, the reactions occur most frequently in areas of the product that have been dehydrated, such as near the surface.

The first step in the Maillard reaction involves Schiff base formation between the carbonyl group of a reducing sugar and the free amino group of an amino acid, peptide, or protein (Fig. 2). The Schiff base then cyclizes to yield a N-substituted aldosylamine that is converted to the 1-amino-1-deoxy-2-ketone (Amadori product) by the acid-catalyzed Amadori rearrangement (Fig. 2A). When a ketose, rather than an aldose, sugar is involved, a ketosylamine is formed that undergoes Heyns rearrangement to form a 2-amino-2-deoxyaldose (Heyns product) (Fig. 2B). Amadori/Heyns products do not contribute to flavor directly, but are important precursor compounds. They are thermally unstable and undergo dehydration and deamination reactions to give

Fig. 2. Maillard reaction pathway for the formation of (A) Amadori and (B) Heyns intermediates through the interaction of reducing sugars and amino compounds and their subsequent decomposition. For pentoses - R' = CH₂OH and R* = H; for hexoses R' = CHO-CH₂OH and R* = CH₃. (After Hodge, 1953 and Mottram, 1994.)

Table 3. Examples of volatile aroma compounds.^{z,y}

Class	Basic Structure	Example	(Odor)
Furans			2-furaldehyde (sweet)
Furanones			4-hydroxy-2,5-dimethyl-3(2H)-furanone (sweet, cotton candy)
Pyranones			2-methyl-3-hydroxy-4H-pyran-4-one (sweet, caramel)
Pyrroles			2-acetyl-5-chloropyrrole (almond)
Pyridines			2-pentyl-pyridine (green pepper)
Pyrimidines			4,6-dimethyl-pyrimidine (roasted, nut-like)
Pyrazines			2,5-dimethyl-3-ethyl-pyrazine (earthy, baked potato)
Thiophenes			5-methyl-2-thiophene-carbaldehyde (cherry-like)
Dihydro-thiophenes			2-methyl-2,3-dihydrothiophene (cabbage-like)
Oxazoles			4,5-dimethyloxazole (green, sweet, vegetable)
Oxazolines			4,5-dipropyl-2-isopropyl-3-oxazoline (banana)
Thiazoles			4-butyl-5-ethylthiazole (bell pepper)
Thiazolines			2,4-trimethyl-3-thiazoline (nutty, onion-like)
Aldehydes		CH ₃ CHO	ethanal (green, sweet)
Ketones		CH ₃ COCOC ₂ H ₅	2,3-pentanedione (nily-buttery)
Cyclopentan-ones			5-imino-2-methyl-1-cyclopenten-1-ol (cooked rice)
Non-cyclic sulfur compounds		CH ₃ SH	methanethiol (cooked cabbage)

^zAfter For (1983).^yLatin binomials: green pepper (*Capsicum annuum* L. Grossum Group); cabbage (*Brassica oleracea* L. var. *capitata* L.); onion (*Allium cepa* L. Cepa Group); rice (*Oryza sativa* L.).Table 4. Variation in aroma within the pyrazines.^z

Compound	Aroma description
2-Methylpyrazine	Nutty, roasted
2-Ethylpyrazine	Buttery, rum
2-Propylpyrazine	Green, vegetable
2-Isobutylpyrazine	Green, fruity
2,5-Dimethylpyrazine	Grassy
2,6-Dimethylpyrazine	Fried potatoes
2-Ethyl-3-methylpyrazine	Raw potato, earthy, nutty
2-Ethyl-6-vinylpyrazine	Buttery, baked potato
2-Methyl-6-propylpyrazine	Burnt, butterscotch
2-Isobutyl-3-methylpyrazine	Bell pepper
2,3,4-Trimethylpyrazine	Baked potato, roasted peanut
2,3-Dimethyl-5-ethylpyrazine	Nutty, roasted
2,3-Dimethyl-5-butylpyrazine	Sweet, earthy
2,3-Dimethyl-5-pentylpyrazine	Sweet, smoked, caramel-like
2,3-Dimethyl-5-isopentylpyrazine	Caramel-like, coffee, sweet
2,3-Dimethyl-5-(1-methylbutyl)pyrazine	Honey-like, sweet
2,3-Dimethyl-5-(2,2-dimethylpropyl)pyrazine	Brown sugar-like
2,3-Dimethyl-5-(1,5-dimethyl-4-hexenyl)pyrazine	Roasted nut
2,3,5,6-Tetramethylpyrazine	Fermented soybeans ^y
2-Acetylpyrazine	Popcorn ^x , nutty
6-Acetyl-2-methylpyrazine	Popcorn ^x
2-Ethyl-3-methoxypyrazine	Raw potato, earthy
2-Propyl-3-methoxypyrazine	Bell pepper
3-Isopropyl-2-methoxypyrazine	Earthy, bellpepper, raw potato
2-Methoxy-3-isopropyl-5-methylpyrazine	Green bean ^w -like
2-Isobutyl-3-methoxy-3-methylpyrazine	Licorice ^v -woody
5-(2-Methylpentyl)-2-methoxy-3-methylpyrazine	Burdock ^u
2-Isobutyl-3-methoxy-5,6-dimethylpyrazine	Minty-camphoraceous
2-Ethoxy-3-ethylpyrazine	Raw potato
3-Butoxy-3-methylpyrazine	Floral
3-Butoxy-3-propylpyrazine	Medicinal
2-Methylthio-3-methylpyrazine	Cooked meat
5-Methylthio-2-methylpyrazine	Meaty
2-Methylthio-3-isobutylpyrazine	Roasted peanuts
2-Methyl-3-(furfurylthio)pyrazine	Coffee

^zAfter For (1983).^y*Glycine max* (L.) Merr.^x*Zea mays* L. subsp. *mays*.^w*Phaseolus vulgaris* L.^v*Glycyrrhiza glabra* L.^u*Arctium lappa* L.Table 5. Major volatile compounds formed when tristerin is heated to 192 °C in air.^z

Alcohols	Acids
Octanol	Hexanoic acid
Nonanol	Pentanoic acid
Decanol	Butanoic acid
γ-Lactones	Aldehydes
4-Butanolide	Hexanal
4-Pentanolide	Hepanal
4-Heptanolide	Octanal
Hydrocarbons	Methyl ketones
Heptadecane	2-Heptanone
Nonane	2-Nonanone
Decane	2-Decanone

^zAfter Selke et al. (1975).

numerous rearrangement and degradation products. Often these products react with other compounds in that particular product to yield a diverse assortment of volatile compounds. Thus, the steps in the Maillard reaction can be summarized as: 1) formation of a glycosylamine and its subsequent rearrangement; 2) degradation to furan derivatives, reductones, and other carbonyl compounds; and 3) conversion of furan and carbonyl intermediates to aroma compounds (Mottram, 1994)—usually via reaction with other intermediates, such as amino compounds or amino acid or lipid degradation products.

An extremely diverse array of volatile compounds is synthesized by way of the Maillard reaction, and these can be classified according to their primary precursor: 1) simple sugar degradation/fragmentation products, such as furans, pyrones (e.g., maltol), cyclopentenones, carbonyl compounds, and acids; 2) simple amino acid degradation products, such as aldehydes, sulfur compounds such as hydrogen sulfides and methanethiol, and nitrogen compounds such as ammonia and amines; and 3) volatiles produced by further reactions, such as pyrroles, pyridines, pyrazines, imidazoles, oxazoles, compounds from aldol condensations, thiazoles, thiophenes, di- and trithiolanes, di- and trithianes, and furanthiols (Nursten, 1980). Some of the classes of volatiles formed via thermal reactions are presented in Table 3. Note the diversity of classes of compounds and odors. The odors cited in the table are simply examples and are not indicative of the odor of all compounds in the class.

Diversity in odor within a class is illustrated by the pyrazines (Table 4). By simply altering side groups, the aroma goes from buttery to potato (*Solanum tuberosum* L.) to floral to meaty. Note that some individual compounds have more than one aroma descriptor listed. This is in part due to variation among individuals in odor discrimination, and descriptors such as “baked potato” generally are comprised of multiple compounds. While one individual may detect a “baked potato aroma,” another may associate it with a different odor.

The Maillard reaction has a number of effects on the product in addition to the synthesis of flavor volatiles. It also results in: color formation (i.e., browning reactions); nutritional losses because of the utilization of amino acids, ascorbic acid and other compounds that participate in the reaction; the formation of possible toxic compounds such as imidazoles and methylglyoxal, which are carcinogenic; and the synthesis of antioxidants.

Lipid degradation also results in numerous odorous aliphatic compounds having both positive and negative impacts on food quality; hence, lipids are also a significant source of aroma compounds. The compounds formed through autoxidation reactions give rise to unpleasant aromas, such as the rancid aroma of old or improperly stored oil seed crops (St. Angelo, 1996). The impact of these volatiles is illustrated by the fact that one seldom needs to place a rancid peanut (*Arachis hypogaea* L.) in the mouth before the brain emits a rejection signal. While autoxidation reactions are extremely important in flavor (both positive and negative), we will focus on the formation of volatiles from lipids by thermally mediated reactions.

Lipids comprise a significant portion of horticultural crops, ranging, for example, from 74% of the fresh weight (fwt) in seeds of some pecan [*Carya illinoensis* (Wang.) K. Koch] cultivars to 0.4% of the fwt in banana (*Musa paradisiaca* L. var. *paradisiaca*) fruits, and are primary components of the cell's membrane system. Hence, all living cells have a small but significant lipid component. Given the tremendous diversity in the chemistry of plant cells and the logarithmic increase in complexity as these compounds undergo high temperature degradative and synthetic reactions, many investigators have utilized model systems (Whitfield, 1992). Such systems have afforded the most desirable means of understanding reactions that can occur in intact systems. For example, on heating tristearin, a triacylglycerol in which the three acyl side chains are identical (octadecanoic acid), to 192 °C in the presence of air, 18 major compounds were formed (Table 5) of which aldehydes and methyl ketones comprised 36.1% and 38.4%, respectively (Selke et al., 1975). Because many fatty acids are components of triacylglycerols [for example, 22 fatty acids are found in the pecan (Senter and Horvat, 1976, 1977)], and because altering the glycerol carbon position of only two fatty acids gives six possible lipids, tristearin represents a very simple model. In addition to triacylglycerols, plant products contain a wide assortment of phospho-

Table 6. Volatile heterocyclic compounds formed during the thermal interaction of 2,4-decadienal with either cysteine or glutathione.^a

Compounds	Quantities produced ^b (mg·mol ⁻¹)	
	Cysteine	Glutathione
<i>Furans</i>		
2-Butylfuran	12.8	3.1
2-Pentylfuran	6.4	trace
2-Hexylfuran	trace	12.8
<i>Thiophenes</i>		
Thiophene	3.5	7.2
2-Methylthiophene	---	34.4
Tetrahydrothiophen-3-one	10.5	---
2-Propylthiophene	---	2.3
Methylpropylthiophene	---	3.8
2-Butylthiophene	57.2	56.6
3-Methylthiophene-2-carboxaldehyde	29.8	---
Methylbutylthiophene	---	4.6
2-Pentylthiophene	13.1	14.6
Methylpentylthiophene ¹	18.7	46.5
Methylpentylthiophene ¹	17.5	---
2-Hexylthiophene	42.0	87.8
2-Heptylthiophene	1.8	---
3-(1-Hexanoyl)thiophene	9.3	60.8
Formylpentylthiophene	15.6	21.0
<i>Thiazoles</i>		
Thiazole	25.6	16.0
2-Methylthiazole	---	15.8
5-Methylthiazole	---	14.5
3-Methylisothiazole	2.0	---
2-Acetylthiazole	2.2	3.8
<i>Other sulfur-containing compounds</i>		
Butanediol	6.2	---
2-Methyl-1,3-dithiolane	5.0	---
3,4,5,6-Tetrahydro-2,4,6-trimethyl-2H-thiadiazine	828.5	---
3,5-Dimethyl-1,2,4-trithiolane ²	122.8	162.1
3,5-Dimethyl-1,2,4-trithiolane ²	18.2	206.4
5,6-Dihydro-2,4,6-trimethyl-4H-1,3,5-dithiazine	284.2	---
3-Methyl-1,2,4-trithiane	42.5	1.6
3,6-Dimethyl-1,2,4,5-tetrathiane	---	59.2
3,6-Dimethyl-1,2,4,5-tetrathiane	---	1.1
4,6-Dimethyl-1,2,3,5-tetrathiane	---	76.1
1,2,5-Trithiepane	trace	---
3,5,7-Trimethyl-1,2,4,6-tetrathiepane ³	---	6.4
3,5,7-Trimethyl-1,2,4,6-tetrathiepane ³	---	1.6
5,6-Dihydro-2,4-dimethyl-6-pentyl-4H-1,3,5-dithiazine	18.9	---
5,6-Dihydro-4,6-dimethyl-2-pentyl-4H-1,3,5-dithiazine	28.7	---
3-Methyl-5-pentyl-1,2,4-trithiolane	14.3	---
4,7-Dimethyl-1,2,3,5,6-pentathiepane ⁴	6.7	---
4,7-Dimethyl-1,2,3,5,6-pentathiepane ⁴	6.3	---
5,6-Dihydro-6-pentyl-2-propyl-4-methyl-4H-1,3,5-dithiazine	2.9	---
3-Methyl-6-pentyl-1,2,4,5-tetrathiane ⁵	---	6.4
3-Methyl-6-pentyl-1,2,4,5-tetrathiane ⁵	---	3.1
5,6-Dihydro-4-butyl-6-pentyl-2-methyl-4H-1,3,5-dithiazine	0.9	---
<i>Pyridines</i>		
1-(2-Pyridinyl)pentanone	5.1	6.8
2-Pentylpyridine	501.5	1219.0

^aAfter Zhang and Ho (1989).

^bMilligrams of volatile compound per mol of respective amino acid.

^cCompounds with the same superscript (^{1, 2, 3, 4, 5}) are isomers.

lipids and glycolipids.

Progressing to the next level of complexity in a model system by reacting a lipid with an amino acid, an even more diverse array of compounds is formed (Table 6) (Zhang and Ho, 1989). Altering the amino acid (cysteine vs. glutathione) distinctly changes the qualitative and quantitative profile of compounds. Thus, in the highly complex systems found in fruits and vegetables, with numerous lipids and hundreds of potential reactants such as those formed in the Maillard

Table 7. Volatile thermolytic products identified from sweetpotatoes, sweetpotato fractions, and sugar standards.^z

Compounds	Sweetpotato		Fractions			Sugars	
	Baked	Thermolysis	Insoluble	Nonpolar	Polar	Maltose	Standard ^y
Acetol	+ ^x	+	+	+	+	+	+
Acetic acid	—	+	+	—	—	—	—
Furyl aldehyde	+	+	+	+	+	+	+
2-Acetylfuran	+	+	+	—	—	+	+
Benzaldehyde	+	+	+	—	—	—	—
5-Methyl-2-furfural	+	+	+	+	+	+	+
Phenylacetaldehyde	+	—	—	—	—	—	—
Furfuryl alcohol	+	+	+	+	+	—	+
3,4-Dihydropyran	+	+	+	—	—	—	+
β-Ionone	—	—	—	+	—	—	—
3-Hydroxy-2-methyl-4-pyrone (maltol)	+	+	+	—	—	—	—
Unknown	+	+	+	—	—	+	+
2-Hydroxyacetyl furan ^w	+	+	+	—	—	—	+
5-Hydroxy-methyl-2-furfural	+	+	+	—	+	+	+

^zAfter Sun et al. (1995).^yA sugar standard of glucose, fructose, sucrose, and maltose (12, 12, 43, and 36 g, respectively, in 10 mL distilled water) in the same ratio as in baked sweetpotatoes.^xPresent (+), not detectable (—).^wTentatively identified using mass spectral data.

reaction, hundreds of potential volatiles can be formed. In roasted coffee (*Coffea arabica* L.) beans, >800 volatiles have been identified, a majority of which are formed by Maillard reactions (Holscher and Steinhart, 1994). Another example is the baked potato, in which over 70 compounds have been identified, with critical flavor components being a mixture of pyrazines, thiazoles, and oxazoles (Buttery et al., 1973; Coleman et al., 1981; Pareles and Chang, 1974).

Likewise, the sweetpotato also presents a complex mixture of thermally induced volatile compounds. Precursors of critical volatiles were identified by fractionating the root tissue into polar (methanol-soluble), nonpolar (methylene chloride-soluble) and insoluble fractions (Sun et al., 1995). The fractions were then heated (200 °C) and the volatiles produced identified (Table 7). Initial reactions in the formation of critical volatiles occurred in the insoluble fraction, comprised of starch, cellulose, hemicellulose, proteins and other insoluble high molecular weight components. One character-impact volatile (3-hydroxy-2-methyl-4-pyrone) forms via the Maillard reaction; however, synthesis first involves the activity of α- and β-amylase, which hydrolyze starch to maltose. Maltose is subsequently degraded to monosaccharides that undergo the Maillard reaction. Hence, the synthesis of critical volatiles in the sweetpotato involves both enzymatic and thermal reactions.

b. Factors affecting thermally generated flavors. A wide range of factors can modulate the profile of volatiles formed. In general these can be separated into two categories: cooking-related and product-related. With cooking, initial and final temperature, length of the cooking cycle, moisture conditions, method of heat introduction, and other factors are critical in determining the final flavor of the product.

The effect of temperature on the synthesis of maltose during cooking is illustrated in Fig. 1. The amylase system functions at a high temperature relative to other enzymes, most of which are denatured at lower temperatures. Heat enters the product as an inward-progressing thermal wave with the highest temperature at the outside. Maillard reactions are favored by dry conditions, hence we would anticipate that a significant portion of these aroma compounds are synthesized near the surface of the product.

The method of heat introduction is also critical. If sweetpotatoes are heated with microwaves instead of a conventional convection oven, the microwaves deactivate the amylase system. Therefore, very little maltose is formed, resulting in a pronounced shift in the aroma of the cooked product (Table 8).

Both the rate of heat introduction and the duration of thermal treatment are also critical. In the sweetpotato, rapid heating alters the formation of precursors to critical flavor compounds, in particular maltol. Likewise, the volatiles produced change with time during heating. With extended exposure, overcooked and burned flavor volatiles are eventually formed.

The cultivar used is a primary factor affecting the eventual flavor of the cooked product. Table 9 illustrates the variation in volatile

Table 8. Volatiles emanating from conventionally baked vs. microwaved 'Jewel' sweetpotatoes.

Volatile	Relative concn ^z (μg·kg ⁻¹ fresh weight)	
	Baked	Microwaved
Pyridine	1.68	0.24
1,2,4-Trimethyl benzene	0.67	0.13
3-Furaldehyde	4.81	0.01
Xylene	0.03	---
2-Furmethanol	3.84	0.48
Furfuryl alcohol	0.39	0.01
2-Acetyl furan	0.59	0.14
Benzaldehyde	0.41	0.10
5-Methyl-2-furfural	0.14	0.02
2-Pentyl furan	0.31	0.01
2,3-Pentanedione	0.18	0.04
Phenylacetaldehyde	6.27	0.04
Limonene	tr	tr
3,4-Dihydropyran	0.22	0.02
2-Acetyl pyrrole	tr	0.02
Maltol	3.70	0.04
Linalool	0.24	0.04
Isopulegone	tr	tr
Geraniol	0.20	0.01
2,4-Nonadienal	0.89	0.14
Cyclohexanol	0.49	0.04
n-Decanal	tr	---
2,2-Dimethyl-1,3-cyclohexanediol	tr	0.02
2,3-Nonadecanediol	0.73	---
2,4-Decadienal	tr	---
Octyl ketone	tr	tr
Methyl geranate	tr	tr
Germacrene D	0.28	0.06
β-Caryophyllene	tr	0.02
β-Farnesene	0.17	0.06
α-Copaene	tr	0.01
α-Bisabolene	tr	0.06
Bohlmann 176	0.16	0.06
2(4H)-Benzofuranone	0.27	0.07
β-Ionone	0.68	0.06
Nerolidol	tr	0.11
4-Decanolide	tr	---
Unknown	tr	tr
Tetradecanoic acid	0.19	0.05
Total	26.87	1.73

^zRelative concentrations were calculated from gas chromatograph (GC) peak areas relative to those of internal standard. Volatiles were collected after cooking using a purge and trap system with product held at 50 °C. Trace concentrations (tr) are <1%, based on GC peak areas; (—) = not detectable by GC or olfactory analysis. (Wang and Kays, unpublished data).

Table 9. Effect of curing on volatile constituents of two sweetpotato lines during baking.^z

Volatile compound	Relative concn (µg·kg ⁻¹ fresh wt)			
	Jewel		GA90-16	
	Noncured	Cured	Noncured	Cured
Pyridine	1.5	5.6	tr ^y	1.7
1,2,4-Cyclopentanetriol	0.6	1.2	tr	0.7
1,2,4-Trimethyl benzene	1.3	2.7 ^x	0.1	2.4 ^x
3-Furaldehyde	8.0	14.5	0.2	2.4
Xylene	tr	0.3	---	0.1
2-Furmethanol	13.1	14.1 ^x	1.5	1.8
Furfuryl alcohol	1.2	1.3	0.3	2.8
2-Acetyl furan	1.2	4.4	0.3	2.8
Benzaldehyde	1.0	2.1	tr	0.5
5-Methyl-2-furfural	0.2	0.9	---	0.7
2-Pentyl furan	0.2	1.2	---	0.1
2,3-Pentanedione	0.5	0.7	0.1	1.5
Phenylacetaldehyde	3.8	29.7 ^x	0.4	20.9 ^x
Limonene	---	tr	---	tr
3,4-Dihydropyran	0.4	2.1	tr	1.0
2-Acetyl pyrrole	0.6	0.3 ^x	tr	0.1 ^x
Maltol	12.3	30.8 ^x	0.4	0.7
Linalool	1.1	0.8	---	0.2
Isopulegone	tr	0.8	---	0.8
4,5-Dimethyl-4-hexen-3-one	tr	tr	---	tr
Geraniol	tr	0.4 ^x	---	0.1 ^x
2,4-Nonadienal	0.1	1.2	tr	---
2-Naphthalenone	1.5	1.2	---	---
Cyclohexanol	tr	5.4	---	tr
n-Decanal	---	tr ^x	---	tr ^x
2,2-Dimethyl-1,3-cyclohexanediol	tr	0.4	---	0.2
2,3-Nonadecanediol	0.2	0.5	---	2.5 ^x
2,4-Decadienal	tr	0.6 ^x	---	1.9 ^x
Octyl ketone	tr	tr	tr	0.3 ^x
Methyl geranate	tr	tr ^x	tr	tr ^x
Germacrene D	0.6	0.9	tr	0.6
β-Caryophyllene	tr	0.3	tr	0.2
Cyperene	---	---	0.4	1.8 ^x
β-Farnesene	tr	0.3	tr	0.3
α-Copaene	0.1	0.3 ^x	tr	0.2 ^x
α-Bisabolene	---	0.3	tr	0.2
Bohlmann 176	1.3	1.5	0.2	0.3
2(4H)-Benzofuranone	0.4	1.3	0.1	0.3
β-Ionone	1.3	1.6 ^x	0.5	0.8 ^x
Nerolidol	tr	0.2	tr	0.1
4-Decanolide	tr	tr	---	tr
Unknown	tr	1.0 ^x	---	0.2 ^x
Tetradecanoic acid	1.3	4.2	0.3	0.5
10-Heneicosene(c,t)	1.1	0.5	0.5	0.3
Palmitic acid	32.1	54.1	33.5	26.1
Octadecanol	2.1	2.6	1.5	1.6
1-Nonadecanol	16.5	24.0	16.2	6.0
9,12-Octadecadienoic acid	3.4	2.4	1.2	1.6
Total of identified compounds	109.0	227.9	58.4	84.3
Total of odor-active compounds	51.7	141.6	5.5	47.8

^zAfter Wang et al. (1998).^y(-) = Not detectable by gas chromatography (GC) and olfactory analysis. Trace concentrations (tr) are <1%, based on GC peak areas.^xCompounds are important contributors to odor.

profiles between two sweetpotato cultivars with distinctly different aromas. The first, 'Jewel', has the classical U.S. sweetpotato aroma with an intense sweet odor note provided largely by maltol. The second, in contrast, smells very much like a baked white potato. Hence, there are often extremely wide differences in the aroma profiles among cultivars, especially when genetic diversity within the gene pool is extreme (McLaurin and Kays, 1992).

A myriad of preharvest factors, even factors as simple as product size, can modulate the cooked flavor of horticultural products. When large sweetpotato roots are baked, the additional mass alters the thermal dynamics within the root, affecting the eventual flavor. The

Table 10. Outline of conventional selection schemes for potato and sweetpotato breeding programs.^z

Clonal population remaining (%)	Selection parameter
<i>Potato</i>	
100.0	Greenhouse screening for virus and nematode resistance
35.0	General agronomic traits
3.0	General agronomic traits and disease resistance
0.9	Yield quality, disease resistance, storability, agronomic assessment
0.4	Yield quality, disease resistance, storability, agronomic assessment
<i>Sweetpotato</i>	
100.0	Greenhouse screening for disease and nematode resistance
10.0	Field planting-evaluation for general agronomic characteristics, insect resistance, yield, root color.
1.0	Quality: fiber, absence of discoloration, flavor, general appearance after baking

^zData after Jones (personal communication) and MacKay (1987).

presence of disease, even extremely slight amounts, can also significantly alter aroma. In the sweetpotato, certain pathogens, insects, and stresses induce the synthesis of toxic furanoterpenoids, which have a major negative impact on the aroma. Other postharvest factors, such as handling, storage conditions and duration, and postharvest treatments can modulate eventual flavor of the cooked product. For example, the standard postharvest curing treatment significantly alters the aroma and taste of the sweetpotato after cooking (Wang et al., 1998) (Table 9).

Alteration of flavor thorough plant breeding. One of the real advantages of being a horticulturist is that we can implement ideas developed in the laboratory and actually see them through to a final product. Interfacing analytical techniques with plant breeding is one way to have a significant impact on flavor chemistry.

Most conventional breeding programs determine: 1) what traits are to be used in the selection process; 2) the priority that will be placed on each trait; and 3) what criteria will be used in assessment of individual traits. Typical selection programs for potatoes and sweetpotatoes are presented in Table 10. Selection generally occurs initially in the greenhouse, where a large number of clones can be tested for disease and nematode resistance, and other traits under controlled conditions. At each step in the selection protocol, clones not displaying the desired trait(s) are discarded. With each reduction in the population size, the chance of selecting previously unselected traits diminishes, because the rate of genetic gain is a function of the heritability selection intensity, degree of genetic variance in the population, amount of time per selection cycle, and the precision of measurement of the trait selected. In typical potato (MacKay, 1987) and sweetpotato (Jones, personal communication) breeding programs (Table 10), 98% to 99% of the lines are eliminated by the end of the first year. Thus screening for flavor usually occurs after a major portion of the clonal population has been discarded. The lower priority for flavor in the selection sequence stems in part from the difficulty of measuring flavor using conventional sensory analysis. A routine test can assess only five to eight samples at one sitting and due to the subjective nature of flavor analysis, reasonably large panels (i.e., > 15 individuals) are required to obtain an accurate estimate of preference. This greatly reduces the number of clones that can be screened for flavor, hence the lower priority in a selection process even though eating quality may be considered as a top priority (Martin and Jones, 1986). Thus the discrepancy between what is thought to be needed and what is actually practiced is often wide.

Using an analytical selection method (Sun et al., 1995), the number of clones that can be screened can be increased to ≈40 to 50 a day per gas chromatograph while greatly increasing precision. This allows evaluation of flavor earlier in the selection sequence. An analytical method does not, however, completely eliminate use of sensory panels, although it does allow moving large numbers of progeny through several selection cycles prior to final substantiation using conventional sensory techniques (Kays and Horvat, 1983). Use of an

analytical selection protocol requires understanding the basic chemistry of the flavor traits desired, but allows the imposition of a substantially increased selection pressure for the desired trait. Advantages of an analytical vs. a subjective approach to selection of flavor include: 1) the trait is well-defined; 2) accurate parent line selection; 3) increased sample population; 4) improved accuracy of progeny selection; 5) the ability to simultaneously select for multiple consumer groups with distinctly different flavor preferences; 6) the ability to select new, unique flavor types; 7) the potential for a centralized analytical program; and 8) a data base for future use (Kays, 1988). The approach we have taken with the sweetpotato is to: 1) identify the major positive and negative flavor components; 2) assess the range in flavor within the gene pool (McLaurin and Kays, 1992); 3) develop an analytical procedure for rapid screening of large numbers of parent lines and progeny (Sun et al., 1993); 4) characterize the chemistry of flavor preference of target consumer populations; and 5) identify desirable clones using chemical analyses interfaced with sensory analyses.

In conclusion, two critical ideas should be reiterated. First, thermally derived flavors are the norm, not the exception, for horticultural products. Secondly, we as horticulturists have the critical responsibility for creating and delivering a product to the processor or consumer that will have the desired flavor upon cooking.

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