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Suppression of Ethylene Perception Extends Shelf-life and Quality of 'Sunrise Solo' Papaya Fruit at both Pre-ripe and Ripe Stages of Development

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Summary

Papaya fruit (*Carica papaya* L. cv. 'Sunrise Solo') at pre-ripe (10 to 20 % surface yellow coloration) and ripe stages (70 to 80 % surface yellow coloration) of development were treated with 9 ∝l l–1 of the ethylene antagonist 1-methylcyclopropene (1-MCP) for 18 h at 20 ºC and then stored at the same temperature. The hypothesis addressed was that fruit at both early and advanced stages of ripening would respond beneficially, in terms of extended shelf-life, and quality retention, to exposure to 1-MCP. For fruit of both ripening categories, respiration and ethylene production, firmness, electrolyte leakage, titratable acidity, pH, soluble solids, and visual changes were recorded during storage. Pre-ripe fruit treated with the ethylene antagonist exhibited a 2-day delay in the respiratory climacteric maximum and showed suppressed but steadily increasing ethylene production throughout storage. A reduction in respiration and ethylene production were also noted for fruit treated with 1-MCP at the ripe stage. The rate of softening of fruit of both ripening categories was significantly reduced in response to 1-MCP. Firmness of pre-ripe fruit declined 52 % over 9 days of storage compared with 30 % for 1-MCP-treated fruit over the same time period. Firmness of ripe fruit at the start of storage was initially 60 % lower than initial values for pre-ripe fruit; however, 1-MCP significantly suppressed further softening of ripe fruit, with 1-MCP-treated fruit declining only 15 % over 8 days of storage whereas controls softened 60 % over a 6-day period. Electrolyte leakage in pre-ripe fruit was significantly suppressed by 1-MCP treatment through 11 days of storage. Efflux was higher in ripe fruit compared with pre-ripe fruit, but leakage values in ripe fruit were not significantly affected by 1-MCP. Soluble solid levels were not significantly influenced by 1-MCP for fruit of either developmental stage whereas the ethylene antagonist affected titratable acidity and mesocarp pH. Fruit treated with 1-MCP showed delayed loss of surface green colour in pre-ripe fruit and suppressed the intensity of yel- low colour development of fruit treated when ripe. In informal sensory analyses, the period of table-ripe edibility of fruit treated when pre-ripe or ripe was extended 4 to 5 days and 3 to 6 days, respectively.

Zusammenfassung

Die Unterdrückung der Ethylen-Perception verlängert die Haltbarkeit und Qualität von unreifen und reifen Papayafrüchten. Papayas (*Carica papaya* L. cv. 'Sunrise Solo') im unreifen (10 % bis 20 % gelbfarbige Schale) und im reifen Stadium (70 % bis 80 % gelbfarbige Schale) wurden für 18 Stunden bei 20 ºC mit 9 ∝l l–1 des Ethylen-Antagonisten 1-Methylcyclopropen (1-MCP) behandelt und dann bei derselben Temperatur gelagert. Die Hypothese war, dass sowohl unreife als auch reife Früchte, die 1-MCP ausgesetzt werden, eine verlängerte Lagerfähigkeit und bessere Beibehaltung der Qualität zeigen würden. Während der Lagerungszeit wurden Atmung, Ethylenproduktion, Festigkeit, Elektrolytverlust, titrierbare Säure, pH-Wert, lösliche Feststoffe und sichtbare Änderungen bei den Früchten beider Reifestadien aufgezeichnet. Unreife Früchte, die mit dem Ethylen-Antagonisten behandelt wurden, zeigten eine zweitägige Verzögerung des klimakterischen Atmungsmaximums und eine unterdrückte, aber stetig ansteigende Ethylenproduktion während der Lagerungszeit. Eine Abnahme der Atmung und der Ethylenproduktion war auch bei reifen Früchten, die mit 1-MCP behandelt wurden, bemerkbar. Durch den Einsatz von 1-MCP konnte die Geschwindigkeit des Weichwerdens der Früchte in beiden Reifekategorien merklich verringert werden. Bei einer Lagerungszeit von neun Tagen verringerte sich die Festigkeit der unreifen Früchte in der Kontrollgruppe um 52 %, verglichen mit 30 % bei den mit 1-MCP behandelten Früchten. Die Festigkeit der reifen Früchte lag am Anfang der Lagerungsperiode bei 60 % der Festigkeit von unreifen Früchte; 1-MCP verlangsamte jedoch das weitere Weichwerden der reifen Früchte. Mit 1-MCP behandelte reife Früchte wurden über einen Zeitraum von 8 Tagen um 30 % weicher, während die unbehandelte Kontrollgruppe innerhalb von nur 6 Tagen um 60 % weicher wurde. Der Elektrolytverlust wurde durch 1-MCP über eine elftägige Lagerungszeit merklich verringert. Der Verlust war bei reifen Früchten höher als bei unreifen Früchten, wobei die Verluste nicht signifikant von 1-MCP beeinflusst wurden. Der lösliche Feststoffgehalt wurde durch 1-MCP in beiden Reifekategorien ebenfalls nicht beeinflusst. Der Ethylen-Antagonist beeinflusste allerdings die titrierbare Säure und den pH-Wert des Mesocarps. Mit 1-MCP behandelte Früchte zeigen im

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unreifen Stadium eine verzögerte Abnahme der grünen Bereiche auf der Schale und im reifen Stadium eine schwächere Ausbildung der gelben Bereiche. Eine formlose sensorische Analyse ergab eine verlängerte Zeitspanne für servierfertige Früchte von 4 bis 5 Tagen bei unreifen und 3 bis 6 Tagen bei reifen Früchten.

Introduction

Papaya fruit (*Carica papaya* L. cv. 'Sunrise Solo') harvest- ed at the colour break stage can be kept for periods of up to 16 d at 10 to 16 ºC; otherwise, their storage life is about 1 week under ambient tropical conditions (SANKAT and MAHARAJ 1997). The fruit are commonly harvested at the mature-green stage for distant markets to extend storage life and reduce post-harvest loses at the commercial and consumer level (PAULL et al. 1997). According to Hawaiian grade standards, however, papaya must have at least 6 % surface yellow coloration to meet the minimum grade requirement of 11.5 % soluble solids concentration (AKAMINE and GOO 1971). For local markets, papaya fruit are harvested ripe, exhibiting fairly yellowish-orange surface coloration, approximately 80 % (MORTON 1987), and subsequently stored above 7 °C. Storage at lower temperatures may cause low-temperature injuries, depending on the variety and maturity stage (PAULL and CHEN 1983; SANKAT and MAHARAJ 1997).

Approaches to extending the postharvest quality and duration of the chill-sensitive papaya have included the use of controlled-atmosphere storage, polymeric films and wax coatings, gamma irradiation (SANKAT and MAHARAJ 1997), and methyl jasmonate fumigation (GONZALES-AGUILAR et al. 2003). MAHARAJ and SANKAT (1989) reported that papaya fruit harvested at colour break and stored under 1.5 to 2 % O_2 and 5 % CO_2 at 16 ºC remained acceptable for 17 to 29 d.

Another approach for extending the storage life and quality of papaya fruit has been through the application of 1-methylcyclopropene (1-MCP), a potent ethylene antagonist (SISLER and SEREK 1997; SISLER et al. 2003). 1-MCP applied at 90 or 270 nl l^{-1} extended the storage life of 'Sunrise Solo' papaya fruit treated at early ripening from 4 to 6 d at 20 ºC (JACOMINO et al. 2002). 1-MCP at the relatively high concentration of 25 ∝l l^{-1} to 'Solo' papaya at commercial harvest maturity increased the number of days to ripen from approximate- ly 5 to 20 d (HOFMAN et al. 2001). 1-MCP has been favoured among other cyclic olefins as a candidate for suppressing ethylene perception (SISLER and SEREK 1997, 1999) due to its undetectable odour, nonphytotoxic properties, and stability and activity at low concentrations (ppb range).

Aside from its effects in extending the storage life of commodities at pre-ripe or early stages of ripening, a few studies have reported that the efficacy of 1-MCP action extends to fruit in which ripening has progressed to relatively advanced stages (BLANKENSHIP and DOLE 2003). Examples include apple (FAN et al. 1999; PRE-AYMARD et al. 2002) and, to a lesser extent, tomato (WILLS and KU 2002; HOEBERICHTS et al. 2002). The change in effectiveness of 1-MCP as fruit ripen might depend on the degree to which ethylene is required to initiate versus promote the continuation of ripening and also reflects the degree to which specific ripening parameters are dependent on ethylene.

The purpose of the present study was to investigate the efficacy of 1-MCP at influencing the postharvest storage potential and quality of papaya fruit when applied at either pre-ripe or full-ripe stages of development. Analyses included the effects of the ethylene antagonist on postharvest ethylene production and respiration, compositional features, firmness, and general sensory properties. Beneficial responses of ripe or nearly full ripe papaya will have possible implications for application in the fresh-cut fruit industry.

Materials and Methods

Plant material

Papaya fruit (*Carica papaya* L. cv. 'Sunrise Solo') originating from Belize (no thermal or wax treatments) were obtained from Brooks Tropicals Inc., Homestead, Fla. 'Sunrise Solo' variety was chosen due to its year-round availability. The fruit were received at a full mature green stage and transported to Homestead, Fla. at approximately 13 to 15 °C. After transfer to the postharvest facilities in Gainesville, fruit were selected on the basis of uniformity of size (280 to 320 g) and freedom from surface defects. The fruit were gently brushed and washed with tap water, dipped in 200 ∝l l^{-1} chlorinated water for 1 min, rinsed with tap water and dried. Fruit at the pre-ripe stage (PRP, 10 to 20 % surface yellow coloration) were used directly whereas other fruit were ripened (RP, 70 to 80 % surface yellow coloration) at 20 ºC prior to 1-MCP application.

1-MCP treatment

Approximately 3 g of 1-methylcyclopropene (1-MCP, *SmartFresh*®, AgroFresh, Inc.) in 0.14 % powder formulation were dissolved in 50 ml of deionized water in a 136-ml glass vial and sealed with a septum. The vial was placed briefly on an oscillating shaker (1.4 cycles sec^{-1}) at room temperature. 1-MCP concentration in the vial headspace was measured using a gas chromatograph (GC) (Hewlett Packard-5890, Avondale, Pa) equipped with 80–100 mesh Chromosorb PAW stainless column (1.8 m x 3.18 mm i.d) (Supelco, Bellefonte, Pa). Injector, oven, and detector (FID) temperatures were maintained at 150, 70, and 200 °C, respectively. Isobutylene gas, which has a detector (FID)

response similar to that of 1-MCP (JIANG et al. 1999), was used as an external standard. A volume of vial headspace (about 3.3 ml) was injected into sealed 18.9 l containers (each containing 20 fruits) having approximately 10 l free space, yielding a final 1-MCP concentration of 9 ∝l l–1 and maintained for 18 h at 20 °C. Air-treated fruit were maintained under similar conditions but provided with no 1-MCP. Following treatment, fruit were transferred to 15 ºC storage facilities. 1-MCP concentration effects were investigated using early-ripe papaya (20 to 30 % surface yellow coloration) treated with air (control), 0.9, or 9 ∝l l–1 1-MCP for 18 h at 20 ºC and stored at 15 °C.

Respiration and ethylene production

Individual fruit (5 fruit/treatment) were sealed in 2 l airtight plastic containers for 1 h prior to sampling. A 0.5 ml headspace sample for respiration or a 1 ml headspace gas sample for ethylene production was withdrawn using a hypodermic syringe and measured gas chromatographically. Carbon dioxide and ethylene were measured using a Gow-Mac GC (Series 580, Bridge Water, N.J.) equipped with a thermal conductivity detector (TCD), and a Hewlett Packard-5890 GC equipped with a flame ionization detector (FID), respectively. The carrier gas for the Gow-Mac GC was helium (30 ml min–1 flow rate), and the oven, detector, and injector were set at 40, 27 and 27 °C, respectively. The carrier gas for the Hewlett Packard GC was nitrogen (30 ml min–1), and oven, injector, and detector were set at 200, 70, and 250 °C, respectively.

Firmness

Firmness was measured at two equidistant points on the equatorial region of fruit using an Instron Universal Testing Instrument (Model 4411-C8009, Canton, Mass.) equipped with a 5 kg load cell and an 8-mm convex probe. The probe was positioned at zero force contact with the pared fruit surface, and driven to a depth of 10 mm at a crosshead speed of 50 mm min–1. Firmness data are expressed as the maximum force (N) attained during penetration.

Electrolyte efflux

Fruit cylinders (5 per fruit) removed from the equatorial region of a fruit using a 8-mm steel cork borer. The cylinders were trimmed to produce 8-mm thick disks using the centremost region of each cylinder. The disks (5 per fruit) were rinsed briefly with deionized water to remove loosely adhering tissue, blotted on moistened Whatman filter paper, and placed in 15 ml of 500 mM mannitol. The conductivity of the bathing solution was measured immediately using a YSI-31A Conductivity Bridge equipped with a Conductivity Cell (Model 3403, Yellow Springs, Ohio). The disks and bathing solution were incubated on an oscillating shaker (1.4 cycles sec–1) at room temperature for 7 h and conductivity of the bathing solution was again measured. Total electrolyte content was determined after freezing (24 h at –20 °C), thawing, and heating the disks and bathing solutions in a boiling water bath for 30 min. Electrolyte efflux was expressed as a percentage of total tissue electrolytes.

Soluble solids concentration, titratable acidity, and pH

Partially thawed mesocarp tissue (80 g) was ground using a mortar and pestle and centrifuged at 10,000 g for 10 min at 20 °C. Soluble solids concentration (SSC) in the supernatant was determined with a digital refractometer (Abbe Mark-10480, Buffalo, N.Y.), titratable acidity (TA) with an automatic dispenser (Fisher 395, Pittsburg, Pa) and an electrometer (Fisher 380, Pittsburgh, Pa), and pH with a digital pH meter (Corning 340, Corning, N.Y.). Six ml of the supernatant were titrated with 0.1 N NaOH to an end point of pH 8.2, and TA was calculated from the volume of ml NaOH added and expressed as % malic acid equivalents.

Informal quality evaluation and statistical analysis

Informal quality evaluation was performed by no fewer than 8 members of the postharvest staff to determine the sensory acceptability of fruit during ripening in response to 1-MCP application. Parameters assessed included fruit surface and flesh appearance, odour, flavour, and texture preferences. For the purposes of this study, fruit judged to be of acceptable quality for consumption ranged in surface skin yellowing from 55 to 90 %.

All data were subject to the general linear model (PROC GLM) of SAS (SAS institute, Carry, NC), and Duncan's multiple range test (P∂0.05) was performed for completely randomized designs.

Results

1-MCP concentration

A preliminary study employing two concentrations (0.9 and 9 ∝l l–1) of 1-MCP was conducted with fruit at an early to mid-stage of ripening (20 to 30 % skin yellowing) to determine the effect of the ethylene antagonist on the general ripening pattern of papaya, with emphasis on firmness. The fruit used in this experiment were slightly more advanced in development than the fruit designated as PRP in subsequent experiments. This assessment is based on the more advanced skin colour (20 to 30 % skin yellowing) and lower initial firmness values (approximately 7 to 8 N) compared with PRP fruit (10 to 20 % surface yellow, 15 N) used in subsequent analyses. Also, the storage temperature in this initial study was 15 ºC compared with the 20 ºC used in all other experiments described herein.

Fruit of all treatments softened during storage at 15 ºC (Fig. 1). Firmness differences were evident immediately following removal from the 18 h 1-MCP treatment, with fruit treated at either 1-MCP concentration exhibiting approximately 20 % higher firmness values (8.1 N) compared with control fruit (6.8 N). This divergence in firmness during 1-MCP exposure likely reflects the rapid efficacy of the ethylene antagonist, even during short-term exposure (BLANKENSHIP and DOLE 2003), and the fact that 1-MCP treatment was performed at 20 °C. Thereafter, the rate of softening was comparable for all treatments, with fruit treated at the higher 1-MCP concentration (9 ∝l l–1) remaining significantly firmer than the air control. Following 19 d storage, fruit treated at 9 ∝l l–1 1-MCP had the highest firmness (5.2 N), fol-

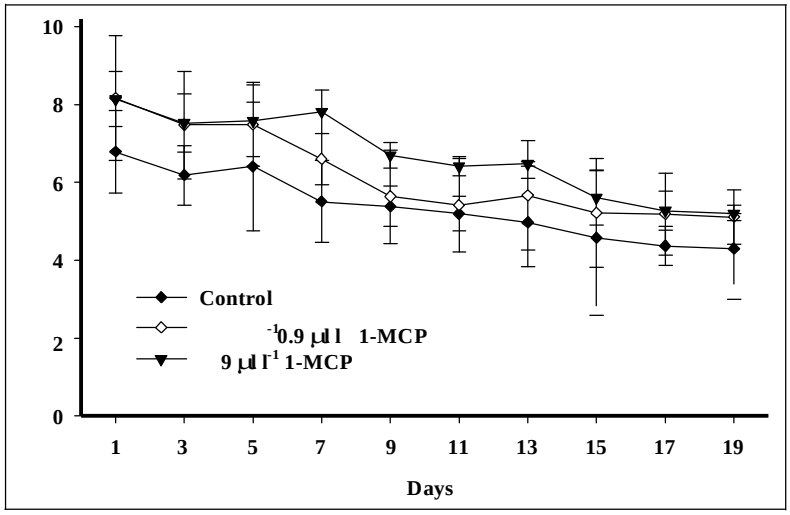

Fig. 1. Firmness of 'Sunrise Solo' papaya (20 to 30 % skin yellowing) treated with air (control), 0.9 ∝l l–1, and 9 ∝l l–1 1-MCP at 20 to 30 % skin yellowing ripening stage and stored at 15 °C. Vertical bars represent standard deviations of the means (n = 5).

lowed by fruit treated with 0.9 ∝l l–1 1-MCP (5.1 N), and air (4.3 N). Since firmness retention was of particu- lar interest in this study, subsequent experiments were performed using 1-MCP at 9 ∝l l–1 and storage at 20 °C.

Respiration and ethylene production

Respiration rates of control and 1-MCP-treated PRP (10 to 20 % surface yellow coloration) fruit were similar through the first 5 d of storage, with controls exhibiting a climacteric-like rise to about 24 ml CO_2 kg–1 h–1 at 6 d (Fig. 2A). 1-MCP-treated PRP fruit exhibited a gradual increase in respiration, reaching a maximum of about 25 ml CO_2 kg–1 h–1 at 8 d and thereafter declining through 10 d (Fig. 2A). Ethylene production in PRP control fruit increased through 5 d, reaching a maximum of 1.8 ∝l kg–1 h–1. Ethylene production in 1-MCP-treated PRP fruit remained unchanged during the first 4 d, thereafter exhibiting a slow, continuous increase through 10 d of storage (Fig. 2A). Production rates for 1-MCP-treated fruit remained below 1.5 ∝l kg–1 h–1 and did not exhibit a distinct peak during the storage period (Fig. 2A). The initiation of the ethylene rise and the maximum ethylene production rates of 1-MCP-treated PRP fruit were delayed about 3 and 5 d, respectively, compared with control fruit.

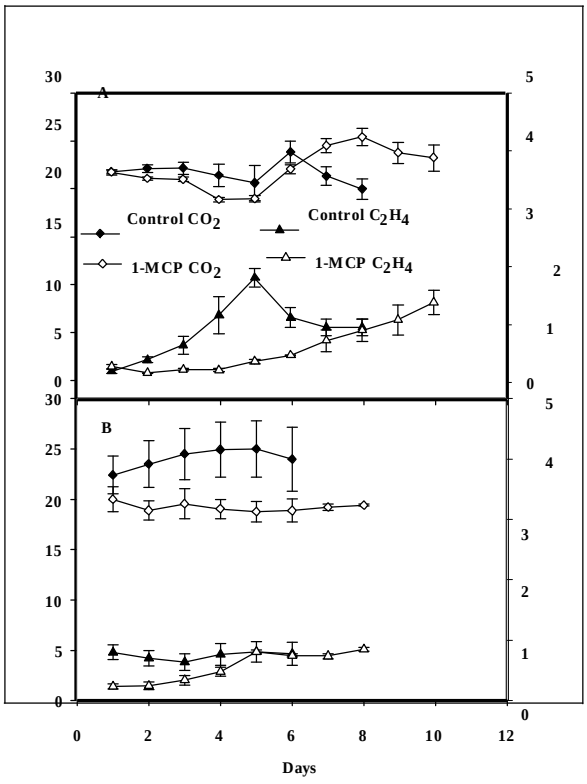

Fig. 2. Fig. 2. Respiration and ethylene production of 'Sunrise Solo' papaya treated with air (control) or 9 ∝l l–1 1-MCP at PRP (A) and RP (B) stages of development and stored at 20 °C. Vertical bars represent standard deviation of the means (n = 5).

RP fruit displayed nearly constant (1-MCP-treated) or slightly increasing (control) respiratory drifts during storage at 20 ºC (Fig. 2B), with rates for 1-MCP-treated fruit averaging about 20 to 25 % lower than those of control fruit. Ethylene production of fruit treated with 1-MCP was significantly lower than the control through 4 d, thereafter increasing to rates comparable to the control (Fig. 2B). The patterns of ethylene production and respiration of PRP and RP papaya are consistent with their developmental designation as pre- and post-climacteric, respectively, based on external colour.

Firmness

Firmness of both control and 1-MCP-treated PRP fruit averaged about 14.5 N following the period (18 h) of 1-MCP treatment and declined at nearly constant rates during the initial 3 d of storage (Fig. 3A), with 1-MCP-treated fruit showing a deceleration in the rate of softening by 5 d. Control fruit continued to soften, although at a reduced rate, and after 9 d average firmness values (6.8 N) were approximately 52 % lower than initial values. 1-MCP-treated PRP fruit after 5 d showed minimal softening through 10 d, retaining firmness values of near 10 N and representing a 30 % decline relative to initial values. The firmness of

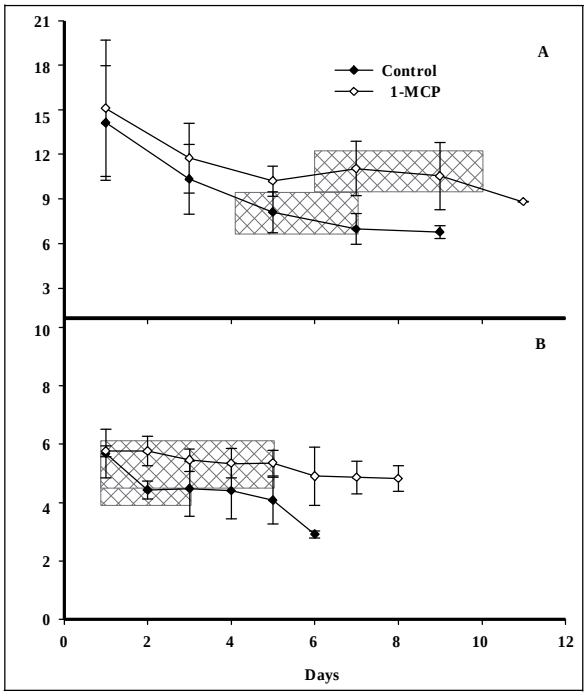

Fig. 3. Firmness of 'Sunrise Solo' papaya treated with air (control) or 9 ∝l l^{-1} 1-MCP at PRP (A) and RP (B) stages of development and stored at 20 °C. Shaded areas indicate the range of time during which the fruit were judged to be acceptable for consumption. Vertical bars represent standard deviation of the means (n = 5).

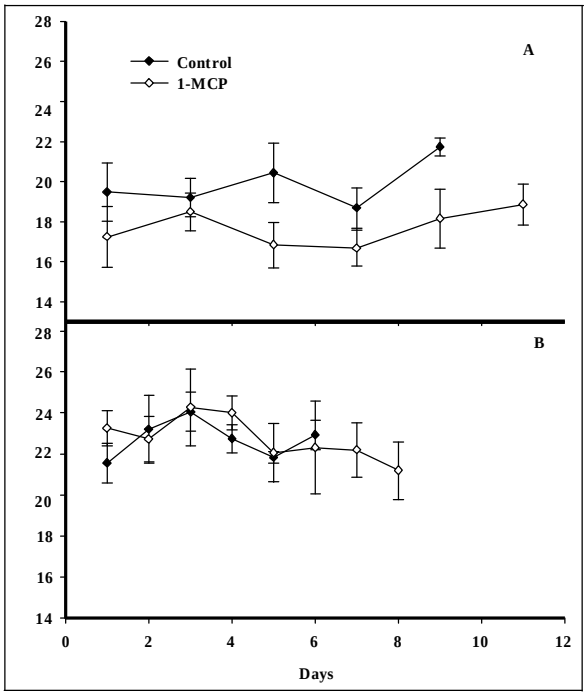

Fig. 4. Electrolyte leakage of mesocarp tissue of 'Sunrise Solo' fruit treated with air (control) or 9 ∝l l^{-1} 1-MCP at PRP (A) and RP (B) stages of development and stored at 20 °C. Vertical bars represent standard deviation of the means (n = 5).

1-MCP-treated fruit at day 11 (8.8 N) was comparable to that of control fruit at day 5 (8.1 N).

Firmness properties of RP fruit is shown in Fig. 3B. As confirmation of the RP status of these fruit at the time of 1-MCP application, the firmness values at initial storage (about 6 N) were similar to those of PRP control fruit ripened during storage (Fig. 3A). Within 2 d, the firmness of RP control fruit had declined about 22 %, thereafter remaining nearly constant for 3 d before again declining through 6 d to about 2.9 N, representing an overall decline of about 50 % compared with initial values. In contrast, the firmness of 1-MCP-treated RP fruit decreased only about 16 % through 8 d of storage.

Electrolyte efflux

Electrolyte efflux of PRP and RP papaya fruit is illustrated in Fig. 4 (A and B). Efflux changed minimally during storage of fruit of either ripening category, although values from fruit treated with 1-MCP at the PRP stage were consistently lower than control fruit (Fig. 4A). Leakage values were higher in RP compared with PRP fruit (Fig. 4B); however, differences between RP fruit (1-MCP versus air) were not noted.

Soluble solids concentration, titratable acidity, and pH Soluble solids concentration (SSC) of PRP fruit re- mained nearly constant during storage (12.4 to 13.7 %), but no significant differences were noted between treatments (data not shown). SSC values for RP fruit (11.1 to 12.8 %), while slightly lower than levels for PRP fruit, also varied little during storage, and were not affected by 1-MCP treatment. Titratable acidity (TA) of PRP fruit increased during storage, with values for control and 1-MCP-treated fruit diverging significantly after 3 d of storage (Fig. 5A). This divergence involved a significant increase in TA levels of control fruit while levels in 1-MCP-treated fruit remained nearly constant. TA levels in RP fruit showed trends similar to those of PRP fruit in that 1-MCP appeared to suppress the increase noted in control fruit (Fig. 5B). Mesocarp pH values of PRP fruit (Fig. 6A) were generally consistent with the data for TA in that 1-MCP-treated fruit maintained significantly higher mesocarp pH compared with control fruit. In RP fruit, both treatments showed steady declines in pH, from initial values of around 5 to about 4.7 to 4.8 (Fig. 6B).

Fruit quality assessment

Based on informal quality analysis of peel colour (PAULL and CHEN 1997) and flesh colour, aroma, texture, and flavour (O'CONNOR-SHAW et al. 1994), the period of table-ripe edibility PRP fruit ranged from 4 through 7 d for control and 6 through 10 to 11 d for 1-MCP-treated fruit, representing an average shelf-life extension of about 3 to 4 d. Most participants in the informal test panel preferred the higher, more persistent

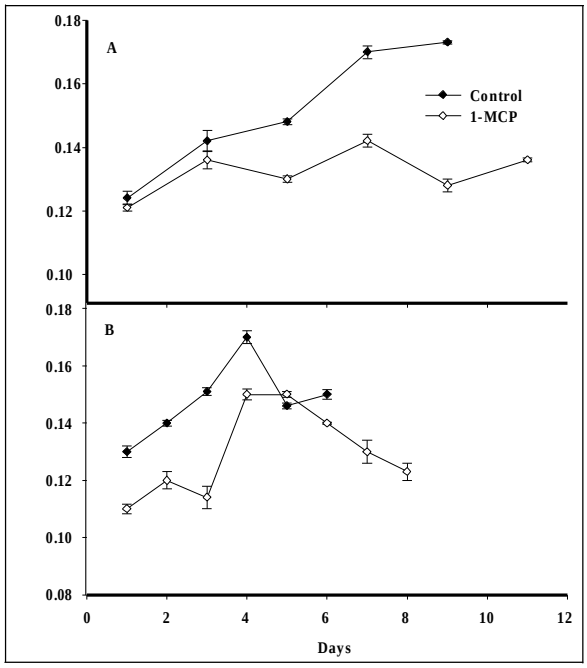

Fig. 5. Titratable acidity for 'Sunrise Solo' papaya treated with air (control) or 9 ∝l l–1 1-MCP at PRP (A) and RP (B) stages of development and stored at 20 °C. Vertical bars represent standard deviation of the means (n = 5).

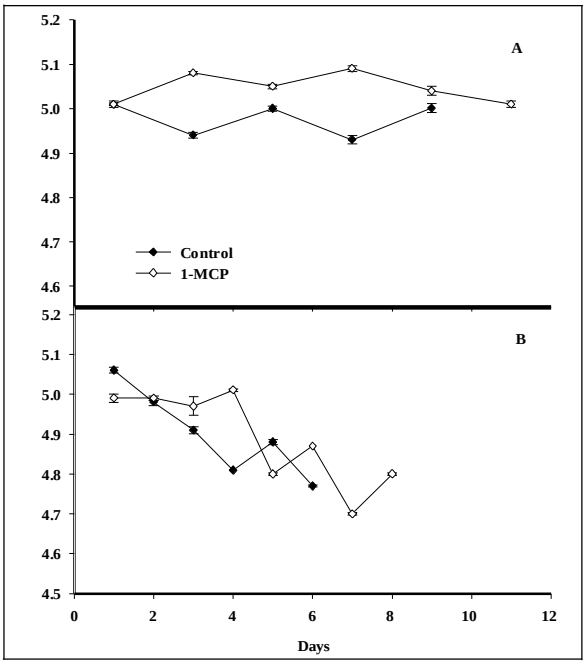

Fig. 6. Mesocarp pH of 'Sunrise Solo' papaya treated with air (control) or 9 ∝l l–1 1-MCP at PRP (A) and RP (B) stages of development and stored at 20 °C. Vertical bars represent standard deviation of the means (n = 5)

firmness of fruit ripened following treatment with 1-MCP when PRP. In similar informal tests with fruit treated with 1-MCP when RP, control and treated fruit remained of acceptable quality through 3 and 6 d of storage, respectively, representing a doubling of the period of table-ripe edibility. 1-MCP delayed the surface colour change (visual assessment) from green to yellow in PRP fruit and from light yellow to dark yellow in RP fruit. No external decay was evident in either control or 1-MCP-treated PRP fruit through 7 d of storage. Thereafter, nearly 17 % and 10 % of the control and 1-MCP-treated fruit, respectively, were eliminated from the tests due to decay. Decay was evident primarily as stem-end rot, the incidence of which increases with ripening of many tropical fruits, including papaya (ALVAREZ and NISHIJIMA 1987). Decay incidence during the relatively short-term storage of fruit treated with 1-MCP when RP was negligible.

Discussion

'Sunrise Solo' papaya fruit at both PRP and RP stages of development responded beneficially to pre-storage 1-MCP treatment at 9 ∝l l–1. JACOMINO et al. (2002) reported that much lower 1-MCP concentrations (90 or 270 nl l–1) were effective in extending the storage life of 'Sunrise Solo' papaya treated at an early stage of ripening (colour break). 'Solo' papaya treated at harvest maturity (pre-ripe) with 25 ∝l l–1 1-MCP required an additional 15 d (compared with controls) to reach an soft, edible condition (5 to 7 N) (HOFMAN et al. 2001). In our study, the effective storage duration of PRP (pre-climacteric) papaya treated with 9 ∝l l–1 1-MCP was 11 d compared with about 7 d for control fruit. The responses of fruit to 1-MCP are dependent on many factors, including fruit maturity at the time of application (BLANKENSHIP and DOLE 2003). Fruit employed in the present study were obtained from a commercial importer. Consequently, the ripening behaviour in response to the ethylene antagonist would likely reflect the time elapsed from harvest as well as holding conditions during transit. The response of tomato fruit to 1-MCP, in terms of both gene expression and ripening behaviour, has been shown to be tightly dependent on maturity at the time of 1-MCP application (HOEBERICHTS et al. 2002). Beneficial effects of 1-MCP on full-ripe tomato required concentrations of 20 ∝l l–1 (WILLS and KU 2002).

PRP papaya exhibited typical postharvest climacteric behaviour during storage, with respiration peaking at about 24 ml kg–1 h–1 and ethylene production at about 1.8 ∝l kg–1 h–1. Similar respiration rates and ethylene production were reported by PAULL and CHEN (1997) in 'Sunset' papaya harvested at colour break. In the cv. 'Solo', maximum respiration and ethylene production ranged from 19.3 to 67.1 ml kg–1 h–1 and 1.5 to 14.7 ∝l kg–1 h–1, respectively (WILLS and WIDJANARKO 1995). As shown in the present study, climacteric respiration and ethylene production in PRP 'Sunrise Solo' papaya were significantly delayed in response to the ethylene antagonist. Ethylene production of PRP papaya fruit treated with 1-MCP continued to increase slowly during storage, eventually reaching values comparable to control fruit but without evidence of a production peak.

Respiration and ethylene production were also suppressed in 'Sunrise Solo' fruit treated with the ethylene antagonist when RP, although the levels of ethylene produced were low in both treatments. These data are consistent with the expected post-climacteric status of fruit categorized on the basis of skin colour as RP. Reduced ethylene production and respiration at advanced stages of ripening were also reported for 1-MCP-treated tomato (WILLS and KU 2002) and 'Golden Delicious' apple (JIANG and JOYCE 2002) fruits. The 1-MCP-induced delay in the respiratory climacteric peak in PRP 'Sunrise Solo' and persistent respiration in RP fruit indicate that linkage between ethylene production and respiration are not tightly linked or that the linkage becomes less pronounced with advanced ripening. Consistent with this idea, reports for tomato (SALTVEIT 1993) and muskmelon (Shellie and SALTVEIT 1993) fruits have viewed the respiratory (versus ethylene) climacteric as an anomaly of harvest, possibly reflecting a response to preharvest factors and the stress of harvesting and handling (BOWER et al. 2002).

The rate and extent of softening of 'Sunrise Solo' papaya were significantly suppressed in response to 1-MCP. The inhibitory effect on softening is particular- ly noteworthy for RP fruit, and indicates that softening metabolism retains ethylene dependency well into the ripening process. The influence of 1-MCP at nearly arresting softening suggests that continued synthesis of ethylene-sensitive enzymes is required for the progression of softening, and is consistent with the idea that otherwise active cell wall enzymes exhibit finite catalyt- ic capacity in situ, possibly due to steric entrapment (SMITH et al. 1989; RUSHING and HUBER 1990) and/or restricted enzyme mobility.

Electrolyte efflux, often interpreted as evidence of membrane dysfunction in senescing or otherwise stressed tissues (MARANGONI et al. 1996), remained relatively constant during storage and ripening of PRP fruit and was only slightly reduced in response to 1-MCP. Leakage in RP fruit, while significantly higher than values for PRP fruit, was not influenced by 1-MCP. The disparity between leakage (minimal effects of 1-MCP), and firmness (significantly retained in response to 1-MCP) differences suggest that the two phenomena are not closely related in papaya. This is in contrast to observations for watermelon fruit, in which suppression of ethylene perception by 1-MCP significantly and simultaneously suppressed electrolyte leakage, lipase activities, and firmness loss during postharvest storage (MAO et al. 2004).

1-MCP had minimal influence on soluble solid levels in 'Sunrise Solo' fruit. HOFMAN et al. (2001) reported that 'Solo' papaya fruit treated with 1-MCP at an early stage of ripening had slightly but significantly higher levels of soluble solids at the edible soft stage. In their study, control fruit (10 % SSC) reached an edible stage in 4 to 5 d whereas 1-MCP-treated fruit (11.5 % SSC) required nearly 21 d. In view of the prolonged period required for ripening of 1-MCP-treated fruit, the higher SSC levels might be due in part to water loss. Higher soluble solids were reported for 1-MCP-treated 'Delicious' and 'Fuji' apples after prolonged storage (6 to 7 months, 0 °C) (FAN et al. 1999), and for pre-climacteric 'Elberta' peach treated with 1-MCP and ripened at 20 ºC (FAN et al. 2002). The variable effects of the ethylene antagonist on SSC in different fruits (BLANKENSHIP and DOLE 2003) may reflect differences in duration of storage time, maturity at the time of treatment, or on whether soluble sugar levels are dependent on import prior to harvest or on starch metabolism following harvest. 1-MCP suppressed the increase in TA in both PRP and RP 'Sunrise Solo' fruit. These findings contrast with other fruits including 'Gala' apple (FAN and MATTHEIS 2001) and 'Royal Zee' plum (DONG et al. 2002) wherein TA levels were higher in fruit treated with 1-MCP at an early stage of ripening. 1-MCP treatment maintained TA levels in tomato fruit when applied at advanced stages of ripening (WILLS and KU 2002) and was without affect on TA levels in 'Anna' apple (PRE-AYMARD et al. 2002).

The surface colour change of PRP and RP 'Sunrise Solo' fruit was significantly delayed by 1-MCP (data not shown). Similar effects of 1-MCP have been reported for banana (GOLDING et al. 1998) and avocado (JEONG et al. 2002) fruits. PRE-AYMARD et al. (2002) reported that 1-MCP delayed the surface colour change from green to yellow in 'Anna' apple fruit treated with 1-MCP at an advanced stage of ripening. The variable effects of 1-MCP on pigmentation changes among different fruit types and to some extent within different tissues (epidermal versus mesocarp) support the conclusion that the ethylene dependency of colour change varies according to pigment type and fruit species (LELIEVRE et al. 1997).

The most prominently affected ripening parameters for 1-MCP-treated 'Sunrise Solo' papaya included firmness and surface colour. On the basis of firmness and peel colour, the period of acceptable quality for papaya fruit treated at the PRP stage was reached at approximately 4 d and persisted through 7 d (see Fig. 3) whereas the comparable period for 1-MCP-treated fruit ranged from 6 through 10 d. While this represents an extension of only 1 d in the period of edibility, the extension in total storage potential averaged about 3 d. The edible period for fruit treated with 1-MCP when RP lasted 3 d whereas 1-MCP-treated fruit averaged about 6 d, representing a doubling in useful shelf-life.

1-MCP-treated PRP papaya fruit showed less incidence of decay compared with non-1-MCP-treated fruit. During storage of PRP fruit, 16.6 % of control fruit and 10 % of fruit treated with 1-MCP were lost to decay. These losses were due primarily to stem-end rots (SER), which can develop rapidly in ripe papaya and other fruits (ALVAREZ and NISHIJIMA 1987). The reduced decay in 1-MCP-treated PRP fruit might a consequence of the reduced rate of ripening of these fruit or on effects of 1-MCP on ethylene-responsive defense mechanisms. The pathogens responsible for the SER in these experiments were not identified. In contrast to PRP fruit, RP fruit displayed minimal evidence of decay during storage. This is likely explained by the fact that fruit selected for 1-MCP treatment when RP were visually free of surface defects and overall storage periods were relatively short. HOFMAN et al. (2002) noted that 'Solo' fruit treated with 25 $\propto$l l^{-1} 1-MCP when commercially mature (pre-ripe) showed higher disease incidence (stem black rots, anthracnose) upon reaching a ripe stage than did fruit not treated with the ethylene antagonist. The authors speculated that the longer time to ripen for 1-MCP-treated fruit (20 d) compared with

the 4 to 5 d for control fruit may have resulted in a reduction in endogenous anti-fungal compounds.

In summary, our results indicate that suppression of ethylene action in 'Sunrise Solo' papaya extends the useful storage life of fruit treated at either PRP or RP stages of development. The influence of the ethylene antagonist was much more pronounced for firmness and peel colour compared with SSC and TA. In view of the significantly more rapid softening of papaya processed as fresh-cut products compared with intact fruit stored under identical conditions (KARAKURT and HUBER 2003), current studies are addressing whether the beneficial effects of 1-MCP noted for whole fruit are maintained in fruit processed as fresh-cut products.

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