

Rice Aroma and Flavor: A Literature Review

By Champagne, Elaine T

ABSTRACT Descriptive sensory analysis has identified over a dozen different aromas and flavors in rice. Instrumental analyses have found over 200 volatile compounds present in rice. However, after over 30 years of research, little is known about the relationships between the numerous volatile compounds and aroma/flavor. A number of oxidation products have been tagged as likely causing stale flavor. However, the amounts of oxidation products, singly or collectively, that need to be present for rice to have stale or rancid flavor have not been established. Only one compound, 2-acetyl-1-pyrroline (2-AP; popcorn aroma) has been confirmed to contribute a characteristic aroma. Furthermore, 2-AP is the only volatile compound in which the relationship between its concentration in rice and sensory intensity has been established. This article discusses the challenges of measuring aroma and flavor instrumentally and by human sensory panels and reviews research examining the effects of genetic, preharvest, and postharvest factors on volatile compound profiles and the aroma and flavor of cooked rice.

Rice is an important provider of nourishment for the world's population. Unlike most food crops, rice is generally eaten whole without seasoning, making the sensory properties of the rice grain itself important. Small variations in sensory properties, especially aroma, can make rice highly desired by or unacceptable to consumers (Yau and Liu 1999). Consequently, aroma and flavor have been rated as the major criteria for preference among consumers (Del Mundo and Juliano 1981).

There has been a quest for >30 years to understand how genetic, preharvest (e.g., environment, cultural methods), and postharvest (e.g., drying, milling, storage, cooking method) factors affect the aroma and flavor of cooked rice and to relate these effects to the numerous volatile compounds in rice. The desired outcome is to identify important marker compounds that will allow preharvest and postharvest strategies to be enacted to assure that cooked rice will have the expected aroma and flavor. Most researchers have taken the approach of correlating preharvest and postharvest variables with changes in volatile compounds and have drawn conclusions as to which compounds possibly affect aroma and flavor based on concentration or aroma value (AV). Few have conducted preference or descriptive sensory analyses with concurrent volatile analyses. The result is that, with the exception of 2-acetyl-1-pyrroline (popcorn aroma), no single marker compound has been identified to allow monitoring and control of preharvest and postharvest factors that affect aroma and flavor. This article will focus on the challenges of measuring rice aroma and flavor and using these measures to understand what effects these sensory properties in cooked rice.

ISOLATING AND QUANTIFYING VOLATILE COMPOUNDS

Methods for the determination of the volatile compounds in rice have schemes for collection, concentration, separation, and quantification. Traditional methods have involved static headspace, purge and trap, steam distillation-solvent extraction (including simultaneous distillation/extraction), and direct solvent extraction for collection/concentration (Reineccius 2006). Separation is by gas chromatography (GC) with flame ionization or mass spectrometer (MS) as detector. The GC effluent to the MS can be split with a portion going to a sniffer port for human detection. Vogue since introduction in the mid 1990s (Yang et al 1994; Steffen et al 1996) has been collection of rice volatile compounds using solid-phase microextraction (SPME) followed by GC-MS (Grimm et al 2001; Lam and Proctor 2003; Wongpornchai et al 2004; Champagne et al 2004b, 2005; Zheng et al 2007). In this technique, an inert fiber coated with an adsorbent is placed in the headspace above a rice sample and allowed to adsorb volatile compounds. The fiber containing the adsorbed volatile compounds is then thermally desorbed into a GC carrier gas flow.

The number and amount of volatile compounds isolated from rice are method dependent. In static headspace analyses using a gas-tight syringe for collection, only the most abundant volatile

compounds ($>10^{-7}$ g/L) are detectable. In purge and trap methods, the compounds with the highest vapor pressure are preferentially removed and, of these, the compounds trapped on Tenax depend on their polarity. Tenax has low adsorption capacity and a low affinity for polar compounds and a high affinity for nonpolar compounds (Reineccius 2006). In steam distillation-solvent extraction, the volatile profile obtained is influenced by volatility of the aroma compounds (initial isolation), solubility during solvent extraction of the distillate, and volatility again during the concentration of the solvent extract (Reineccius 2006). In simultaneous distillation/extraction, the prepared aroma isolate contains nearly all the volatile compounds in rice; however, their proportions may poorly represent the true profile. In direct solvent extraction, recoveries of volatile compounds depend on the solvent chosen.

The number and amount of volatile compounds isolated from rice also depend on how the sample is prepared. The volatile profile of cooked rice differs from that of uncooked rice; the profile of flour differs from that of intact grains. Higher amounts of lipid oxidation products are observed in flour compared with intact grains. This may be a matrix effect or due to accelerated oxidation. The composition of the headspace of rice can be readily changed by the addition of water and temperature. For targeted analysis, such as 2-acetyl-1-pyrroline (2-AP), the addition of a small amount of water is advantageous, whereas for other compounds the addition of water may suppress recovery (Grimm et al 2002). The addition of water can further complicate analysis because it can induce enzymatic action, leading to increases in volatile compounds.

Quantification is difficult with the described methods. In headspace methods, the data obtained reflects the amount of volatile compounds in the headspace which is influenced by the food matrix. Interactions between volatile compounds and starch matrices may increase retention (Arvisenet et al 2002; Boutboul et al 2002; Jouquand et al 2006). In particular, the linear amylose of starch is able to form inclusion complexes with a wide variety of volatile compounds that may affect the intensity of perceived aromas. Interactions of aroma compounds with lipids and proteins also affect their volatility.

Quantifying 2-AP and Distinguishing Fragrant and Nonfragrant Cultivars

The high demand for fragrant rice cultivars in markets worldwide has driven the development of methods for quantifying 2-AP and distinguishing fragrant and nonfragrant cultivars. Fragrant rice cultivars contain $<<0.04$ - 0.09 ppm of 2-AP; whereas nonfragrant cultivars have $<< 1983$). al et (Buttery ppm) (

Purge and trap (Buttery et al 1988), simultaneous steam distillation-solvent extraction (Buttery et al 1986; Lin et al 1990; Petrov et al 1996; Widjaja et al 1996; Tava and Bocchi 1999; Mahatheeranont et al 2001), microsteam distillation-solvent extraction (Tanchotikul and Hsieh 1991), direct solvent extraction (Fushimi et al 1996; Bergman et al 2000; Mahatheeranont et al 2001; Itani et al 2004), SPME (Grimm et al 2001; Wongpornchai et al 2004), and static headspace (Sriseadka et al 2006) have been used for the isolation and concentration of 2-AP from rice samples. The long extraction time in steam distillation-solvent extraction methods, and thus low sample throughput per day, makes them impractical for use in breeding programs. The extraction method developed by Bergman et al (2000) requires only 0.3 g of brown or milled rice, a 2.5 hr extraction in methylene chloride at 85°C, and a 25-min GC run allowing 50 samples to be analyzed per day. One extraction solubilized $<<80\%$ of the 2-AP with a coefficient of variation of 7.9% and standard error of 14. GC analysis had a coefficient of variation of 3.1% and a standard error of 5.0. SPME has been reported as a successful tool for screening but not for the quantitation of 2-AP in fragrant rice (Grimm et al 2001). In the Grimm et al (2001) study, SPME gave $<0.3\%$ recovery. Because of this low recovery, there was a large error associated with absolute concentrations of 2-AP in rice. The average standard deviation was 11% with white rice and 20% error with brown rice. The static headspace gas chromatography method developed by Sriseadka et al (2006) was validated for quantitative analysis of 2-AP. The most effective amount of rice sample (1 g) provided a 51% recovery. The sensitivity of the method was enhanced by using a megabore-fused silica capillary column in conjunction with a nitrogen-phosphorus detector. Method validation demonstrated 5-8000 ng of 2-AP/g of rice sample. The limit of detection was 5 ng of 2-AP and limit of quantitation was 0.01 g of brown rice. Reproducibility calculated as

intraday and interday coefficients of variation were 1.87% RSD (n = 15) and 2.85% RSD (n = 35), respectively.

Identification of the fragrance gene and a molecular marker for detecting it led to the development of a PCR assay for fragrance genotyping (Bradbury et al 2005). The allele specific amplification (ASA) technique allows discrimination between fragrant cultivars that carry the 8-bp deletion and those without. An alternative method for rapid discrimination of fragrant and nonfragrant cultivars is by SPME/MS coupled with SIMCA statistical analysis (Laguerre et al 2007). 2-AP, pyridine, 2-acetylpyrrole, and an unidentified fragment (145 m/z) contributed to the discriminating fingerprint. Laguerre et al (2007) concluded that pyridine and 2-acetyl-pyrrole may serve as indirect indicators of aroma. The odor thresholds for these compounds are too high to play significant roles in rice aroma.

Identifying Volatile Compounds Affecting Rice Aroma and Flavor

A large number of compounds contribute to the aroma and flavor of rice. However, of the >200 volatile compounds observed in rice, only a few have been identified as affecting the aroma and flavor of cooked rice. Determining which volatile compounds are responsible for the perceived aroma/flavor of rice is a difficult task. With the exception of 2-AP (popcorn aroma), no one single compound can be said to contribute a characteristic aroma. Additionally, perceived aroma/flavor is not strictly additive but may result from interactions of several volatile compounds. Several researchers (Buttery et al 1988; Jezussek et al 2002; Lam and Proctor 2003) have taken methodical approaches to determining which of the numerous volatile compounds in rice are candidates as important contributors to its aroma and flavor. Buttery et al (1988) and Lam and Proctor (2003) calculated and compared aroma values (AV) to determine which lipid oxidation products are likely contributors to off-flavor. The higher the ratio of a volatile compound concentration to its odor threshold (AV), the more probable that the compound will contribute to the overall aroma or flavor of rice. Buttery et al (1988) found that the aldehydes (E)2-nonenal (threshold [T] = 0.08 ppb) and (E,E)- 2,4-decadienal (T = 0.07 ppb) had the lowest odor threshold and, considering the amounts in rice, were considered to likely contribute to the aroma. Other aldehydes with relatively low thresholds that are also likely to contribute were (E)-2-decenal (T = 0.4 ppb), octanal (T = 0.7 ppb), nonanal (T = 1 ppb), and decanal (T = 2 ppb). Lam and Proctor (2003) concluded, based on AV, that hexanal (grassy flavor) and 2-pentylfuran (beany) probably contributed more to flavor change in milled rice early in storage rather than later. 2-Nonenal (rancid flavor) and octanal (fatty flavor) contributed more to the overall flavor of milled rice during long-term storage.

The approach of calculating and comparing AV has been extended to a screening method referred to as aroma extract dilution analysis (AEDA) in which the volatile components in serial dilutions of a rice extract are evaluated by gas chromatography/olfactometry. The greater the number of dilutions a volatile compound is sensed, the higher its dilution value (DV), which would correspond with AV. Jezussek et al (2002) used this method to identify 41 odor-active compounds in cooked brown rice. Among newly identified constituents, 2-amino acetophenone (medicinal, phenolic) had the highest DV and was concluded to be an important odorant. The previously unknown rice aroma compound 3-hydroxy-4,5-dimethyl-2(5H) furanone (Sotolon; seasoning-like) differed in DV among the cultivars. Table I lists olfactory-active volatile compounds identified in rice that may affect aroma and flavor.

Another approach for determining which volatile compounds are important contributors to aroma and flavor or serve as markers for sensory quality has been through examining how genetic, preharvest, and postharvest factors affect formation and concentration and subsequently the aroma and flavor of the rice. Following this approach, a degree of success has been achieved in determining which lipid oxidation products may be likely contributors to the off-flavor of stale rice. As discussed above, Buttery et al (1988) and Lam and Proctor (2003) identified key oxidation products based on the increase during storage and AV. However, researchers have not discerned at what level particular lipid oxidation products need to be present to result in stale aromas and flavor.

A side-by-side comparison of odor-active compounds in rice with those in other grains has not been published. Hougen et al (1971) noted that different grains commonly have similar volatile compound profiles but in different concentrations. This is observed particularly for oxidation products,

which, as in rice, are also important contributors to aroma and flavor in other grains. For example, oxidation products 1-octen-3-ol, 3-methylbutanal, 2-methylbutanal, hexanal, 2-hexenal, 2-heptenal, 2-nonenal, and decanal were identified as key aroma compounds in 12 barley cultivars based on odor thresholds in water (Cramer et al 2005). In wholemeal and white wheat flour, (E)-2-nonenal, (E,Z)- and (E,E)-2,4-decadienal, 4,5-epoxy-(E)-2-decenal, and 3-hydroxy-4,5-dimethyl-2(5H)-furanone were odor-active based on AEDA (Czerny and Schieberle 2002). Most of these compounds are also odor-active in rice. Of interest would be to determine the qualitative and quantitative composition differences in odor-active compounds that differentiate the sensory properties of rice from other grains. Such a comparison has been reported for the rye and wheat flour (Czerny and Schieberle 2002; Kirchoff and Schieberle 2002).

The search for understanding the composition of fragrant rices and how it differs from nonfragrant cultivars has been through comparisons of volatile profiles. Buttery et al (1982, 1983) reported 2-AP to be the volatile compound defining the characteristic popcorn aroma of fragrant rice. Only fragrant rice cultivars possess the genetic potential (Lorieux et al 1996; Bradbury et al 2005) for accumulating 2-AP. Hussain et al (1987) compared the volatile profiles of an aromatic Basmati rice with a nonfragrant rice. More pentadecan-2-one, hexanol, and 2-pentylfuran were found in the Basmati rice. In another comparison, Petrov et al (1996) found nine compounds to discriminate fragrant and nonfragrant rice: pentanol, hexanol, 2-AP, (E)-hept-2-enal, benzaldehyde, octanal, pentadecan-2-one, 6, 10, 14-trimethyl-pentadecan-2-one, and hexadecanol. However, based on AV, only 2-AP would be olfactory-discriminant. Widjaja et al (1996), in a comparative study of nonfragrant and fragrant rice, found nonfragrant rice contained much more n-hexanal, (E)-2-heptenal, 1-octen-3-ol, n-nonanal, (E)-2-octenal, (E)-2, (E)-4-decadienal, 2-pentylfuran, 4-vinylguaicol, and 4-vinylphenol, than the four fragrant rices. In these three studies, oxidation products were identified as discriminants. However, the preharvest and postharvest growing/handling of nonfragrant and fragrant rices were not the same for the two rice types in these studies. Therefore, the predominance of lipid oxidation products in one type may have been due to growing/handling differences and not whether or not it was fragrant. Comparison studies need to be conducted on larger sets of fragrant and nonfragrant cultivars grown under identical conditions and handled identically postharvest.

TABLE I

Olfactory-Active (AV or FD > 1) Volatile Compounds Identified in Rice That May Affect Aroma and Flavor"

A new approach was taken by Laguerre et al (2007) to identify volatile compounds that differentiate the aroma of 61 rice cultivars (29 fragrant and 32 nonfragrant). Of particular interest, was determining compounds contributing to the diversity of aroma encountered in fragrant rices. It is unlikely that 2-AP is the only compound that contributes to the unique aroma of these rices. Their method used SPME for volatile collection coupled directly with mass spectrometry with no chromatography for selection. No differentiating compounds, other than 2-AP, were found in the fingerprints with odor thresholds low enough to contribute to rice aroma.

Tava and Bocchi (1999) also observed through a comparison of fragrant cultivars that the only differences were in contents of 2AP and lipid oxidation products, with the latter being ascribed to differences in postharvest handling.

In conclusion, other than lipid oxidation products and 2-AP, researchers have not been successful in conclusively identifying specific volatile compounds or classes of compounds that contribute to other desirable or undesirable aroma or flavor attributes in rice.

SENSORY ANALYSIS OF AROMA AND FLAVOR

The aroma of rice is detected when its volatile compounds enter the nasal passage and are perceived by the millions of tiny, hair-like cilia that cover the epithelium located in the roof of the nasal cavity (Meilgaard et al 2007). The sensitivity of receptors to different volatile compounds varies over a range of $>10^{12}$ (Harper 1972; Meilgaard 1975). Generally there is only a 100-fold difference

between the threshold (minimum detectable level) and concentration that produces saturation of the receptors. A good perfumer can differentiate 150-200 odorous qualities (Meilgaard et al 2007). Rice aroma is typically described by trained panelists using a lexicon with 10-12 descriptors.

Flavor is the impression perceived through the chemical senses from a product in the mouth (Caul 1957). According to Meilgaard et al (2007), when defined in this manner, flavor includes aromatics (olfactory perceptions caused by volatile substances released from a product in the mouth through the posterior nares); tastes (gustatory perceptions [salty, sweet, sour, bitter] caused by soluble substances in the mouth); chemical feeling factors that stimulate nerve ends in the soft membranes of the buccal and nasal cavities (astringency, spice heat, cooling, bite, metallic flavor, umami taste).

The aroma and flavor of rice can be characterized and analytically measured by panelists trained in descriptive sensory analysis (Meilgaard et al 2007). Descriptive analysis is useful in evaluating sensory changes over time with respect to preharvest and postharvest conditions and shelf life (Meilgaard et al 2007). Combined use of descriptive and preference sensory panels can provide accurate assessment and identify quality characteristics desired by various markets. Descriptive scores can also be correlated to volatile compound concentrations using various statistical methods to determine which compounds are responsible for perceived aroma and flavor or serve as markers for these attributes. Some researchers have developed statistical correlations based primarily on linear regression (Bett and Boylston 1992), while others have used multivariate statistics to correlate two sets (or more) of measurements. Multivariate statistical analysis (multiple linear regression, principle component analysis, and partial least squares) allows for the integration of all the individual volatile compounds in a mixture to be related to sensory responses (Meilgaard et al 2007). The advantage of this approach is that it more accurately models the synergistic and interactive nature of flavor and nonflavor active components that produce the total sensory impression. The disadvantage is that some components may be chosen for the flavor model only because they were highly correlated but not causative agents (Nobler and Ebler 2002). To eliminate this problem, researchers have developed models from only those compounds shown to be flavor active from gas chromatography-olfactometry (GC- O) (Luning et al 1994; van Ruth and Roozen 1994).

Following the principles and concepts of descriptive sensory analysis, lexicons for aroma and flavor are developed by having a panel rigorously evaluate various rice samples to identify and describe the aroma and flavor. References are established and the panel uses them to come to consensus on the definitions of the descriptors. As described by Goodwin et al (1996), a rice aroma/ flavor lexicon was developed in the early 1990s by panelists at the Sensory Analysis Center of Kansas State University. The trained descriptive panel at the USDA ARS Southern Regional Research Center uses this lexicon to evaluate rice aroma and flavor. Similar rice lexicons were developed by Meullenet et al (1999, 2000) and Park et al (2001). Figure 1 lists the aroma and flavor descriptors, the definitions, and references as developed by Goodwin et al (1996), Meullenet et al (1999, 2000), and Park et al (2001). Other groups have developed lexicons that contain these and other descriptors. Piggott et al (1991) recruited 18 Malaysian students to develop descriptors for aroma and flavor of undermilled and well-milled rice. The resulting descriptors developed were fragrant, pungent, sour, smooth, sweet, sulphury, muddy, earthy, bread-like, hay-like, buttery, nutty, coconut, oily grassy, mouldy, and musty. The descriptive panelists trained by Yau and Liu (1999) described 11 attributes in cooked rice defined by raw and cooked grains: cold- steam bread aroma, hot-steam-bread aroma, raw-dough aroma, rice- milk aroma, corn aroma, corn-leaf aroma, pear-barley aroma, burnt aroma (dried baked rice), stale aroma (raw flour), fermented-sour aroma (fermented dough), and brown rice aroma.

Using descriptive analysis, the intensity of each descriptor is scored by the panelists. The choice of scale and references used to rate intensities is particularly important in rice, where aroma and flavor differences can be small. The spectrum descriptive analysis method uses a universal scale for all foods (Meilgaard et al 2007). Champagne et al (2004, 2005) and Meullenet et al (1999) have employed this scale in their research programs. The scale is 0-15 with flavor components of U.S. name brand products with defined intensities. For example, the soda flavor in Nabisco saltine crackers has an intensity rating of 2; the grape flavor of Kool-Aid has a rating of 4.5. With the absolute values on this scale, sensory intensities can be compared even if testing dates are spread over a long period of time. The maximum rating for rice aroma/flavor descriptors is generally >>5 when this scale is used. Most rice descriptors, however, have intensity ratings in the 1-3 range. This is problematic if panelist use

integers (whole numbers) to rate the intensities. This leads to large standard deviations, and therefore significant differences are not observed. The established universal scale does not have enough reference points between integers to allow panelists to be more precise with their ratings. Of value for the world rice community would be to develop additional low intensity references for the universal scale.

FACTORS AFFECTING RICE AROMA AND FLAVOR

Genetics

Fragrance in rice has been shown to be due to an eight-base pair deletion in exon 7 of a gene on chromosome 8 (Lorieux et al 1996; Jin et al 2003; Chen et al 2006) that encodes a putative betaine aldehyde dehydrogenase 2 (BAD2) (Bradbury et al 2005). This deletion results in a loss of function of the encoded enzyme and, consequently, 2-AP accumulates in fragrant cultivars.

Recently, Fitzgerald et al (2008) analyzed 464 samples recorded as fragrant from the Genetic Resources Center of the International Rice Research Institute (IRRI). A number of these cultivars, primarily from South and Southeast Asia, did not carry the 8-bp deletion even though they contained 2-AP. After eliminating the possibility of a Maillard reaction product, the authors concluded that the 8-bp deletion in the fragrance allele is not the only cause of aroma, and that at least one other mutation drives the accumulation of 2-AP.

Preharvest

Environment, fertilization, and cultural practices affect the amylose and protein contents of rice cultivars which in turn may influence the aroma and flavor of the cooked rice. Low protein rice samples of the same cultivar are reported to be more flavorful than those with higher protein (Juliano et al 1965). This observation was corroborated by two descriptive sensory panels (Park et al 2001; Champagne et al 2004), who found rice with lower protein content to have higher levels of desirable sweet aroma/taste and lower levels of undesirable flavor attributes. In 17 diverse cultivars grown over two crop years in one location, hay-like and sweet aromatic flavors were significantly ($P < 0.005$) correlated positively ($r = 0.53$) and negatively ($r = -0.49$), respectively, with protein content (Champagne et al 2004). In the Park et al study (2001), protein content of a short grain cultivar milled to different degrees (8- 14%) correlated highly and positively with hay-like ($r = 0.90$), puffed corn ($r = 0.94$), raw rice ($r = 0.91$), and wet cardboard ($r = 0.92$) and negatively with sweet taste ($r = -0.90$).

Other studies did not find a relationship between protein content and aroma or flavor. In a recent study by Champagne et al (2007), the aroma and flavor of five diverse cultivars grown conventionally with 50 and 100% of the typically used nitrogen rate and with chicken litter using organic management were compared. The low protein (mean 7.7% with organic management; 7.5% with 50% N rate) rice samples did not differ in aroma or flavor from those with higher protein (mean 9.2% with 100% N rate). In support of this finding, Terao et al (2005) found that growing the rice cultivar Akitakomachi under elevated CO₂ concentration decreased the protein content but did not change the sensory properties to a level that could be detected by taste panel evaluation.

Fig. 1. Descriptive sensory analysis attributes and definitions used to evaluate cooked rice aroma and flavor.

Amylose content, the most important determinant of cooked rice texture, correlated highly and negatively ($P < 0.05$) with grain flavor ($r = -0.88$) in the study of 17 diverse cultivars (Champagne et al 2004). With delay (15-day interval) in transplanting seedlings from eight cultivars, amylose content increased and protein content decreased (Akbar et al 1993). Aroma score for the cooked rice increased.

The concentration of 2-AP varies with environmental conditions. The 2-AP concentration was higher in brown rice ripened at a low temperature (day 25°C; night 20°C) than that ripened at a high temperature (day 35°C; night 30[degrees]C) in both short-grain cultivar Hieri and long-grain cultivar Sari (Itani et al 2004).

Drain and Harvest Dates

Timing of field draining and harvesting of rice with consideration of physiological maturity, moisture content, and meteorological conditions can allow growers to foster conditions for high head rice yield. However, there may be a trade-off in flavor. Draining fields early may cause moisture stress in grains before they are physiologically mature, affecting metabolic processes and, in turn, volatile flavor compounds. Harvesting early at higher moisture contents, while improving head rice yield (Kester et al 1963), may lead to problematic microbial growth with associated off-flavor metabolites if drying is delayed (Champagne et al 2004b). In a study to determine the effects of varying drain and harvest dates on rice sensory properties, M-202, the predominant cultivar produced in California, demonstrated stable flavor with timing of field draining (14-day span) and harvesting (32-48 days after flowering) (Champagne et al 2005). The lowest levels of lipid oxidation products 1-pentanol, hexanal, and nonanal occurred in rice with the lowest harvest moisture content. However, differences in levels of lipid oxidation products did not lead to significant ($P > 0.05$) differences in flavor.

Rice cultivar IR42 was harvested at seven times 20-38 days after 50% flowering (Marzempi et al 1990). With increase in harvesting time, amylose and protein content increased. Aroma and flavor decreased with maturity, with the best flavor found at 20 days after 50% flowering. Arai and Itani (2000) found that when rice was harvested 10 days before the ordinary time of harvesting (42 days after heading), the cooked rice was sweeter and more "delicious." Tamaki et al (1989) also found flavor declined with maturity. Playing a role in the flavor of rice, the amount of free amino acids in the exterior of cooked rice declined continuously with maturation. Flavor was considered to be rich in immature rice but poor in over-ripened rice. The influence of harvest time during ripening on the 2-AP concentration in two cultivars was examined (Itani et al 2004). During grain development in an early-heading cultivar, the 2-AP concentration in the brown rice reached a peak at four or five weeks after heading (WAH) and then decreased rapidly to 20% of the maximum at seven or eight WAH. In a late-heading cultivar, the 2-AP concentration peaked at four WAH then gradually decreased to 40% of the maximum at eight WAH.

Harvest Moisture Content

Between harvest and the start of drying, paddy may be held for more than 24 hr at moisture contents from 16 to >26%. Microbes found on the freshly harvested rice grow under these conditions and may produce volatile compounds that affect the flavor or aroma of the white rice obtained after drying and milling. A comparison was made of the contents of 10 volatile microbial metabolites in white rice obtained from paddy (cvs. M-202 and Akitakomachi) harvested at differing moisture contents and immediately dried or held for 48 hr before drying (Champagne et al 2005). No increases in volatile microbial metabolite levels were observed in white rice obtained from paddy rice that was stored at 17-21% moisture contents for 48 hr. No changes in the intensities of the flavor attributes were observed. This was in agreement with the observations of Meullenet et al (1999). Wet holding of rice harvested at 20.5% moisture for 86 hr did not significantly affect starch note (grain flavor), cardboard note (stale), sulfur note (off-note), or overall flavor impact. In white rice from paddy rice stored at >24% moisture content, 3-methyl-butanol, 2-methylbutanol, acetic acid, 2,3-butandiol, and ethyl hexadecanoate increased markedly with time (Champagne et al 2005). Also, in these samples, as determined by a descriptive panel, sour/silage and alfalfa/grassy/green bean flavors significantly increased ($P < 0.1$) in intensity. Sour/silage correlated highly with 2,3-butandiol ($r = 0.98$) and ethanol ($r = 0.99$).

Rough Rice Drying Conditions, Final Moisture Content, and Storage Conditions

Meullenet et al (1999) examined the effects of rough rice drying conditions on the starch note (grain flavor), cardboard note (stale), sulfur note (off-note), and overall flavor impact. Drying treatment

(high 54.3[degrees]C and 21.9%rh and low 33[degrees]C and 67.8% rh) did not significantly affect these flavor notes in cooked rice before storage. Likewise, Champagne et al (1997) observed no trends indicating an increase or decrease in flavor attributes with increased drying temperatures (18-600C). Higher levels of the aroma compound 2-AP and lower levels of off-flavor compounds, such as 2-pentylfuran and n-hexanal, were obtained at lower drying temperatures when rice was dried by sun, in modified air (at 30-40[degrees]C), and in hot air (at 40, 50, and 700C) (Wongpornchai et al 2004). In contrast, Sunthonvit et al (2005) reported that 2-AP tended to increase in concentration with increasing drying temperature from 100 to 1500C.

Intensities of desirable and undesirable flavor attributes were higher in rice dried to 15% moisture compared with 12% moisture (Champagne et al 1997).

The temperature and time rough rice is stored can affect the aroma and flavor of the white rice obtained from it upon milling. Rice dried at 43.40C and 38.2% rh was allowed to equilibrate in air-controlled chambers until reaching moisture contents of 10, 13, and 14% and stored at 4, 21, and 380C for 0, 6, 12, 24, and 36 weeks (Meullenet et al 2000). At each storage temperature, sulfur notes increased with storage time; the increase was slight at the highest storage temperature (Meullenet et al 2000). In an earlier study, however, Meullenet et al (1999) observed a significant decrease in sulfury notes after 20 weeks over the same storage temperatures (4, 21, 38[degrees]C). In both studies, sulfur notes significantly decreased as storage temperature increased from 4 to 38[degrees]C. Sulfur compounds were probably volatilized at a higher rate as temperature increased (Meullenet et al 1999). Cardboard notes, an indicator of slightly oxidized fats and oils, increased with storage duration and storage temperature (Meullenet et al 1999, 2000). Starchy aroma notes decreased with increasing storage duration (Meullenet et al 2000). Grainy notes consistently decreased with time for the first 25 weeks of storage and increased during subsequent storage (Meullenet et al 2000). The panelists may have perceived off-flavors developing during storage as grainy notes. Cardboard notes, an indicator of slightly oxidized fats and oils, increased with storage duration and storage temperature.

Drying rice at high temperature lowered 2-AP concentrations (Itani and Fushimi 1996). Regardless of drying method (sundried, modified air at 30 or 400C, hot air at 40, 50, or 700C), 2-AP decreased during 10 months storage for rough rice, with the highest rate of decrease at the beginning of storage (Wongpornchai et al 2004). The average concentration of 2-AP of all of the rice samples subjected to the six different drying methods after one month storage (4.02 ± 0.60 ppm) was slightly more than double that after four months (1.88 ± 0.27 ppm) and more than four times that after 10 months of storage (0.89 ± 0.12 ppm). In another study, 2-AP in stored rice was about half that of a fresh rice sample (Laksanalamai and Ilangantileke 1993).

Degree of Milling

The aroma of milled rice differs with the degree of milling. Four types of rice milled to different degrees (92, 85, 75, and 50% milled rice) were subjected to odor evaluation. Significant differences in odor of cooked rice and in quantity of volatile components between 92% milled rice and 85, 75, and 50% of milling were observed (Tsugita et al 1980). Higher concentrations of lipid oxidation products in the 92% milled rice compared with levels in deeper milled rice was probably because these products were contained in residual bran on the surface of the 92% milled rice.

Puffed corn flavor, raw rice flavor, wet cardboard flavor, hay-like flavor, and bitter taste were lower, while sweet taste was higher with increased milling from 8 to 14% (Park et al 2001). Samples milled 6% were more sour, less smooth (mouthfeel), more pungent, less smooth (aroma), and had less sweet taste than those milled at 8.8% (Piggott et al 1991). Champagne et al (1997) found the effects of degree of milling on flavor attribute intensities to be dependent on moisture content and cultivar or location.

Milled Rice Storage Temperature and Time

Milled rice develops stale or "komai-shu" flavor during storage. During storage, surface lipids undergo hydrolysis to form free fatty acids that are susceptible to oxidation (Yasumatsu and Moritaka 1964). Lipase of residual bran on the surface of the milled rice will contribute to the formation of these free fatty acids. Additionally, oxidation of unsaturated fatty acids, particularly linoleic and linolenic acids, proceeds with the eventual formation of various secondary oxidation products such as aldehydes, ketones, alcohols, furanones, acids, lactones, and hydrocarbons that are ultimately responsible for the development of off-flavors and odors (Yamamatsu et al 1966; Grosch 1987). The milling process accelerates the process by disrupting cells, releasing lipoxygenase.

Numerous researchers (Tsugita et al 1983; Piggott et al 1991; Tsrai 1995; Widjaja et al 1996; Lam and Proctor 2003; Tran et al 2005) have examined the effects of different storage conditions on volatile components and flavor properties. GC analyses of the volatiles of cooked rice showed that a larger amount of pentanal, hexanal, heptanal, alkenals, ketones, 2-pentylfuran, 4-vinylphenol, and a smaller amount of 1-pentanol and 1-hexanol was found in milled rice stored for 60 days at 40°C compared with rice stored 4[degrees]C (Tsugita et al 1983). These authors found that 4-vinylphenol has a characteristic off-flavor and may partly contribute to the off-flavor of cooked old rice (Fujimaki et al 1977). Widjaja et al (1996) found an increase in levels of most of the carbonyl compounds and in n-pentanol, 2-pentylfuran, 1-octen-3-ol, and 4-vinylguaiacol in milled rice stored for three months at 30[degrees]C. (E)-22, (E)-4-Decadienal, identified earlier by the authors as an important contributor to the character of fragrant rice flavor, also increased in concentration with storage. This compound imparts a desirable flavor at relatively low levels and a distinct rancid aroma at higher concentrations. In a more recent study (Lam and Proctor 2003), the concentrations of 2-nonenal, hexanal, and octanal increased during storage (37°C, 70% rh) and remained high during the 50-day time frame. The concentrations of heptanal, 2-pentylfuran, and 3-penten-2-one remained low. As discussed earlier, the authors concluded, based on aroma values (AV) that hexanal (grassy flavor) and 2-pentylfuran (beany) probably contributed more to flavor change in milled rice early in storage rather than later. 2-Nonenal (rancid flavor) and octanal (fatty flavor) contributed more to the overall flavor of milled rice during long-term storage.

Hydrogen disulfide (H₂S) is an indispensable component of cooked rice aroma and it is thought that H₂S is generated from the sulphhydryl groups of proteins. The amount of H₂S in the volatiles of cooked rice was higher in rice stored at 50°C than in rice stored at 40°C (Moritaka and Yasumatsu 1972). Sugars such as glucose and sucrose, and amino acids such as glutamic acid and aspartic acid, are the main components that affect the sweetness and umami tastes of rice (Fukui and Nikuni 1959; Tajima et al 1992; Saikusa et al 1994; Kasai et al 2001). The sweetness (sucrose) and umami tastes of rice were reduced during storage, whereas glucose and fructose increased (Tran et al 2005). Rice content of 2-AP decreased 40-50% in all forms of rice (paddy, brown, white), irrespective of whether three-month storage was in air or under partial vacuum (Widjaja et al 1996). 2-AP content decreased faster at higher storage temperature (Yoshihashi et al 2005). Fat acidity of rice increased during storage and was inversely correlated with 2-AP content at an early stage of storage. Packaging material moderately affected preservation of 2-AP.

The effects of storage on the flavor of undermilled and wellmilled rice were determined by a descriptive panel (Piggott et al 1991). Samples stored at 30[degrees]C had higher scores for pungent, oily, moldy/musty, sour (taste), bitter, sour (aroma), and muddy/earthy, while those stored at -20[degrees]C had higher scores for sweet (taste), fragrant, smooth (aroma), sweet (aroma), grassy, and smooth (mouthfeel). Scores for oily and starchy (mouthfeel), fragrant, smooth (aroma), and muddy/earthy increased with storage time. Both the under-milled and well-milled samples underwent these changes during storage at 30[degrees]C but they were greater for the under-milled rice. Free fatty acids (FFA) formed a greater proportion of the total surface lipid in the under-milled than in the wellmilled samples for the high-temperature stored samples. Storage at -20[degrees]C completely suppressed this increase in FFA. Hexanal and carbonyls followed the same trend as the FFA.

Washing

Rice that had been washed three times showed less deterioration in flavor during holding of the cooked rice for up to 24 hr than for rice washed once (Fukai and Tukada 2006). Monsoor and Proctor

(2002) demonstrated that >>60-80% of total surface lipids were removed by water washing, with a reduction of free fatty acid and conjugated dienes relative to unwashed control samples. The total surface free fatty acid content of first-, second-, and third-break milled rice was reduced by >50% of the original value by washing. Increases in free fatty acids and conjugated dienes in washed rice after seven days storage at 37[degrees]C and 70% rh were much lower than those of unwashed controls. Water washing may be a practical means of reducing off-flavor development in milled rice (Monsoor and Proctor 2002).

Soaking

Water soaking for >30 min before cooking is a traditional practice in Japan, Korea, and other Asian countries. Soaking facilitates uniform cooking and shortens gelatinization time. Soaking also leads to chemical changes in the grain that could affect the aroma and flavor of the rice. A considerable amount of oligosaccharides are formed through activation of amylases in the outer layers (510% of the milled kernel) during soaking (Tajima et al 1992). Water soaking of flours prepared from outer layers of milled kernels also led to increases in most free amino acids (Saikusa et al 1994). Contents of free sugars and free amino acids are believed to play a role in the flavor of cooked rice by influencing sweetness and umami (Matuzaki et al 1992; Tajima et al 1992; Tamaki et al 1993; Saikusa et al 1994; Tran et al 2005).

Recently a study was undertaken to determine the effects of presoaking on the flavor of cooked rice and whether flavor differences are associated with textural changes that could influence retention of the aroma compounds (Champagne et al, in press). Eleven samples of short-, medium-, and long-grain milled rice representing scented and nonscented rice and a wide range of amylose contents were presented to a descriptive sensory panel. For the set of all rice samples, undesirable sewer/animal flavor significantly increased and sweet taste significantly decreased with presoaking for 30 min. Presoaking also resulted in significant increases in summed negative flavor attributes and significant decreases in summed positive flavor attributes for the set of all rice samples. The effects of presoaking on texture, as measured by TPA hardness and chewiness, did not explain the observed increases in negative flavor attributes. An increase in free-sulfurcontaining free amino acids with presoaking could have resulted in an increase of their breakdown products, thereby contributing to the increase in sewer/animal flavor. The decreases in sweet taste and summed positive flavor attributes were likely the result of masking caused by the increases in sewer/animal and summed negative flavor attributes.

Cooking Method

Methods for cooking rice include the excess water to optimum cooking time method (Excess method), rice cooker optimum water method (Pilaff method), and steaming (Juliano 2003). In a comparison of the Excess and Pilaff methods, a consumer panel found rice cooked by the Pilaf method had more acceptable flavor than excess cooking (Crowhurst and Creed 2001). Possibly flavor compounds were lost during draining following cooking using the Excess method.

Influence of Water-to-Rice Ratio on Cooked Rice Flavor

The water-to-rice ratio used in the Pilaff method did not significantly affect flavor attributes across all cultivars (Bett- Garber et al 2007).

Serving Temperature of Cooked Rice

Yau and Huang (1996) found that the aroma of cooked rice would change with serving temperatures and that aroma should be the summation or mixture of specific attributes. In a follow-up study, Yau and Liu (1999) found that there was no clear temperature effect trend for all rice samples. In terms of total volatile content (TVC), TC Sen 10 contained higher TVC at 60[degrees]C, TNU 67 at 25[degrees]C, and TC 189 and TNU 70 at 18[degrees]C. Temperature affected the contents of certain compounds of individual cultivars differently. Aromas for samples held at 60[degrees]C were higher for hot steam bread, corn, corn-leaf, and brown rice, while 18[degrees]C samples were higher in cold-

steam bread and fermented-sour aromas. In another study (Liu et al 1996), aroma of cooked samples of four cultivars was evaluated at 18 and 60[degrees]C using modified descriptive analysis. Sweet, earthy, burnt rice, rancid, acid, moldy, and sulfur attributes were assessed. Samples evaluated at 18[degrees]C rated higher in sweetness, while samples evaluated at 60[degrees]C scored higher in earthy, burnt rice, rancid, moldy, and sulfur.

CONCLUSIONS

Descriptive sensory analysis has identified over a dozen different aromas and flavors in rice. Instrumental analyses have found over 200 volatile compounds present in rice. Among these compounds, possible contributors to rice aroma and flavor have been identified through determination of AV or DV. A number of oxidation products have thus been tagged as likely causing stale flavor. However, the amounts of oxidation products, singly or collectively, that need to be present for rice to have stale or rancid flavor have not been established. Only one compound, 2-AP (popcorn aroma) has been confirmed to contribute a characteristic aroma. Furthermore, 2- AP is the only volatile compound in which the relationship between its concentration in rice and sensory intensity has been established (Itani et al 2004).

Despite 30 years of research, still little is known about the relationships between the numerous volatile compounds and aroma/ flavor. A knowledge-base for predicting how preharvest and postharvest factors will affect the levels of these volatile compounds and consequently aroma and flavor is lacking. Research is still needed to identify important marker compounds that will allow preharvest and postharvest strategies to be enacted to assure that cooked rice will have desired aroma and flavor.

Cereal Chem. 85(4):445-454

LITERATURE CITED

Akbar, A., Arshed, K., Liaquat, A., Shahid, A. S., and Abdul, M. 1993. Effect of transplanting date on grain quality in fine-grain varieties/ strains. Pakistan. J. Sci. 45:64-69.

Arai, E., and Itani, T. 2000. Effects of early harvesting of grains on taste characteristics of cooked rice. Food Sci. Technol. Res. 6:252-256.

Arvisenet, G, Le Bail, P., Voilley, A., and Cayot, N. 2002. Influence of physicochemical interactions between amylose and aroma compounds on the retention of aroma in food-like matrices. J. Agric. Food Chem. 50:7088-7093.

Bergman, C. J., Delgado, J. T., Bryant, R., Grimm, C, Cadwallader, K. R., and Webb, B. D. 2000. Rapid gas chromatographic technique for quantifying 2-acetyl-1-pyrroline and hexanal in rice (*Oryza sativa*, L.) Cereal Chem. 77:454-458.

Bett, K. L., and Boylston, T. D. 1992. Effect of storage on roasted peanut quality. Pages 322-343 in: Lipid Oxidation in Foods. A. J. St. Angel, ed. ACS: Washington, DC.

Bett-Garber, K. L., Champagne, E. T, Ingram, D. A., and McClung, A. M. 2007. Influence of water to rice ratio on cooked rice flavor and texture. Cereal Chem. 84:614-619.

Boutboul, A., Giampaoli, P., Feigenbaum, ?, and Ducruet, V. 2002. Influence of the nature and treatment of starch on aroma retention. Carbohydr. Polym. 47:73-82.

Bradbury, L. M. T., Henry, R. J., Qingsheng, J., Reinke, R. F, and Waters, D. L. E. 2005. A perfect marker for fragrance genotyping rice. MoI Breeding 16:279-283.

Buttery, R., Ling, L., and Juliano, B. O. 1982. 2-acetyl-l- pyrroline: An important aroma compound in cooked rice. *Chem. Ind. Dec*:958.

Buttery, R., Ling, L. C, Juliano, B. O., and Turnbaugh, J. G. 1983. Cooked rice aroma and 2-acetyl-l-pyrroline. *J. Agrie. Food Chem.* 31:823-826.

Buttery, R. G., Ling, L. C, and Mon, T. R. 1986. Quantitative analysis of 2-acetyl-l-pyrroline in rice. *J. Agrie. Food Chem.* 34:112-1 14.

Buttery, R., Turnbaugh, J., and Ling, L. 1988. Contributions of volatiles to rice aroma. *J. Agrie. Food Chem.* 36:1006-1009.

Callier, P. 1996. La cartographie des preferences. Son application en milieu industriel et son extension aux plans incomplets. These de l'Universite de Montpellier: Montpellier, France.

Caul, J. F. 1957. The profile method of flavor analysis. *Adv. Food Res.* 7:1

Champagne, E. T., Bett, K. L., Vinyard, B. T., Webb, B. D., McClung, A. M., Barton, II, F. E., Lyon, B. G, Moldenhauer, K., Linscombe, S., and Kohywey, D. 1997. Effects of drying conditions, final moisture content, and degree of milling on rice flavor. *Cereal Chem.* 74:566-570. Champagne, E. T, Bett-Garber, K. L., McClung, A. M., and Bergman, C. 2004a. Sensory characteristics of diverse rice cultivars as influenced by genetic and environmental factors. *Cereal Chem.* 81:237-243.

Champagne, E. T., Thompson, J. F, Bett-Garber, K. L., Mutters, R., Miller, J. A., and Tan, E. 2004b. Impact of storage of freshly harvested paddy rice on milled white rice flavor. *Cereal Chem.* 8 1 : 444-449.

Champagne, E. T., Bett-Garber, K. L., Thompson, J., Mutters, R., Grimm, C. C, and McClung, A. M. 2005. Effects of drain and harvest dates on rice sensory and physicochemical properties. *Cereal Chem.* 82:369374.

Champagne, E. T., Bett-Garber, K. L., Grimm, C. C, and McClung, A. M. 2007. Effects of organic fertility management on physicochemical properties and sensory quality of diverse rice cultivars. *Cereal Chem.* 84:320-327.

Champagne, E. T, Bett-Garber, K. L., Thomson, J. L., Shih, F. F, Lea, J., and Daigle, K. 2008. Impact of presoaking on the flavor of cooked rice. *Cereal Chem.*: in press.

Chen, S. H., Wu, J., Yang, Y., Shi, W. W., and Xu, M. L. 2006. The fgr gene responsible for rice fragrance was restricted within 69 kb. *Plant Sci.* 171:505-514.

Cramer, A. C. J., Mattinson, D. S., Fellman, J. K., and Baik, B. K. 2005. Analysis of volatile compounds from various types of barley cultivars. *J. Agrie. Food Chem.* 53:7526-7531.

Crowhurst, D. G, and Creed, P. G. 2001. Effect of cooking method and variety on the sensory quality of rice. *Food Serv. Technol.* 1 : 133-140.

Del Mundo, A. M., and Juliano, B. O. 1981. Consumer preference and properties of raw and cooked milled rice. *J. Texture Stud.* 12:107-120.

Dutta, R. K., Lahiri, B. P., Khanam, S., and Rahman, S. 1999. Aroma synthesis in Basmati rice in relation to temperature and nitrogen. *Indian J. Plant Physiol.* 4:215-218.

- Fitzgerald, M. A., Hamilton, N. R. S., Calingacion, M. N., Verhoeven, H. A., and Butardo, V. M. 2008. Is there a second fragrance gene in rice? *Plant Biotechnol. J.* 6:416-423.
- Fukai, Y, and Tukada, K. 2006. Influence of pre-washing on quality of cooked rice maintained at a constant temperature. 1. Influence of cooking conditions on quality of cooked rice. *Nippon Shokuhin Kagaku KogakuKaishi* 53:587-591.
- Fukui, T., and Nikuni, Z. 1959. Changes in sugar contents during the germination of rice seed. Application of the ion exchange resin chromatography. *Nippon Nogel Kagaku Kaishi* 33:72-78.
- Fujimaki, M., Tsugita, T., and Kurata, T. 1977. Fractionation and identification of volatile acids and phenols in the steam distillate of rice bran. *Agrie. Biol. Chem.* 41:1721-1725.
- Fushimi, T, Itani, T, Kohyama, N., and Sekiya, K. 1996. Variation of 2acetyl-1-pyrroline concentration of the aromatic rice (cv. Hieri) cultivated at Kubokawa-area in Kochi Prefecture. Pages 738- 739 in: *Crop Research in Asia, 1996: Achievements and Perspective. Proc. 2nd Asia Crop Sci. Conf.* R. Ishii and T. Horie, eds. Fukui: Japan.
- Goodwin, Jr., H. L., Koop, L. A., Rister, M. E., Miller, R. K., Maca, J. V, Chambers, E., Hollingsworth, M., Bett, K., Webb, B. D., and McClung, A. M. 1996. Developing a common language for the U.S. rice industry: Linkages among breeders, producers, processors and consumers. TAMRC Consumer Product Market Research CP2-96. Texas A&M: College Station, TX.
- Grimm, C. C, Bergman, C. J., Delgado, J. T., and Bryant, R. 2001. Screening for 2-acetyl-1-pyrroline in the headspace of rice using SPME/GC/MS. *J. Agrie. Food Chem.* 49:245-249.
- Grimm, C, Champagne, E. T., and Ohtsubo, K. 2002. Analysis of volatile compounds in the headspace of rice using SPME/GC/MS. Pages 229-248 in: *Flavor, Fragrance, and Odor Analysis.* R. Marsili, ed. Marcel Dekker: New York.
- Grosch, W. 1987. Reactions of hydroperoxides - Products of low molecular weight. Pages 95-140 in: *Autoxidation of Unsaturated Lipids.* 1st ed. H. W. S. Chan, ed. Academic Press: London.
- Guadagni, D. G., Buttery, R. G., and Harris, J. 1966. Odor intensities of hop oil components. *J. Sci Food Agrie.* 17:142-144.
- Harper, R. 1972. *Human Senses in Action.* Churchill Livingstone: London.
- Hougen, F. W., Quilliam, M. A., and Curran, W. A. 1971. Headspace vapors from cereal grains. *J. Agrie. Food Chem.* 19: 182-183.
- Hussain, A., Mujtaba-Naqvi, S. H., and Hammerschmidt, F. J. 1987. The isolation and identification of volatile components from basmati rice (*Oryza sativa* L.). *Flavor Science and Technology: Proc. 5th Weurman Flavour Res. Symp.* Wiley: New York.
- Itani, T, and Fushimi, T. 1996. Influence of pre- and post- harvest conditions on 2-acetyl-1-pyrroline concentration in aromatic rice. *Crop Research in Asia: Achievements and Perspective.* ACSA: 728-729.
- Itani, T, Tamaki, M., Hayata, Y, Fushimi, T, and Hashizume, K. 2004. Variation of 2-acetyl-1-pyrroline concentration in aromatic rice grains collected in the same region in Japan and factors affecting its concentration. *Plant Prod. Sci.* 7:178-183.
- Jezussek, M., Juliano, B. O., and Schieberle, P. 2002. Comparison of key aroma compounds in cooked brown rice varieties based on aroma extract dilution analyses. *J. Agrie. Food Chem.* 50:1101-1105.

- Jin, Q. S., Waters, D., Cordeiro, G. M., Henry, R. J., and Reinke, R. F. 2003. A single nucleotide polymorphism (SNP) marker linked to the fragrance gene in rice (*Oryza sativa* L.). *Plant Sci.* 165:359-364.
- Jouquand, C, Ducruet, V, and Le Bail, P. 2006. Formation of amylose complexes with C6-aroma compounds in starch dispersions and its impact on retention. *Food Chem.* 96:461-470.
- Juliano, B. O., Onate, L. U., and del Mundo, A. M. 1965. Relation of starch composition, protein content, and gelatinization temperature to cooking and eating qualities of milled rice. *Food Technol.* 19:10061011.
- Kasai, M., Ohishi, K., Shimada, A., and Hatae, K. 2001. Taste properties of cooked rice based on an analysis of the cooked rice extracts. *J. Cook. Jpn.* 34:373-379.
- Kato, H., Ohta, T, Tsugita, T., and Hosaka, Y 1983. Effect of parboiling on texture and flavor components of cooked rice. *J. Agrie. Food Chem.* 31:818-823.
- Kester, E. B., Lukens, H. C, Ferrei, R. E., Mohammad, A., and Finrock, D. C. 1963. Influence of maturity on properties of Western rices. *Cereal Chem.* 40:323-336.
- Kirchhoff, E., and Schieberle, P. 2002. Quantitation of odor- active compounds in rye flour and rye sourdough using stable isotope dilution assays. *J. Agrie. Food Chem.* 50:5378-5385.
- Laguerre, M., Mestres, C, Davrieux, F, Ringuet, J., and Boulanger, R. 2007. Rapid discrimination of fragrant rice by solid- phase microextraction, mass spectrometry, and multivariate analysis used as a mass sensor. *J. Agrie. Food Chem.* 55:1077-1083.
- Laksanalamai, V, and Ilangantileke, S. 1993. Comparison of aroma compound (2-acetyl-1-pyrroline) on leaves from pandan (*Pandanum amaryllifolius*) and Thai fragrant rice (Khao Dawk Mali-1 05) *Cereal Chem.* 70:381-384.
- Lam, H. S. and Proctor, A. 2003. Milled rice oxidation volatiles and odor development. *J. Food Sci.* 68:2676-2681.
- Lin, C, Hsieh, T, and Hoff, B. 1990. Identification and quantification of the "popcorn"-like aroma in Louisiana Aromatic Delia Rice (*Oryza sativa* L.). *J. Food Sci.* 55:1466-1467.
- Liu, T. T, Wu, C. M., and Yau, N. J. N. 1996. Descriptive analysis of odor of cooked rice maintained at 18[degrees]C and 60[degrees]C. *Food Sci.* 23:761-766.
- Lorieux, M., Petrov, M., Huang, N., Guiderdoni, E., and Ghesquiere, A. 1996. Aroma in rice: Genetic analysis of a quantitative trait. *Theor. Appi. Gen.* 93:1145-1151.
- Luning, P. A., de Rijk, T, Wichers, J. J., and Roozen, J. P. 1994. Gas chromatography, mass spectrometry, and sniffing port analyses of volatile compounds of fresh bell peppers (*Capsium annuum*) at different ripening stages. *J. Agrie. Food Chem.* 42:977- 988.
- Lyman, W. J., Reehl, W. P., and Rosenblatt, D. H. 1982. *Handbook of Chemical Property Estimation Methods*, Section 14. McGraw-Hill: New York.
- MacLeod, A. J., and Cave, S. J. 1975. Volatile flavour components of eggs. *J. Sci. Food Agrie.* 26:351-360.

- Mahatheeranont, S., Keawsaard, S., and Dumri, K. 2001. Quantification of the rice aroma compound, 2-acetyl-1-pyrroline, in uncooked Khao Dawk Mali 105 brown rice. *J. Agric. Food Chem.* 49:773- 779.
- Marzempi, Sastrodipuro, D., and Edi, S. 1990. Effect of harvesting time on the cooling and eating quality of rice. *Pemberitaan Penelitian Sukarami.* 17:19-22.
- Meilgaard, M. C. 1975. Flavor chemistry of beer. II. Flavor and threshold of 239 aroma volatiles. *Tech. Q. Master Brew. Assoc. Am.* 12:151.
- Meilgaard, M., Civille, G. V, and Carr, B. T. 2007. *Sensory Evaluation Techniques.* CRC Press: Boca Raton, FL.
- Meullenet, J. F, Marks, B. P, Griffin, K., and Daniels, M. J. 1999. Effects of rough rice drying and storage conditions on sensory profiles of cooked rice. *Cereal Chem.* 76:438-486.
- Meullenet, J. F, Marks, B. P., Hankins, J. A., Griffin, V. K., and Daniels, M. J. 2000. Sensory quality of cooked long-grain rice as affected by rough rice moisture content, storage temperature, and storage duration. *Cereal Chem.* 77:259-263.
- Mitsuda, H., Yamamoto, A., Ominami, H., and Nakamura, T. 1999. Methods for improving the quality of aged and imported rice. *J. Jpn. Soc. Nutr. Food Sci.* 52:91-96.
- Monsoor, M. A., and Proctor, A. 2002. Effect of water washing on the reduction of surface total lipids and FFA on milled rice. *J. AOCS* 79:867-870.
- Moritaka, S., and Yasumatsu, K. 1972. Studies on cereals. X. The effect of sulphhydryl groups on deterioration of milled rice during storage. *J. Jpn. Soc. Food Nutr.* 25:59-62.
- Nobler, A., and Ebler, S. 2002. Use of multivariate statistics in understanding wine flavor. *Food Rev. Int.* 18:1-21.
- Park, J. K., Kim, S. S., and Kim, K. O. 2001. Effect of milling ratio on sensory properties of cooked rice and on physicochemical properties of milled and cooked rice. *Cereal Chem.* 78: 151-156.
- Petrov, M., Danzart, M., Giampaoli, P., Faure, J., and Richard, H. 1996. Rice aroma analysis: Discrimination between a scented and a nonscented rice. *Sci. AHm.* 16:347-360. Piggott, J. R., Morrison, W. R., and Clyne, J. 1991. Changes in lipids and in sensory attributes on storage of rice milled to different degrees. *Int. J. Food Sci Technol.* 26:615-628.
- Reineccius, G. 2006. *Flavor Chemistry and Technology.* Taylor & Francis: Boca Raton, FL.
- Rothe, M. 1976. Aroma values - A useful concept? *Die Nahrung* 20:259-266.
- Rousset, S., and Martin, J.-F. 2001. An effective hedonic analysis tool: Weak/strong points. *J. Sensory Stud.* 16:643-661.
- Saikusa, T, Horino, T, and Mori, Y. 1994. Distribution of free amino acids in the rice kernel and kernel fractions and the effect of water soaking on the distribution. *J. Agric. Food Chem.* 42:1122- 1125.
- Srisawas, W., and Jindal, V. K. 2007. Sensory evaluation of cooked rice in relation to water-to-rice ratio and physicochemical properties. *J. Texture Stud.* 38:21-41.

Sriseadka, T, Wongpornchai, S., and Kitsawatpaiboon, P. 2006. Rapid method for quantitative analysis of the aroma impact compound, 2-acetyl-1-pyrroline, in fragrant rice using automated headspace gas chromatography. *J. Agric. Food Chem.* 54:8183-8189,

Steffen, A., and Pawliszyn, J. 1996. Analysis of flavor volatiles using headspace solid-phase microextraction. *J. Agric. Food Chem.* 44:2187-2193.

Sunthonvit, N., Srzednicki, G. S., and Craske, J. 2005. Effects of hightemperature drying on the flavor components in Thai fragrant rice. *Drying Technol.* 23:1407-1418.

Tajima, M., Horino, T, Maeda, M., and Rok Son, J. 1992. Maltooligosaccharides extracted from outer-layer of rice grain. *Nippon Shokuhin Kogyo Gakkaishi.* 39:857-861.

Tamaki, M., Ebata, M., Tashiro, T, and Ishikawa, M. 1989. Physicoecological studies on quality formation of rice kernel. II. Effects of ripening stage and some ripening conditions on free amino acids in milled rice kernel and in the exterior of cooked rice. *Jpn. J. Crop Sci.* 58:695-703.

Tanchotikul, U., and Hsieh, T. C. Y. 1991. An improved method for quantification of 2-acetyl-1-pyrroline, a "popcorn"-like aroma, in aromatic rice by high-resolution gas chromatography/mass spectrometry/selected ion monitoring. *J. Agric. Food Chem.* 39:944- 947.

Tava, A., and Bocchi, S. 1999. Aroma of cooked rice (*Oryza sativa*): Comparison between commercial Basmati and Italian line B5- 3. *Cereal Chem.* 76:526-529.

Terao, T, Miura, S., Yanagihara, T, Hirose, T, Nagata, K., Tabuchi, H., Kim, H. Y., Lieffering, M., Okada, M., and Kobayashi, K. 2005. Influence of free-air CO₂ enrichment (FACE) on the eating quality of rice. *J. Sci Food Agric.* 85:1861-1868.

Tran, T. U., Suzuki, K., Okadome, H., Ikezaki, H., Homma, S., and Ohtsubo, K. 2005. Detection of changes in taste of japonica and indica brown and milled rice (*Oryza sativa* L.) during storage using physicochemical analyses and a taste sensing system. *J. Agric. Food Chem.* 53:1108-1118.

Tsrai, K. Y. 1995. A review of studies in volatile components of cooked rice. *Food Sci. (China)* 16:7-9.

Tsugita, T, Ohta, T., and Kato, H. 1983. Cooking flavor and texture of rice stored under different conditions. *Agric. Biol. Chem.* 47:543-549.

Tsugita, T, Kurata, T., and Kato, H. 1980. Volatile components after cooking rice milled to different degrees. *Agric. Biol. Chem.* 44:835-840.

Weast, R. C, ed. 1985. *Handbook of Chemistry and Physics, Section D, 66th Ed.* CRC Press: Boca Raton, FL.

Widjaja, R., Craske, J. D., and Wootton, M. 1996. Changes in volatile components of paddy, brown, and white fragrant rice during storage. *J. Sci. Food Agric.* 71:218-224.

Williams, A. A. 1978. Interpretation of the sensory significance of chemical data in flavor research. III. Sensory analysis. *Int. Flav. Food Addit.* 9:171-175.

Wongpornchai, S., Dumri, K., Jongkaewwattana, S., and Siri, B. 2004. Effects of drying methods and storage time on the aroma and milling quality of rice (*Oryza sativa* L.) cv. Khao Dawk Mali 105. *Food Chem.* 87:407-414.

van Ruth, S. M., and Roozen, J. P. 1994. Gas chromatographic/ sniffing port analysis and sensory evaluation of commercially-dried bell peppers (*Capsium annuum*) after rehydration. *Food Chem.* 51:165- 170.

Yamamatsu, K., Moritaka, S., and Wada, S. 1966. Stale flavour of stored rice. *Agrie. Biol. Chem.* 30:483-486.

Yang, X., and Peppard, T. 1994. Solid-phase microextraction for flavor analysis. *J. Agrie. Food Chem.* 42:1925-1930.

Yasumatsu, K., Moritaka, S., and Wada, S. 1966. Studies on cereals. V. Stale flavor of stored rice. *Agrie. Biol. Chem.* 30:483- 486.

Yau, N. J. N., and Huang, J. J. 1996. Sensory analysis of cooked rice. *Food Qual. Pref.* 7:263-270.

Yau, N. J. N. and Liu, T. T. 1999. Instrumental and sensory analysis of volatile aroma of cooked rice. *J. Sens. Stud.* 14:209- 233.

Yoshihashi, T. Huong, N. T. T., Surojanametakul, V, Tungtrakul, P., and Varanyanond, W. 2005. Effect of storage conditions on 2- acetyl-lpyrroline content in aromatic rice variety. *Khao Dawk Mali* 105. *J. Food Sci.* 70:S34-S37.

Zheng, Z., and Zhang, H. 2007. Direct extraction of volatiles of rice during cooking using SPME. *Cereal Chem.* 84:423-427.

[Received October 2, 2007. Accepted January 27, 2008.]

Elaine T. Champagne¹

¹ USDA ARS Southern Regional Research Center, New Orleans, LA 70124. Fax: 504-286-4430. E-mail: etchamp@srrc.ars.usda.gov

doi:10.1094/CCHEM-85-4-0445

This article is in the public domain and not copyrightable. It may be freely reprinted with customary crediting of the source. AACC Internatio

Story from REDORBIT NEWS:
<http://www.redorbit.com/news/display/?id=1521336>

Published: 2008/08/14 03:00:34 CDT

© RedOrbit 2005