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Physico-chemical and Sensory Evaluation of Strawberries after Acetic Acid Vapour Treatment

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Summary

Grey mould, caused by *Botrytis cinerea*, is the main reason of decay in harvested strawberries. Acetic acid (AA) vapour treatment considerably inhibits the growth of *B. cinerea*. For practical application, it is a prerequisite that antimicrobial treatments are gentle and guarantee the maintenance of internal quality, and fruit odour and flavour. Previous studies found indications that the odour of strawberries was affected by AA fumigation. Therefore, a panel test was performed to evaluate the conditions when strawberries were affected by AA treatments. For this purpose, fruit were fumigated with different AA concentrations (0, 2 and 4 mg l^{-1}) and stored for different times (2 and 26 h) in boxes wrapped with perforated plastic film. Concomitant with the sensory tests, mass losses and stiffness of fruit as well as their contents of soluble sugars (glucose, fructose, and sucrose), titratable acidity, vitamin C and total osmotic substances were determined.

AA treatment of strawberries resulted in significantly increased water losses leading to fruit that are less stiff. While the soluble sugar or acid contents of fruit were not affected by AA fumigation, this treatment diminished the increase in vitamin C generally observed during storage. Strawberries did not show significant differences in flavour, independent of the AA concentration and storage time. However, members of a consumer panel noticed a significant change in odour even at an AA concentration of 2 mg l^{-1}. The perception of unpleasant fruit odour increased during storage, though differences were not statistically significant compared with the results of the initial evaluation. In conclusion, AA vapour fumigation is not a suitable technique for strawberry disinfection.

Key words. acetic acid vapour – strawberry – flavour – odour

Introduction

Strawberries are one of the most popular fruits which are mainly eaten fresh. In 2003, the Food Agriculture Organization (FAO) listed 71 countries where strawberries are grown, and the total world production of strawberries was approximately 3.2 million tons (FAO 2004). Nevertheless, strawberries are perishable and susceptible to fungal decay. Grey mould, caused by *Botrytis cinerea*, is the main cause of losses in harvested strawberries. In recent years, several reports have shown that treatment of several types of fruit such as apples, pears, apricots, and plums with acetic acid (AA) vapour was effective in suppressing fungal decay (SHOLBERG and GAUNCE 1995, 1996; SHOLBERG et al. 2000, 2004; LIU et al. 2002). Also, AA treatment of strawberries has been successful in suppressing *B. cinerea* growth (MOYLS et al. 1996; HASSENBERG et al. 2010). Best control was achieved by triple treatment with 2 mg l^{-1} AA for 90 min without any phytotoxicity to the fruit (HASSENBERG et al. 2010). These studies indicate that the application of AA seems possible for post-harvest fruit disinfection.

In principle, the application of AA should be harmless, based on the fact that AA is a universal metabolic intermediary and occurs in plants and animals. It is commonly used by food manufacturers as an antimicrobial preservative or acidulant in a variety of food products (DAVIDSON and JUNEJA 1990). However, AA is a strong acid and some authors observed stem browning and brown streaks caused by increasing AA concentration (SHOLBERG and GAUNCE 1996; CHU et al. 1999).

An important requirement for the use of a sanitizer is the quality guarantee of the produce. Beside the analysis of objectively measurable parameters such as vitamin C, total soluble solids content, fruit softening and water losses during storage, panel tests are required to verify the acceptance of consumers. Therefore, in the present study, the potential effects of AA fumigation at two concentrations on the nutritional and physico-chemical quality of strawberries were analyzed. In a parallel sensory test, panelists determined whether AA-treated strawberries had acquired the taste and/or smell of AA. So, the objective of this study was to determine if AA treatment is effective in extending the shelf life of strawberries without affecting fruit quality.

Materials and Methods

Plant material

Organically grown strawberries ('Pegasus') were obtained from a local farmer (Potsdam, Germany) directly after harvest and immediately used for experiments.

Fumigation treatment and evaluation of physico-chemical fruit quality parameter

For analysis of quality parameters, strawberries were randomly sorted into nine batches of 20 fruit each. Quality parameters of freshly harvested fruit were determined on an additional 40 strawberries. Three batches of fruit were used as untreated controls. Following the method of SHOLBERG and GAUNCE (1995) as applied by HASSENBERG et al. (2010), the six remaining groups of strawberries were fumigated with acetic acid (100 %, Carl Roth GmbH & Co., Germany) in a sealed Perspex box (volume = 22.4 l) at 23 °C for 30 min (Fig. 1).

The box lid was fitted with a gasket and flanged to permit hermetic sealing of the chamber. The chamber was humidified for 30 min before fumigation resulting in a nearly water-saturated atmosphere. Therefore, tissue paper soaked with deionized water was placed in the chamber and an axial blower (XD 8025 HS, XINDA Electric CO., LTD., China) ensured adequate air movement and a well-mixed atmosphere. After stopping the axial blower and removing the tissue paper, 20 strawberries (4 rows of 5 each) were placed on a grid in the chamber, and AA, at two different concentrations (2 and 4 mg l^{-1}, related to the chamber volume), was injected with a syringe onto a paper filter through a port in the lid. After the injection, the axial blower, located under the paper filter, was turned on again. During treatments, temperature and relative humidity were kept constant. After AA treatment, fruit were packed in batches (see above). The potential effects of AA fumigation on fruit quality were assessed during 4-d storage in a climate chamber (WK 111-600-BSB, Weiss Umwelttechnik GmbH, Germany) at 2 °C and 95 % RH (water vapour saturation deficit, Δw, approx. 0.35 kPa MPa^{-1}) using a randomised arrangement. Fresh mass (FM) of fruit was determined at regular intervals during storage with an electronic balance (BP 210 S, Sartorius AG, Göttingen, Germany). Relative mass losses (%) were calculated from the difference in fruit mass before and during storage and related to the initial fresh mass.

In addition, from fruit water losses (Δm_{H2O}) per time (Δt) and molar mass of water (M_{H2O}), fruit surface (A_{fruit}) related molar transpiration rates (J_{H2O}) were estimated as

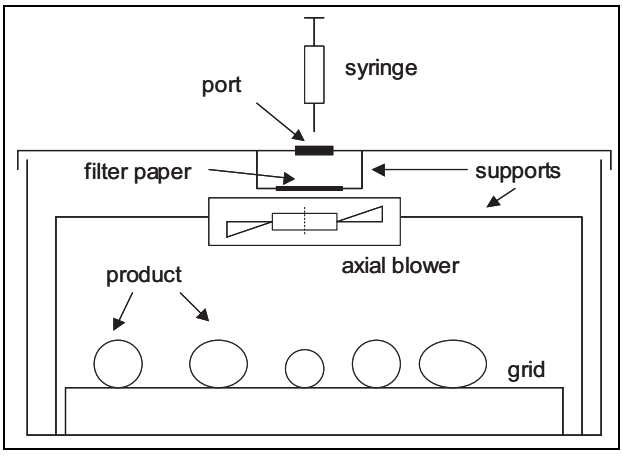


Fig. 1. Scheme of fumigation chamber.

$$J_{H2O} = \Delta m_{H2O} * \Delta t^{-1} * A_{fruit}^{-1} * M_{H2O}^{-1} \text{ [mol s}^{-1} \text{ m}^{-2}\text{]}.$$

Surface area was estimated assuming the fruit to be a triaxial ellipsoid. From J_{H2O} and the water vapour saturation deficit between the fruit and surrounding air (Δw; VON WILLERT et al. 1995), the fruit surface conductance for water vapour transfer g_{H2O} was calculated as

$$g_{H2O} = J_{H2O} * \Delta w^{-1} \text{ [mol s}^{-1} \text{ m}^{-2}\text{]}.$$

Produce elasticity was non-destructively established from compression tests (velocity = 10 mm min^{-1}, spherical steel body, diameter d = 6.35 mm) with a universal testing machine (Zwicki 1120, Zwick, Ulm, Germany). Assuming the fruit to be spherical, the apparent quasi-static elastic modulus *E* was calculated from the length of depression (D) at a maximum force (F) of 0.4 N according to ASAE (1999) as

$$E = \frac{0.531 \times F \times (1-\mu)}{D^{1.5}} \times \left(\frac{2}{R} + \frac{4}{d}\right)^{0.5}$$

μ = Poisson's-ratio = 0.49 (MOHSENIN 1986)
R = mean radius of the fruit at the measuring position

The mean radius of the fruit body was calculated from its diameter (at the smallest and the widest position) and its length (from tip to peduncle, without sepals).

Afterwards, strawberries were cut into halves; one half was used to express tissue sap with a garlic press. The sap was collected in a 1.5 ml micro test tube (Eppendorf AG, Hamburg, Germany) and centrifuged at 14000 rpm for 3 min (MiniSpin® plus, Eppendorf AG, Hamburg, Germany). Osmotic content (c_{osm}, mmol kg^{-1}) of the supernatant was determined with a vapour pressure osmometer (VAPRO 5520, Wescor Inc., Logan, USA) and its total soluble solid content with a digital refractometer (ATAGO PR 1, Leo Kuebler GmbH, Karlsruhe, Germany). An aliquot of the sap was then filtered and diluted with distilled water (1:2) before the vitamin C content was measured using a 'Reflectoquant' test set (Merck, Darmstadt, Germany). Vitamin C concentrations are given as mmol l^{-1}. From the supernatant, 0.25 ml were diluted in 20 ml distilled water and titrated to pH 7.0 with 0.01 mmol l^{-1} NaOH. Acidity was calculated as molar malic acid equivalents (mmol l^{-1}).

From the other halves of the strawberries, fresh (FM) and dry mass (DM) were obtained, the latter after oven-drying at 85 °C (24 h). Fruit water content was calculated as (FM-DM) DM^{-1}.

For HPLC analysis of free sugar content, 0.15 ml of fruit sap were diluted with distilled water to a volume of 1.5 ml and cleared by micromembrane filtration (0.45 µm PVDF-Spritzenfilter, Rotilabo®, Carl Roth GmbH + Co. KG, Karlsruhe, Germany). After clearing, the extracts were stored on ice until HPLC-analysis with a Dionex HPLC (Dionex, Sunnyvale, USA) using a Eurokat H column (300 mm × 8 mm, 10 µm) and 0.01 N H_2SO_4 as the mobile phase (rate: 0.8 ml min^{-1} at 63 Pa) and a refractive index detector (RI 71, Shodex, Techlab, Erkerode, Germany).

Sensory evaluation

For sensory evaluation, strawberries were randomly sorted into three groups with 92 fruit each (2 × 20 fruit for the

first flavour test, 2 × 20 fruit for the second flavour test, 2 × 6 fruit for odour test, which were used for both evaluations). One group of 92 fruit was used as a control (method I). The other groups were fumigated with AA (2 or 4 mg l^{-1}, method II and III) as described above. After AA treatment, fruit were randomly packed in plastic punnets (PET, 500 g capacity), commonly used for strawberry sale. Boxes were wrapped with a perforated plastic film (PE, perforation diameter = 8 mm, distance of perforation: 40 mm × 30 mm) and stored at 23 °C for 2 h until the start of the first flavour and odour test. Twenty fruit of each treatment were placed on a ceramic plate for the flavour test and 6 strawberries were placed in a plastic punnet (PET, 100 × 75 × 40 mm) with a removable lid for the odour test. The lids were closed before the test started to retain strawberry odour. After these tests, the remaining fruit (including the fruit of the odour test) were stored at 2 °C and 95 % RH in a climate chamber (WK 111-600-BSB, Weiss Umwelttechnik GmbH, Germany) and used for a second test, which started 24 h after the first test. Thirty minutes before the second test, strawberries were placed in the laboratory at 23 °C. All tests were done in duplicate.

Due to the fact that the sensation of freshness may differ between professionals and consumers (Cardello and Schutz 2003; Péneau et al. 2007), the sensory test was performed by an untrained panel of 8 female and 7 male, all employees of the institute. The members of the panel had a mean age of 43.7 years (youngest member: 29 years, oldest member: 59 years). All panel tests were conducted in a blind fashion (i.e. members were unaware of the treatments used and of the score of the other panel members). During each test, the members at first tested the flavour of the fruit, presented in a random order, and indicated the presence or absence of AA flavour. Members of the panel rinsed their mouths with water between sample tests. In addition, members lifted the lids of the punnets and smelled the samples in random order indicating the presence or absence of AA odour. In both odour and taste tests, the order of the fruit presented was randomized.

The sensory tests were performed in 2006, 2008 and 2010, yielding very similar results; thus, only the results of the experiments in 2010 are presented.

Statistical Analysis

Data of fruit parameter were statistically analyzed (Townend 2003) with WinSTAT (R. Fitch Software, Bad Krozingen, Germany). Treatment means were compared using the Duncan's multiple range test ($\alpha = 0.05$).

For data of sensory evaluation, a generalized mixed linear model was fitted using the GLIMMIX procedure of SAS Version 9.2 (SAS Institute Inc., Cary, NC, USA) to model the probabilities of unusual odour or flavour occurring after the different treatments or periods of time. Therefore, the observations y_i were binary coded (0 – normal odour/flavour, 1 – unusual odour/flavour) and, thus, were assumed to be Bernoulli-distributed depending on the parameter μ_{ijk} ($y_{ijk} \sim ber(\mu_{ijk})$ with a logit link function ($\eta_{ijk} = logit(\mu_{ijk})$).

$$(1) \qquad P(\underline{y}_{ijk} = y_{ijk}) = \mu_{ijk}^{y_{ijk}} \cdot (1 - \mu_{ijk})^{1 - y_{ijk}}$$

$$(2) \qquad E(\underline{y}_{ijk}) = \mu_{ijk} = \frac{\exp(\eta_{ijk})}{1 + \exp(\eta_{ijk})}; \exp(\eta) = e^{\eta}$$

$$(3) \qquad \text{with } \eta_{ijk} = \mu_0 + C_i + TP_j + PM_k + e_{ijk}$$

with

η_{ijk}: linear predictor for the modelled event (unusual odour or flavour);
μ_0: general mean;
C_i: fixed effect of the i-th concentration (i = 1, 2, 3);
TP_j: fixed effect of the j-th period of time (j = 1, 2);
PM_k: random effect of k-th panel member; (k = 1, ..., 15)
e_{ijk}: random residual.

Global hypotheses for the fixed effects were tested with F-tests at a significance level of $\alpha = 0.05$. Within fixed effects, differences between the concentrations were tested by pairwise t-tests. The SIMULATE option was used to keep a global significance level of $\alpha = 0.05$ when adjusting P-values for multiple testing. Mean probabilities were calculated using the inverse link function shown in (2).

Results

Effect of AA vapour on physico-chemical fruit quality parameter

Although fruit were stored at low temperature (2 °C) in nearly water vapour-saturated air, the strawberries lost water (Fig. 2A); however, water losses were negligible after the second day in storage. Initial transpiration rates of fruit treated with 2 and 4 mg l^{-1} AA vapour were approx. 40 and 90 % higher than those of untreated controls, respectively (Table 1). As a result of these high transpiration rates on the first day of storage, the relative water loss of strawberries fumigated with 4 mg l^{-1} AA was significantly higher than that of untreated controls for all sampling days. Therefore, the elastic modulus of fruit fumigated with the higher AA concentration significantly declined during initial storage, but remained constant in strawberries in all other treatments (Fig. 2B).

The concentration of soluble sugars of strawberries was little affected by either storage or fruit treatment (Fig. 3). Mean sucrose concentration was 35.1 ± 12.4 mmol l^{-1}, those of glucose and fructose were 131.9 ± 23.2 and 166.1 ± 26.6 mmol l^{-1}, respectively. Total sugar concentration remained constant at 333.2 ± 54.7 mmol l^{-1}. Nevertheless, sucrose concentration declined by approx. 30 % in controls and more than 40 % in fruit of both treatments on the third day of storage. Although changes in sucrose concentration were not accompanied by an increase in those of glucose or fructose, the total osmotic content of fruit did not change during storage or in response to AA fumigation (Fig. 4A).

Acidity of all fruit slightly increased during storage (Fig. 4B). Hence, the sugar to acidity ratio significantly declined by approx. 25 % in these fruit by the end of the storage time (data are given to calculate it). In all fruit, vitamin C concentrations (Fig. 4C) significantly increased during storage; however, changes were most pronounced in controls and least in strawberries fumigated with 4 mg l^{-1} AA.

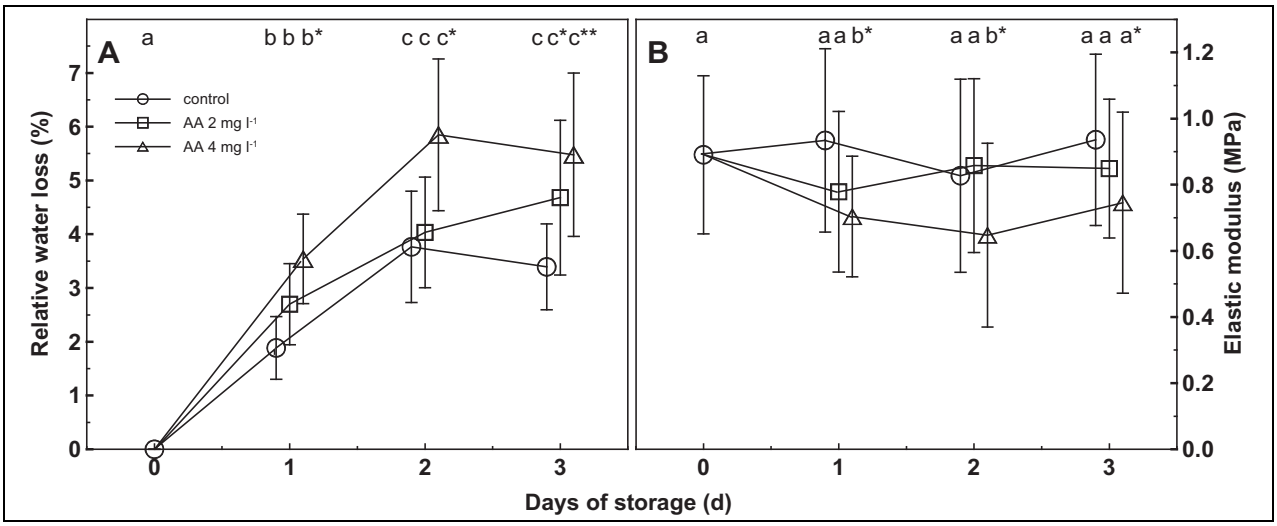


Fig. 2. Relative water losses (A) and modulus of elasticity (B) of untreated strawberries (circles) and fruit fumigated with 2 (squares) or 4 mg l^{-1} AA vapour (triangles), respectively, and stored at 2 °C for up to 3 d. Given are means ± standard deviations of 20 fruit each. Different letters indicate significant differences from references, while asterisks denote significant differences between treatments.

Table 1. Initial means (± SD) of transpiration (J_{H2O}) and total surface conductance for water vapour (g_{H2O}) of untreated strawberries (controls) and those, fumigated with either 2 or 4 mg l^{-1} AA vapour. Different letters indicate statistically different values ($P < 0.05$).

	controls	2 mg l^{-1} AA	4 mg l^{-1} AA
J_{H2O} (µmol m^{-2} s^{-1})	49.2 ± 16.2[a]	70.4 ± 21.2[b]	94.3 ± 24.8[c]
g_{H2O} (mmol m^{-2} s^{-1})	140.8 ± 46.3[a]	201.7 ± 60.6[b]	270.1 ± 70.9[c]

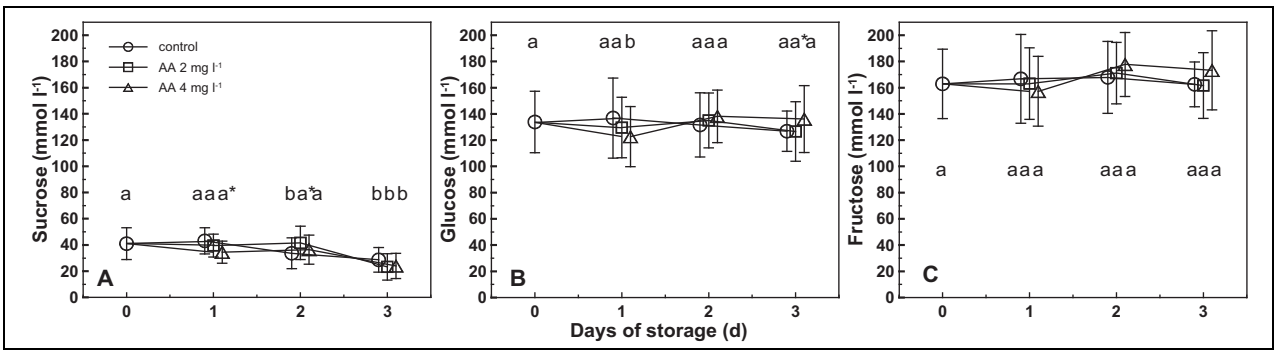


Fig. 3. Variations in sucrose (A), glucose (B) and fructose (C) content of untreated strawberries (circles) and fruit fumigated with 2 (squares) or 4 mg l^{-1} AA vapour (triangles), respectively, and stored at 2 °C for up to 4 d. Given are means ± standard deviations of 20 fruit each. Different letters indicate significant differences from references, while asterisks denote significant differences between treatments.

Effect of AA vapour on sensory quality of strawberries

In addition to fruit fumigated with either 2 or 4 mg l^{-1} AA vapour, strawberries of two untreated control batches (control I.I and I.II) were analysed. In both controls, a modified taste was recognized by 26.7 % of the members of the panel 2 h after fumigation, indicating a basic probability of erroneous perception of 21.7 % as determined by the statistical model applied. After additional 23.5 h at 2 °C, the percentage of control strawberries, evaluated as 'modified', even decreased. Flavour of AA treated strawberries did no significantly vary compared to untreated controls, irrespective of AA concentration and storage time (Table 2).

In the odour test, fruit of control I.I and I.II were initially evaluated as 'modified' by 33.3 % and 0.0 % of

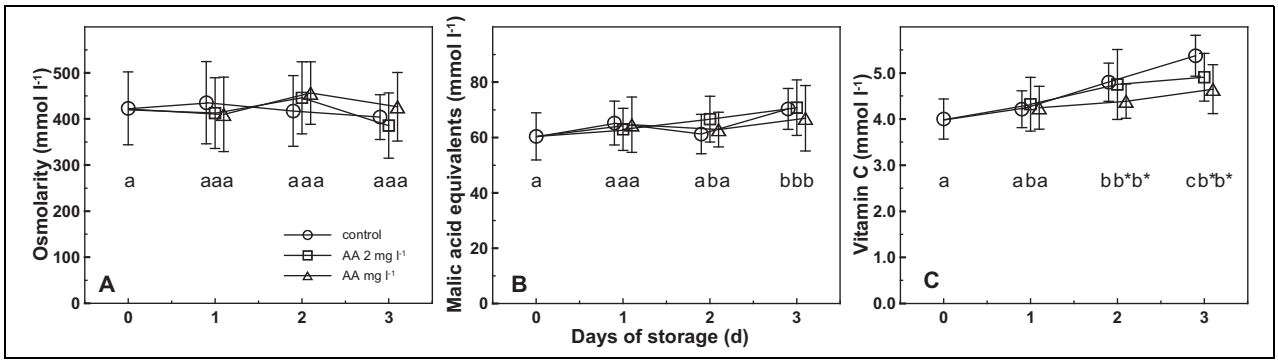


Fig. 4. Variation of osmotic content (A), titratable acidity (B; given as malic acid equivalents) and vitamin C concentration (C) of untreated strawberries (circles) and fruit fumigated with 2 (squares) or 4 mg l^{-1} AA vapour (triangles), respectively, and stored at 2 °C for up to 4 d. Given are means ± standard deviations of 20 fruit each. Different letters indicate significant differences from references, while asterisks denote significant differences between treatments.

Table 2. Panel evaluation of strawberry flavour and odour after AA vapour treatment. Different letters indicate significant differences between treatments, while asterisks denote significant differences after storage ($P < 0.05$).

Method		Perception of modified taste [%]		Perception of modified odour [%]	
		Time after treatment		Time after treatment	
		2 h	26 h	2 h	26 h
I.I	untreated	26.7[a]	13.3[a]	33.3[a]	20.0[a]
I.II	untreated	26.7[a]	20.0[a]	0.0[a]	6.7[a]
II.I	2 mg l^{-1} AA	0.0[a*]	33.3[a*]	40.0[b*]	66.7[b**]
II.II	2 mg l^{-1} AA	13.3[a*]	20.0[a*]	53.3[b*]	73.3[b**]
III.I	4 mg l^{-1} AA	46.7[a*]	33.3[a*]	53.3[b*]	80.0[b**]
III.II	4 mg l^{-1} AA	26.7[a*]	13.3[a*]	73.3[b*]	86.7[b**]

panelists (i.e. 14 % probability of perception). After 23.5 h of storage, rating as 'modified' slightly decreased in average.

However, changes of odour became significant when strawberries were treated with AA. Already a low AA concentration of 2 mg l^{-1} resulted in the perception of AA odour by 40 % and 53.3 % of subjects (58 % probability of perception; method II.I and II.II). Fumigation of strawberries with 4 mg l^{-1} AA resulted in increased olfactory perception by panelists (Table 2; 78 % probability of perception). After additional 23.5 h of storage, AA perception further increased to 66.7 and 73.3 % (method II.I and II.II) as well as 80 and 86.7 % (method III.I and III.II), but were not statistically significant compared to the results of the first analysis. Irrespective of AA concentrations applied, the probability of perception of unusual odour increased from 39 to 56 % after 24 h of storage.

Additionally, the effects of AA vapour treatment, followed by 26 h storage in punnets without plastic film, were analysed in previous experiments, indicating the same results. The flavour of strawberries was regular; however, odour of fruit was negatively affected (data not shown).

Discussion

Large economic losses in harvested strawberries often result from grey mould infection, caused by *B. cinerea* (Legard et al. 2001). In conventional horticultural practice, a pre-harvest application of fungicides is an accepted method to prevent the risk of infection. However, consumers are increasingly aware of the negative effects of the use of pesticides on both human health and the environment (Cao et al. 2010). Consequently, there is a great need for rapid, mild, and inexpensive alternative postharvest sanitation treatments (El-Mougy et al. 2008). In this context, it has been shown that fumigation of strawberries with AA gas successfully inhibits grey mould without significantly affecting the aerobic mesophilic total bacterial count of fruit (Hassenberg et al. 2010). No information on the effects of AA fumigation on sensorial and overall fruit quality, however, is available. Based on this, the present investigation focussed on the evaluation of potential influences of effective AA fumigation, on important physico-chemical and sensory properties of strawberries.

Strawberries are generally rated as a highly perishable fruit that are especially prone to mechanical damage and physiological dysfunction (Pérez et al. 1999; Sallato et al. 2007). Hence, in the present experiments, special care was taken to prevent any mechanical injury during fruit handling. In contrast to many other decay control treatments (heat treatment, UV-C irradiation, CA storage etc.), which are known to affect colour, flavour, or texture of strawberries (Sallato et al. 2007), fumigation is certainly a very gentle postharvest treatment.

Effects of AA fumigation on physico-chemical fruit quality parameter

Short-term exposure to AA vapour significantly increased water losses during storage. Such water losses were higher at the higher AA vapour concentration indicating that this water loss cannot be ascribed to damages by mechanical impacts to fumigated strawberries because all these fruit were handled in the same manner.

Hence, AA vapour treatment may directly affect water vapour permeability of strawberries. Decades ago, it was shown that simulated acid rain may increase conductivity of leaves in a species-specific and age-dependent manner (Haines et al. 1985). This was valid even after short-term (30 min) applications (Caporn and Hutchinson 1986). On the other hand, using scanning electron microscopy, Delaquis et al. (1999) found no indications of changes in surface microstructures after AA fumigation of mung bean seeds. Although seed surfaces are certainly more robust than the epidermis of accessory fruit such as strawberries, no visible surficial changes or damage were observed in this study. On the other hand, AA vapour may condense on the fruit surface. This aerosol may then act as a desiccant, thus passively increasing overall water losses, as proposed by Burkhardt (2010). Nevertheless, the exact cause of the largely increased conductance for water vapour and the resultant water losses observed in this study are unclear and in need of further investigations.

Fumigation with the highest AA vapour concentration resulted in more elastic fruit, compared to the untreated controls. This short-term reduction in tissue stiffness may be closely related to the higher water losses observed. A direct interaction between changes in tissue water content and those in tissue elastic properties has been shown in other parenchymatous produce such as radish tubers (Landahl et al. 2004). On the other hand, no significant effects on fruit firmness of AA fumigated 'Hedelfinger' sweet cherries were obtained after 10 weeks of storage at 0 °C (Chu et al. 1999). Hence, a direct effect of AA treatment on biochemical or biophysical cell wall properties or structure, the major determinants of tissue strength (Herppich and Huyskens-Keil 2008), may be excluded.

The lack of a direct internal effect of AA treatment is in accordance with the absence of fumigation induced changes in the contents of flavour components such as soluble sugars, titratable acidity, and total osmolarity. Similar results were found by Chu et al. (1999) for AA treated cherries. Furthermore, treating strawberries with other sanitation methods such as ozone fumigation (Pérez et al. 1999), UV-C irradiation, and/or heat treatment (Vicente et al. 2006; Pan et al. 2004), as well as high CO_2 storage (Pelayo et al. 2003), did not affect contents of the substances mentioned above.

It has long been established that ascorbic acid (vitamin C) is an essential central component of metabolic protection and control in plants; its contents often increase in response to various stressors (Smirnoff 1996; Debolt et al. 2007). In general, this also applies to fruit on the plant and after harvest (Davey et al. 2000; Gomez and Lajolo 2008). In the present study, vitamin C contents of strawberries increased during postharvest storage. In most cases, storage is inevitably linked to some desiccation stress, as is reported here. Storage is also accompanied by aging of the fruit tissue. Both desiccation and senescence are known to induce the formation of reactive oxygen species (ROS), which, in turn, may activate the synthesis of ascorbic acid, effectively functioning as an antioxidant (Davey et al. 2000). AA fumigation significantly reduced the rates of vitamin C formation in a concentration-dependent manner. It is not clear whether this results from an inhibition of metabolic activity or a diminution of stress effects. Unaltered sugar metabolism may cast doubts on the first mechanism. Consequently, the metabolic effects of AA fumigation largely differs from that of heat (Vicente et al. 2006; Shafiee et al. 2010) and ozone treatment (Pérez et al. 1999), both of which resulted in increased ascorbic acid content of fruit. On the other hand, AA fumigation significantly suppresses the growth of *B. cinerea* (Hassenberg et al. 2010). This may reduce the ROS stress exposed by this pathogen to the fruit, and thus, may diminish the formation of antioxidants such as vitamin C.

Effects of AA fumigation on sensory fruit quality

To analyse the practical potential of AA vapour treatment for strawberry disinfection, the acceptance of the consumer must be considered. The evaluation of flavour and odour of fruit by an untrained consumer panel is a difficult task due to the largely varying sensorial capabilities of the members of the panel and the variability of fruit flavour and odour. Therefore, the sensorial analyses of the effect of AA on strawberries were performed in three years. In spite of a large variability in the data, all the sensorial analyses clearly indicated that 'Pegasus' strawberries did not retain any detectable AA flavour after fumigation, independent of AA concentration and storage time. In contrast, the odour of fruit was significantly affected by AA fumigation even at low concentrations of 2 mg l^{-1} and increased with AA concentration.

Changes in sensory quality of strawberries were also reported for other disinfectants. Gaseous ozone treatment (0.35 ppm, 3 d, 2 °C) resulted in a change of fruit aroma by reducing the emission of volatile esters by 40 % (Pérez et al. 1999). This agrees with observations of Nadas et al. (2003), who reported that cold storage at 1.5 ppm ozone concentration (3 d, 2 °C) reduced decay of naturally infected strawberries but also resulted in losses of fruit aroma.

In additional experiments, the off-odour should be eliminated by addition of sodium hydroxide solution-soaked pads to the batches (data not shown). However, this resulted in a rapid loss of the fresh appearance of fruit. Also, the elimination of off-odour by forced convection seems not to be an acceptable solution due to the high water losses of fruit.

In summary, application of AA vapour to disinfect strawberries seems not to be a proper technique for quality assurance of strawberries in practice despite its efficacy in reducing microbial load on the fruit. After AA treatment, consumers' acceptance of strawberries significantly declined. Hence, best strategy to minimize fruit losses is a high hygienic standard during cultivation and harvest combined with rapid postharvest cooling of fruit. In this context, Nunes et al. (2005) found that prompt cooling reduces incidence and severity of decay caused by *B. cinerea* in strawberries.

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References

ASAE 1999: Compression test of food materials of convex shape. ASAE Standards, Standards engineering practices data, 46th edition, 570–575. ASAE, St. Joseph, MI, USA.

BURKHARDT, J. 2010: Hygroscopic particles on leaves: nutrients or desiccants? Ecol. Monograph **80**, 369–399.

CAPORN, S.J.M. and T.C. HUTCHINSON 1986: The contrasting response to simulated acid rain of leaves and cotyledons of cabbage (*Brassica oleraceae* L.). New Phytol. **103**, 311–324.

CARDELLO, A.V. and H.G. SCHUTZ 2003: The concept of food freshness: uncovering its meaning and importance to consumers. In: CADWALLADER, K.R. and H. WEENEN (eds.), Freshness and shelf life of foods. American Chemical Society, Washington, 22–41.

CAO, S., Z. HU and B. PANG 2010: Optimization of postharvest ultrasonic treatment of strawberry fruit. Postharvest Biol. Technol. **55**, 150–153.

CHU, C.L., W.T. LIU, T. ZHOU and R. TSAO 1999: Control of postharvest gray mold rot of modified atmosphere packaged sweet cherries by fumigation with thymol and acetic acid. Can. J. Plant Sci. **79**, 685–689.

DAVIDSON, P.M. and V.K. JUNEJA 1990: Antimicrobial agents. In: BRANEN, A.L., P.M. DAVIDSON and S. SALMINEN (eds.): Food Additives. Marcel Dekker, New York, 83–137.

DAVEY, M.W., M.V. MONTAGU, D. INZÉ, M. SANMARTIN, A. KANELLIS, N. SMIRNOFF, I.J.J. BENZIE, J.J. STRAIN, D. FAVELL and J. FLETCHER 2000: Plant L-ascorbic acid: chemistry, function, metabolism, bioavailability and effects of processing. J. Sci. Food Agric. **80**, 825–860.

DEBOLT, S., V. MELINO and C.M. FORD 2007: Ascorbate as a biosynthetic precursor in plants. Ann. Bot. **99**, 3–8.

DELAQUIS, P.J., P.L. SHOLBERG and K. STANICH 1999: Disinfection of mung bean seed with gaseous acetic acid. J. Food Protect. **62**, 953–957.

EL-MOUGY, N.S., N.G. EL-GAMAL and M.A. ABDALLA 2008: The use of fungicide alternatives for controlling postharvest decay of strawberry and orange fruits. J. Plant Protect. Res. **48**, 385–395.

FAO 2004: The state of agricultural commodity markets 2004. FAO, Rome, Italy.

GOMEZ, M.L.P.A. and F.M. LAJOLO 2008: Ascorbic acid metabolism in fruits: activity of enzymes involved in synthesis and degradation during ripening in mango and guava. J. Sci. Food Agric. **88**, 756–762.

HAINES, B.L., J.A. JERNSTEDT and H.S. NEUFELD 1985: Direct foliar effect of simulated acid rain. II. Leaf surfaces characteristics. New Phytol. **99**, 407–416.

HASSENBERG, K., M. GEYER and W.B. HERPPICH 2010: Effect of acetic acid vapour on the natural microflora and *Botrytis cinerea* of strawberries. Europ. J. Hort. Sci. **75**, 141–146.

HERPPICH, W.B. and S. HUYSKENS-KEIL 2008: Cell wall biochemistry and biomechanics of harvested white asparagus shoots as affected by temperature. Ann. Appl. Biol. **152**, 377–388.

LANDAHL, S., W.B. HERPPICH, B. HEROLD, M. GEYER and J. DE BAERDEMAEKER 2004: A comprehensive evaluation of the interactions between produce elasticity and water status. Europ. J. Hortic. Sci. **69**, 250–257.

LEGARD, D.E., C.L. XIAO, J.C. MERTELY and C.K. CHANDLER 2001: Management of *Botrytis* fruit rot in annual winter strawberry using captan, thiram, and iprodione. Plant Dis. **85**, 31–39.

LIU, W.T., C.L. CHU and T. ZHOU 2002: Thymol and acetic acid vapours reduce postharvest brown rot of apricots and plums. HortScience **37**, 151–156.

MOHSENIN, N.N. 1986: Physical Properties of Plant and Animal Materials. Structure, physical characteristics and mechanical properties. Gordon and Breach Publishers, New York, USA.

MOYLS, A.L., P.L. SHOLBERG and A.P. GAUNCE 1996: Modified-atmosphere packaging of grapes and strawberries fumigated with acetic acid. HortScience **31**, 414–416.

NADAS, A., M. OLMO and J.M. GARCÍA 2003: Growth of *Botrytis cinerea* and strawberry quality in ozone-enriched atmosphere. J. Food Sci. **68**, 1798–1802.

NUNES, M.C.N., A.M.M.B. MORAIS, J.K. BRECHT, S.A. SARGENT and J.A. BARTZ 2005: Prompt cooling reduces incidence and severity of decay caused by *Botrytis cinerea* and *Rhizopus stolonifer* in strawberry. HortTechnology **15**, 153–156.

PAN, J., A.R. VINCENTE, G.A. MARTINEZ, A.R. CHAVES and P.M. CIVELLO 2004: Combined use of UV-C irradiation and heat treatment to improve postharvest life of strawberry fruit. J. Sci. Food Agric. **84**, 1831–1838.

PELAYO, C., S.E. EBELER and A.A. KADER 2003: Postharvest life and flavour quality of three strawberry cultivars at 5 °C in air or air +20 kPa CO_2. Postharvest Biol. Technol. **27**, 171–183.

PÉNEAU, S., P.B. BROCKHOFF, F. ESCHER and J. NUESSLI 2007: A comprehensive approach to evaluate the freshness of strawberries and carrots. Postharvest Biol. Technol. **45**, 20–29.

PÉREZ, A.G., C. SANZ, J.J. RÍOS, R. OLÍAS and J.M. OLÍAS 1999: Effects of ozone treatment on postharvest strawberry quality. J. Agric. Food Chem. **47**, 1652–1656.

SALLATO, B.V., R. TORRES, J.P. ZOFFOLI and B.A. LATORRE 2007: Effect of boscalid on postharvest decay of strawberry caused by *Botrytis cinerea* and *Rhizopus stolonifer*. Span. J. Agric. Res. **5**, 67–78.

SHAFIEE, M., T.S. TAGHAVI and M. BABALAR 2010: Addition of salicylic acid to nutrient solution combined with postharvest treatments (hot water, salicylic acid and calcium dipping) improved postharvest fruit quality of strawberry. Sci. Hort. **124**, 40–45.

SHOLBERG, P.L. and A.P. GAUNCE 1995: Fumigation of fruit with acetic acid to prevent postharvest decay. HortScience **30**, 1271–1275.

SHOLBERG, P.L. and A.P. GAUNCE 1996: Fumigation of stonefruit with acetic acid to control postharvest decay. Crop Protection **15**, 681–686.

SHOLBERG, P., P. HAAG, R. HOCKING and K. BEDFORD 2000: The use of vinegar vapor to reduce postharvest decay of harvested fruit. HortScience **35**, 898–903.

SHOLBERG, P.L., T. SHEPHARD, P. RANDALL and L. MOYLS 2004: Use of measured concentrations of acetic acid vapour to control postharvest decay in d'Anjou pears. Postharvest Biol. Technol. **32**, 89–98.

SMIRNOFF, N. 1996: The function and metabolism of ascorbic acid in plants. Ann. Bot. **78**, 661–669.

TOWNEND, J. 2003: Practical statistics for environmental and biological scientists. John Wiley & Sons, Ltd, Chichester, UK.

VON WILLERT, D.J., R. MATYSSEK and W.B. HERPPICH 1995: Experimentelle Pflanzenökologie – Grundlagen und Anwendungen. Georg Thieme Verlag, Stuttgart, Germany.

VICENTE, A.R., G.A. MARTINEZ, A.R. CHAVES and P.M. CIVELLO 2006: Effects of heat treatment on strawberry fruit damage and oxidative metabolism during storage. Postharvest Biol. Technol. **40**, 116–122.

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