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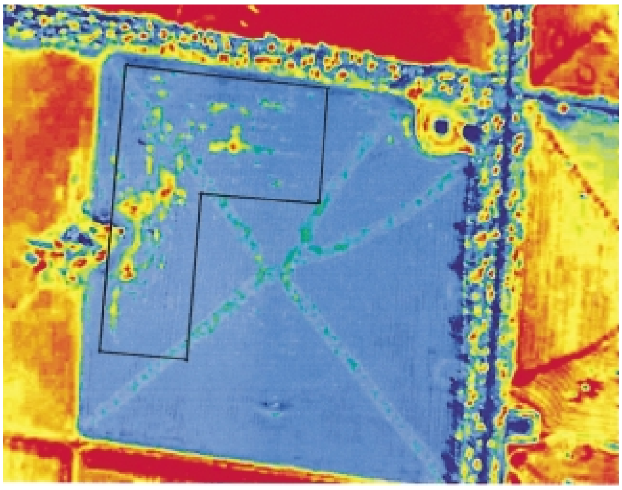

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Ripening of climacteric fruits initiated at low ethylene levels

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Abstract. Mature, unripe mango, peach, custard apple, kiwifruit and tomato were stored at 20°C in air containing ethylene at <0.005, 0.01, 0.1 1.0 and 10 µL/L. The time to ripen of all the climacteric fruits increased linearly with logarithmic decrease in ethylene concentration over the whole concentration range examined. Similar observations were also obtained with kiwifruit and custard apple held at 0 and 14°C, respectively. However, the sensitivity of fruits to ethylene varied with banana and kiwifruit > custard apple and mango > tomato, avocado and peach. Since the ethylene level around horticultural produce during marketing is always >0.005 µL/L, the time climacteric fruit can be held in an unripe condition is currently less than optimal but intervention to limit ethylene action would appear to be only warranted for the most sensitive fruits.

Introduction

Ethylene has been well known for many years to initiate the ripening of climacteric fruits whether the ethylene is derived endogenously or from exogenous sources. The effect on ripening is universally accepted to follow a time–concentration relationship with the higher the concentration of ethylene and the longer the exposure time to ethylene, the faster the initiation of ripening (Wills *et al.* 1998). Most quantitative studies on the relationship between ripening time of climacteric fruits and ethylene exposure have examined relatively high concentrations of ethylene as these are commonly used in commercial situations (e.g. Gazit and Blumenfeld 1970; Agar *et al.* 1999; Ritenour *et al.* 1999). Recommended concentrations for the induction of ripening of avocados, bananas, honeydew melons, kiwifruit, mangoes, stone fruits and avocados are between 10 and 100 µL/L (Saltveit 1999).

By comparison, much less effort has been expended on defining the lower limits of ethylene that will initiate ripening. Knee (1985) reported a threshold level of 0.1–0.5 µL/L to initiate the ripening of avocado, banana, honey dew melon and pear. However, more recent studies on kiwifruit have found that ripening was initiated by levels of 0.01 µL/L (Arpaia *et al.* 1987; Mitchell 1990). Furthermore, Peacock (1972) has speculated that for banana there is no effective threshold level of ethylene that induces ripening, although he examined short term exposure to ethylene levels >0.1 µL/L rather than longer exposure to concentrations <0.1 µL/L.

Ethylene has also been known to accelerate the senescence of non-climacteric produce. Recent studies on strawberry, green bean, lettuce, 4 leafy Asian vegetables and orange (Wills and Kim 1995, 1996; Kim and Wills 1995; Wills and Wong 1996; Wills *et al.* 1999*b*) exposed produce continuously to ethylene at concentrations from 10 to <0.005 µL/L and showed a deleterious linear response to logarithmic increase in ethylene over the whole concentration range. In addition, Wills *et al.* (1999*b*) reported that a further 15 non-climacteric produce showed a greater postharvest life at <0.005 µL/L than at 0.1 µL/L. They suggested that since the level of ethylene that accumulates around produce in commercial situations is always >0.005 µL/L, there is no effective threshold concentration of ethylene for non-climacteric produce.

Wills and Gibbons (1998) held Hass avocados at 10 and 20°C in ethylene concentrations ranging from 1 to <0.005 µL/L and found that, at both temperatures, the time to ripen increased linearly as the $\log_{10}$ ethylene concentration was decreased. This paper examines whether this relationship extends to other climacteric fruits by determining the time to ripen of 5 types of climacteric fruit held in air containing ethylene over the range <0.005 to 10 µL/L.

Materials and methods

Source of fruit

Mature but unripe mango (*Mangifera indica* L. cv. Kensington Pride), and custard apple (*Annona atemoya* L. cv. Pink's Mammoth) were obtained from the Sydney wholesale markets and kiwifruit [*Actinidia deliciosa* (A.Chev.) C.F. Liang et A.R. Ferguson cv. Hayward], peach [*Prunus persica* (L.) Batsch. cv. Fragar, Coronet, Loring and Flordagold] and tomato (*Lycopersicon esculentum* Mill. cv. Floradade) from farms on the Central Coast of New South Wales. The produce was replicated with purchases made on 3 occasions for mango and tomato, 4 occasions for custard apple, peach (1 replicate for each of the 4 cultivars) and kiwifruit. All fruit in each purchase were transported to the laboratory on the day of purchase where they were sorted to select only quality fruit of uniform size and maturity and

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randomly distributed into treatment units of an appropriate size. A treatment unit for each batch of produce consisted of 5 mangoes, 6 peaches, 4 custard apples, 9–10 kiwifruit, and 5 tomatoes.

Fruit treatment

The treatment units were packed into storage containers that were ventilated continuously with air containing a controlled concentration of ethylene. All produce was held at 20°C with kiwifruit and custard apple also held at 0 and 14°C, respectively.

Controlled levels of ethylene were obtained by mixing 0.1% ethylene gas (BOC, Sydney) with air through flow meters to generate concentrations of 0.01, 0.1 and 1.0 and 10 µL/L ethylene in the gas stream, which was passed through the containers holding the produce at 20 L/h. The relatively high flow rate ensured that endogenous ethylene production did not influence the behaviour of adjacent fruits. The lowest ethylene concentration was obtained by passing air through a column containing alumina impregnated with potassium permanganate (Purafil, Doraville, GA, USA). The concentration of ethylene in the air stream leaving the column was <0.005 µL/L, the limit of detection. The level of ethylene in the gas streams was monitored daily by flame ionisation gas chromatography (Varian 1400, Walnut Creek, CA, USA) using a 90-cm stainless steel column packed with Porapak Q (80-100 mesh) (Supelco, Bellefonte PA) with operating conditions of oven temperature 50°C, injector and detector temperature 135°C, nitrogen carrier gas-flow rate 50 mL/min, hydrogen flow rate 40 mL/min, air-flow rate 300 mL/min, and injected gas sample volume 1 mL.

At regular intervals, a single observer manually examined fruit texture by hand pressure on all produce, except tomato, until each item was considered to have softened to a full ripe stage. Ripeness of tomato was assessed visually for fruit colour until each fruit had attained a full red colour typical of ripe fruit. The time taken for each fruit to ripen was noted. A mean time to ripen was obtained for all fruit in each treatment unit. The relationship between time to ripen and ethylene concentration was statistically examined by regression analysis. Fruits held at <0.005 µL/L ethylene were considered more appropriately assigned to be at 0.005 µL/L in the regression calculation rather than at 0 µL/L.

Results and discussion

The data in Table 1 show the time to ripen of mango, peach, custard apple, kiwifruit and tomato held at 20°C and kiwifruit and custard apple held at 0 and 14°C, respectively, in air containing ethylene from <0.005 to 10 µL/L. The data was evaluated by regression analysis and Table 2 shows that for all climacteric fruits held at both ambient and reduced storage temperatures, the relationship between time to ripen and ethylene concentration was best represented by a linear increase in ripening time with logarithmic increase in ethylene concentration. The equations indicate that since there was an increase in time to ripen over the whole concentration range examined, any threshold level for ethylene action is below 0.005 µL/L, the lowest concentration that could be measured in the study. However, all reported studies of the concentration of ethylene around fruit and vegetables during transport and marketing have recorded levels >0.005 µL/L (Morris *et al.* 1978; Ku 2000; Wills *et al.* 2000). This indicates that in current commercial situations unripe climacteric fruits are always exposed to ethylene levels that reduce the time to ripen. The source of ethylene can be from endogenous production, other produce held nearby, or pollution from industrial sites and motor vehicle exhaust (Saltveit 1999). It is therefore extremely difficult to prevent ethylene accumulating around produce and suggests that preferred methods for preventing premature ripening of climacteric fruits is through compounds such as 1-methylcylcopropene (Sisler and Serek 1997) and nitric oxide (Leshem and Wills 1998) that inhibit ethylene action.

The introduction of any technique to inhibit ethylene action on climacteric fruits will need demonstration of a cost benefit to be obtained from use of the technique. Such assessment requires the ability to calculate the loss of potential storage life that occurs in the ethylene concentration found in marketing situations. If 0.005 µL/L is accepted as the lowest possible ethylene concentration, then the time to ripen of every climacteric fruit at this concentration represents the maximum storage life for that fruit, that is, 100% of potential storage life. While the desired storage life will vary greatly with different marketing strategies, the experimentally derived regression equations can be used to calculate the ethylene concentration that will result in the loss of any designated percentage of storage life. Table 2 shows calculations for the fruits used in this study, plus published data for Williams banana and Hass avocado, of the ethylene concentrations that give rise to a loss of 10 and 30% of potential storage life. The criteria for these

Table 1. Time to ripen (days) of climacteric fruit held in air with ethylene at 10 to <0.005 µL/L

Fruit	Temp. (°C)	Ethylene concentration (µL/L)[A] 10	1.0	0.1	0.01	<0.005
Kiwifruit	20	3.3	7.7	9.4	11.7	15.6
Kiwifruit	0	—	27.7	39.4	44.7	52.6
Custard apple	20	2.8	3.8	4.5	4.8	5.8
Custard apple	14	8.3	9.7	9.0	11.0	11.3
Mango	20	7.5	8.2	9.7	12.0	12.8
Peach	20	12.3	13.2	14.2	15.7	16.0
Tomato	20	—	10.3	11.6	13.1	13.5

[A]Ethylene concentration (µL/L) in the atmosphere around fruit.

Table 2. Relationships between time to ripen (y) and $\log_{10}$ ethylene concentration (x) for climacteric fruits at ambient and reduced temperatures

Fruit	Temp. (°C)	Regression equation	Ethylene (µL/L) 10% loss	Ethylene (µL/L) 30% loss	Percentage loss of time to ripen at 0.1 µL/L
		Ambient temperature			
Banana	20	$y = -9.24x + 3.3$[A]	0.009	0.03	49
Kiwifruit	20	$y = -3.21x + 7.11$**	0.014	0.11	30
Custard apple	20	$y = -0.79x + 3.7$**	0.026	0.65	19
Mango	20	$y = -1.64x + 8.6$**	0.027	0.89	17
Tomato	20	$y = -1.40x + 10.3$**	0.048	4.05	13
Avocado	20	$y = -1.28x + 10.0$[B]	0.047	5.05	13
Peach	20	$y = -1.15x + 13.3$***	0.132	>10	9
Mean			0.043	2.97	21
		Reduced temperature			
Kiwifruit	0	$y = -9.78x + 28.2$**	0.017	0.18	25
Avocado	10	$y = -2.51x + 20.4$[B]	0.065	6.62	13
Custard apple	14	$y = -0.83x + 9.2$*	0.112	>10	10

*$P<0.05$; **$P<0.01$; ***$P<0.001$. [A]Wills *et al.* (1999*a*). [B]Wills and Gibbons (1998).

limits were that a 10% loss in storage life would be tolerable in most marketing situations while a 30% loss could be limiting marketing opportunities. The values were obtained by calculating the time to ripen at 0.005 µL/L ethylene, subtracting 10 and 30% from this time and then solving the equations to obtain the ethylene concentrations for these times to ripen. The data in Table 2 show that for fruits held at 20°C, mean ethylene concentrations of 0.043 and 2.97 µL/L resulted in 10 and 30% loss of storage life, respectively (the value for peach at 30% loss was taken as 10 µL/L. However, the sensitivity of individual fruits to ethylene varied greatly. Banana and kiwifruit were the most sensitive with 30% loss in storage life occurring with ethylene at 0.029 and 0.113 µL/L, respectively, while peach, avocado and tomato were the least sensitive at >4 µL/L, and custard apple and mango were of intermediate sensitivity at 0.65 and 0.89 µL/L, respectively. This suggests that no uniform benchmark for the detrimental effects of ethylene can be set for climacteric fruits but one needs to be established for each fruit. The benefit of any intervention technique to inhibit ethylene action will therefore vary between fruits. This is in contrast to non-climacteric fruit and vegetables which Wills *et al.* (2000) found to be more uniform in response to ethylene with a 10% loss in postharvest life for 9 produce ranging from 0.010 to 0.018 µL/L and for 30% loss from 0.043 to 0.221 µL/L, and allowed them to set benchmarks of 0.015 and 0.1 µL/L as acceptable and unacceptable levels of ethylene during marketing.

Kiwifruit, custard apple and avocado held at subambient temperature all showed a higher ethylene concentration was needed to give 10 and 30% loss in storage life than for fruit held at 20°C. It also shows that the mean loss in storage life of all fruits held at 20°C in a previously considered (Kader 1985; Knee *et al*. 1985) threshold level of 0.1 µL/L ethylene was 21%, with values ranging from 9% for peach to 49% for banana.

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