Taste and aroma of fresh and stored mandarins

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Abstract

During the last decade there has been a continuous rise in consumption of fresh easy-to-peel mandarins. However, mandarins are much more perishable than other citrus fruit, mainly due to rapid deterioration in sensory acceptability after harvest. In the current review we discuss the biochemical components involved in forming the unique flavor of mandarins, and how postharvest storage operations influence taste and aroma and consequently consumer sensory acceptability. What we perceive as mandarin flavor is actually the combination of basic taste, aroma and mouth-feel. The taste of mandarins is principally governed by the levels of sugars and acids in the juice sacs and the relative ratios among them, whereas the aroma of mandarins is derived from a mixture of different aroma volatiles, including alcohols, aldehydes, ketones, terpenes/hydrocarbons and esters. During postharvest storage and marketing there is a gradual decrease in mandarin sensory acceptability, which has been attributed to decreases in acidity and typical mandarin flavor, paralleling an accumulation of off-flavor. Biochemical analysis of volatile and non-volatile constituents in mandarin juice demonstrated that these changes in sensory acceptability were concomitant with decreases in acidity and content of terpenes and aldehydes, which provide green, piney and citrus aroma on the one hand, and increases in ethanol fermentation metabolism products and esters on the other, which are likely to cause ‘overripe’ and off-flavors. Overall, we demonstrate the vast importance of the genetic background, maturity stage at harvest, commercial postharvest operation treatments, including curing, degreening and waxing, and storage duration on mandarin sensory quality.

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Keywords: aroma; Citrus reticulata; flavor; mandarin; off-flavor; postharvest; sensory quality; taste

INTRODUCTION

During the last decade, there has been a continuous decrease in consumption and global marketing of difficult-to-peel citrus fruits, such as oranges, grapefruit and pummelo, accompanied by a parallel rise in consumption of, and demand for, fresh easy-to-peel mandarins.1 Nevertheless, despite their attractive appearance and convenience for consumption, common mandarins (Citrus reticulata Blanco) are much more perishable than other citrus fruit, and suffer from a much shorter postharvest storage life, especially flavor life, due to rapid deterioration in fruit flavor and sensory acceptability after harvest.2–4

Citrus fruit are well appreciated for their eating quality and health benefits, and each type of citrus, such as orange, grapefruit, lemon or mandarin, has a unique and special flavor of its own. In fact, what we call flavor is actually the combination of basic taste, aroma and mouth-feel sensations that are perceived simultaneously by the brain during the eating of foods.5 Aroma is the description of sensations induced by volatile compounds via the olfactory bulb in the nose cavity and processed in the brain; it involves thousands of different volatiles providing various kinds of floral, fruity, minty, woody, mushroom, etc. aromas.6 Taste is the response of receptors on the tongue and in the mouth to soluble components and provides the sweet, sour, bitter, salty and umami attributes of a food. Other non-volatile compounds may induce a physical sensation, such as phenolic compounds or some limonoids in citrus that may be perceived as astringent.7 Finally, macromolecules such as pectin in citrus juice may create a certain mouth-feel, interact with volatile compounds and change flavor perception.8

The major taste attributes of citrus fruit are sweetness, sourness and bitterness. The perception of sweetness is due to the presence of glucose, fructose and sucrose, whereas sourness is due to the presence of acids, mainly citric acid, but also small amounts of other types of acids like malic and succinic acids.1,9 These two components of taste interact by suppressing each other,10 so that a solution containing sucrose and citric acid will be less sour if sucrose concentration is increased, and less sweet if citric acid is increased. Bitterness, which is perceived mainly by the presence of the bitter flavonoid naringin, is an important flavor attribute of grapefruit and pummelo, but not so much in oranges and mandarins that accumulate the tasteless flavonoid hesperidin rather than naringin.11 However, some orange cultivars such as Navel, and possibly some mandarins, may develop bitterness after...
juicing, due to cleavage of the bitter limonoid limonin from the tasteless limononic acid A-ring lactone.12

Most of the knowledge gained so far on aroma of citrus fruit comes from studies with oranges and grapefruit, which are the major products of the citrus juice industry and with most of the studies analyzing the flavor of pasteurized juices, rather than fresh fruits.13–17 Various studies have shown that the pleasant aroma of orange juice is formed by a mixture of at least 36 different aroma volatiles that include 14 aldehydes, 7 esters, 6 alcohols, 5 terpenes and 4 ketones.16 The typical odor of grapefruit also evolves from a mixture of volatiles, but pure grapefruit aroma may also be attributed to specific volatiles, namely nootkatone and p-menthene-8-thiol,13,14 which are considered character-impact aroma compounds for this fruit. The odor of mandarin has not yet been analyzed in as much detail as that of orange and grapefruit but, like in orange, it seems to be derived from a mixture of different volatiles rather than from any specific character-impact compounds.18,19 Overall, this paper will discuss factors governing taste and aroma of mandarins, and how postharvest operations and storage conditions influence the chemical composition of taste and aroma components and fruit sensory quality.

TASTE AND AROMA OF FRESH MANDARINS

Non-volatile components in mandarin

The taste of mandarin fruit is principally governed by the levels of sugars and acids in the juice sacs and the relative ratio among them; the latter is also termed fruit maturation index calculated as the ratio of total soluble solids (TSS) to titratable acidity (TA). TSS is easily measured using a refractometer, and it provides a reliable indication for total sugar levels, since sugars consist approximately 80–85% TSS.1 Acidity is usually measured by titrating juice samples with 0.1 mol L−1 NaOH until the pH reaches 8.2 and, since the amount of base used for titration depends on acid concentration, it provides a simple and reliable means for calculation of acidity levels.1 Within a cultivar, TSS levels normally increase from ~90 g L−1 at the beginning of commercial harvest and rises to ~150 g L−1 at the end of the harvesting season. In contrast, TA levels decrease from ~15 g L−1 at the beginning of harvest to ~6 g L−1 at the end of the season.20 Overall, it was reported that the average TSS and acidity levels of various mandarin cultivars grown in different countries and harvested at optimum maturity were in the range of 100–130 g L−1 TSS and 7–14 g L−1 acidity.9 Correspondingly, the average TSS : TA ratios of mandarins at optimum maturity were between 8.6 and 18.1.9

Because of these dynamic changes in TSS and TA levels during fruit maturation (continuous increase in TSS and decrease in acidity), the overall taste of mandarins depends on the ripening stage: within each cultivar, early-season fruit are more sour than late-season fruit, which in turn often lack appropriate acidity.21 To make sure that mandarins will not be harvested too early when they may be too sour for the market, maturity and grade standards were developed and enforced by local plant protection and inspection services.22 For example, in Florida, it is permitted to harvest tangerines only when their TSS levels are above 90 g L−1 and TSS : TA ratios are higher than 7.5.22 In Israel, it is permitted to export early-season Satsuma mandarins only when TSS levels are above 90 g L−1, juice acidity levels are below 13 g L−1 and TSS : TA ratios are higher than 7.0.21 However, much work still needs to be done for each variety. As with oranges, there is no one indicator of maturity that is applicable to all mandarin cultivars. For example, a TSS : TA ratio of 8, considered the minimum maturity standard for Navel oranges in California, was proven to be too low for consumer acceptability.23

Obenland and collaborators further tested an alternative formula to TSS : TA ratio, developed by Jordan et al.,24 called BrimA index. BrimA is obtained by subtracting a multiple of TA from TSS: BrimA = TSS − k(TA), with constant k being characteristic of a fruit product.24 Using multiple consumer and untrained staff location taste panels, Obenland et al.23 found a better correlation between flavor hedonic scores and sugar and acid concentrations using BrimA (with k = 3) than TSS : TA ratio; also, the response of flavor to BrimA was linear, unlike the response to TSS/TA ratio. These authors attributed the superior accuracy of the BrimA index in predicting flavor liking because it more efficiently considers low-acid fruit.23 Additionally, Plotto and co-workers (unpublished results) found a better correlation between sweetness intensity determined by a trained panel and BrimA (R2 = 0.92) than using TSS : TA ratio (R2 = 0.76) or TSS alone (R2 = 0.74). Overall, consumer panels revealed high correlations between TSS and TA levels and liking, with higher correlation to the BrimA index for Navel orange.

Nevertheless, in spite of the importance of the fruit ripening ratio (TSS : TA ratio) on fruit flavor and sensory acceptability, it was demonstrated that a good tasty fruit requires high levels of sugars and moderate levels of acidity rather than any other combination resulting in a similar ripening ratio.25 For example, a mandarin with 120 g L−1 TSS and 10 g L−1 TA has a ripening ratio of 12, and is perceived as very tasty. In contrast, a mandarin with just 60 g L−1 TSS and 5 g L−1 acidity will have the same ripening ratio but will result in a lower flavor score.

Non-volatile components, including small molecules such as simple sugars and acids as well large molecules like lipids, proteins, flavonoids, polysaccharides and pectin, are also likely to have an indirect effect on mandarin flavor by forming chemical (covalent) and hydrophobic interactions with volatile compounds either by absorbing them or affecting their partition coefficient and volatilization.26,27 Also, the problem of development of bitterness after juicing, known in the orange cultivar Navel, has not been studied yet in mandarins because mandarins are mostly consumed as fresh fruit. However, in the future, as production increases in certain areas, processing of mandarin juice may become a value-added product for growers, and the presence of the bitter compound limonin may be a problem in some mandarin juices.28 Finally, non-volatile carotenoids play an important indirect role in mandarin flavor by being precursors of potent aroma-active volatiles.29 Carotenoids produced by mandarins are similar to those produced by oranges; however, they differ in the quantities of individual compounds produced.30 As an example, β-cryptoxanthin is present in higher amounts in mandarins than in oranges, whereas cis-violaxanthin is accumulated in higher amounts in oranges.30

Volatile compounds in mandarin

Unlike the vast amount of literature available on aroma composition of oranges and orange juice,16 relatively little is yet known regarding the nature and content of aroma volatiles that determine the unique aroma of fresh mandarins. The first comprehensive study aimed at elucidating the biochemical nature of mandarin aroma was conducted by Moshonas and Shaw.18 They generated an initial database from juices of 15 different mandarin and mandarin hybrid cultivars and listed 42 volatile constituents. The main volatile constituents present in high amounts were myrcene, limonene, linalool and γ-terpinene. More recently,
Elmaci and Altug found, using headspace (HS) gas chromatography–mass spectrometry (GC-MS), that γ-terpinene, α-pinene, and α-pinene were the most abundant volatiles produced by Turkish mandarins in addition to limonene. Limonene and γ-terpinene accounted for approximately 88% of the total aroma volatiles. quantified by GC-MS the contents of 32 volatile compounds in Hernandina fresh mandarins and found the profile to be similar to that of the varieties Dancy and Murcott described by Moshonas and Shaw. Another group, and Carbonell-Barrachina quantified the contents of 12 aroma volatiles in the juice of two Spanish mandarin varieties, and concluded that D-limonene, myrcene, sabine, α-pinene and linalool were the predominant compounds in mandarin juices. Furthermore, it was suggested that D-limonene, linalool, α-pineneol and terpinen-4-ol could be used as quality control parameters in mandarin juices, since contents of α-pineneol and terpinen-4-ol increased in processed juices and their accumulation was negatively correlated with juice acceptability. The presence of these volatiles provides an indication of oxidation of terpenes such as limonene and valencene and, indeed, is considered to impart lower quality to citrus juice. They are also an indication of peel oil components, richer in terpene compounds and usually higher in commercially processed juice.

et al. detected 41 aroma volatiles in the juice of an Asian mandarin, Citrus reticulata Blanco, cv. Dalandan, which included terpenes, carbonyls, alcohols, esters and hydrocarbons, with limonene being the main compound. By comparing volatile profiles of Dalandan mandarins with Citrus sinensis Osbeck (Mossambi orange) and Citrus nobilis Lour. var. microcarpa Hassk. (Poniantan orange), these authors noted that some compounds were only present in the mandarin sample: α-phellandrene, 1-terpinolene, trans-β-terpinolene, p-cymene-8-ol, thymol, and traces of β-damascenone, α-farnesene and α-sinensial. Thymol, together with methyl-N-methylantranilate (MNMA), have been mentioned as important odorants in mandarin oil. In fact, Elmaci and Altug detected MNMA in Clementine mandarin, described with an orange blossom aroma. Another study conducted by and used HS GC-MS to identify and characterize aroma volatiles in juices of various mandarin cultivars. It was found that each variety included between 66 and 73 aroma volatiles, and 29 constituents were common for juices of all three varieties. Overall, the compounds detected in the largest amount in Satsuma mandarins were limonene, linalool, γ-terpinene, β-myrcene, α-pinene and octanal. Finally, recently quantified the contents of 44 aroma volatiles in juices of various mandarin hybrids, and suggested that the ratios between limonene and γ-terpinene contents could be used to discriminate between different hybrids of crosses between mandarin (Citrus reticulata Blanco) and Clementine (Citrus reticulata × Citrus sinensis).

Recently, volatiles were characterized and quantified in fresh and stored Or and Mor mandarins from Israel. Mor mandarins had a total of 62 aroma volatiles, including 17 alcohols, 17 aldehydes, 12 esters, nine hydrocarbons, five ketones and two acids, while Or mandarins had a total amount of 60 aroma volatiles, including 10 alcohols, 12 aldehydes, 15 esters, 19 hydrocarbons and four ketones. Overall, these findings are in agreement with recent observations by , and co-workers, who determined the aroma profiles of about 60 new mandarin hybrids as part of an ongoing breeding program in Florida, and found that mandarin fruit typically produce a total of about 60–70 different volatile compounds. It is to be noted that sample preparation may have a large effect on citrus volatile content. In the studies with fresh fruit, authors took special steps to exclude peel oil components in the samples. However, when fruit is juiced using commercial extractors, more peel oil compounds are present. Clearly showed differences between volatiles present in peel oil and flesh of citrus Dekopon (Shiranuhi mandarin): monoterpenes and sesquiterpenes except limonene and valencene were absent from the juice sacs, while many aliphatic alcohols, esters and acids were found only in the juice sacs. In addition, sampling for GC analysis affects the volatile profile: solvent extractions tend to recover low-volatility and oil-soluble compounds such as MNMA, α-sinensial and β-damascenone, which may be missed when using HS techniques.

In order to summarize all of the data gathered so far in different laboratories regarding the composition of aroma volatiles in mandarins, we compared the GC-MS data generated in various studies conducted by Moshonas and Shaw, Elmaci and Altug, and and Tietel and and identified a total amount of 37 aroma volatiles that were detected in mandarin juices in at least four different experiments. The final list of this comparison is presented in Table 1. It can be seen that these mandarin consensus volatiles include seven alcohols, nine aldehydes, one ketone, 15 terpenes/hydrocarbons and five esters (Table 1). Furthermore, we detected nine aroma volatiles that were detected in at least seven out of the eight different reports and thus definitely can be considered as core aroma volatiles in mandarin juice. These volatiles include linalool (floral, citrus), α-terpinene (floral), terpinen-4-ol (woody, earthy), nonanal (piney, floral, citrusy), decanal (fatty, musty), carvone (spearmint, caraway), limonene (citrus-like), α-pinene (pine-like) and myrcene (musty, wet soil) (Table 1).

Despite the importance of initial characterization of volatile profiles of fresh mandarins, only some of the detected volatiles are likely to have actual aroma activity. Aroma-active compounds are volatile whose concentrations in the fruit samples are equal to or greater than their odor thresholds. Measuring thresholds for individual compounds is tedious and very time consuming. Another way to identify volatile aroma activity is by GC-olfactometry (GC-O) (or ‘sniffing’), where the effluent of the GC is smelled by a human subject. In these studies, the impact of odorants in the juice matrix is analyzed by the selective sensitivity of a human nose. As far as we are aware, the only comprehensive GC-O analysis study conducted and published to date aiming to identify important odorants in fresh mandarin juices was conducted by using freshly homogenized Clementine segments. In this work, a total of 38 odor active compounds were detected. The most odor-active compounds were 3-sec-butyl-2-methoxypyrazine (pea-like smell), ethyl-2-methylbutanoate (fruity), 3-isopropyl-2-methoxyprpyrazine (earthy), (Z)-hex-3-enal (green note), ethyl cinnamate (sweet), ethyl-2-methylpropanoate (fruity), ethyl butanoate (fruity) and (E)-β-damascenone (cooked apple). Interestingly, the same group also found linalool (floral), (E,E)-deca-2,4,6-trienyl (fatty) and winelactone (sweet) to be major aroma contributors in Clementine peel oil. Peel oil contributes to the sensory experience when peeling a mandarin fruit, the oil being the first component smelled when breaking the oil glands in the peel, and the contribution of these compounds should not be neglected when studying mandarin quality.

In a recent study by Miyazaki, it was found that about one third of the total number of volatiles detected in five mandarin
Table 1. Consensus aroma volatiles of fresh mandarin fruit

<table>
<thead>
<tr>
<th>Compound</th>
<th>Descriptiona</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alcohols (7)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>–</td>
<td>18,32,37,39,41,42</td>
</tr>
<tr>
<td>Octanol</td>
<td>Soapy</td>
<td>18,32,39,41,42</td>
</tr>
<tr>
<td>(Z)-p-Mentha-2,8-dien-1-ol</td>
<td>–</td>
<td>31,32,39,41,42</td>
</tr>
<tr>
<td><strong>Linalool</strong></td>
<td>Floral, green, citrus</td>
<td>18,31,32,37,39,40,41,42</td>
</tr>
<tr>
<td><strong>α-Terpineol</strong></td>
<td>Floral, lilac-like</td>
<td>18,31,32,37,39,40,41,42</td>
</tr>
<tr>
<td><strong>Terpinen-4-ol</strong></td>
<td>Woody, earthy</td>
<td>18,32,37,39,40,41,42</td>
</tr>
<tr>
<td>Citronellol</td>
<td>Rose-like, fresh</td>
<td>32,39,40,41,42</td>
</tr>
<tr>
<td><strong>Aldehydes (9)</strong></td>
<td></td>
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<tr>
<td>Acetaldehyde</td>
<td>Pungent, solventy</td>
<td>32,37,41,42</td>
</tr>
<tr>
<td>Hexanal</td>
<td>Fatty, green, grassy, powerful</td>
<td>18,39,41,42</td>
</tr>
<tr>
<td>(E)-2-hexenal</td>
<td>Green, banana-like</td>
<td>18,39,41,42</td>
</tr>
<tr>
<td>Heptanal</td>
<td>Oily, fatty, rancid, powerful</td>
<td>18,39,41,42</td>
</tr>
<tr>
<td>Octanal</td>
<td>Tallowy, citrus-like</td>
<td>18,32,37,39,41,42</td>
</tr>
<tr>
<td><strong>Nonanal</strong></td>
<td>Piney, floral, citrusy</td>
<td>18,32,37,39,40,41,42</td>
</tr>
<tr>
<td><strong>Decanal</strong></td>
<td>Beefy, musty, marine, cucumber</td>
<td>18,32,37,39,40,41,42</td>
</tr>
<tr>
<td>Neral</td>
<td>Lemony, citrusy</td>
<td>18,37,39,41</td>
</tr>
<tr>
<td>Perillaldehyde</td>
<td>Green, oily, fatty, cherry</td>
<td>18,37,39,40,41,42</td>
</tr>
<tr>
<td><strong>Ketones (1)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carvone</td>
<td>Spearmint = R (−), caraway = S (+)</td>
<td>18,32,37,39,40,41,42</td>
</tr>
<tr>
<td><strong>Terpenes – hydrocarbons (15)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limonene</td>
<td>Citrus-like, fresh</td>
<td>18,31,32,37,39,40,41,42</td>
</tr>
<tr>
<td>α-Terpene</td>
<td>Lemony, citrusy</td>
<td>31,39,40,41,42</td>
</tr>
<tr>
<td>γ-Terpene</td>
<td>Lemony, lime-like</td>
<td>18,31,37,39,40,42</td>
</tr>
<tr>
<td>α-Terpinolene</td>
<td>Citrus, pine</td>
<td>31,37,39,40,41,42</td>
</tr>
<tr>
<td>α-Thujene</td>
<td>–</td>
<td>37,39,40,42</td>
</tr>
<tr>
<td>Sabinene</td>
<td>Warm, oily, peppery, green</td>
<td>18,31,32,37,39,42</td>
</tr>
<tr>
<td>δ-3-Carene</td>
<td>Sweet</td>
<td>18,32,39,40</td>
</tr>
<tr>
<td>α-Pinenone</td>
<td>Pine-like, resinous</td>
<td>18,31,32,37,39,40,41,42</td>
</tr>
<tr>
<td>B-Pinenone</td>
<td>Resinous, dry, woody</td>
<td>31,32,37,39,40</td>
</tr>
<tr>
<td>α-Copaene</td>
<td>–</td>
<td>31,37,39,40,41,42</td>
</tr>
<tr>
<td>(E)-β-Caryophyllene</td>
<td>Woody, spicy</td>
<td>31,39,40,41,42</td>
</tr>
<tr>
<td><strong>Myrcene</strong></td>
<td>Musty, wet soil</td>
<td>18,31,32,37,39,40,41,42</td>
</tr>
<tr>
<td>(E)-β-Farnesene</td>
<td>Sweet, mild</td>
<td>31,37,40,42</td>
</tr>
<tr>
<td>(E)-β-Ocimene</td>
<td>Herbaceous, tropical, sweet, warm</td>
<td>37,39,40,41,42</td>
</tr>
<tr>
<td>δ-Cadinene</td>
<td>Woody, dry, mild</td>
<td>31,37,40,41,42</td>
</tr>
<tr>
<td><strong>Esters (5)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>Pleasant, ethereal, fruity</td>
<td>18,32,37,39,41,42</td>
</tr>
<tr>
<td>Ethyl butyrate</td>
<td>Fruity</td>
<td>32,37,39,42</td>
</tr>
<tr>
<td>Ethyl hexanoate</td>
<td>Fruity</td>
<td>18,32,39,42</td>
</tr>
<tr>
<td>Neryl acetate</td>
<td>Fruity, floral, very sweet</td>
<td>37,39,40,41</td>
</tr>
<tr>
<td>Citronellyl acetate</td>
<td>Fresh, rosy, fruity</td>
<td>39,40,41,42</td>
</tr>
</tbody>
</table>

Consensus mandarin aroma volatiles were designated as compounds reported to be present in mandarin juices in at least four out of eight different publications. Volatiles detected in at least seven out of eight different experiments are in **bold** type.

a Flavor descriptions were taken from the University of Florida citrus flavor database (http://www.crec.ifas.ufl.edu/rouseff/#).

Juices were perceived in a consensus by three panelists by GC-O.47 Compounds were classified according to their odor activities: fruity, green/metallic/fatty, terpeney, green/grassy, citrus, mushroom and floral. Most compounds with aroma activity were terpene hydrocarbons, aldehydes and esters, as well as alcohols, ketones and sulfur compounds. GC-O analysis revealed compounds that were not detected by GC-MS, which included some unsaturated aldehydes and nor-isoprenoids with associated descriptors of fatty, apple sauce and floral.47 Chisholm et al.48 also noticed the preponderance of aldehydes, including unsaturated aldehydes with low odor thresholds in Clementine peel oil.

**Mandarin sensory profiles**

The sensory quality of fruits and vegetables, and of mandarins particularly, is determined by the perception and integration of many different attributes. For example, in a detailed sensory analysis study of Spanish mandarin juices, 29 attributes were chosen to describe appearance, odor, taste and texture (mouth-feel) of fresh and processed mandarin juice.49 Another study by Gmitter, Plotto and co-workers chose to describe the sensory quality of tangerine hybrids with a trained panel using 10 aroma descriptors and three basic taste descriptors.50
Figure 1. Sensory profiles of Or and new mandarin hybrids. Sensory profiles of freshly harvested mandarins were determined by a trained taste panel consisting of 10 persons.

Mandarin sensory profiling using a trained taste panel was also performed by Tietel and collaborators and Elmaci and Altung. The sensory profile of Or mandarin, which is considered the best mandarin variety in Israel and yields exceptionally high profits in export markets due to its excellent taste and flavor, was characterized by high sweetness, moderate acidity, high typical mandarin aroma and minimum off-flavor (Fig. 1). Furthermore, by conducting similar sensory evaluations of new mandarin hybrids in the Israeli citrus breeding program, it was found that all of the new varieties that achieved high sensory quality evaluation by the trained panelists had similar sensory profiles to that of Or mandarins, whereas inferior varieties differed from Or mandarins in various attributes. For example, the ARO-4 variety was more sour and had less typical mandarin aroma, and ARO-6 variety was gummy (difficult to chew) and somewhat bitter (Fig. 1). The results of these findings are also in agreement with the general assumption that good tasty fruit contains high levels of sugars, moderate acidity and a desirable amount of odor-active volatiles. Elmaci and Altug further found with the aid of a trained taste panel that Clementine mandarin flavor was characterized by high sweetness and floral and orange odors; Satsuma mandarin was also high in sweetness but low in floral, lemon and orange odors; and Bodrum mandarin had very high sourness, and floral and lemon odors. These studies should be followed by consumer panels to predict the desirable characters of mandarins. In another study, describing about 60 mandarin hybrids among the University of Florida citrus breeding program, principal components analysis (PCA) showed separation among hybrids based on sweet, sour and bitter tastes. Some flavor descriptors were highly correlated with basic tastes: e.g. sweet taste was correlated with ‘fruity’ and ‘cooked’ flavors, ‘fresh’ and ‘grapefruit’ flavors were associated with sour taste, and ‘sulphury’ flavor was associated with bitter taste. Other descriptors were correlated with each other, such as ‘floral’ and ‘orange’ flavor. Panelists could also distinguish between samples harvested multiple times from the same hybrid by increasing sweetness or decreasing sourness with later harvests. No typical ‘mandarin’ aroma or flavor was detected in the juice by panelists, mostly because samples were juiced with minimum peel oil components. Overall, there is a lack of published consumer studies to explain specific parameters of acceptance of mandarins.

EFFECTS OF POSTHARVEST OPERATIONS ON MANDARIN FLAVOR

In commercial practice, citrus fruit are often exposed after harvest to curing or ethylene degreening treatments, and afterwards are subjected to a number of processes on the packing line, including...
washing, rinsing, waxing, drying, sizing and packaging, all of which may alter flavor quality. In this section we will further discuss the effects of curing, ethylene degreening and waxing treatments on mandarin flavor and sensory acceptability.

### Effects of curing on mandarin flavor

Citrus fruits are often exposed to high temperatures (hot air or hot water) after harvest in order to allow wound healing, to reduce decay development and to enhance chilling tolerance. Nevertheless, heat treatments, and especially those involving exposure to high temperatures for long periods of time, may also adversely affect internal quality and flavor. Among heat treatments, curing (or high-temperature conditioning) involves holding the fruit at high temperatures of 30–38 °C and 94–98% relative humidity (RH) for a relatively long period of 3 days, and is applied mainly for decay control purposes. Recently, Burdon et al. showed that high-temperature conditioning at 30 °C for 3–5 days may also reduce juice acidity levels in early-season Satsuma mandarins. For example, it was reported that after 3 days at 30 °C juice acidity was reduced from 14.8 g L\(^{-1}\) at harvest to 10.6 g L\(^{-1}\), resulting in a remarkable increase in juice TSS : TA ratio from 6.67 at harvest to 9.37 after the heat treatment. These findings, although to a somewhat lesser extent, were recently confirmed by Tietel and collaborators. Thus high-temperature conditioning treatments may be applied to reduce acidity and improve taste of early-season mandarins, but yet special care must be taken to avoid excessive weight loss following exposure to high temperatures. In another study, Perez et al. reported that intermittent curing of Hernandina mandarins at a high temperature of 38 °C (18 h at 38 °C followed by 6 h at 20 °C and finally 18 h at 38 °C) did not cause any detrimental effects on fruit aroma or sugar and acid composition.

### Effects of ethylene degreening on mandarin flavor

The commercial practice of ethylene degreening was developed to promote external color development of green or poor-colored citrus fruit, i.e. to accelerate degradation of the green chlorophyll pigments and accumulation of orange/yellow carotenoid pigments. However, ethylene degreening may also have adverse effects on fruit internal and external quality, resulting in increased waste and accumulation of off-flavors. Tietel and collaborators found that degreening of early-season Satsuma mandarins by exposure for 3–5 days to 4 µL L\(^{-1}\) ethylene at 20 °C did not harm fruit sensory quality. On the contrary, combining ethylene degreening with high-temperature conditioning (degreening with ethylene for 5 days at a high temperature of 30 °C) rather improved fruit taste and sensory quality by reducing juice acidity levels, making the fruit less sour. Nevertheless, preliminary observations in our laboratory indicate that exposure of mature mid- and late-season mandarins to ethylene may harm fruit sensory quality by enhancing accumulation of off-flavors (Porat and Tietel, unpublished). Thus, to maintain mandarin flavor quality, it is probably preferable to degreen only less mature, early-season fruit but not mature fruit.

### Effects of waxing on mandarin flavor

All citrus fruits are commercially coated with waxes, which impart shine and reduce water loss and shrinkage. However, application of waxes also restricts gas exchange through the peel surface, so that the internal atmosphere of the fruit is modified, with enhanced CO\(_2\) and reduced O\(_2\) levels. The consequent buildup of anaerobic conditions in waxed fruit leads to enhanced anaerobic respiration and increased production of off-flavor volatiles, such as ethanol and acetaldehyde. It was recently reported that mandarins are much more sensitive to anaerobic conditions as compared with other citrus fruit, resulting in enhanced anaerobic respiration and production of off-flavor volatiles. Examination of various types of waxes revealed that polyethylene-based coatings are much more permeable to gas exchange than shellac- and wood rosin-based coatings and, therefore, are more suitable for coating mandarins. Furthermore, reducing the amounts of oxidized polyethylene solids and shellac in ‘Tag’, a commercial mandarin wax formulation, resulted in reducing the build-up of anaerobic conditions in the internal atmosphere of the fruit, and subsequent accumulation of ethanol and off-flavors. Therefore, it is recommended to coat mandarins with the most permeable wax available, even at the cost of reduced gloss and shine. Nowadays, there is an increasing interest in development of food-grade edible coatings for mandarins as well as other citrus fruit, with enhanced gas permeability properties and reduced effect on fruit flavor.

Sensory evaluation of fruit flavor by a trained taste panel revealed that coating Mor mandarins with commercial ‘Tag’ wax reduced flavor scores from between ‘good’ and ‘excellent’ in control unwaxed fruit to just ‘fair’ in wax-coated fruit after 7 days of shelf-life at 20 °C (Fig. 2(A)). Furthermore, the observed deterioration in flavor of waxed fruit was attributed to a slight decrease in sourness, but mainly to a decrease in typical mandarin flavor and enhanced accumulation of off-flavors (Fig. 2(B)). Thus application of wax coatings resulted in both a decrease in sensation of desired typical mandarin flavor and increase in the sensation of undesired off-flavors (Fig. 2).

### EFFECTS OF POSTHARVEST STORAGE ON MANDARIN FLAVOR

In current global markets, fresh mandarins are shipped across continents and thus need to be held in cold storage during transport and maintain their external and internal quality for at least 3–4 weeks after harvest for relatively short marketing distances, but often for even much longer periods of up to 6–8 weeks after harvest. For example, shipment of mandarins from South America to European markets requires maintaining fruit quality for at least 5–6 weeks after harvest, including 4 weeks of shipment by sea, followed by ground transportation by trucks, logistic distribution within supermarket chains and marketing at the retail shops. Since mandarins are much more perishable and have shorter postharvest storage lives than other citrus fruits, these long transport and distribution periods impose a major challenge for maintaining mandarin fruit quality and preventing deterioration in sensory acceptability during the postharvest marketing chain. Recent sensory evaluation studies conducted with Or, Mor and Clemenules mandarins demonstrated that during prolonged storage there is a gradual decrease in mandarin acceptability, which was attributed to decreases in acidity and typical mandarin flavor on the one hand, and accumulation of off-flavors on the other.

One of the major problems concerning preservation of mandarin fruit taste after harvest is the rapid decrease in juice acidity. Citric acid is utilized as the main respiratory substrate in citrus juice sacs and it is oxidized via the tricarboxylic acid (TCA) cycle to form adenosine triphosphate (ATP), resulting in a gradual decrease in citric acid intracellular reserves. Overall, in typical postharvest
storage trials, it was observed that juice TSS remained more or less constant during storage, whereas juice acidity gradually decreased by 2–3 g L\(^{-1}\) after 3 weeks + 3 days under shelf-life conditions and by 5–6 g L\(^{-1}\) after a longer storage period of 6 weeks + 3 days under shelf-life conditions.\(^{41,42,69}\) In the case of postharvest storage or shipment of early- or mid-season mandarins, which are harvested with relatively high juice acidity levels of between 11 and 15 g L\(^{-1}\), the subsequent decrease in juice acidity to final levels of 8–11 g L\(^{-1}\) might not be as serious, and will not have severe effects on overall fruit sensory acceptability. However, in the case of late-season mandarins (fruit harvested between end of February until April in the Northern Hemisphere), which are harvested when their initial juice acidity levels are relatively low, between 6 and 9 g L\(^{-1}\), any further decrease in these initially low-acid fruit during storage or transport may be detrimental to sensory quality, resulting in perception of bland fruit.\(^{70}\)

Unlike with juice TSS and TA levels, relatively little is known regarding aroma volatiles involved in determining the postharvest decrease in mandarin flavor and accumulation of off-flavors. Changes in composition and content of aroma volatiles were measured in Mor mandarins at harvest and after 3 and 6 weeks of cold storage at 5 °C.\(^{41}\) Analyses of variance (ANOVA) with pairwise contrasts showed decreases by at least 50% of the levels of 23 aroma compounds, and significant increases by at least twofold in the contents of 12 other aroma volatiles (Fig. 3). Hence the contents of many aroma volatiles that were present at high levels in fresh harvested Mor mandarins decreased after harvest and, therefore, might account for the observed decrease in typical mandarin flavor. The aroma volatiles whose content decreased most were linalool and β-myrcene, followed by pentanal, β-citronellol, 1-octanol, decanal, octanal, α-terpineol, α-pinene and terpinolene (Fig. 3(A)). It should be noted that most of these volatiles are key consensus aroma compounds in mandarins (Table 1) and, therefore, the decrease in their content during storage would likely result in loss of typical mandarin aroma. Overall, volatiles with the most pronounced decrease after harvest in Mor mandarins included four alcohols, three aldehydes and three terpenes, almost all of which have pleasant, desirable, sweet, floral, fruity and citrus aromas.

In contrast, the aroma volatiles that increased the most after harvest in homogenized segments of Mor mandarins were mainly ethanol and ethyl acetate, followed by ethyl propanoate, as well as various other compounds, such as acetaldehyde, (E)-2-octenal, acetic acid, (E)-2-hexenal, ethyl 2-methylpropanoate, ethyl 2-methylbutanoate, ethyl dodecanoate, 3-methylbutanol and ethyl hexanoic acid; some of these compounds have solventy, green, malty and ethereal aromas, associated with perception of off-flavors (Fig. 3(B)). The most pronounced increases of aroma volatiles during postharvest storage of Mor mandarins were from ethanol and ethyl acetate, which are main products of the ethanol fermentation and the anaerobic respiration pathway, known to be involved in causing off-flavors in mandarins.\(^{3,60,63,64}\) Nevertheless, an increase in esters, which have fruity aroma, concomitant with a decrease in terpenes and aldehydes, which have green, piney, citrus aroma, is likely to create a flavor that is not typical of citrus, and likely to be perceived as ‘overripe’ and ‘off flavored’ (Fig. 3(B)).

**CONCLUSIONS AND FUTURE PERSPECTIVES**

Along with the continuous increase in global consumption of easy-peeling mandarins and the demand of consumers to purchase high-quality and tasty fruit, it became a high priority to further investigate the biochemical nature and molecular components involved in creating the pleasant desired mandarin flavor, and learn how various pre- and postharvest factors may influence mandarin taste and aroma and consequently consumer sensory acceptability. The main factor that affects mandarin flavor is first of all the genetic background; hence, as shown in Fig. 1, it is crucial to breed and select mandarin varieties with superior taste and aroma. Another important aspect that is critical to mandarin flavor is the time of harvest, with a special consideration to fruit maturity stage at harvest since, as demonstrated in this review, early-season fruit may be too sour whereas late-season fruit often lack appropriate acidity and become tasteless and bland. In this paper, special attention was paid to the importance of postharvest handling operations in governing mandarin taste and aroma and eventually impacting sensory quality. In this respect, the commercial benefits of curing, ethylene degreening and waxing in reducing decay, accelerating peel color development and imparting shine, respectively, were emphasized but their possible detrimental effects on fruit sensory acceptability were also indicated. Finally, the effects of prolonged storage on fruit sensory quality was discussed, including observed decreases in acidity and typical mandarin flavor and accumulation of off-flavors, as well as which aroma volatiles may be involved in governing these processes.

In the future, we foresee continuing research on mandarin flavor in the following main directions: (1) further identify by means of GC-O (‘sniffing’ techniques) key aroma volatiles involved in formation of pleasant desired mandarin flavor on
one hand, and undesired off-flavors on the other; (2) further elucidate the biochemical and molecular mechanisms involved in biosynthesis of aroma compounds in mandarins, including use of proteomic, transcriptomic and metabolomic tools; (3) further understand the underlying genetic basis of flavor and aroma to facilitate the breeding of new mandarins with superior flavor; (4) further examine the effects of various preharvest factors, such as rootstock/scion combinations, and horticultural management (irrigation, fertilization, and sprays with plant growth regulators) on mandarin flavor; and (5) further examine the effects of postharvest operations and storage conditions, including temperature management and search for alternatives to the currently used waxes etc. on preservation of mandarin fruit flavor during the postharvest marketing chain.

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