Fungicidal Activity of Plant Volatile Compounds for Controlling *Monilinia laxa* in Stone Fruit

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ABSTRACT

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Nine plant-volatile compounds were tested for their activity against *Monilinia laxa*, the cause of brown rot in stone fruit. In vitro trials on conidial germination and mycelial growth showed a consistent fungicidal activity of *trans*-2-hexenal, carvacrol, and citral, whereas *trans*-cinnamaldehyde, hexanal, (-)-carvone, eugenol, 2-nonanone, and *p*-anisaldehyde exhibited a progressively lower inhibition. The best inhibitor of conidial germination was *trans*-2-hexenal (effective dose for 50 and 90% inhibition [ED₅₀ and ED₉₅] = 7.53 and 9.4 µl/liter, respectively; minimal inhibitory concentration [MIC] = 12.3 µl/liter), whereas carvacrol was the best inhibitor of mycelial growth (ED₅₀ and ED₉₅ = 2 and 3.4 µl/liter, respectively; MIC = 6.1 µl/liter). The three most active compounds in in vitro studies also were tested in vivo as postharvest biofumigants. The best control of brown rot was with *trans*-2-hexenal (efficacy ranging from 46.2 to 80.3%, depending on cultivar), whereas citral and carvacrol resulted in a lower efficacy of 40 and 32.9%, respectively. Fumigation with *trans*-2-hexenal at concentrations that stopped decay did not cause any visible disorders to plum, whereas it was phytotoxic to apricot, peach, and nectarine and produced off-odors or off-flavors in all species of stone fruit tested.

Additional keywords: aroma compounds, sensory evaluation

Brown rot is one of the main diseases in stone fruit (7,32,34) and occurs both in the field and after harvest. Three species of *Monilinia* are recognized as causal agents of brown rot. *Monilinia laxa* (Aderhold & Ruhland) Honey is the most common pathogen in European and South African growing areas. *M. fructicola* (G. Winter) Honey is the most important causal organism in North America, Australasia, Japan, and Brazil, whereas it is a quarantine organism in Europe. *M. fructigena* (Aderhold & Ruhland) Honey occurs on both stone and pome fruit in Europe, but does not cause the extensive crop loss that *M. laxa* does. Losses are particularly severe if humidity, warm temperatures, and abundant rainfall prevail prior to harvest. *M. laxa* germination proceeds rapidly on wet fruit and is faster on ripening fruit than on fruit at pit hardening; in addition, germ tube growth is restricted when fruit are dry (18). The pathogen invades the fruit through wounds caused by insects or adverse weather and injuries caused by harvesting and handling operations. The co-

nidia also can penetrate through microlesions, stomata, and lenticels of fruit skin (31). In some cases, infections occurring in the field remain quiescent until favorable conditions allow the pathogen to overcome host defenses, such that disease symptoms frequently develop during the postharvest phase. Postharvest losses are estimated to be 5 to 10% when postharvest fungicides are used; in countries where these treatments are not authorized, losses may reach 50% or more when favorable conditions are present (28).

In Italy, brown rot is controlled by fungicide spray programs in the field, whereas postharvest fungicide application is not allowed. The public demand to reduce the use of synthetic pesticides in the environment and the amount of chemical residues on fruit have stimulated the search for methods that are safe for humans. Among nonconventional treatments, several naturally occurring volatiles in the aroma component of fruit and vegetable products or in essential oils of spices and herbs have shown antimicrobial, antifungal, and insecticidal properties (14,21,38). In addition, some of these compounds may play an interesting role in the control of defense gene expression, probably as a signal mediator within and between plants (17). Some studies on antifungal activity by plant aroma compounds against *M. laxa* or *M. fructicola* have been carried out in in vitro (10,39,43) and in vivo trials (13). In

other experiments, *trans*-2-hexenal (3–5,41) and citral (11,35,39,40,45) have shown fungal inhibition against many fungal pathogens, but were not tested against *M. laxa*. The search for fumigants for postharvest disease control seems to be particularly interesting because of minimal handling and absence of wetting of fruit involved in vapor treatments.

The present study aimed to determine the efficacy of some plant volatiles against *M. laxa* in vitro and to test promising compounds as fumigants for postharvest treatments against brown rot in stone fruit.

MATERIALS AND METHODS

Volatile compounds. The aldehydes (hexanal, *trans*-2-hexenal, citral, *trans*-cinnamaldehyde, and *p*-anisaldehyde), the phenols (carvacrol and eugenol), and the ketones (2-nonanone and (-)-carvone) were screened for their ability to control *M. laxa* conidia germination and mycelial growth. The volatile compounds, as commercial preparations with a nominal purity of least 95%, were purchased from Sigma-Aldrich (Milan, Italy). The concentrations reported are expressed as liquid volume of volatile compound on filter paper per dish volume (in vitro) and as liquid volume of volatile compound in the flask per air volume inside the treatment apparatus (in vivo).

The pathogen. A monoconidial culture of *M. laxa* (isolate FF 34, from our collection) was grown on V8 agar (V8A; 250 ml of V8 vegetable juice and 40 g of agar per 1,000 ml of distilled water). Culture plates were incubated at 25°C under a photoperiod of 12 h of light and 12 h of dark for 10 to 14 days. For in vitro tests and fruit inoculation, conidial suspensions of *M. laxa* were prepared by washing the pathogen colonies with sterile distilled water containing 0.05% (vol/vol) Tween 80. Spore concentrations were determined with a hemacytometer and adjusted to 10³ conidia/ml.

In vitro experiments. The effect of the volatile compounds on conidial germination and mycelial growth of *M. laxa* was tested on malt extract agar, as described in a previous article (29). Liquid volumes of volatile compounds were added to 90-mm paper filter placed on the cover inside the dish. The dishes then were covered quickly and wrapped in parafilm. At least five concentrations of compounds were tested and

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varied from 0.4 to 393.7 µl/liter and from 3.1 to 984.2 µl/liter for mycelial growth and conidial germination, respectively. Control treatments consisted of distilled water. For each treatment, for each compound at each of the concentrations tested, eight petri dishes (replications) were used. The number of germinated conidia and colony diameter were recorded after 3 and 7 days of incubation with volatile compounds, respectively. Minimum inhibitory concentration (MIC) was considered as the lowest concentration of the test compound at which no conidial germination or mycelial growth was observed. In turn, parafilm and filter papers were removed from the dishes and another assessment was carried out after 7 days at 20°C in order to evaluate whether the activity of the compounds was fungistatic or fungicidal. The experiments were performed twice.

Fruit. Apricot (cv. Tyrinthos), nectarine (cvs. Laura, Independence, Spring Bright, Stark Red Gold, and Weinberger), peach (cv. Elegant Lady), and plum (cvs. Angelino, Blackamber, Black Gold, and TC Sun) fruit harvested at commercial maturity were purchased from the Emilia-Romagna Growers' Cooperative Intesa. Only visibly undamaged and disease-free fruit were used in the experiments. Fruit were stored at 0°C and used within 7 days after harvest.

Inoculation. Fruit were wounded with a sterile nail (one wound per fruit, in the equatorial zone, 2 by 2 mm) and dipped for 1 min in a conidial suspension (10^3 conidia/ml) of *M. laxa* prepared as described above. Inoculated fruit were kept for 1 h at room temperature (20°C) before treatment with volatile compounds. The control was represented by nontreated fruit, wounded and inoculated as described above. Four replicates were used in each treatment and 26 fruit were used in each replication.

Effects of volatile compounds on brown rot control and fruit quality. Fruit were exposed to the vapor of the compounds in a cabinet with a capacity of 100 liters, as previously described (29). Treatments were performed at 20°C over a 24-h period using the compounds that showed the best results in *in vivo* preliminary trials (*data not reported*). In order to find the concentration effective against brown rot and not phytotoxic to fruit, the following concentrations were tested: 5, 10, 20, and 40 µl/liter for *trans*-2-hexenal; 25, 50, and 100 µl/liter for carvacrol; and 25, 50, and 200 µl/liter for citral. After treatment, fruit were removed from the cabinet and kept at 20°C and 95% relative humidity. Nontreated fruit were closed in a cabinet at 20°C for 24 h with air circulation and then placed under the same conditions of temperature and humidity as treated fruit. The percentage of infected wounds was recorded 4 days after inoculation. All experiments were performed twice. The pos-

sible phytotoxic response and the effect on fruit odor were examined both after treatments and after 3 days at 20°C following treatment (simulation of fruit market life at ambient temperature). Then, a 10-member, trained panel described and compared fruit odor of treated and nontreated fruit using an intensity scale increasing from 1 (= no off-odors) to 9 (= very strong off-odors). For trials in which no visible injuries occurred after exposure to *trans*-2-hexenal, the effect of treatment on fruit sensory traits (sweetness, sourness, fruitiness, off-flavors, hardness, and juiciness) also was tested using fruit held for 3 days at 20°C following treatment. For the evaluation, 10 fruit from each treatment and the control were selected for homogenous firmness from samples of 26 noninoculated fruit. Firmness expressed as Newton was measured, after removing the skin, on opposite sides of each fruit using a Chatillon digital penetrometer fitted with an 8-mm fruit tester probe. The fruit were cut into six pieces and given to 10 tasters, each of whom assessed six pieces from different fruit. The samples, coded with three numbers, were presented at random one at a time. The tasters were instructed to rinse out their mouths with water between samples. Sensory profile was assessed using a nine-category scale. The intensity of the descriptors increased from 1 (= none) to 9 (= extreme) for juiciness, sweetness, sourness, fruitiness, off-odors, and off-flavors. For hardness, 1 = extremely hard and 9 = extremely soft; for sweet-acid balance, 1 = mainly sour, 5 = balanced, and 9 = mainly sweet. Training of panelists and general testing conditions followed fundamental principles of good practice in sensory evaluation of food (22,27).

Statistical analysis. For each volatile compound, the effective dose (ED) for 50 and 95% inhibition (ED₅₀ and ED₉₅, respectively) was calculated using probit-analysis applied to the percentages of conidial germination and mycelial growth obtained from *in vitro* experiments. Regression lines between the logarithm of the

compound concentrations and the effectiveness indices transformed in probit were calculated. The data from the *in vivo* experiments were combined based on Bartlett's Test, which indicated homogeneity. Means were separated using the least significant difference test at $P \leq 0.05$. The data were processed using the statistical package Statistica for Windows (StatSoft Italia srl, Padova, Italy).

RESULTS

In vitro experiments. The regression lines of the logarithm of the compound concentrations and the effectiveness indices transformed in probit, which were used to calculate the ED₅₀ and ED₉₅, were highly significant (correlation coefficients between 0.91 and 0.99, confidence limits 95%, $P \leq 0.01$; *data not reported*). The most active compounds against *M. laxa* were found to be *trans*-2-hexenal, carvacrol, and citral, and they inhibited either conidial germination or mycelial growth (Table 1). In particular, *trans*-2-hexenal was the best inhibitor of conidial germination (ED₅₀ = 7.5 µl/liter, ED₉₅ = 9.4 µl/liter, and MIC = 12.3 µl/liter), whereas carvacrol was the best mycelial growth inhibitor (ED₅₀ = 2 µl/liter, ED₉₅ = 3.4 µl/liter, and MIC = 6.1 µl/liter). Neither conidial germination nor mycelial growth was observed at 20°C 7 days after the filter papers that were treated with *trans*-2-hexenal and carvacrol at the MIC level had been removed from the dishes. For citral, MIC for both conidial germination and mycelial growth was 24.6 µl/liter; however, higher concentrations were required to inhibit the resumption of pathogen growth during the week after the treatment was removed (36.9 and 49.2 µl/liter for mycelial growth and conidial germination, respectively). Better inhibition against mycelial growth (MIC = 24.6 µl/liter and inhibition after the removal of treatment = 30.7 µl/liter) than against conidial germination (MIC = 98.4 µl/liter) was exhibited by *trans*-cinnamaldehyde. The opposite was found for hexanal and 2-nonanone, which exhib-

Table 1. Minimum inhibitory concentrations (MICs) and effective dose for 50 and 95% inhibition (ED₅₀ and ED₉₅, respectively; µl/liter) of the treatments with different volatile compounds measured by conidial germination and mycelial growth of *Monilinia laxa*

Compound	Conidial germination ^x			Mycelial growth		
	ED ₅₀	ED ₉₅	MIC	ED ₅₀	ED ₉₅	MIC
<i>trans</i> -2-Hexenal	7.5	9.4	12.3 ^y	23.0	28.3	36.9 ^y
Carvacrol	7.1	14.7	24.6 ^y	2.0	3.4	6.1 ^y
Citral	11.4	19.3	24.6 ^z	5.2	13.3	24.6 ^z
<i>trans</i> -Cinnamaldehyde	5.0	23.7	98.4 ^y	9.7	17.3	24.6 ^z
Hexanal	15.6	20.1	24.6 ^z	57.2	91.0	123.0 ^y
(-)-Carvone	41.3	63.1	73.8 ^z	10.0	33.0	73.8 ^z
Eugenol	19.7	84.7	246.1 ^y	4.2	17.4	36.9 ^y
2-Nonanone	33.6	43.6	49.2 ^z	47.1	132.6	393.7 ^z
<i>p</i> -Anisaldehyde	109.9	266.5	984.2 ^y	71.5	213.6	295.3 ^y

^x Fungicidal activity was evaluated 7 days after removal of parafilm and the filter paper containing the volatile compound. Means of 16 replicates.

^y MICs that did not result in growth after removal of filter paper.

^z MICs that did result in growth after removal of filter paper.

ited considerable inhibitory activity only with regard to conidial germination (MICs = 24.6 and 49.2 µl/liter, respectively). Moreover, higher concentrations of hexanal and 2-nonanone were needed to inhibit the resumption of conidial germination during the week after their removal from dishes: 196.8 µl/liter for hexanal and >147.6 µl/liter for 2-nonanone (*data not determined*). Eugenol showed consistent inhibition of mycelial growth at 36.9 µl/liter, but only slight inhibition of conidial germination (MIC = 246.1 µl/liter). (–)-Carvone inhibited both conidial germination and mycelial growth at 73.8 µl/liter, whereas concentrations of 123 and 98.4 µl/liter for conidial germination and mycelial growth, respectively, were needed to inhibit the regrowth of pathogen during the week after the removal of treatment. *p*-Anisaldehyde and 2-nonanone were the least active compounds for restricting conidial germination and mycelial growth, respectively.

In vivo experiments. Treatment with *trans*-2-hexenal at 5 µl/liter was found to be ineffective in brown rot control, and severe phytotoxicity resulted from treatment with 20 µl/liter in apricot or with 40 µl/liter of *trans*-2-hexenal in peach and nectarine, stimulating the development of infections by *M. laxa* and *Penicillium expansum* on damaged tissues (*data not reported*). Hence, *trans*-2-hexenal concentrations of 10 or 20 µl/liter were chosen for subsequent experiments. The most effective doses of *trans*-2-hexenal were 10 µl/liter in apricot (efficacy of 68.5%) and 20 µl/liter in peach, nectarine, and plum, with efficacy varying from 80.3% in cv. Weinberger to 46.2% in cv. Black Gold (Figs. 1 and 2). The only positive results with citral (40% efficacy) or with carvacrol (32.9% efficacy) were obtained on ‘Spring Bright’ nectarine at a rate for each compound of 50 µl/liter (Table 2). Lower or higher concentrations of citral (25 and 200

µl/liter) and carvacrol (25 and 100 µl/liter) were not effective. In some cases, suberization of the epidermal tissues surrounding the wound was observed in fruit treated with *trans*-2-hexenal compared with nontreated controls, particularly for the highest concentrations of the compound.

Different fruit response to *trans*-2-hexenal treatment was exhibited among stone fruit species (Table 3). No visible disorders were observed in plum fruit exposed to *trans*-2-hexenal at 10 or 20 µl/liter. In contrast, phytotoxic symptoms were induced in all cultivars of apricot, nectarine, and peach by treatment with *trans*-2-hexenal at 20 µl/liter and in apricot cv. Tyrinthos, nectarine cv. Weinberger, and peach cv. Elegant Lady by with the compound at 10 µl/liter. Phytotoxicity caused by *trans*-2-hexenal consisted of irregular dark-yellow or brown surface blemishes in peach and nectarine, and dark orange blemishes in apricot. In Weinberger

Fig. 1. Effect of *trans*-2-hexenal on brown rot control in apricot, nectarine, and peach. Fruit were wounded and inoculated with *Monilinia laxa* (10^3 spores/ml). Means are averaged values of two experiments, each containing four replicates of 26 fruit each per treatment. Disease was assessed 4 days after pathogen inoculation. Within each cultivar, means followed by different letters are significantly different according to the least significant difference test ($P \leq 0.05$). Asterisk (*) indicates data were not recorded, due to the development of secondary infections on tissues damaged by treatment.

Fig. 2. Effect of *trans*-2-hexenal on brown rot control in plum. Fruit were wounded and inoculated with *Monilinia laxa* (10^3 spores/ml). Means are averaged values of two experiments, each containing four replicates of 26 fruit each per treatment. Disease was assessed 4 days after pathogen inoculation. Within each cultivar, treatments means followed by different letters are significantly different according to the least significant difference test ($P \leq 0.05$).

nectarine, surface crackings also were observed. The exposure to *trans*-2-hexenal induced off-odors in fruit, described as a “green” (leafy) and “butyric” aroma in nectarine and peach and as a “green,” “fermented-acetic,” and “cheesy” aroma in plum (33). The intensity of fruit off-odors decreased during ripening. However, anomalous odors were still noticeable in several cultivars after 3 days at 20°C. The effect on other sensory attributes was assessed in trials where no visible injury occurred, in plum and Stark Red Gold

nectarine fruit treated with *trans*-2-hexenal at 10 to 20 µl/liter. “Green and bitter” flavors (grapefruit-like) rated from slight to moderate-high intensity were associated with these treatments (Table 3). Texture attributes were not affected by exposure to *trans*-2-hexenal vapor (*data not reported*). No detrimental effects on sensory traits were perceived after ripening in peach, nectarine, and plum fruit treated with *trans*-2-hexenal at 5 µl/liter or in apricot treated with the compound at 2.5 µl/liter (*data not reported*). Neither phytotoxicity symptoms nor fruit off-odors were observed in peach and nectarine fruit treated with carvacrol (25 to 100 µl/liter) or citral (25 to 200 µl/liter). Moreover, no fermented aroma or other off-odors or flavors were perceived in control fruit.

DISCUSSION

In this study, we demonstrated that *trans*-2-hexenal, carvacrol, and citral consistently exhibited fungicidal activity against *M. laxa* in in vitro tests, whereas *trans*-cinnamaldehyde, hexanal, (–)-carvone, eugenol, 2-nonanone, and *p*-anisaldehyde were less effective. In accordance with our previous work on *Penicillium expansum* (29), *trans*-2-hexenal was the best inhibitor of *M. laxa* conidial germination and carvacrol the best inhibitor of mycelial growth. Our results were consistent with reports in the literature that describe carvacrol as an inhibitor of conidial germination and mycelial growth of several post-harvest pathogens, including *M. laxa* and *M. fructicola* (6,10,39,40). They also found significant antifungal activity exhibited by *trans*-2-hexenal (3–5,41) and citral (11,35,39,40,45) in in vitro or in vivo trials against other postharvest pathogens, such

as *Botrytis cinerea*, *Alternaria alternata*, *P. italicum*, *P. digitatum*, and *Geotrichum candidum*.

The α,β-unsaturated aldehyde *trans*-2-hexenal is one of the most widespread volatile compounds naturally occurring in vegetables and fruit, including stone fruit, common in the human diet, contributing flavors described as “green notes” (8,25,26,42,44). Its production increases rapidly in damaged plant tissues, a result of the activation of the lipoxygenase hydroperoxide lyase enzymatic pathway in response to wounding or pathogen attack (15,19,20). The phenol carvacrol occurs particularly in the essential oils from Greek and Spanish oregano (*Origanum vulgare* and *Thymus capitatus*), in which it represents the characteristic odor of the product (9), and the aldehyde citral, having the typical odor of lemon, is contained inside oil glands of lemon and lime (36).

Previous studies on *B. cinerea* with *trans*-2-hexenal (16) and on *Cladosporium herbarum* with carvacrol (1) showed that these compounds cause severe damage to fungal membranes and cell walls, which leads to morphological deformations and collapse and deterioration of conidia or hyphae. The fungicidal activity of *trans*-2-hexenal and citral aldehydes may be ascribed to the high electrophilic properties of the carbonyl group adjacent to the double bond that make these compounds particularly reactive with nucleophiles, such as protein sulfhydryl and amino groups of the pathogen (2). The toxicity effects of carvacrol may be due to the interaction of the phenolic hydroxyl group with the pathogen cell membrane (37). The efficacy of some compounds depended on the pathogen growth stage. *M. laxa* mycelial

Table 2. Effect of citral and carvacrol treatments on brown rot control in several cultivars of nectarines^y

Compound, cultivar	Treatment	Infected wounds (%) ^z
Citral		
Independence	Control	50.0 a
	25 µl/liter	55.0 a
Laura	Control	48.1 a
	200 µl/liter	43.3 a
Spring Bright	Control	57.7 a
	50 µl/liter	34.6 b
Carvacrol		
Laura	Control	56.7 a
	25 µl/liter	53.8 a
Spring Bright	Control	81.7 a
	50 µl/liter	54.8 b
Stark Red Gold	Control	72.1 a
	100 µl/liter	65.4 a

^y Fruit were wounded and inoculated with *Monilinia laxa* (10³ spores/ml).

^z Means are averaged values of two experiments, each containing four replicates of 26 fruit each per treatment. Disease was assessed 4 days after pathogen inoculation. Within each cultivar and compound, means followed by different letters are significantly different according to the least significant difference test ($P \leq 0.05$).

Table 3. Effect of *trans*-2-hexenal vapor treatment on fruit quality

Stone fruit, cultivar	Dose (µl/liter)	Phytotoxic symptoms after ^y		Off-odors after ^z		Off-flavors after ^z
		Treatment	3 days at 20°C	Treatment	3 days at 20°C	3 days at 20°C
Apricot						
Tyrinthos	10	4	5	3*	2*	n.d.
Nectarine						
Laura	10	1	1	3*	2*	3*
	20	2	3	5*	3*	n.d.
Stark Red Gold	10	1	1	3*	2*	3*
	20	4	5	5*	3*	n.d.
Weinberger	10	2	3	3*	2*	n.d.
	20	5	7	5*	3*	n.d.
Peach						
Elegant Lady	10	2	4	5*	4*	n.d.
	20	4	5	6*	4*	n.d.
Plum						
Angeleno	10	1	1	3*	1	3*
	20	1	1	5*	3*	5*
Blackamber	10	1	1	4*	3	3*
	20	1	1	5*	3*	5*
Black Gold	10	1	1	4*	3*	4*
	20	1	1	5*	4*	6*
TC Sun	10	1	1	4*	2*	3*
	20	1	1	6*	4*	5*

^y Degree of skin damage severity: 1 = none, 3 = slight, 5 = moderate, 7 = severe, and 9 = extreme.

^z Intensity: 1 = none, 3 = slight, 5 = moderate, 7 = high, 9 = extreme, n.d. = not determined, and * = significantly different from the control based on least significant difference. Neither off-odor nor off-flavor was perceived in control fruit.

growth was more sensitive to the phenols carvacrol and eugenol and to the aromatic aldehydes *trans*-cinnamaldehyde and *p*-anisaldehyde than was conidial germination, whereas the opposite was found for the aliphatic aldehydes *trans*-2-hexenal and hexenal and the ketone 2-nonanone. A greater sensitivity of conidia than mycelia to *trans*-2-hexenal vapors also was found in *B. cinerea* (16).

Bioassay results confirmed the antifungal activity against *M. laxa* by *trans*-2-hexenal vapor treatment (20 µl/liter in peach, nectarine, and plum and 10 µl/liter in apricot), with efficacy varying from 42.6 to 97.1%. Citral and carvacrol (50 µl/liter) showed moderate effects on the pathogen. In addition to the high reactivity of the compound, the antifungal activity of *trans*-2-hexenal may be attributed to its volatility relative to that of citral and carvacrol. (12). In addition to a direct effect on the fungal pathogen, *trans*-2-hexenal may stimulate fruit defense mechanisms. Recent studies in *Arabidopsis thaliana* have shown that *trans*-2-hexenal treatment to control *B. cinerea* activates several defense-related genes, such as allene oxide synthase and lipoxygenase 2 (23). In addition, the treatment induces lignification of leaves, and accumulation of protein plant defensin 1.2 and pathogenesis-related protein 3 transcripts and camalexin (24). In our study, a suberization of the epidermal tissues surrounding the wound also was observed in some fruit treated with *trans*-2-hexenal compared with the control. The treatment probably stimulated wound repair mechanisms, acting as a physical barrier to the penetration of the *M. laxa* hyphae.

Compared with our previous studies (29,30), stone fruit were found to be more sensitive to *trans*-2-hexenal injury than were pome fruit. A differential sensitivity to *trans*-2-hexenal also was observed among stone fruit species, increasing from plum, to nectarine and peach, to apricot. No phytotoxic effect was observed in plums treated with *trans*-2-hexenal at 10 or 20 µl/liter. By contrast, the same concentrations caused phytotoxicity in most apricot, nectarine, and peach cultivars in the present study. Probably, more *trans*-2-hexenal was absorbed by apricot, nectarine, and peach fruit than by plum fruit, causing differences in the aroma compound metabolism and in the phytotoxic response. As found in other studies on strawberry, blackberry, and grape (4,5), *trans*-2-hexenal is absorbed and metabolized by fruit; however, the level of adsorption, the products of the metabolism, and the fruit sensitivity to the compound vary among fruit species and cultivars. In addition, *trans*-2-hexenal treatment using concentrations effective in brown rot control induced off-odors or off-flavors in all cultivars of stone fruit, and these problems persisted, although with less intensity, even after ripening.

The results obtained in this study showed a significant activity of *trans*-2-hexenal vapor treatment in the control of *M. laxa* in in vitro and in vivo trials. The efficacy in brown rot control and the natural occurrence of *trans*-2-hexenal in many edible products, suggesting it has a low toxicity to humans, could make *trans*-2-hexenal a potential postharvest biofumigant. However, the phytotoxic response found in apricot, nectarine, and peach makes practical application of *trans*-2-hexenal vapor treatment on these fruit species difficult. In contrast, fumigation with *trans*-2-hexenal seems to be more promising in plum fruit, due to their higher tolerance to the compound, if treatment conditions that eliminate detrimental effects on sensory traits are found in further studies.

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