

EFFECTS OF TEMPERATURE AND ETHYLENE ON  
PAPAYA (*Carica papaya* L., CV. SUNSET) RIPENING

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By

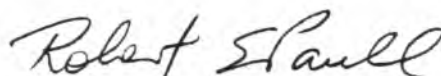
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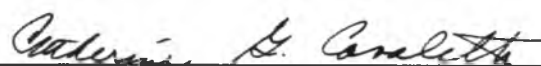
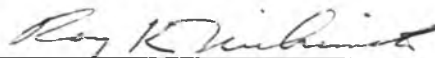
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## ABSTRACT

Temperatures at or higher than 30°C adversely affected the marketability of papayas. Papayas stored at 32.5°C for 10 days failed to ripen normally as evidenced by poor color development, abnormal softening, surface pitting, off-flavor, and a higher susceptibility to decay. The rates of fruit ripening were slow at 17.5° and 20°C. Thus, the optimal temperature range from 22.5° to 27.5°C was used to establish the time-temperature relationship for papaya ripening. Skin yellowing and softening of papayas exhibited a quadratic response to ripening time within the optimal ripening range. Flesh color development of non-cold-stored fruit did not change significantly during the first six days, then rapidly increased; while that of cold-stored fruit exhibited a quadratic response for each ripening temperature.

Ethylene hastened papaya ripening rate uniformly during ripening with or without cold storage. However, ethylene could not ripen immature papaya completely in terms of skin and flesh color development. Papayas treated with ethylene for 30 and 48 hrs did not show significant difference in fruit quality about one day after ethylene treatment (90 to 130 ppm).

Cold-stored papayas exhibited faster ripening rate, e.g. degreening, softening and flesh color development. Cold storage also reduced the severity of retardation on papaya ripening caused by high temperature, 32.5°C.

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## LITERATURE REVIEW

### INTRODUCTION

#### Papayas

The papaya (*Carica papaya* L.) is a major economic crop of Hawaii. It belongs to the family *Caricaceae*, which is native to tropical and subtropical areas of North and South America (Nagy and Shaw, 1980). It is a rapid-growing, herbaceous dicotyledonous perennial. In general, the trees are classified into three sex types : staminate, pistillate, and hermaphroditic. Usually it is single- and hollow-stemmed bearing heads of palmately lobed leaves. The fruit enclosing a 5-angled cavity and blackish seeds is formed at the leaf axils and remains on the tree until the lower leaves have fallen (Nagy and Shaw, 1980; Storey, 1969).

The papaya was distributed along the tropical trade routes and is grown extensively throughout the tropical regions. The fruit have increased in popularity in the past 80 years, and the tree has become an important plantation crop in Hawaii, South Africa, Australia, India, Ceylon, the Philippines, and several countries in tropical America and Southeast Asia (Storey, 1969).

Papaya trees can produce fruit without interruption the whole year round, although the production decreases in winter. Under favorable environmental conditions and proper cultural practice, the tree begins producing fruit within one year from planting. It can continue to bear fruit for 25 years or more (Storey, 1969).

The shape of papaya fruit ranges from almost spherical-shaped and pear-shaped to elongated or cylindrical. The fruit shape is related to

the type of flower. For instance, Solo variety bears small pyriform fruit from hermaphroditic trees and spherical-shaped ones from female trees (Burkner and Kinch, 1968). Fruit from hermaphroditic trees are considered most acceptable commercially. The size of fruit varies with different strains within the 300 g to 3 kg range (Nagy and Shaw, 1980).

The firmness of papayas declines as the fruit ripen. The fruit at the stage of mature green may turn from dark to light green at the blossom end. During ripening the skin color turns from green to yellow. The change in color is due to the degradation of chlorophyll in the epidermal tissue, which leads to the unmasking of carotenoids, and the development of additional carotenoids in the cells (Chen, 1963). The carotenoids start to develop before the external color change. The internal color changes from yellow or light orange starting from the seed cavity, spreading to the skin during ripening. Cryptoxanthin is the main carotenoid present in papayas (Yamamoto, 1964). Carotenoids in both the yellow and red-fleshed papayas were compared by Yamamoto (1964). The complete absence of lycopene in the yellow-fleshed type is the major difference between the two varieties.

Papaya seeds are black in color, roundish and wrinkled in form with a transparent seed coat (Storey, 1941). The funiculi and placenta are spongy and are difficult to separate from the flesh until the fruit is fully ripe. As the fruit approaches maturity the seeds change from white to black.

Papaya flesh is composed mostly of water, ca. 87%, and carbohydrates, ca. 12% (Chan and Tang, 1979). No starch or other

storage polysaccharide has been detected in papayas (Chan, 1979). Sugars present in ripe papayas range from about 10% to 15% of the fresh weight (Chen, 1963). Sugar composition of ripe papayas was determined by Chan and Kwok (1975) to be 48% sucrose, 30% glucose, and 22% fructose by inactivating the invertase with microwave heating.

A sweet flavor predominates in papayas due to a greater sugar content than acidity (Chan and Tang, 1979). Papaya fruit (var. Solo) contained the following titratable acids in decreasing amounts : citric, malic, ascorbic, alpha-ketoglutaric, galactouronic, tartaric and pectic (Chan *et al.*, 1971). The first four acids constituted 85% of the total acid in papayas.

The most abundant amino acids present in papayas were identified to be aspartic acid, glycine, gamma-amino butyric acid, alanine, and glutamic acid (Chen, 1963). A total of 106 volatile flavor compounds was identified with the concentrates by combined chromatograph-mass spectrometry (Flath and Forrey, 1977).

### Harvesting Criteria

The degree of maturation at harvest is the major factor affecting fruit quality maintenance. Several criteria are used to judge maturation. Traditionally, external color estimated visually has been used as the harvesting criterion in papayas. Hence, personal experience significantly influences the quality of harvested papayas. Total soluble solids (TSS), measured in °Brix, is often used as an indicator of fruit quality and maturity. In Hawaii, the standard of Department of Agriculture requires a minimum TSS of 11.5%. To meet this standard, it

is recommended that the fruit should have at least 6% skin yellow (Akamine and Goo, 1971a). Force-deformation ratio, a non-destructive maturation test, was found to be a more sensitive index for papaya maturation than color grade (Burkner and Kinch, 1968). This is because the color index lacks the characteristics that force deformation ratio has, such as the fineness of gradation and statistical reliability. External color (Hunter or C.I.E. color readings  $L$ ,  $a$ ,  $b$ ) was investigated as a maturity index for papayas (Peleg and Gómez Brito, 1974; Peleg and Gómez Brito, 1975; Couey *et al.*, 1984; Couey and Hayes, 1986). Fruit with higher initial Hunter  $b$  values (blue to yellow) tended to soften and developed internal color more rapidly. Hunter  $a$  values (green to red) showed similar function to that of the  $b$  values. The higher the initial Hunter values, either  $a$  or  $b$ , the shorter the ripening time of papayas and the greater the probability of the normal fruit ripening. However, the individual fruit having the same initial coloration intensity ( $a$  value) could ripen at almost any time. Therefore, the initial external Hunter  $a$  value only indicated a tendency of ripening of the majority of the fruit (Peleg and Gómez Brito, 1975). The external Hunter  $b$  value is used as a measure of degrees of ripeness in the hot water insect disinfestation procedure in order to prevent fruit damaged by heat, i.e. Hunter  $b$  value of fruit should be  $< 23.5$  at the blossom end and  $< 27.5$  at the most yellow area of the fruit (Couey and Hayes, 1986).

## PATTERNS OF RIPENING IN PAPAYAS

### Respiration

#### Normal Respiratory Pattern of Papayas

Papaya is a climacteric fruit (Biale *et al.*, 1954). Mature-green papayas show a typical preclimacteric minimum followed by a respiratory rise and decline when ripened at 25°C (Akamine, 1966). The peak concentrations of CO<sub>2</sub> and C<sub>2</sub>H<sub>4</sub> occur when the fruit (var. Solo) are about 80% yellow. Fruit harvested after the color turning stage do not show the preclimacteric minimum in respiration, indicating that the preclimacteric minimum has already occurred before harvest. The CO<sub>2</sub> content in the fruit cavity increases with maturity (Wardlaw and Leonard, 1935; Akamine and Goo, 1979). The percentages of CO<sub>2</sub> contained in the fruit cavity of papayas harvested at the maturity stage from green to overripe increases from 1.5 to 13.5%, while O<sub>2</sub> decreases from 17.5 to 3.5% (Jones and Kubota, 1940). Attached papayas have the same pattern of CO<sub>2</sub> and C<sub>2</sub>H<sub>4</sub> evolution in the cavity as the detached ones (Akamine and Goo, 1979).

#### Effects of Temperature

The production of CO<sub>2</sub> increases with increasing temperatures during ripening (Jones, 1942). The temperature coefficients of papayas are to be 1.5 between 4.4° and 7.2°C, 3.3 between 7.2° and 10°C, 2.2 between 10° and 12.8°C, and 2.2 between 12.8° and 15.6°C.

### Effects of Quarantine Disinfestation Treatments

Most fresh commodities are disinfested by approved quarantine treatments before shipping to the U.S. mainland from Hawaii (Akamine, 1966). Three principal quarantined insects in Hawaii are the oriental fruit fly (*Dacus dorsalis* Hendel), the melon fly (*Dacus cucurbitae* Coquillett) and the Mediterranean fruit fly (*Ceratitis capitata* [Wiedeman]). Several disinfestation procedures, such as vapor heat (Jones, 1939; Shoji, 1951), fumigation (e.g. with EDB) (Havens *et al.*, 1979; Seo *et al.*, 1979), irradiation (Akamine and Wong, 1966), and hot water treatments (Couey and Hayes, 1986), have been employed to kill the eggs and larvae of these fruit flies. They all increase respiration and accelerate the onset of climacteric rise with an associated increased ripening rate (Akamine, 1966).

### Effects of Cold Storage

A lack of the climacteric rise in respiration is one of the phenomena of chill-injury in papayas (Jones and Kubota, 1940). The respiration of firm-ripe papayas stored at 3° to 4°C remains constant during the 11-day period of storage. The ripening process of papayas could not be resumed on removal of the fruit from the cold storage (1.7°C for 11 days) to room temperature.

### Ethylene Evolution

Both detached and attached ripening papayas (*Carica papaya* L., var. Solo) have similar patterns in ethylene evolution (Akamine and Goo, 1977; Akamine and Goo, 1979).

## Changes in Sugar Composition During Papaya Development and Ripening

Generally, fruits exhibit a decrease in acidity and an increase in sweetness during ripening (Rhodes, 1980). The increase in sugars during ripening of the climacteric fruit is due to the degradation of starch and cell wall carbohydrates. For example, banana TSS increases from 2% to about 18% during ripening (Simmonds, 1966). At the full-ripe stage, the flavor and sweetness are at a maximum. Papaya TSS and reducing sugars increase about 2% during ripening from a minimum of about 11.5% in mature-green to about 13.5% in ripe papayas (Jones and Kubota, 1940). The absence of starch in papayas explains the small increase in TSS during ripening.

Chan (1979) showed that total sugars of tree-ripened papayas increase slowly during the first 110 days of development to about 3.4 g 100 g<sup>-1</sup>, then dramatically increase to a peak (9.8 g 100 g<sup>-1</sup>) about 135 days after anthesis for the summer fruit. Sucrose, which is the most abundant sugar in papayas at harvest, makes up 80% of total sugars 135 days after anthesis. Glucose is the predominant sugar (65%) during the first 70 days of fruit growth, then decreases slowly until 110 days, followed by a rapid decline to a minimum of about 20% of the total sugars 135 days after anthesis. Fructose increases slowly during the first 110 days, then decreases rapidly to a minimum of about 10% of the total sugars (Chan, 1979).

In summer fruit, surface yellowing on the blossom end of fruit commenced about 130 days after anthesis and the fruit begin to ripen thereafter. After the fruit reach the color turning stage, sucrose

decline rapidly with an associated increase in glucose and fructose. This indicates that sucrose is inverted to simple sugars during this period. The inversion of sucrose in papayas was demonstrated to be catalyzed by the enzyme, beta-fructofuranosidase (Chan and Kwok, 1975; Chan and Kwok, 1976). Winter fruit take 10 days longer, which is in accord with the previous finding that the winter crop takes longer to reach maturity than the summer fruit.

When mature-green papayas (var. Solo) are harvested and allowed to ripen at room temperature (28°C), only slight changes in total sugar content are found over the ripening period, i.e. from mature green or color break to the stage of full ripening (Chen, 1963). Also, the ratios of sucrose (60%), glucose (24%), and fructose (16%) do not exhibit apparent change throughout ripening of detached papayas.

#### Changes in Enzyme Activities

Much research on enzymatic mechanisms has been reported. In general, factors affecting fruit softening can be divided into enzymatic and non-enzymatic mechanisms (Huber, 1983). Both of these processes change the architecture of the cell wall during fruit softening. Hydrolases believed to be involved in fruit softening are polygalacturonase (E.C. 3.2.1.15) (PGase), cellulase, and pectin methyl-esterases. PGases related to fruit softening are reported to be endo-D-galacturonases, exo-D-galacturonases and oligo-D-galactosiduronate hydrolases.

The quality of ripe papayas is partly determined by fruit softness. A close relationship exists between the rise in the activity of PGase

and xylanase and rises in respiratory climacteric and  $C_2H_4$  evolution, as well as changes in softening and skin color of papayas (cv. Sunrise) (Pauli and Chen, 1983). The maximum activities of PGase and xylanase occur at the same time as the climacteric and  $C_2H_4$  production peak. In papayas, the PGase activity increases during ripening and is highest in the placenta, decreasing towards the exocarp (Chan *et al.*, 1981). Both exo- and endo-PGase are extracted, partially purified and characterized (Chan and Tam, 1982). The molecular weight determined by gel filtration is about 164,000 daltons for the endo-PGase and 34,000 daltons for the exo-PGase. Both enzymes function optimally at pH 4.6 and 45°C.

## ENVIRONMENTAL FACTORS THAT AFFECT FRUIT RIPENING

### Effects of Temperature

Temperature plays an important role in fruit ripening. Many biological reactions show quantitative responses to temperatures. The temperature coefficient value ( $Q_{10}$ ) is about 2 for most biological reactions. Generally, with an increase of 10°C above optimum, the rate of deterioration increases by two to three times and then the  $Q_{10}$  decreases as the temperature is further increased. However, since  $Q_{10}$  values vary greatly with many factors such as the kind of fruit, physiological conditions, duration of storage, it can only be used as a rough approximation. For some fruits like strawberries, peaches, lemons, oranges, there is a higher  $Q_{10}$  at lower temperatures (Haller *et al.*, 1931). Abnormalities may appear when the fruit are exposed to temperatures above the optimal range. The range has a rather narrow limit (approx. from 15° to 30°C). The influence of high temperatures on fruit ripening includes changes in climacteric peak, rate of ethylene production, interference of color development and other disruptions of normal metabolism. The symptoms of injury caused by high temperatures include surface pitting, undesirable flavor and higher susceptibility to decay.

Low temperatures are usually used to delay deterioration of horticultural crops. When the fruit are stored at undesirable low temperatures, they results in physiological disorders, including freezing injury and chilling injury (Kader, 1985a). The capability to tolerate low temperature varies with species, variety and maturity of fruit. Freezing injury occurs when the temperatures are below fruit's freezing

temperatures (ca.  $-1^{\circ}\text{C}$ ). For example, the critical temperatures for temperate fruits such as apples, plums, and peaches are from  $0^{\circ}$  to  $4^{\circ}\text{C}$ ;  $8^{\circ}$  to  $10^{\circ}\text{C}$  for subtropical fruits like citrus and some avocados; and around  $10^{\circ}$  to  $12^{\circ}\text{C}$  for tropical fruits such as tomatoes, bananas and papayas (Lyons, 1975). When the temperature falls below the critical threshold (generally  $10^{\circ}$  to  $12^{\circ}\text{C}$ ), fruits originating in the tropics develop chilling injury symptoms. Chilling injury symptoms include surface and internal discoloration, a decrease in aroma, and an increase in off-flavor development, accelerated incidence of decay fungi, tissue breakdown, pitting, and a lack of the climacteric rise (Kader, 1985a). Riper fruit are more tolerant to low temperature than the less ripe ones.

The response of several kinds of fruit to temperatures is reviewed below:

#### *Avocados*

The climacteric patterns of avocados of various physiological maturities are similar and the preclimacteric period decreases as the fruit mature (Zauberman and Schiffman-Nadel, 1972). Avocado (cv. Hass) climacteric peak increases with increasing temperatures from  $20^{\circ}\text{C}$  to  $35^{\circ}\text{C}$  (Eaks, 1978). Also, the initial respiration rates and the preclimacteric minima increase as temperature increases (Lee and Young, 1984). No climacteric response was observed at  $40^{\circ}\text{C}$ . The peak of  $\text{C}_2\text{H}_4$  production decreases as the temperature increases, but the decrease is not significant between  $20^{\circ}$  and  $25^{\circ}\text{C}$  (Eaks, 1978). At  $40^{\circ}\text{C}$  the fruit do not ripen normally and the tissue become discolored and rubbery. The climacteric rise and ethylene production were not

permanently inactivated by a temperature of 40°C for 2 days. Fruit held at 40°C for 2 days followed by 20°C resume the normal ripening process. For avocados (cv. Fuerte), fruit show typical climacteric rise within 12° to 27°C range and ripen abnormally at higher temperatures (30°, 34°C) (Lee and Young, 1984). At 9°C, respiration rate increases slightly but not climacterically. However, fruit do not soften even after 6 weeks at 9°C, and also developed typical chilling injury as evidenced by gray discoloration of mesocarp tissue after 3 to 4 weeks of storage at 6°C.

### *Mangoes*

The optimal temperature range for ripening mangoes varies with varieties (Proctor and Caygill, 1985). Mangoes (var. Tommy Atkins) exhibit normal softening when ripen at temperatures between 22° and 37°C (Medlicott *et al.*, 1986). This temperature range leads to fruit of good quality characteristics with high chlorophyll breakdown, high pulp carotenoids, a good texture (i.e. a pulp rupture force of less than 1 kg), and a favorable sugar:acid ratio. However, at higher temperature, 37°C, fruit develop a mottled appearance on the peel and the sugar:acid ratio is slightly lowered.

The development of typical aroma, flavor and carotenoid formation of mangoes (var. Alphonso) is adversely affected by storage temperatures below the ambient (25°C) (Thomas, 1975). Fruit held at low temperatures (7° to 20°C) for 16 to 23 days followed by room temperature contain 22 to 53% less carotenoids. Medlicott *et al.* (1986) also reported that fruit held at 12°C for 16 days do not ripen to full

eating quality. Poor pulp color appears after 15 days at 17°C, although they have softened and degreened to an acceptable level. Generally, time to softening decreases with increasing temperature within the 15.5° to 26.7°C range and ranges from 4 to 20 days depending on the variety (Proctor and Caygill, 1985). The sugar:acid ratio is found to be lower when fruit are stored at 12° or 17°C.

### *Bananas*

To achieve optimal banana ripening, pulp temperature should be in the range from 14.4° to 21.2°C (Anon., 1972). The respiration rate of bananas increases with temperature within the 12.5° to 30°C range (Wardlaw and Leonard, 1936). Above 31°C, the peel does not develop the typical yellow color and the pulp becomes liquidified. Cavendish bananas (cv. Williams) held at 15°C followed by higher ripening temperatures of 21° and 27°C have black peel and liquidified pulp (Rippon and Trochoulis, 1976). Whereas, fruit ripened at 15°C for the whole period exhibit slow but normal ripening. Optimum color quality is adversely affected by temperatures above 23.9°C (75°F), however, the eating quality is not severely affected (Peacock, 1980).

If the fruit are ripened below this range, chilling injury develops. A dull, grayish yellow peel color is the main symptom of banana chilling injury. The pulp also has poor flavor and a somewhat hard and dry texture (Anon., 1956). Chilled bananas do not exhibit normal patterns of C<sub>2</sub>H<sub>4</sub> evolution and ripening. Besides these physiological abnormalities, the chilled fruit tissue is also more susceptible to decay.

Rippon and Trochoulis (1976) reported that bananas are adversely affected when ripened at 15° or 17°C with a subsequent temperature either 10°C or temperatures higher than 27°C. The adverse effect may be related to the stage of ripeness at which fruit exhibit high susceptibility to temperature fluctuations, i.e. fruit are moved from 15°C or 17°C to 10°C or 27°C. It may be explained by the occurrence of the climacteric rise in respiration at this stage of development.

### *Tomatoes*

High temperatures affect softening and red color development (Hall, 1964). Mature-green tomatoes held at temperatures above 30°C fail to develop the typical red color (Sayre *et al.*, 1953). This is due to an inhibition of lycopene synthesis. An exposure to a short period of high temperatures (32.2°, 37.8°, 42.2°, 43.3°C) for 6 to 24 hrs after harvest followed by 7 days at 20°C alters the quality of color-turning fruit (Hall, 1964). The development of red skin color is enhanced when tomatoes are stored at 32.2°C for 6 to 24 hrs followed by 7 days at 20°C. Tomatoes stored at temperatures above 30°C result in the inhibition of lycopene synthesis but not that of carotene (Goodwin and Jamikorn, 1952). Lycopene synthesis is resumed and proceeds normally soon after the ripening temperature is reduced to 30°C or lower. Fruit at color-turning stage stored at these high temperatures for 6 hrs followed by a storage of 7 days at 20°C are softer than those stored at 20°C continuously (Hall, 1964). However, periods longer than 6 hrs at temperatures above 42.2°C result in firmer fruit.

Tomatoes ripen at a low temperature range (15°C day; 7.2°C night) get too soft and are more subject to decay before attaining a deep red color (Sayre *et al.*, 1953). The ascorbic acid content of John Bear tomatoes is highest at the lowest temperature and decreases with increasing temperatures. Hobson (1987) studied the low-temperature injury of tomatoes (cv. Sonatine) and showed that temperatures below 9°C give rise to injury symptoms at the green-orange stage of ripening (i.e. "early breaker"). Temperatures of 10°C or less adversely affect the development of red pigment (probably lycopene) as evidenced by a decrease in Hunter *a* values. The progressive malfunction of pigment formation through chloroplast-chromoplast conversion caused by chilling-stress leads to an uneven pigmentation with small irregular green areas on the normal red background. An increase in the rate of loss in firmness is also observed as a minor effect of low-temperature storage which may be elicited by the release of C<sub>2</sub>H<sub>4</sub> due to chilling-stress since C<sub>2</sub>H<sub>4</sub> is known to stimulate the major softening enzyme, PGase (Grierson and Tucker, 1983).

Pharr and Katten (1971) compared the respiration rates of mature green and color-turning tomatoes stored at 24° and 16°C. Low temperature (16°C) slows down ripening and reduces respiratory rates, but low temperature does not delay attainment of the climacteric peak.

### *Papayas*

The ripening rate of papayas varies with different varieties. The optimum ripening temperature for Sunrise Solo papayas is 20°C. Ripening of Sunrise Solo takes 10 to 12 days at 20°C (Broughton *et al.*,

1977). Papayas (var. Taiping) ripen in 6 and 4 days at 20°C and 26°C, respectively (Nazeeb and Broughton, 1978). For Bentong variety, it takes 11 and 7 days at the same temperatures. Neither Taiping nor Bentong variety ripens at 10° and 15°C.

The mature green papayas (var. Solo) ripen normally with a typical respiratory curve at 25°C (Akamine, 1966). Both the climacteric and the ethylene peaks occur earlier at high temperatures. Also, the magnitude of the CO<sub>2</sub> and C<sub>2</sub>H<sub>4</sub> peaks usually increases with temperatures due to the condensing of the ripening period (Broughton *et al.*, 1977; Nazeeb and Broughton, 1978). Fruit stored at 7.2°C (45°F) for 5 days followed by room temperature ripen unevenly, with poor quality, and are subject to decay, while those stored at 10°C (50°F) for 5 days ripen evenly, with high quality and no decay.

PGase activity increases with papaya fruit ripeness and plays an important role in softening (Chan *et al.*, 1981). Extended hot water treatment (46°C for 65 min) delays fruit softening. This may be because the high temperature causes a decrease in PGase amount and/or activity leading to a delay in fruit softening. The riper fruit (quarter or half ripe) are more sensitive to heat treatments and this sensitivity is correlated to the greater decrease in PGase activity in the riper ones. In addition to a delay in ripening, an area of 1- to 1.5-cm-thick hard tissue is found near the seed cavity when riper fruit are subjected to 46°C for 65 and 95 min. Similar results show that riper fruit (riper than firm-ripe but not overripe) are less tolerant than firm-ripe or mature-green fruit to the high-temperature sterilization at 43.3°C (Jones *et al.*, 1939). They reported that riper fruit have soft and

translucent flesh in response to the high temperature sterilization; while in less ripe fruit, the injured part do not ripen and exhibit rubbery pulp texture.

Ethylene is known to stimulate PGase activity in tomatoes along with other ripening processes (Grierson and Tucker, 1983). Ethylene forming enzyme (EFE) system is responsible for the conversion of 1-aminocyclopropane-1-carboxylic acid (ACC) to ethylene. Since EFE is very labile to surfactants, osmotic or cold shocks and is susceptible to heat treatments, it has been proposed to serve as a simple but effective biochemical indicator of fruit injury caused by heat treatments (Chan, 1986). At least two kinds of EFE are found to exist in papayas; heat resistant EFE (HREFE) and heat susceptible EFE (HSEFE). HREFE comprised about 25% of the total EFE activity and HSEFE is about 75%. HSEFE of papayas with a lower activation energy (ca. 51.2 Kcal/mole) seems to be a most heat labile enzyme system because other enzyme systems are found to have higher activation energy, e.g. endo-PGase (92 Kcal), and exo-PGase (102 Kcal), etc. (Chan and Tam, 1982; Chan, 1986). Therefore, the commercial heat treatments (42°C for 30 min plus 49°C for 20 min) affected mainly the HSEFE of papayas which may lead to a decrease in the generation or activation of PGase.

The general effect of high temperature treatment is a marked acceleration of color development (Jones *et al.*, 1939). Fruit treated with heat but uninjured have equal or even better flavor, aroma, color, and texture than non-treated ones.

For processing, papayas can be ripened at higher temperatures from ambient temperature up to 32.2°C to hasten the ripening rate

(Akamine, 1977). Temperatures above 32.2°C cause delayed coloring and ripening, rubbery pulp texture, copious latex oozing, and fruit surface bronzing. The optimum temperatures for hastening ripening are suggested to be from 29.4° to 32.2°C.

The symptoms of papaya chilling injury include skin scald, hard areas in the pulp around the vascular bundles, and water soaking of the tissue. The tolerance of fruit to low temperatures varies with the maturity of fruit (Chen and Paull, 1986). Less ripe fruit are more sensitive to chilling. The development of chilling injury symptoms depends on time-temperature relationship. The lower the storage temperature, the shorter the time before chilling injury occurs. The positive linear relationship between storage temperature and time for symptom development has similar slopes for mature green fruit and 60% yellow papayas with the line for 60% yellow being displaced about 3 to 4 days later.

Chilling temperatures stimulate  $C_2H_4$  production in papayas depending on the temperatures and exposure duration to low temperatures (Chan *et al.*, 1985). Papayas stored at 5°C (chilling temperatures) for more than 4 days produce more  $C_2H_4$  than those stored at 10°C (non-chilling temperatures) upon transfer to 24°C. The difference in  $C_2H_4$  production between 5° and 10°C increases with the storage duration.

#### Effects of Relative Humidity

Relative humidity (RH), along with ambient temperature management and gas composition control are important factors in the

storage and ripening of fruit. Relative humidity during postharvest handling may affect weight loss, gas exchange, respiration and ethylene evolution, pathogen growth, which then influence the storage life and quality of ripening fruit (Grierson and Wardowski, 1978).

### Respiration and Ethylene Evolution

Littmann (1972) reported that moisture loss from preclimacteric avocados, bananas, and pears hasten fruit ripening. Papayas ripened under drier conditions are found to produce  $C_2H_4$  and  $CO_2$  faster than those under high RH (Pharr and Katten, 1971). However, fruit ripened at high RH (100%) are subject to increased fungal attack.

Haard and Hultin (1969) found that green bananas ripened at a relatively low humidity (below 80%) do not have a climacteric peak and ripened abnormally. During ripening of plantains, water stress has no effect on the rate and pattern of the climacteric and green-life (George and Marriott, 1983). Green life in this case is defined as the time from initiation to climacteric onset. The contradictions may be due to the different storage conditions and cultivars or species used.

### Fruit Quality

The rate of water loss from fruit depends both on temperature and relative humidity. At a given temperature and air movement rate, the rate of water loss from the commodity depends on the RH (Kader, 1985a). For bananas, RH of the ripening room should be at about 85 to 90% (Anon., 1972). If RH is too high, fruit may be susceptible to decay and become tender and liable to split; the stem ends of fingers also

become weak (called weak necks). On the other hand, low RH results in excessive weight loss, poor color development, and more pronounced spots. In plantains, water stress delays color development of peel, pulp softening, and starch hydrolysis (George and Marriott, 1983).

During refrigerated storage of many vegetables, such as Brussel sprouts, cabbages, carrots, and cauliflowers, decay of crops held at higher RH (98 to 100%) is found to be less serious than or about equal to those stored at lower RH (90 to 95%) (van den Berg and Lentz, 1978). This is interpreted in terms of host-parasite relationships. Four aspects of host-parasite relationship studied are periderm thickness, fungistatic properties of the tissue, survival of pathogens, pectolytic enzyme production by the pathogens.

#### Effects of Exogenous Ethylene

Exogenous  $C_2H_4$  has been found to hasten ripening and/or results in uniform ripening in mangoes, tomatoes, bananas and avocados (Barmore, 1974; Fuchs *et al.*, 1975; Pratt and Workman, 1962; Ke and Ke, 1980; Proctor and Caygill, 1985). The response to exogenous  $C_2H_4$  is different in non-climacteric fruits and climacteric fruits (Knee, 1985). Exogenous  $C_2H_4$  can stimulate respiration of non-climacteric fruits but the rate will decline when  $C_2H_4$  is withdrawn. Also, to exert its effect on non-climacteric fruits high  $C_2H_4$  concentration is required. In climacteric fruits, usually at the mature green stage,  $C_2H_4$  is used to hasten ripening processes, which include degreening, softening, respiration,  $C_2H_4$  evolution, and changes in sugars, organic acids etc..

Since climacteric fruits produce  $C_2H_4$  during maturation and ripening,  $C_2H_4$  applied has no deleterious effects on fruits.

#### Factors Affecting Ethylene Effects

The factors affecting the effectiveness of  $C_2H_4$  in achieving faster and more uniform ripening are the cultivar, sensitivity to  $C_2H_4$  (i.e. physiological age at harvest),  $CO_2$  and  $O_2$  level,  $C_2H_4$  concentration,  $C_2H_4$  exposure duration, temperature and RH (Proctor and Caygill, 1985; Knee, 1985).

Stages of fruit development respond differently to exogenous  $C_2H_4$ . It has been reported that  $C_2H_4$  exerts its effects only when it is applied before climacteric rise is reached in apples and pears (Gane, 1937; Hansen and Hartman, 1937). In general, less mature fruit require higher  $C_2H_4$  concentrations and take longer to respond to applied  $C_2H_4$  than more mature ones (Pratt, 1975). Moreover, the endogenous  $C_2H_4$  content influences the sensitivity of plant tissues to exogenous  $C_2H_4$  (Knee, 1985). Persimmons (cv. Fuyu), one of the exceptions, seems to decrease in the sensitivity to  $C_2H_4$  as the fruit mature (Takata, 1982). Ethylene cannot ripen immature tomatoes completely so that in order to insure a proper completion of ripening process in response to  $C_2H_4$ , tomatoes require a certain stage of development (Bondad and Pantastico, 1976). For immature mangoes, ethylene can not be used to improve fruit quality (Barmore, 1974). Respiration of immature avocados is stimulated by propylene treated from 1 day after harvest for 1 to 3 days, but returns to the level of untreated fruit within 1 day after removal of propylene (Eaks, 1980). Furthermore, ethylene

synthesis in response to propylene is not found in immature avocados. For the mature avocados, the  $C_2H_4$  production and a climacteric rise are induced by propylene or  $C_2H_4$  (McMurchie *et al.*, 1972; Eaks, 1980). Thus, maturity stages are related to the capacity to synthesize  $C_2H_4$  in response to propylene or  $C_2H_4$  (Eaks, 1980).

Two possible  $C_2H_4$  receptors, of high and low affinities, are proposed to explain different sensitivities to  $C_2H_4$  in various ripening processes (Knee, 1985). Chlorophyll breakdown, softening and mass production of  $C_2H_4$  are supposed to be initiated by  $C_2H_4$  at a high affinity site. The rapid endogenous  $C_2H_4$  synthesis can then be enough to saturate the low affinity site and subsequently elicit maximal respiration rate.

Oxygen is required for  $C_2H_4$  synthesis from ACC (Adams and Yang, 1979). Raising the  $CO_2$  and lowering the  $O_2$  level increase the  $C_2H_4$  concentration required for half maximum response, suggesting that  $CO_2$  is an inhibitor, and  $O_2$  a cooperative factor of  $C_2H_4$  action in pea seedlings (Burg and Burg, 1967). Ethylene accumulation is prevented and the onset of ripening is delayed if the fruit are held in the atmosphere of high  $CO_2$  and low  $O_2$  (Knee, 1985). For example, ethylene effect on banana ripening is reduced under low  $O_2$  levels in bananas (Quazi and Freebairn, 1970; Pratt, 1975). However, the low  $O_2$  level should not fall below 2.5% to ensure that flavor, texture and color are not adversely affected (Hesselman and Freebairn, 1969).

Other factors such as  $C_2H_4$  concentration, exposure duration and temperature are also important. For example, mangoes only need 5 to 10 ppm for 24 to 48 hrs at 30°C (Barmore, 1974), while mature green

bananas need 100 ppm for at least 2 days (Anon., 1972). Temperatures lower than 30°C for C<sub>2</sub>H<sub>4</sub>-treated mangoes can be used, but with a reduced ripening rate (Barmore, 1974).

#### Effects of Applied Ethylene on Respiration of Climacteric Fruits

The climacteric rise of mature-green tomatoes is induced immediately after the application of 1000 ppm C<sub>2</sub>H<sub>4</sub> (Pratt and Workman, 1962). The time to the climacteric and to softening after harvest is shortened in response to C<sub>2</sub>H<sub>4</sub> or propylene treatment in avocados (Eaks, 1980). The respiration of apple bananas (var. Silk fig) increases with low concentration (2 ppm) of C<sub>2</sub>H<sub>4</sub> (Burg and Burg, 1965). Respiratory activities continue to increase during the 12-day ripening period after treatment of 1000 ppm C<sub>2</sub>H<sub>4</sub> for 48 hrs in Cavendish bananas (Henze *et al.*, 1983). Ethylene treatment causes an earlier climacteric and hastens ripening in mature cantaloupes (var. *reticulatis* Naud.) (McGlasson and Pratt, 1964). The respiration of Japanese persimmons (cv. Fuyu) is stimulated by a treatment with 10 ppm C<sub>2</sub>H<sub>4</sub> (Takata, 1982).

#### Effects of Applied Ethylene on Biochemical Changes

During ripening, the major biochemical changes of ripening fruit include changes in the specific activities of citrate synthase, malate dehydrogenase, and malic enzyme, loss of chlorophyll, formation of lycopene, PGase, and increase in invertase. Holding tomatoes at 12°C in 6% CO<sub>2</sub>, 6% O<sub>2</sub>, and 88% N<sub>2</sub> for 1 week prevents C<sub>2</sub>H<sub>4</sub> formation and shows a temporal separation of some biochemical changes associated

with ripening (Jeffery *et al.*, 1984). The changes in organic acids and associated enzymes, which occur immediately after the removal of fruit from the vine, do not correlate with measurable respiratory rise (Goodenough and Thomas, 1981; Tucker and Grierson, 1982). Therefore, changes of organic acids, such as citrate metabolism and malate metabolism, are not stimulated by ethylene and they do not rely on cell wall breakdown by PGase. However, changes in appearance of PGase, and an increase in invertase activity are found to be stimulated by  $C_2H_4$ . Ethylene accelerates starch catabolism without causing any damages at 16° and 18°C in Cavendish bananas (Henze *et al.*, 1983). Temperatures up to 20°C seem to be a stressing condition in  $C_2H_4$ -treated bananas.

### Effects of Applied Ethylene on Fruit Quality

#### *Color*

Ethylene accelerates chlorophyll destruction and stimulates yellowing of green tissues (Kader, 1985b). Degreening rate in Cavendish bananas increases with the treatment of 1000 ppm  $C_2H_4$  during the first two days of ripening (Henze *et al.*, 1983). The increase in degreening rate caused by  $C_2H_4$  is more obvious with increasing temperatures. Degreening increases significantly with a 20-hr exposure to 1000 ppm  $C_2H_4$  at 20°C muskmelons (cv. Honey Dew) (Lipton *et al.*, 1979). Ethephon treatment increases the level of carotenoids in oranges (cv. Mahaley) (Abbas, 1984). In citrus fruit,  $C_2H_4$  applied after harvest enhances external orange and red color by inducing accumulation of specific carotenoids (Stewart and Wheaton, 1972).

However, ethylene may not be the major factor in the endogenous control of ripening (García-Luis *et al.*, 1986). Carotenoid accumulation during natural maturation of mandarins (cv. Satsuma) is thought to be controlled through a different mechanism from chlorophyll degradation because it is reduced by cytokinins and gibberellin A<sub>3</sub>. The lycopene synthesis appears to be regulated by C<sub>2</sub>H<sub>4</sub> in tomatoes (Jeffery *et al.*, 1984).

#### *Firmness*

Generally, climacteric fruit treated with C<sub>2</sub>H<sub>4</sub> soften faster than the untreated ones. This is thought to be correlated with the increase in the PGase activity (Grierson and Tucker, 1983). The response of fruit softening to C<sub>2</sub>H<sub>4</sub> varies with cultivar and temperature in tomatoes (Manzano-Mendez *et al.*, 1984). Ethylene hastens softening only at 20°C in the chilling-sensitive cultivars of tomatoes, while C<sub>2</sub>H<sub>4</sub> hastened ripening in the chilling-tolerant ones at 25°C.

#### *Sugars, Total Soluble Solids, and Organic Acids*

Ethylene treatment shortens the time required for the reduction of acidity and the increase in TSS in mangoes (George and Marriott, 1983). Similar tendency which may be correlated to the starch catabolism is also found in loquats and bananas (Hirai, 1982; Henze *et al.*, 1983).

#### *Others*

Liu (1976) reported that bananas continuously kept in the air with 10 ppm of C<sub>2</sub>H<sub>4</sub> have few or no superficial senescent spot, which is

different from the anthracnose spot caused by *Gloeosporium musarum*. However, ethylene can not inhibit the appearance of anthracnose spots. Exogenous ethylene applied before shipping results in a reduction of the incidence of internal breakdown and a reduction in the development rate of anthracnose in mangoes (cv. Tommy Atkins) (Proctor and Caygill, 1985).

## MATERIALS AND METHODS

Papayas (*Carica papaya* L. cv. Sunset) were obtained from the Poamoho experimental station on Oahu, Hawaii. The fruit were harvested and sorted visually for the color range, color break to about 10% yellow. Fruit were treated with a two-stage hot water immersion to disinfest eggs and larvae of fruit flies. The hot water treatments consist of 30 min at 42°C followed by 20 min at 49°C (Couey and Hayes, 1986). Fruit were then dipped in thiabendazole (TBZ, 650 ppm a.i.) for 5 sec to provide the additional control of fungal decay. A two-week cold storage at 10°C in some experiments was used to simulate surface transportation and storage.

### FRUIT EVALUATION

Fruit ripening rate and quality were assessed on the following : a) initial and final surface color estimated and expressed as % skin yellow of the whole surface area; b) flesh color estimated and expressed as percentage of full-ripened color with normal color development (0 to 100%) and overripe scale (101 to 140%); c) fruit skin color determined objectively using a Minolta Chromometer with a 50 mm head in terms of the brightness (C.I.E. *L* value), the green to red component (C.I.E. *a* value), and the blue to yellow component (C.I.E. *b* value); d) flesh color determined objectively in terms of *L*, *a*, *b* values; e) deformation force in kg, i.e. the force required to push a 1.5 cm plunger 2 mm into the flesh, which was measured by UC Fruit Firmness Tester; f) external and internal abnormalities with 6 grades which were based on the ratio of

the abnormal area to the whole fruit (0 - 0%, 1 - 1 to 10%, 2 - 11 to 35%, 3 - 36 to 65%, 4 - 66 to 90%, 5 - 91 to 100%); g) total soluble solids ( $^{\circ}$ Brix) determined from fruit juice with a refractometer; h) flavor which was divided into 5 grades was dependent on the ripeness and severity of off-flavor (1 - underripe, 2 - ripe and normal, 3 to 5-overripe; increasing with the severity of off-flavor). Flavor was mainly used to judge off-flavor and whether the fruit was edible or not (i.e. softened to the extent that is edible). Ripe papayas refer to the fruit that ripens to the extent that the flesh is soft and edible and the skin is mostly yellow.

A randomized complete block design was used in all experiments. A treatment, with 8 or 10 fruit in different experiments, was roughly divided into 2 ripeness groups as blocks, CB to 5% and 6% to 10%. Results were analyzed using the SAS statistical program (SAS Inc. North Carolina).

#### EFFECTS OF TEMPERATURE

Fruit were ripened at various temperatures; 17.5°, 20°, 22.5°, 25°, 27.5°, 30°, 32.5°C, for 5 and 9 days with and without a prior cold storage. The fruit evaluated after harvest and after cold storage were harvested on the same day. The test was done in July 1986 and repeated in August 1987 with the storage time for 5 and 10 days, respectively. Ten and eight fruit were used in each treatment in July and August harvest, respectively. Based on the July experiment, the temperature range, 22.5° to 27.5°C, was then selected for subsequent tests. Fruit were harvested in August and September to determine the

time-temperature response to this temperature range without and with cold storage, respectively. The fruit were ripened at 22.5°, 25° and 27.5°C for 4 to 10 days (non-cold-stored) and 4 to 12 days (cold-stored). The test without cold storage was repeated with 8 fruit on March 1987 and evaluated from 2 to 8 days after harvest.

## EFFECTS OF ETHYLENE

### Cold Storage Effects on Ethylene-treated Papayas

Fruit harvested in late March 1987 were ripened at 25°C with exogenous ethylene for 48 hrs after harvest and after cold storage. The fruit evaluated after harvest and after cold storage were harvested on the same day. Control fruit were evaluated simultaneously. Ethylene was applied using a continuous flow system, that maintained 50 to 160 ppm and 50 to 130 ppm in the treatments without and with cold storage. Ten fruit were used in each treatment. Observations of various characteristics were made from 2 to 8 days, at 2-day intervals, after harvest or cold storage.

### Effects of Duration of Ethylene Exposure on Papayas

Fruit with a 2-week cold storage prior to ethylene treatment were treated with ethylene from 90 to 130 ppm continuously at 25°C and then stored at 25°C. The durations of ethylene treatment were 30 and 48 hrs. Eight fruit were used in each treatment. Control fruit were examined simultaneously. Fruit were assessed 30 hrs and 2, 3, 5, 7 days and 2, 3, 5, 7 days after cold storage with 30-hr or 48-hr ethylene treatment, respectively.

### Effects of Ethylene on Flesh Color Development

Fruit harvested in May 1988 were ripened at 25°C with ethylene (200 ppm) for 24 hrs after harvest. Control fruit were evaluated simultaneously. Ten fruit were used in each treatment. Papaya flesh color was measured objectively using a chromometer with an 8 mm head to see whether ethylene affects red color development (C.I.E. *a* value) of papaya flesh. The fruit were cut longitudinally into 2 halves and four data were taken from the equatorial area of one half including 2 for the outer flesh and 2 for the inner flesh. Data were also taken from the peduncle and blossom end.

## RESULTS

### EFFECTS OF TEMPERATURE

#### Optimal Temperature Range for Ripening Papayas

Papayas exhibited normal color development and softening when ripened at temperatures between 20° and 30°C for 10 days (Fig. 1-A, 1-B, 1-C). Ripening rate increased with increasing temperatures within this range. Skin yellowing rate showed a linear relationship to the ripening temperature from 17.5° to 30°C (Fig. 1-A). Skin color reached 100% yellow after 10 days at 30°C, but with serious weight loss of 10 to 13% at about 60% RH. Degreening was retarded at 32.5°C with or without cold storage. Serious external abnormalities (irregular brown spots) after 10 days at 32.5°C and shrinkage occurred with weight loss of 11 to 15% at 60% RH. Skin yellowing rate of papayas stored at 17.5° and 20°C without cold storage was slower, ranging from 20 to 40% yellow with a ripening period of 10 days.

There was no significant difference in the deformation force of fruit ripened between 17.5° and 22.5°C for 10 days with or without cold storage (Fig. 1-B). The deformation force exhibited a quadratic relationship to the ripening temperature (17.5° to 30°C) with the  $r^2$  values, 0.763 and 0.401, for fruit ripening without and with cold storage respectively.

Papaya flesh color increased gradually as the temperature increased (Fig. 1-C). A significant increase in flesh color development of cold-stored fruit was observed between 17.5° and 20°C (ca. 43% to 60% full-ripened color), while that of non-cold-stored fruit occurred

between 27.5° and 30°C (ca. 50% to 70%) when ripened for 10 days. Fruit ripened at 32.5°C for 10 days showed poor flesh color development. Although the  $r^2$  values were not high (0.296 and 0.288), statistically the flesh color exhibited a quadratic relationship (0.1% level) to the ripening temperature (17° to 30°C).

Retardation of ripening rate by incubating fruit at 32.5°C for 10 days also occurred in deformation force (Fig. 1-B), flesh color (Fig. 1-C) and flavor (Table 1, only in non-cold-stored fruit). Fruit were overripe and had an off-odor when stored at 32.5°C for 10 days.

An optimal temperature range from 22.5° to 27.5°C was then chosen to establish the time-temperature relationship for papaya ripening.

#### Time-temperature Response for Papaya Ripening within the Optimal Temperature Range

Fruit (March 1987 harvest) not subjected to cold storage exhibited a quadratic response of skin yellowing to ripening time (concave) as the time from harvest increased (Fig. 2-A). During the first four days after harvest, no difference of skin yellowing was found among 22.5°, 25° and 27.5°C at the 5% level of significance and the skin yellowing rate was slow (between ca. 6% and 40% yellow). There was more surface color development at 27.5°C than at 22.5°C about 5 days after harvest. The degreening rate as evidenced by C.I.E. *a* value was significantly different between 22.5° and 27.5°C at the 5% level, and it was supported by C.I.E. *b* value at the 10% level. A significant difference between 25° and 27.5°C in yellowing was observed 6 days

after harvest, but was not significant 8 days after harvest. This was similar to both C.I.E. *a* and *b* values.

Papaya softening rate during ripening was not different between 22.5° and 27.5°C (Fig. 2-B). Deformation force of fruit harvested in March remained at the same level during the first 4 days after harvest. Papayas harvested in August (data not shown) exhibited the same trend except that the fruit began to soften 2 days later than those harvested in March. Flesh color did not change significantly during the first six days, then rapidly increased (Fig. 2-C). Flesh color of papayas ripened at 25°C and 27.5°C was significantly greater than that of fruit ripened at 22.5°C 8 days after harvest at the 5% level.

Cold-stored fruit (October 1986 harvest) showed a quadratic response (convex) of surface color to ripening time after removal from cold storage (Fig. 3-A). Papayas incubated at the three temperatures (22.5°, 25°, 27.5°C) did not exhibit significant difference in yellowing rate at the 5% level.

Cold-stored fruit initially softened slowly for 6 days after removal to ripening conditions, then the rate increased (Fig. 3-B). Therefore, unlike non-cold-stored fruit (Fig. 2-B), softening of cold-stored papayas harvested in summer tended to exhibit a linear response to ripening time (Fig. 3-B). Ten or more days after cold storage, fruit ripened at higher temperatures (25° and 27.5°C) were softer than those at 22.5°C.

Flesh color of cold-stored papayas exhibited a quadratic response for each ripening temperature (Fig. 3-C). During the first 4 days of ripening there was no obvious difference in flesh color between 22.5° and 27.5°C. Flesh color of fruit ripened at 25° and 27.5°C developed

from about 4 days after cold storage. Significant difference in flesh color among incubation temperatures occurred about 6 days after cold storage. Ten days after cold storage, flesh color reached above 96% (% of full-ripened color) regardless of ripening temperatures. Cold-stored papayas ripened at higher temperatures (25° and 27.5°C) for 12 days were overripe.

## EFFECTS OF ETHYLENE

### General Impact of Ethylene on Ripening Papayas

Papayas treated with 90 to 130 ppm ethylene for 48 hrs exhibited faster and more uniform ripening in terms of yellowing rate (Fig. 4-A and 6-A), softening (4-B and 6-B), and flesh color development (7-A and 7-B) with or without cold storage. Visual flesh color of ethylene-treated papayas exhibited a delay of 1 or 3 days after ethylene treatment when skin color reached above 85% yellow with or without cold storage, respectively (Fig. 7-A and 7-B). The outer portion of papaya flesh treated with ethylene started to develop yellow color gradually while it was still pale white in the non-treated ones. A significant increase in orange-pink color in the outer portion of ethylene-treated fruit could be seen after the delay. This phenomenon was supported by C.I.E. *a* values taken from papayas treated with ethylene (200 ppm) for 24 hrs (Fig. 8). C.I.E. *b* values did not follow the same pattern and are not reported here. Ethylene did not ripen immature papaya completely, i.e. flesh was softened (6.6 kg in deformation force) but with little surface color (8% yellow) and no flesh color development.

### Effects of Duration of Ethylene Exposure on Papayas

A 30-hr ethylene treatment hastened papaya yellowing rate uniformly but did not initially increase to full color (Table 2). Ethylene treatment for 48 hours resulted in faster softening than a 30-hr treatment (Table 3). Two days after cold storage, surface color development of fruit with either exposure duration was significantly increased uniformly. Fruit ripened for 3 days after cold storage showed no difference between the two exposure durations on surface color. The delay in flesh color development of fruit treated with ethylene for 30 hrs started 1 to 2 days faster than those treated for 48 hrs (Fig. 9).

## EFFECTS OF COLD STORAGE

### Cold Storage Effects on Ripening Papayas

Surface color, softening and flesh color developed faster in cold-stored fruit (Fig. 1-A, 1-B and 1-C). For the fruit stored at higher temperatures (25° to 30°C) for 10 days, cold storage did not have significant effect on surface color development and softening. Cold-stored fruit yellowed faster than those not cold-stored after 10 days at temperatures between 17.5° and 27.5°C, especially from 17.5° to 22.5°C, in terms of visual (Fig. 1-A) or C.I.E. *L*, *a*, *b* surface color, and between 20° and 30°C for flesh color (Fig. 1-C). Cold-stored fruit softened faster at the lower temperature range (from 17.5° to 22.5°C) than the non-cold-stored (Fig. 1-B). In some experiments (summer fruit), the inner portion of papaya flesh began to soften to the extent that it did not need a squeezer to obtain the fruit juice for TSS determination upon removal of fruit from 10°C cold room.

The extent of retardation due to high temperature (32.5°C) was smaller if the fruit were exposed to a 2-wk cold storage in terms of deformation force and flesh color (Fig. 1-B, 1-C). The difference was not seen in skin yellowing in this experiment (August 1987 harvest), but was significant in the repeated experiment (July 1986 harvest, data not shown).

#### Cold Storage Effects on Ethylene-treated Papayas

Exogenous ethylene increased the rate and uniformity of ripening of non-cold-stored papayas in terms of yellowing and softening as the time from harvest increased (Fig. 4-A, 4-B). Besides visual surface color, the effect of ethylene on degreening was supported by the increased C.I.E. *a* values (Fig. 5). Ethylene hastened both the yellowing and softening rates of cold-stored fruit (Fig. 6-A, 6-B). The fruit softened immediately after removal of fruit from the ethylene chamber and exhibited uniform softness (Fig. 6-B). However, the variability of yellowing rate of cold-stored fruit did not seem to be reduced until the surface color was close to 100% yellow (Fig. 6-A).

The flesh color development rate was increased by ethylene with or without cold storage as the time increased (Fig. 7-A, 7-B). The delay of visual flesh color development was shortened from about 3 days to 1 day by cold storage after ethylene application. Ethylene had a greater effect on cold-stored fruit than fruit not stored in terms of surface color development right after 48-hr treatment, which then developed to the same degree (Fig. 4-A vs. Fig. 6-A).

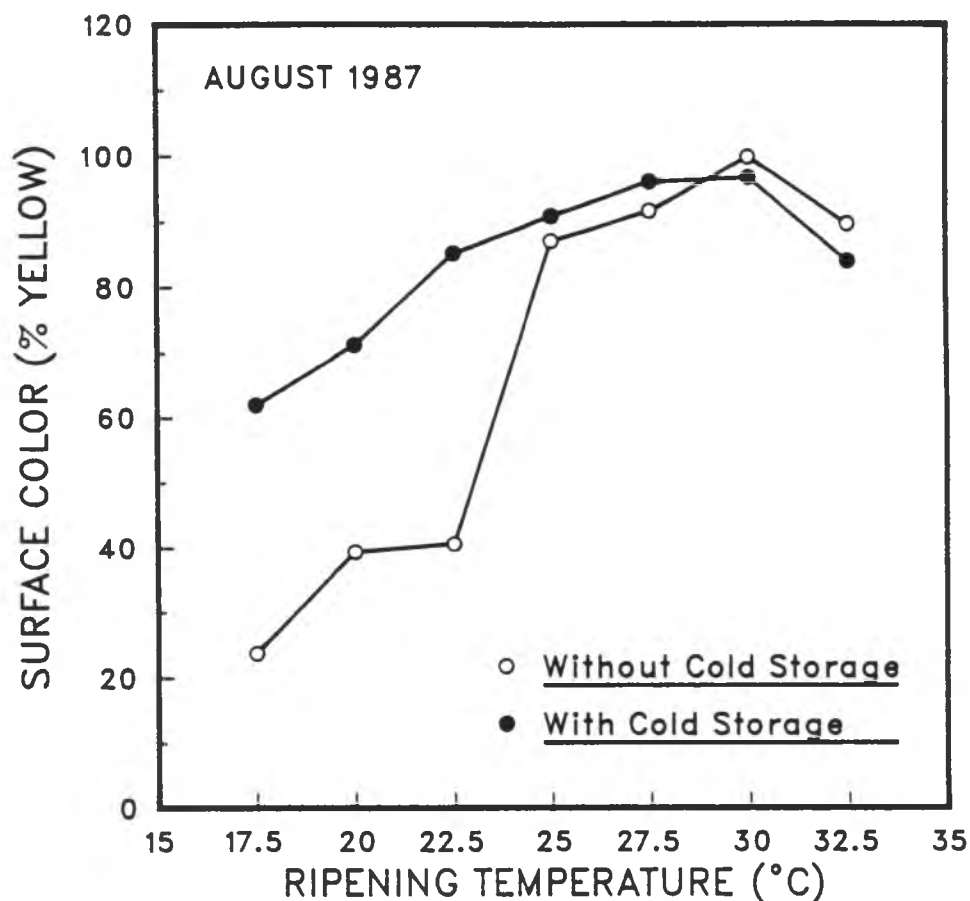


Figure 1-A Effect of temperature on surface color development (% yellow) of ripening papayas 10 days after harvest or after cold storage (10°C for 14 days). All points are means of 8 fruit except that cold-stored fruit ripened at 32.5°C had 6 fruit. Initial values were 4% and 7% yellow at harvest and after cold storage, respectively. Equation lines for the best fit (from 17.5° to 30°C) were  $Y = -95.0 + 6.7X$  ( $r^2 = 0.747$  \*\*\*) and  $Y = 14.4 + 2.9X$  ( $r^2 = 0.406$  \*\*\*) for fruit ripening without and with cold storage, respectively. A significant level of 0.1% for the regression line is designated as \*\*\*. Confidence limits of means are shown in Appendix Table 2.

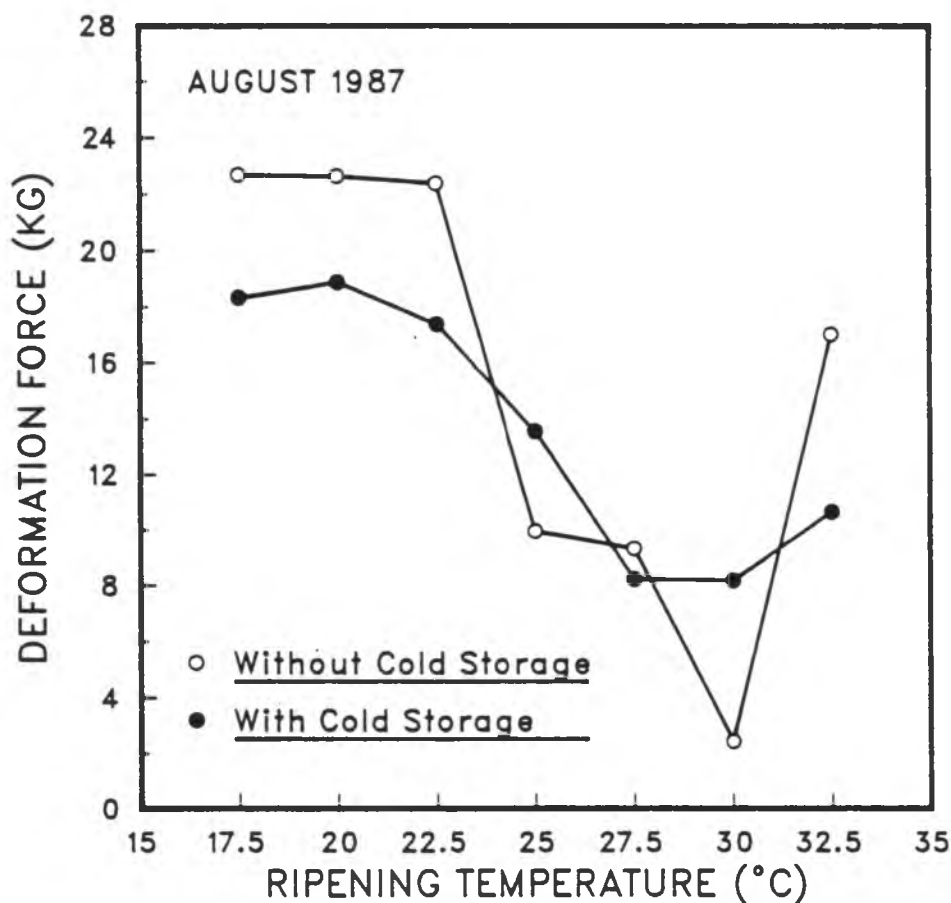


Figure 1-B Effect of temperature on deformation force (kg) of ripening papayas 10 days after harvest or after cold storage (10°C for 14 days). The higher the value, the harder the fruit. All points are means of 8 fruit except that cold-stored fruit ripened at 32.5°C had 6 fruit. Initial values were 23.0 kg and 22.7 kg at harvest and after cold storage, respectively. Equation lines for the best fit (from 17.5° and 30°C) were  $Y=0.81+3.10X-0.10X^2$  ( $r^2=0.763$  \*\*\*) and  $Y=9.17+1.48X-0.052X^2$  ( $r^2=0.401$  \*\*\*) for fruit ripening without and with cold storage, respectively. A significant level of 0.1% for the regression line is designated as \*\*\*. Confidence limits are shown in Appendix Table 3.

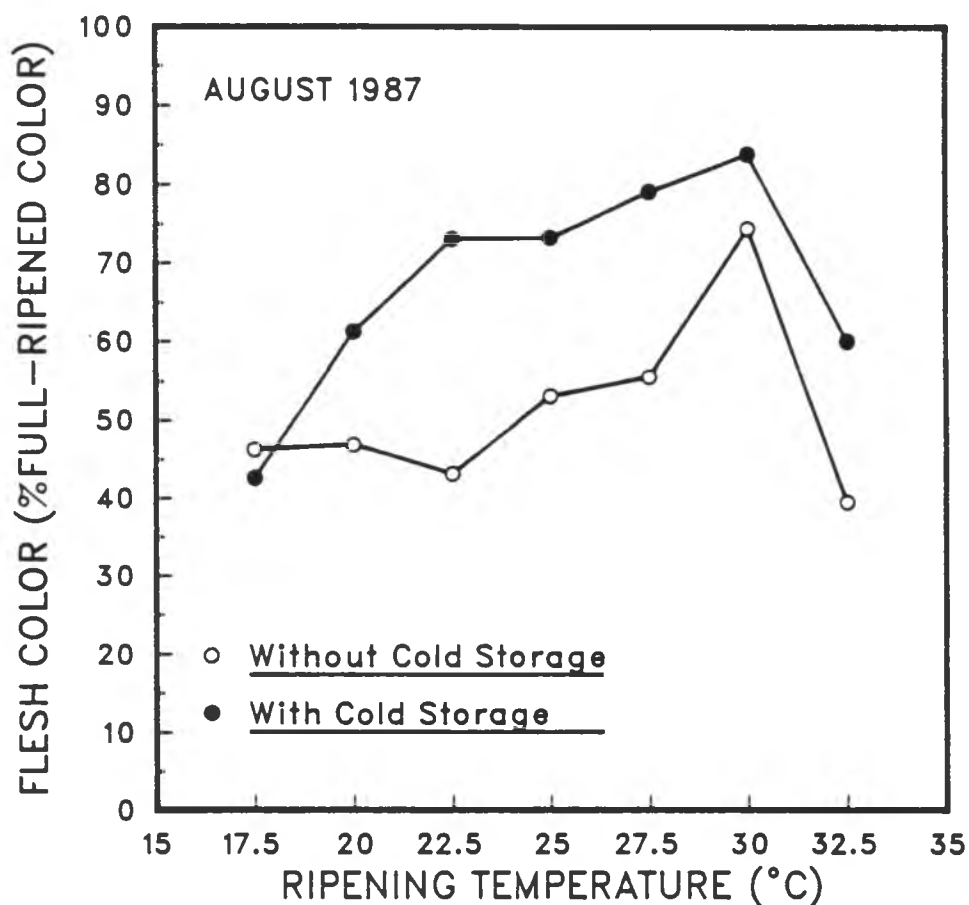


Figure 1-C Effect of temperature on flesh color (% full-ripened color) of ripening papayas 10 days after harvest or after cold storage (10°C for 14 days). All points are means of 8 fruit except that cold-stored fruit ripened at 32.5°C had 6 fruit. Initial values were 44% and 32% at harvest and after cold storage, respectively. Equation lines for the best fit (from 17.5° to 30°C) were  $Y=185.0-13.67X+0.33X^2$  ( $r^2=0.296$  \*\*\*) and  $Y=-148.48+15.14X-0.269X^2$  ( $r^2=0.288$  \*\*\*) for fruit ripening without and with cold storage, respectively. A significant level of 0.1% for the regression line is designated as \*\*\*. Confidence limits are shown in Appendix Table 4.

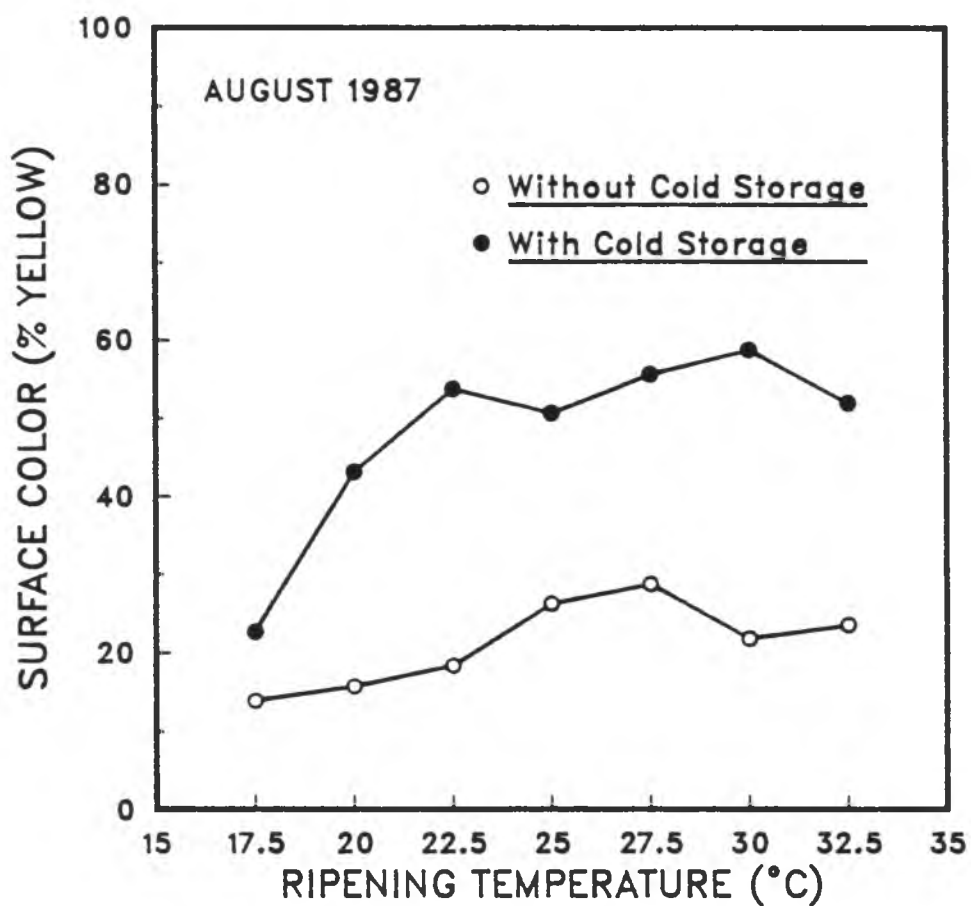


Figure 1-D Effect of temperature on surface color development (% yellow) of ripening papayas 5 days after harvest or after cold storage (10°C for 14 days). All points are means of 8 fruit. Initial values were 4% and 7% yellow at harvest and after cold storage, respectively. Confidence limits are shown in Appendix Table 5.

TABLE 1. Effect of temperature on flavor of ripening papayas 10 days after harvest or after cold storage (10°C for 14 days). Criteria : 1 - underripe, 2 - normal and ripe, 3 to 5-overripe.

Ripening Temperature (°C)	Flavor <sup>x</sup>	
	Not stored	Stored
At harvest	1.0	
After cold storage	1.0	
17.5	1.0 ± 0	1.4 ± 0.2
20	1.0 ± 0	1.4 ± 0.2
22.5	1.0 ± 0	1.5 ± 0
25	1.5 ± 0.3	1.4 ± 0.2
27.5	1.5 ± 0.4	1.6 ± 0.4
30	2.0 ± 0	1.4 ± 0.4
32.5	1.3 ± 0.4	1.3 ± 0.3

<sup>x</sup> Mean ±  $t_{0.05} s_{\bar{y}}$  is the 95% confidence limit of each mean, n=8 except that for 32.5°C (stored), n=6.

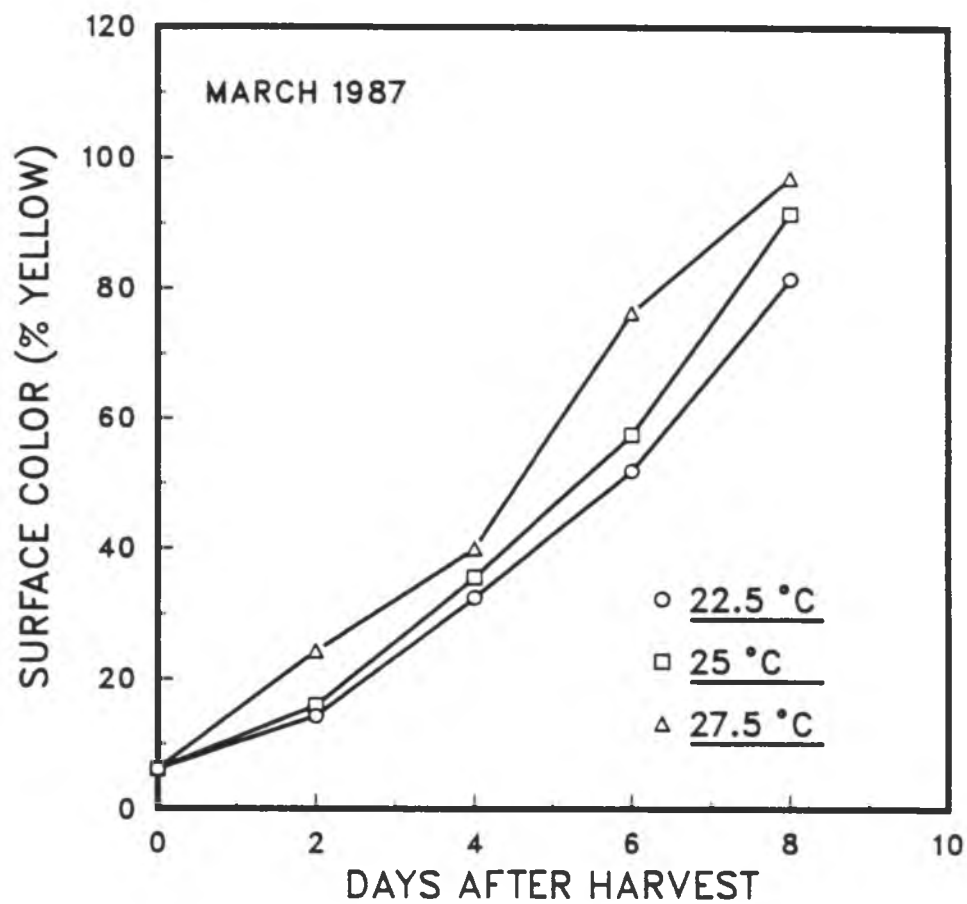


Figure 2-A The time-temperature response of changes in surface color (% yellow). All points are means of 8 fruit. Equation lines for the best fit were  $Y=5.87+3.14X+0.780X^2$  (22.5°C,  $r^2=0.791$  \*\*\*),  $Y=6.08+3.39X+0.904X^2$  (25°C,  $r^2=0.928$  \*\*\*), and  $Y=5.66+7.99X+0.464X^2$  (27.5°C,  $r^2=0.877$  \*\*\*). A significant level of 0.1% for the regression line is designated as \*\*\*.

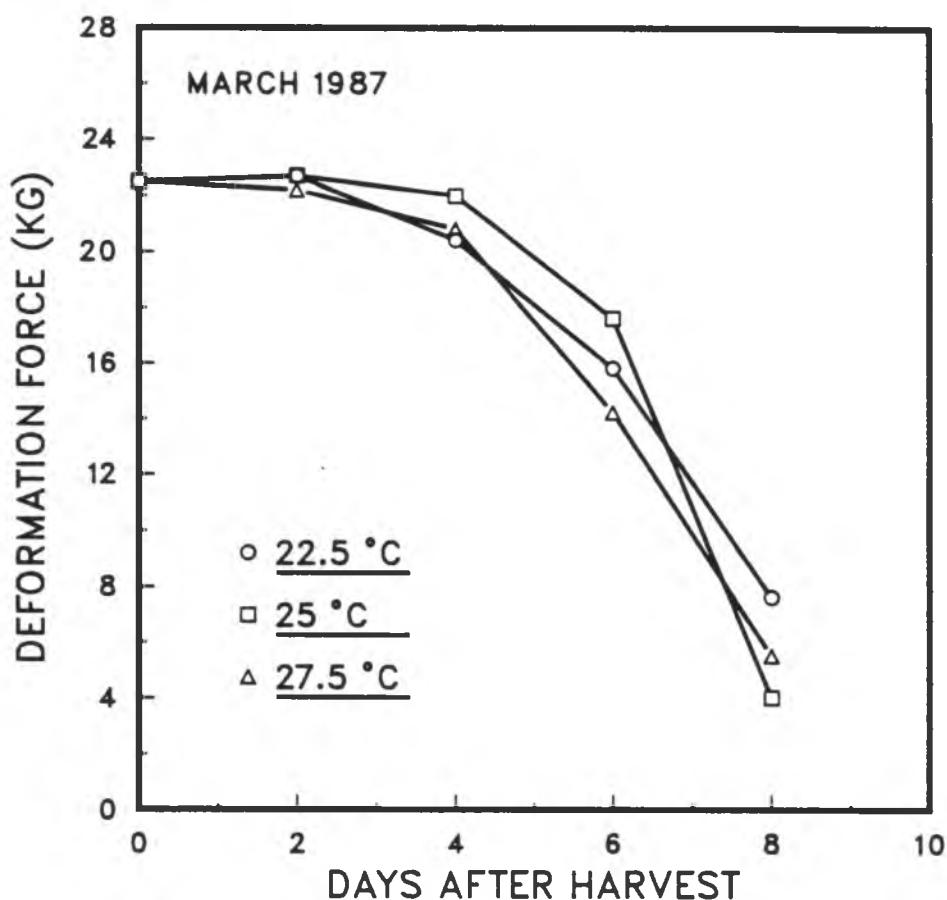


Figure 2-B The time-temperature response of changes in deformation force (kg). The higher the value, the harder the fruit. All points are means of 8 fruit. Equation lines for the best fit were  $Y=22.43+0.88X-0.34X^2$  (22.5°C,  $r^2=0.546$  \*\*\*),  $Y=21.72+2.36X-0.557X^2$  (25°C,  $r^2=0.854$  \*\*\*), and  $Y=22.06+0.96X-0.377X^2$  (27.5°C,  $r^2=0.701$  \*\*\*). A significant level of 0.1% for the regression line is designated as \*\*\*.

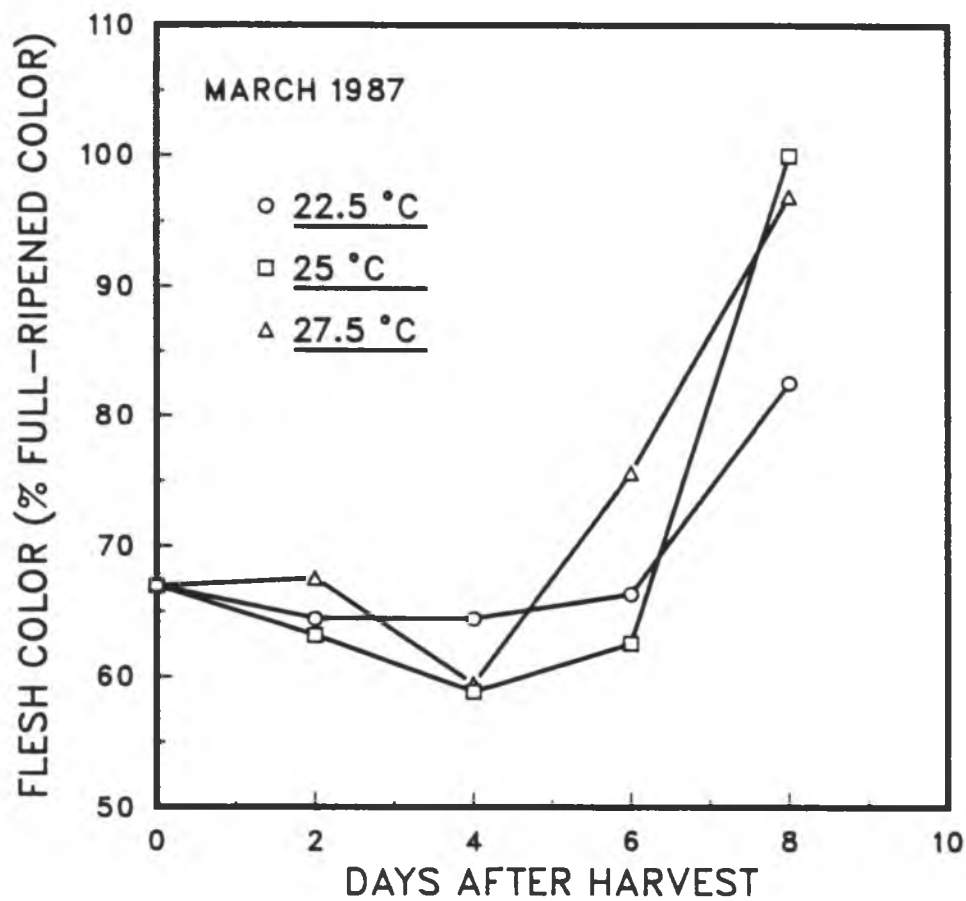


Figure 2-C The time-temperature response of changes in flesh color (% full-ripened color). All points are means of 8 fruit.

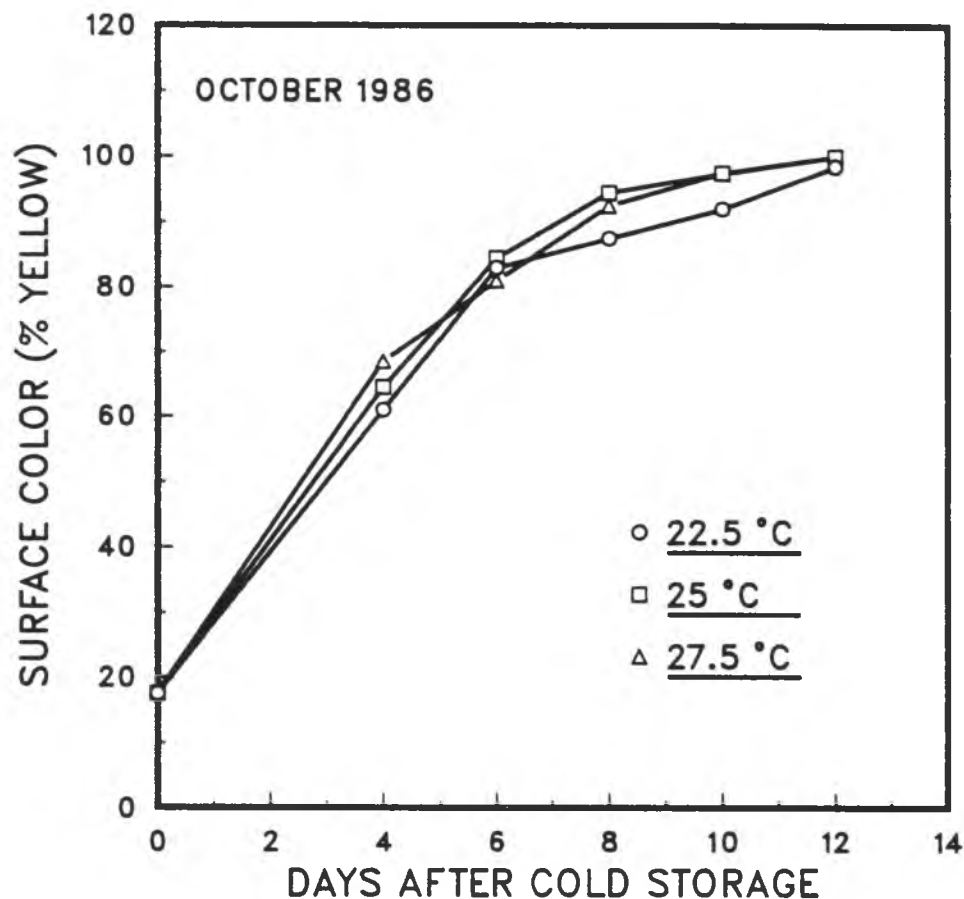


Figure 3-A The time-temperature response of changes in surface color (% yellow). Fruit were stored for 2 weeks at 10°C. All points are means of 10 fruit. Equation lines for the best fit were  $Y=17.64+13.63X-0.588X^2$  (22.5°C,  $r^2=0.872$  \*\*\*),  $Y=17.2+15.0X-0.677X^2$  (25°C,  $r^2=0.932$  \*\*\*), and  $Y=18.22+14.57X-0.653X^2$  (27.5°C,  $r^2=0.885$  \*\*\*). The initial value (after harvest) was 3% yellow. A significant level of 0.1% for the regression line is designated as \*\*\*.

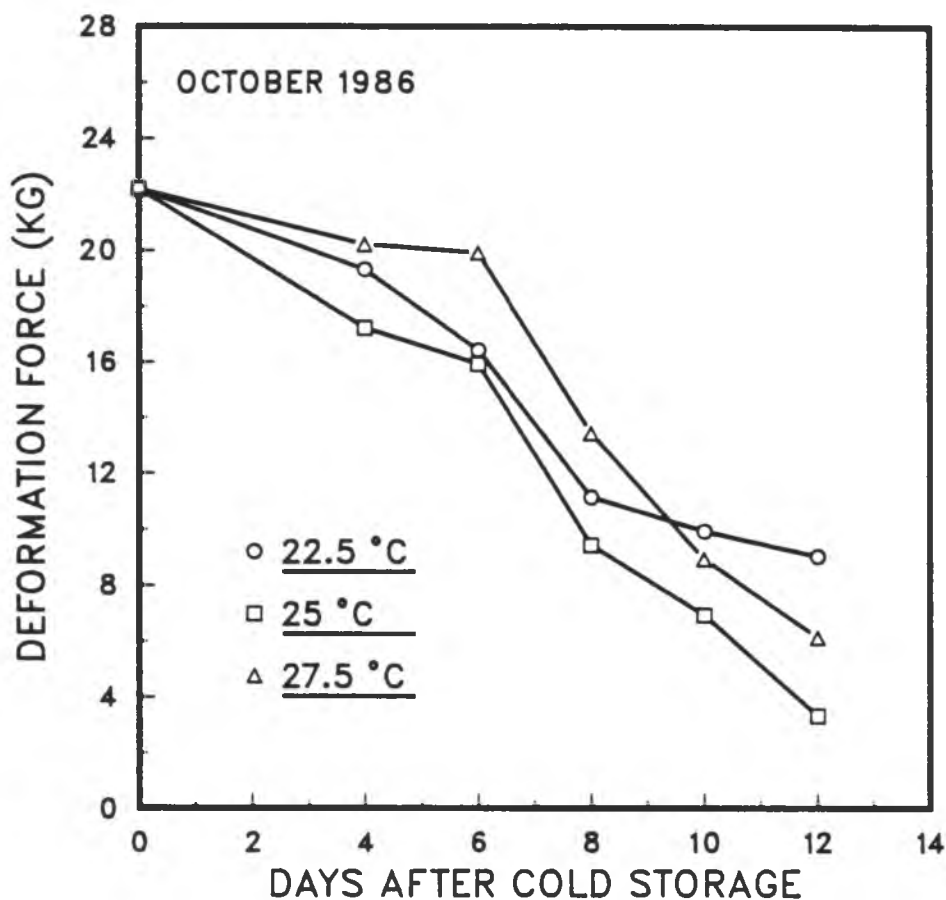


Figure 3-B

The time-temperature response of changes in deformation force (kg). Fruit were stored for 2 weeks at 10°C. The higher the value, the harder the fruit. All points are means of 10 fruit. Equation lines for the best fit were  $Y=22.8-1.2X$  (22.5°C,  $r^2=0.562$  \*\*\*),  $Y=23.3-1.6X$  (25°C,  $r^2=0.795$  \*\*\*), and  $Y=22.42-0.05X-0.116X^2$  (27.5°C,  $r^2=0.789$  \*\*\*). A significant level of 0.1% for the regression line is designated as \*\*\*. The initial value (after harvest) was 22.2 kg.

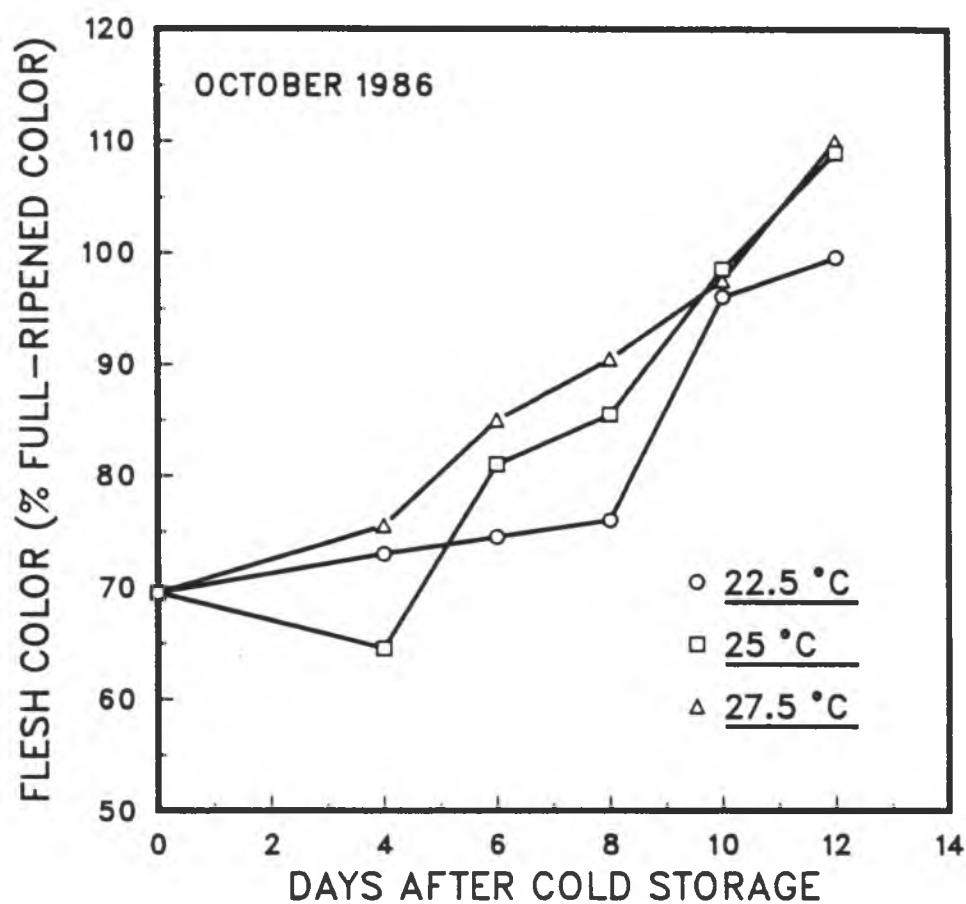


Figure 3-C

The time-temperature response of changes in flesh color (% full-ripened color). Fruit were stored for two weeks at 10°C. All points are means of 10 fruit. Equation lines for the best fit were  $Y=69.92-0.95X+0.298X^2$  (22.5°C,  $r^2=0.420$  \*\*\*),  $Y=67.84-0.65X+0.353X^2$  (25°C,  $r^2=0.609$  \*\*\*), and  $Y=69.41+1.09X+0.192X^2$  (27.5°C,  $r^2=0.613$  \*\*\*). A significant level of 0.1% for the regression line is designated as \*\*\*. The initial value (after harvest) was 63%.

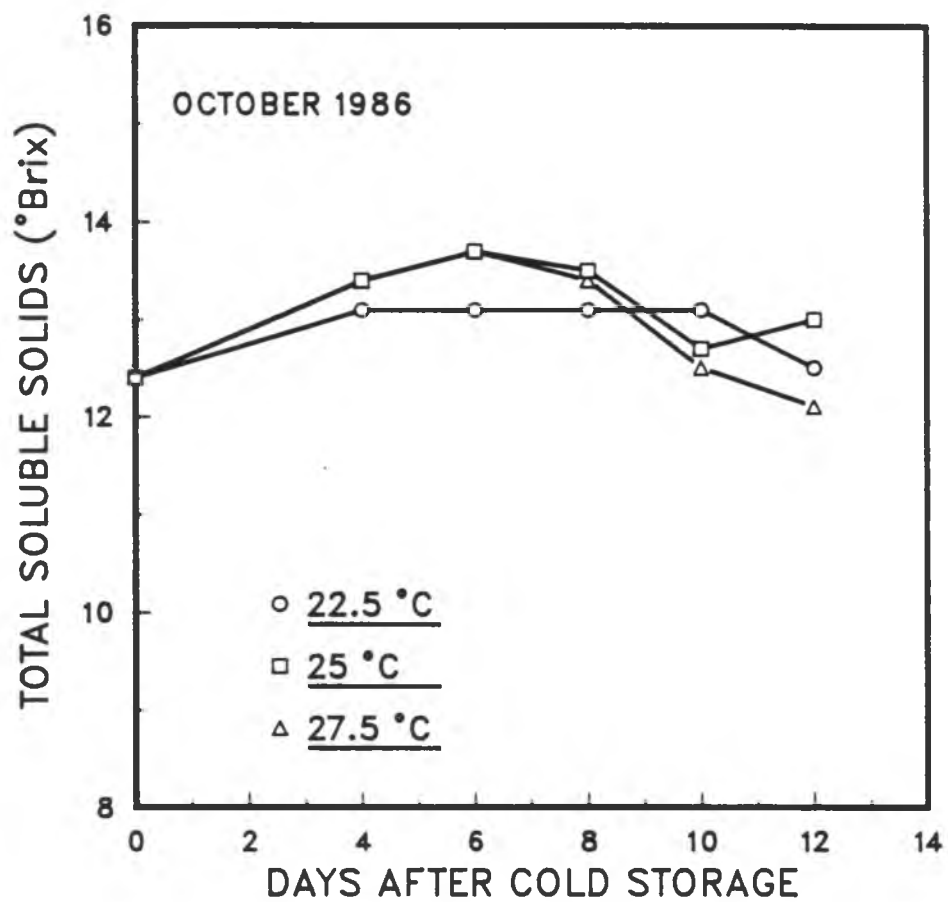


Figure 3-D The time temperature response of changes in TSS (°Brix). Fruit was stored for two weeks at 10°C. All points are means of 10 fruit. The initial value (after harvest) was 11.4 °Brix.

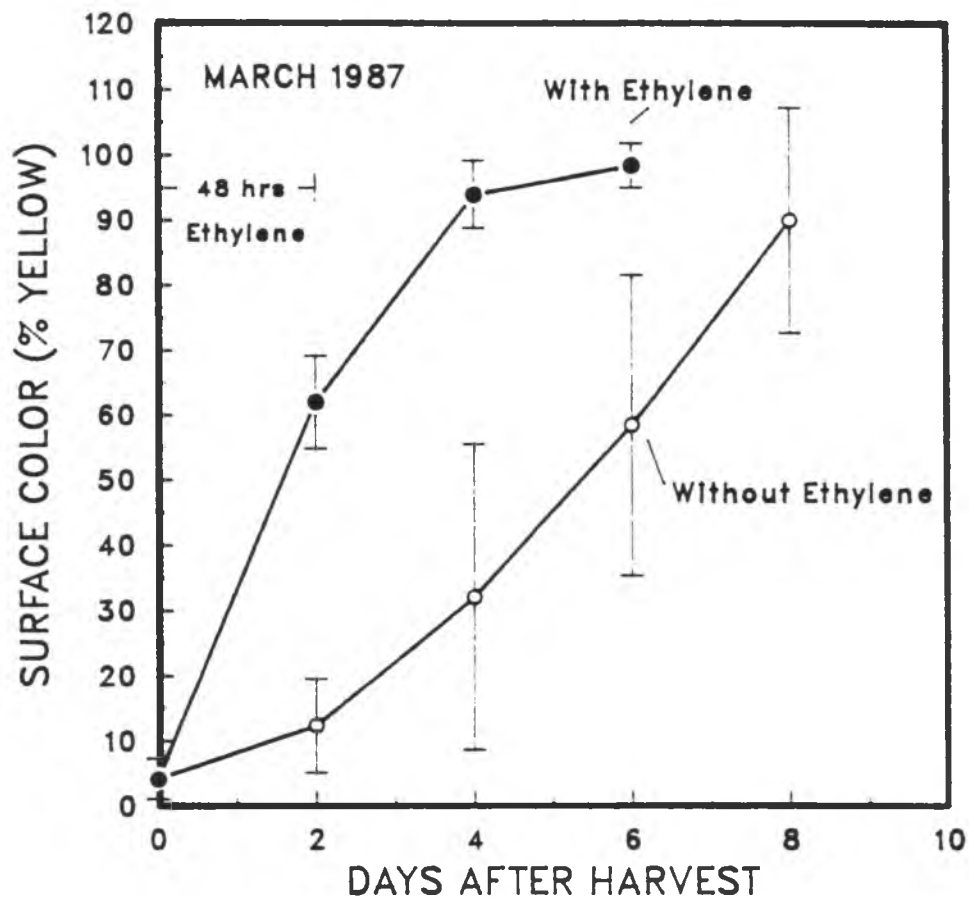


Figure 4-A Effect of exogenous ethylene (50 to 160 ppm, 48 hrs) on surface color (% yellow) changes of papayas ripened at 25°C after harvest. All points are means of 10 fruit. The bars are the standard deviation of mean values.

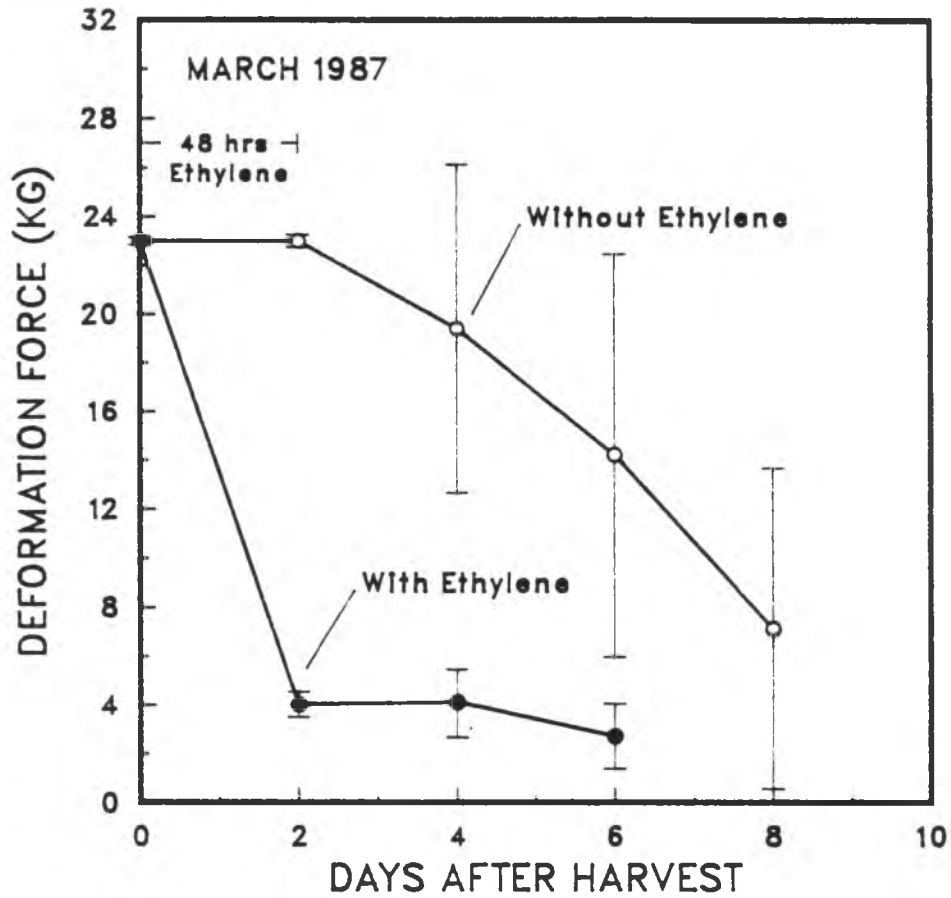


Figure 4-B Effect of exogenous ethylene (50 to 160 ppm, 48 hrs) on changes in deformation force (kg) of papayas ripened at 25°C after harvest. The higher the value, the harder the fruit. All points are means of 10 fruit. The bars are the standard deviation of mean values.

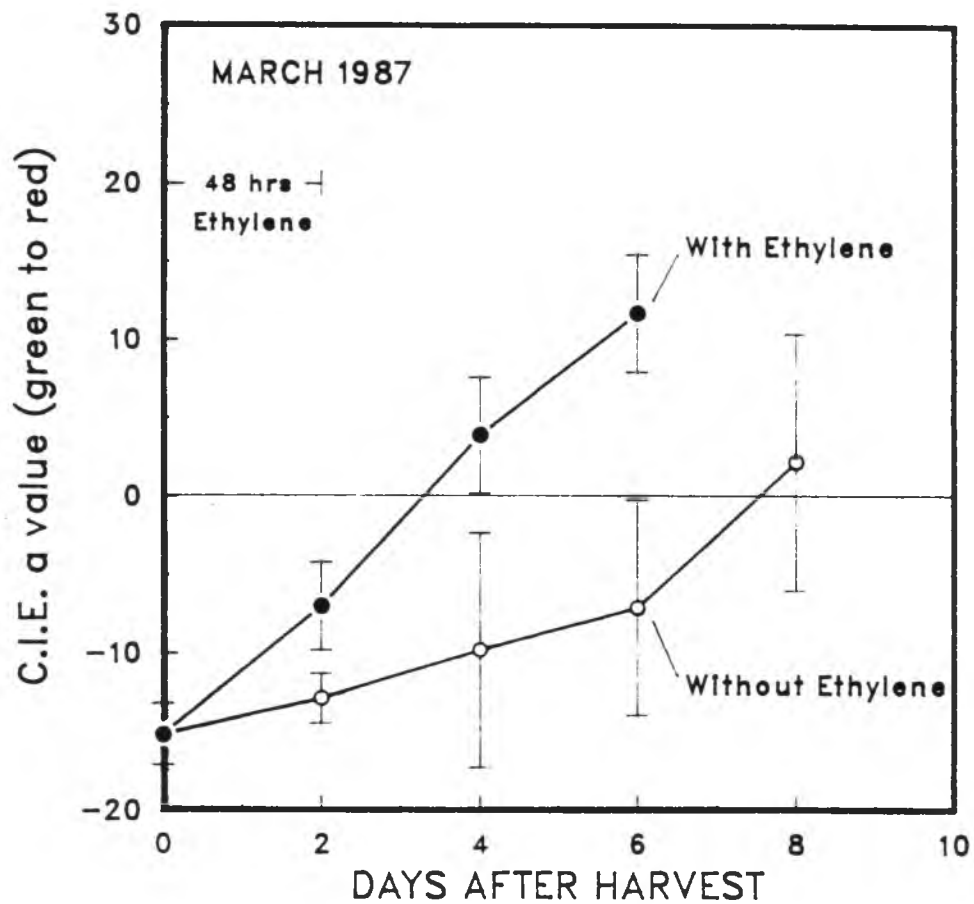


Figure 5

Effect of exogenous ethylene (50 to 160 ppm, 48 hrs) on changes in C.I.E. *a* value (-*a* = green, +*a* = red) of papayas ripened at 25°C after harvest. The lower the value, the greener the skin. All points are means of 10 fruit. The bars are the standard deviation of mean values.

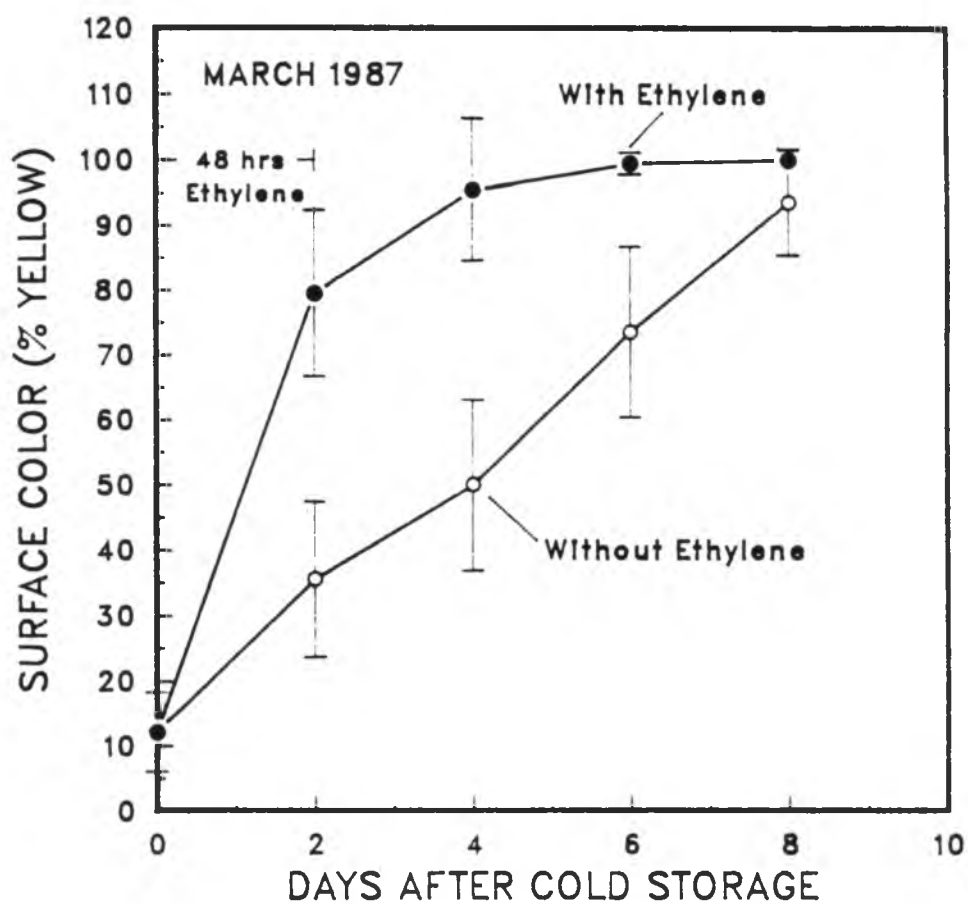


Figure 6-A Effect of exogenous ethylene (50 to 130 ppm, 48 hrs) on changes in surface color (% yellow) of papayas ripened at 25°C after a two-week cold storage at 10°C. All points are means of 10 fruit. The bars are the standard deviation of mean values.

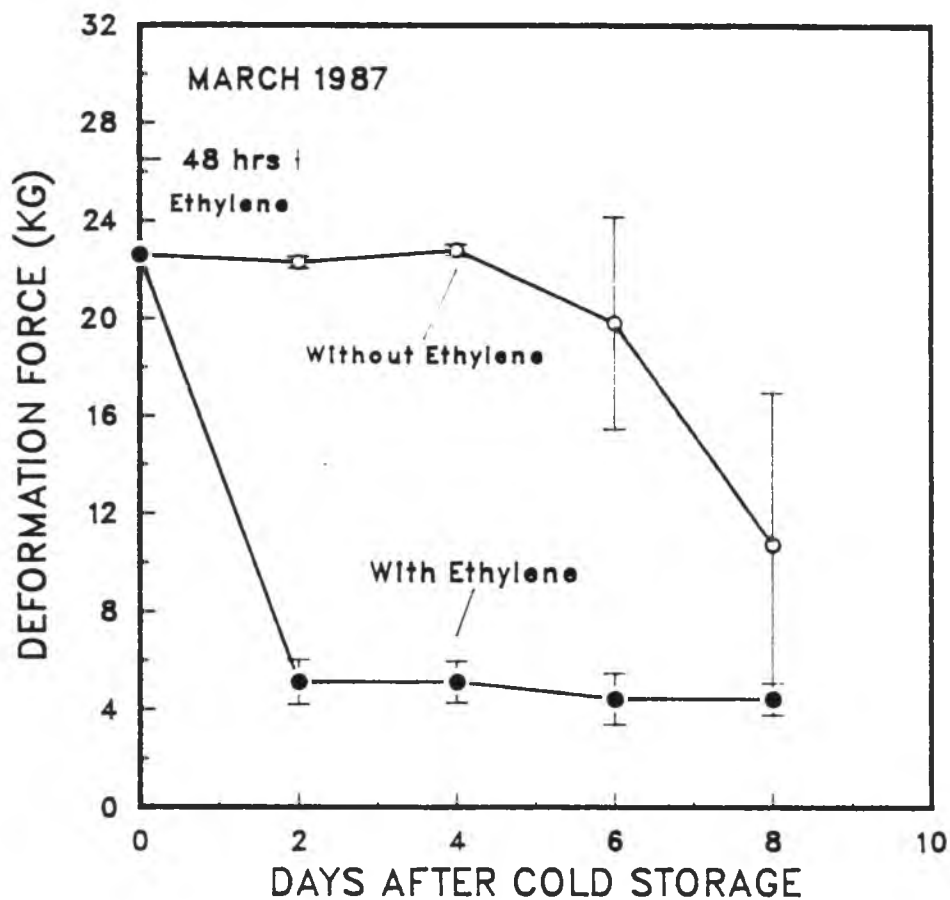


Figure 6-B Effect of exogenous ethylene (50 to 130 ppm, 48 hrs) on changes in deformation force (kg) of papayas ripened at 25°C after two-week storage at 10°C. The higher the value, the harder the fruit. All points are means of 10 fruit. The bars are the standard deviation of mean values.

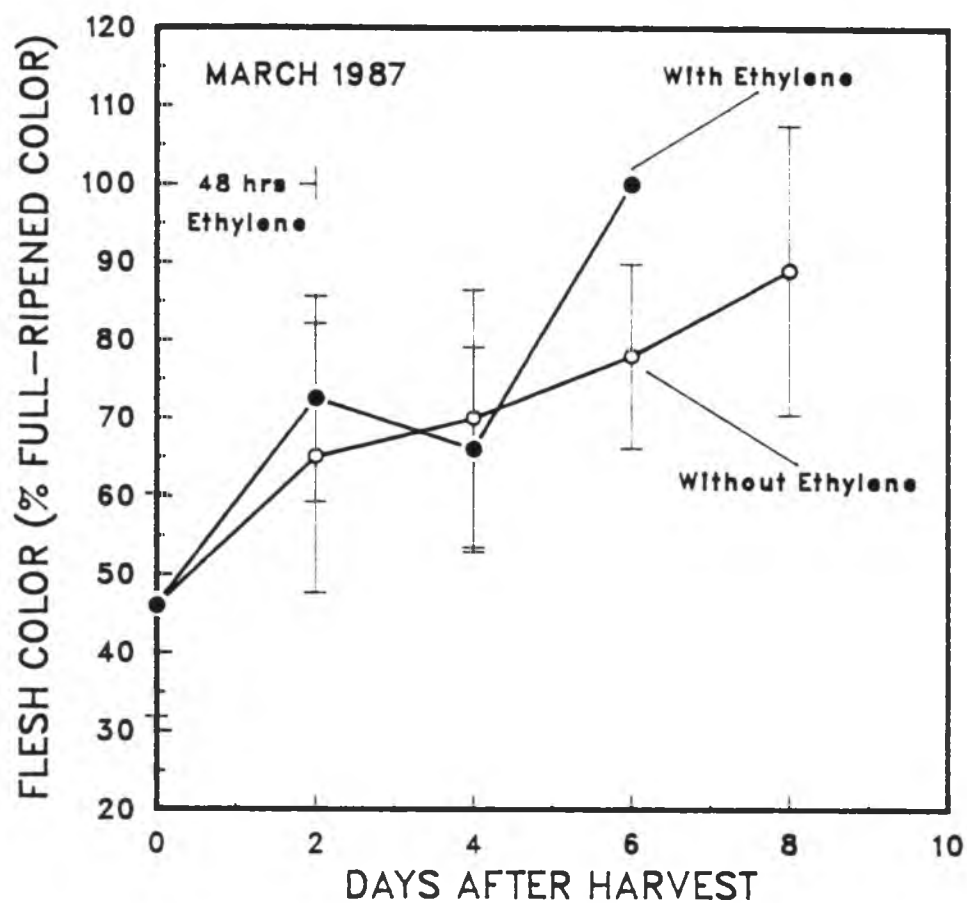


Figure 7-A Effect of exogenous ethylene (50 to 160 ppm, 48 hrs) on changes in flesh color (% full-ripened color) of papayas ripened at 25°C after harvest. All points are means of 10 fruit. The bars are the standard deviation of mean values.

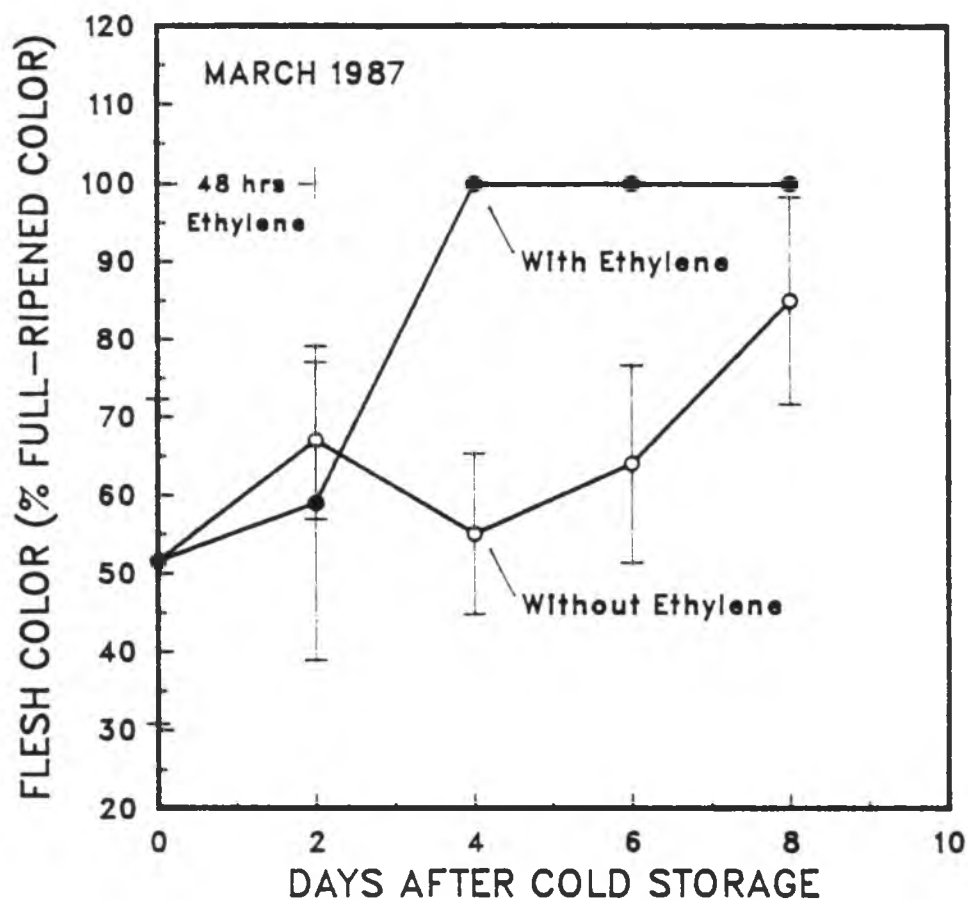


Figure 7-B Effect of exogenous ethylene (50 to 130 ppm, 48 hrs) on changes in flesh color (% full-ripened color) of papayas ripened at 25°C after two-week storage at 10°C. All points are means of 10 fruit. The bars are the standard deviation of mean values.

TABLE 2. Effect of ethylene exposure duration (90 to 130 ppm) on changes in surface color (% yellow). Fruit were stored for two weeks at 10°C prior to ethylene treatment. The ethylene exposure durations were 30 and 48 hrs. Fruit not exposed to ethylene were examined simultaneously.

Days after cold storage	Surface color (% yellow) <sup>x</sup>		
	Without C <sub>2</sub> H <sub>4</sub>	Exposure duration to C <sub>2</sub> H <sub>4</sub> (hrs)	
		30	48
At harvest	5 ± 2 f <sup>y</sup>		
After storage	9 ± 4 f		
1 (30 hrs)	32 ± 17 e	58 ± 17 d	
2	73 ± 10 c	96 ± 2 a	84 ± 5 b
3	78 ± 7 bc	97 ± 3 a	98 ± 2 a
5	82 ± 11 b	100 ± 0 a	100 ± 1 a
7	96 ± 7 a	100 ± 0 a	100 ± 0 a

<sup>x</sup> Data were analyzed by Waller-Duncan K-ratio t test. Any two means having a common letter are not significantly different at 5% level (n=8).

<sup>y</sup> Mean ± SD

TABLE 3. Effect of ethylene exposure duration (90 to 130 ppm) on changes in deformation force (kg). Fruit were stored for two weeks at 10°C prior to ethylene treatment. The ethylene exposure durations were 30 and 48 hrs. Fruit not exposed to ethylene were examined simultaneously.

Days after cold storage	Deformation force (kg) <sup>x</sup>		
	Without C <sub>2</sub> H <sub>4</sub>	Exposure duration to C <sub>2</sub> H <sub>4</sub> (hrs)	
		30	48
At harvest	22.9 ± 0.1 a <sup>y</sup>		
After storage	22.7 ± 0.2 a		
1 (30 hrs)	17.0 ± 4.9 b	5.0 ± 0.8 efg	
2	16.6 ± 4.0 b	5.6 ± 1.2 ef	3.6 ± 0.6 g
3	14.0 ± 3.8 c	5.9 ± 1.2 e	4.3 ± 1.0 efg
5	14.4 ± 3.5 c	4.4 ± 0.6 efg	4.0 ± 0.7 fg
7	9.9 ± 3.3 d	4.1 ± 1.1 efg	3.7 ± 0.7 fg

<sup>x</sup> Data were analyzed by Waller-Duncan K-ratio t test. Any two means having a common letter are not significantly different at 5% level (n=8).

<sup>y</sup> Mean ± SD

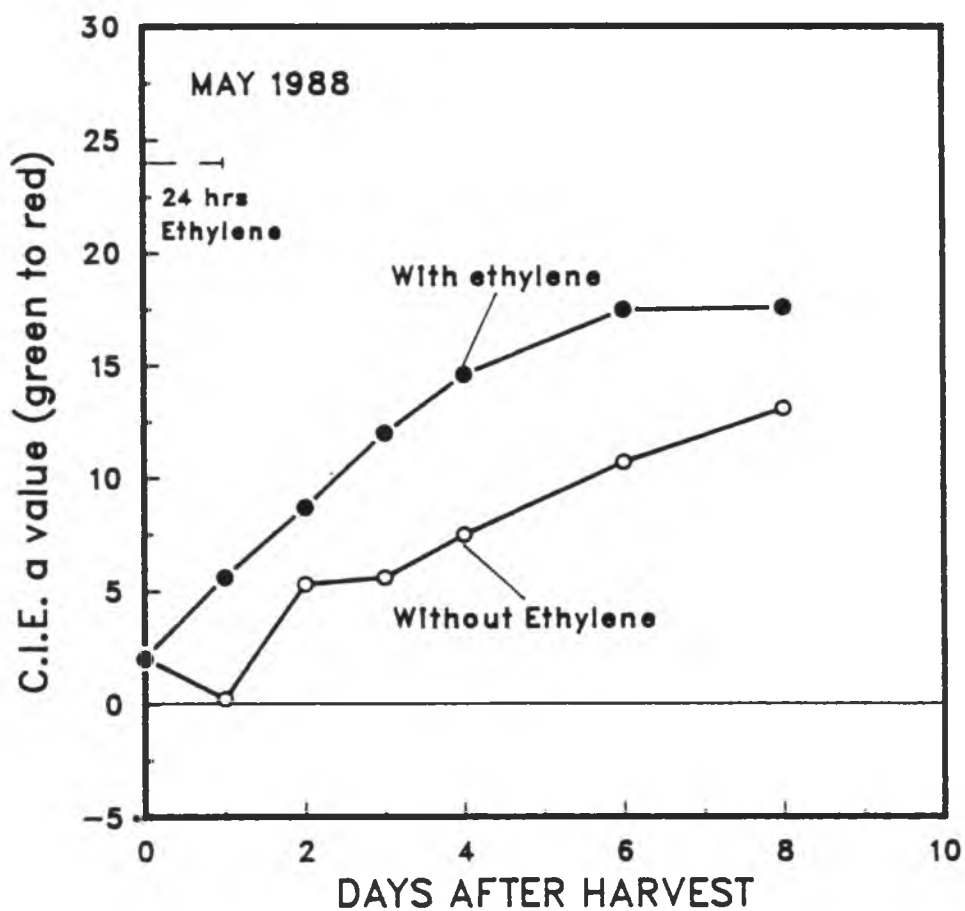


Figure 8 Effect of ethylene treatment (200 ppm, 24 hrs) on papaya flesh color (outer portion of equatorial mesocarp) in terms of C.I.E. *a* values (-*a*=green, +*a*=red). The fruit were ripened at 25°C. All points are means of 10 fruit. Confidence limits are shown in Appendix Table 7.

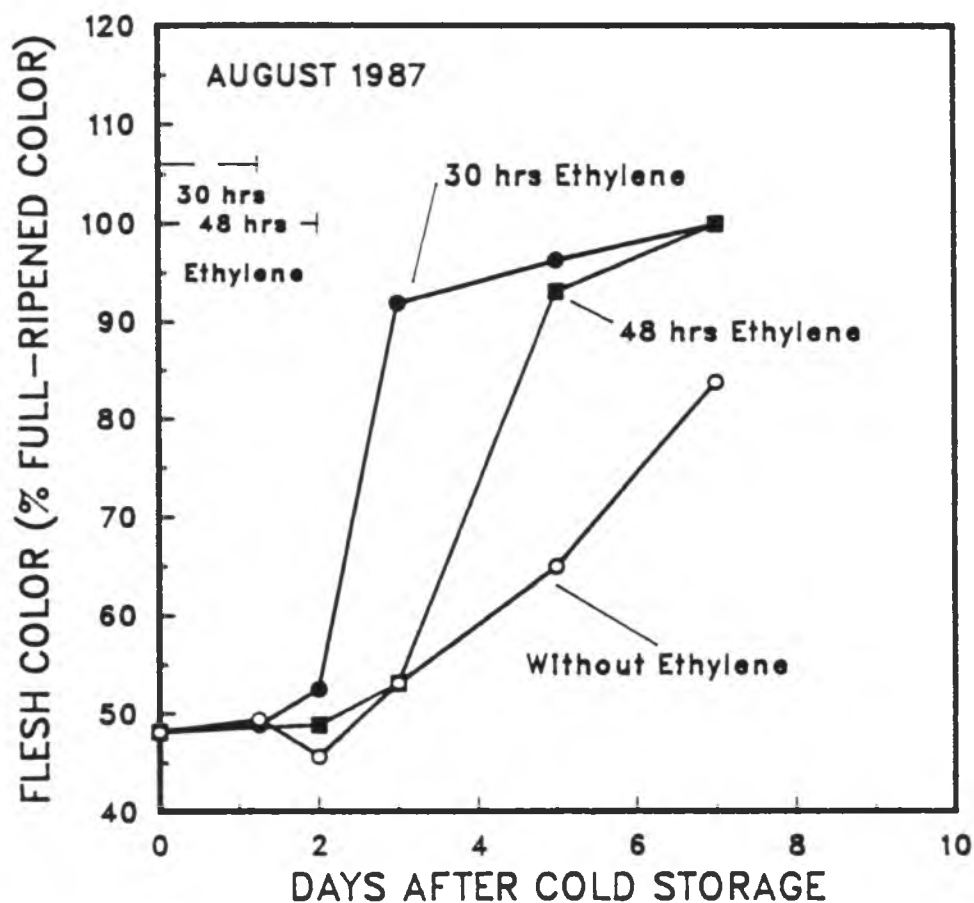


Figure 9 Effect of exposure duration to ethylene (90 to 130 ppm) on changes in flesh color of papayas stored for two weeks at 10°C prior to ethylene treatment. The ethylene exposure durations were 30 and 48 hrs. Fruit not exposed to ethylene were examined simultaneously. All points are means of 8 fruit. The initial value (after harvest) was 49%.

## DISCUSSION

Akamine (1977) reported that temperatures above 32.2°C cause delayed coloring and ripening, rubbery pulp texture, copious latex oozing, and fruit surface bronzing in papayas. Similarly, high temperatures affect red color development and softening in tomatoes (Hall, 1964). The present study show that papayas held at 32.5°C failed to ripen normally, fruit had abnormal softening, poor color development, surface pitting, off-flavor, and a higher susceptibility to decay.

Papaya softening was retarded or delayed during the 10-day period at 32.5°C (Fig. 1-B). Mature green tomatoes did not soften and PGase activity did not appear when stored at 33°C for 15 days, but PGase increased with a delay of 6 days upon transfer to 22°C (Yoshida *et al.*, 1984). The delay in papaya softening due to high temperatures (46°C for 65 min) is explained by a decrease in PGase amount and/or activity (Chan *et al.*, 1981). PGase activity is known to be triggered by ethylene along with other ripening processes during tomato ripening (Grierson and Tucker, 1983). Ogura *et al.* (1976) reported that a 15-day storage at 33°C suppresses ethylene production of mature green tomatoes. A failure of ripening in pears (cv. Bartlett) at 40°C also exhibits a lack of ethylene production and loss of sensitivity to ethylene (Maxie *et al.*, 1974). Two kinds of ethylene forming enzyme (EFE) in papayas are reported : heat resistant EFE (HREFE) and heat susceptible EFE (HSEFE) (Chan, 1986). HSEFE, which comprises about 75% of the total EFE, seems to be a more heat labile enzyme system than endo-PGase and exo-PGase (Chan and Tam, 1982; Chan, 1986).

Therefore, abnormal papaya softening caused by 32.5°C (Fig. 1-B) might have resulted from a failure to produce adequate ethylene for papaya ripening, a decrease in sensitivity in response to ethylene or the damage of PGase system.

Since 'Sunset' is a red-fleshed cultivar, lycopene development contributes to its color quality. Papayas ripened at 32.5°C had poor red color development adversely affecting their marketability (Fig. 1-C). This is similar to the finding that lycopene synthesis, but not that of carotene, is inhibited by temperatures above 30°C in tomatoes (Goodwin and Jamikorn, 1952; Tomes, 1963). Flesh color development of papaya ripening at 30°C was normal, but marketability was adversely affected by surface browning.

Surface color, softening and flesh color developed faster in cold-stored fruit, and the effects appeared within the temperature range, 17.5° to 25°C, 17.5° to 22.5°C, and 20° to 30°C, respectively (Fig. 1-A to 1-D). The rate of chlorophyll breakdown and carotenoid synthesis of ethylene-treated papayas was faster in cold-stored fruit than non-cold-stored fruit (Fig. 4-A vs. 6-A; 7-A vs. 7-B). Hobson (1987) reported that an increase in tomato softening due to cold storage can result from the release of ethylene, which then stimulated the synthesis of PGase. Cold storage also stimulates ethylene production in papayas (Chan *et al.*, 1985). The ethylene level produced is dependent on the temperature and the duration of exposure to low temperatures. Therefore, the ethylene produced by papayas (< 0.1 ppm) during 2-week cold storage at 10°C (Chan *et al.*, 1985) can explain the faster ripening rate of the cold-stored papayas, although the small amount of ethylene

did not cause a significant difference immediately after removal from cold storage (Fig. 1-A to 1-C). However, in some experiments, the inner portion of cold-stored fruit appeared to soften gradually, but softness could not be detected using the penetrometer. Seasonal variation might be one of the reasons since the slight softening related to cold storage seemed to appear in summer fruit, but not in winter fruit. The reason remains unknown.

Three possible reasons might explain the cold storage effect on the response of papayas to ripening temperatures and exogenous ethylene application : a) the fruit ripen at a very slow rate during 2-week storage at 10°C; b) the binding affinity of ethylene to the receptors and/or the number of receptors increases in the fruit tissues during the 2-wk storage (Yang, 1985), so that the enzyme system of cold-stored fruit is more sensitive to the ripening temperatures and exogenous ethylene than those not cold-stored; c) low temperature (10°C) induces a trace amount of ethylene production which influences the sensitivity of fruit tissues to exogenous ethylene (Knee, 1985), and elicits some ripening events. The cold storage effect on papaya ripening was supported by the concave quadratic response of non-cold-stored fruit versus the convex quadratic response of cold-stored fruit and the less dramatic increase in flesh color of cold-stored fruit (Fig. 3-C).

Flesh color development exhibited a dramatic increase regardless of ripening temperature (Fig. 2-C, 3-C), and was more marked for non-cold-stored fruit. This might be because the evaluation was subjective

or the lycopene synthesis is through different pathways from carotene (Thomas and Jen, 1975).

The higher the ripening temperature, the higher the weight loss. Weight loss increased linearly, with high  $r^2$  (ca. 0.6 to 0.9), as temperature increased from 22.5° to 27.5°C. In 'Taiping' and 'Bentong' papayas, the ethylene maximum is lowered by the high RH and days to ripen are longer under high RH (Nazeeb and Broughton, 1978). Hence, in order to estimate the regression lines for the ripening temperatures (22.5°C to 27.5°C), high RH was required for reduction in taste deterioration, wrinkled appearance and sunken spots. However, the higher susceptibility of fruit to fungal attack under high RH needs to be taken into account.

A slight increase in TSS during ripening, ca. 0.5° to 2.5°Brix, occurred after harvest (Fig. 3-D). It then decreased about 8 days after cold storage. The decrease in TSS during ripening might be because the carbohydrates are consumed by respiration of fruit (Akamine and Goo, 1971a). The change in TSS is dependent on harvest time (Chan, 1979), fruit variation or other unknown factors in the field. The insignificant change in TSS during ripening (regardless of ripening temperature) supports the absence of starch or other storage carbohydrates in papayas (Chan, 1979).

Ethylene-treated papayas ripened faster and more uniformly in terms of degreening rate (Fig. 4-A, 6-A), softening (Fig. 4-B, 6-B), and flesh color development (Fig. 7-A, 7-B) without or with cold storage. The results are similar to those of other climacteric fruits, such as mangoes, tomatoes, and bananas (Barmore, 1974; Fuchs *et al.*, 1975;

Pratt and Workman, 1962; Ke and Ke, 1980; Kader, 1985b). Fruit softness reached the edible condition (ca. 5 kg of deformation force) almost immediately after the 30-hr ethylene treatment when surface color was about 60% yellow (Table 2, 3). It suggests that softening may be initiated at a higher ethylene affinity site by treatment than chlorophyll breakdown and carotenoid synthesis.

Ethylene effect on color development of mango peel is limited to yellow color development associated with chlorophyll breakdown, and red color development is not affected (Proctor and Caygill, 1985). However, lycopene synthesis in tomatoes (Jeffery *et al.*, 1984) and citrus fruits (Stewart and Wheaton, 1972) appears to be regulated by ethylene. Visual flesh color of ethylene-treated papayas was not significantly increased until 1 to 3 days after ethylene treatment when skin degreening reached about 80% and 95% yellow with and without cold storage, respectively (Fig. 4-A vs. 7-A and 6-A vs. 7-B). Unlike chlorophyll destruction, carotenoid accumulation in mandarins is reduced both by cytokinins and  $GA_3$ , indicating that their syntheses are controlled through different mechanisms (García-Luis *et al.*, 1986). Therefore, carotenoid synthesis in ethylene-treated papayas might be simultaneously controlled by other hormones so that a delay of ethylene effect occurred in flesh color development but not in chlorophyll destruction. Nevertheless, red color development of papaya flesh was hastened by ethylene treatment (200 ppm) for 24 hrs (Fig. 8).

Duration of ethylene exposure is a major factor affecting the rate and uniformity of ripening (Knee, 1985). Mangoes treated with 10 ppm ethylene for 48 hrs ripened one to two days faster than those exposed

to ethylene for 24 hrs (Barmore, 1974). Therefore, the longer the exposure duration, the faster the ethylene effect on papaya ripening within a certain range of ethylene level. Papayas treated with 30-hr and 48-hr ethylene (90 to 130 ppm) did not have significant difference in quality one day after treatment because 30-hr ethylene treatment might be adequate to stimulate normal ripening processes such as ethylene production, yellowing and softening, etc..

Present results provided objective and subjective measurements and observations about fruit quality of ripening papayas within a temperature range and with exogenous ethylene treatment. Practical evaluation and more information about physiological changes caused by external factors such as high temperatures, cold storage and exogenous ethylene need further studies. Future research is suggested below :

1. *To study high temperature effect (32.5°C for 10 days) on climacteric rise, ethylene evolution and EFE and PGase activities to see how ethylene affects papaya ripening.* Tomatoes stored at 33°C for 12 days exhibit slow respiratory rate and produce little ethylene (Ogura *et al.*, 1976).
2. *To shorten the storage period of high temperature exposure to see whether the normal ripening process will be resumed by optimum ripening temperatures following 32.5°C.* Respiratory rate of tomatoes drops then shows a climacteric rise upon transfer to room temperature from 33°C (for 12 days) (Ogura *et al.*, 1976). Ethylene production is resumed as well as climacteric rise. Avocados ripened at 40°C for 2

days followed by 20°C resume the normal ripening process with a delay of one day (Eaks, 1978).

3. *To extend the ripening time for more than 10 days at 17.5°C and to determine whether non-cold-stored papayas will ripen to full color and/or eating quality.* In mangoes, fruit held at low temperatures (7° to 20°C) for 16 to 23 days followed by room temperature contain 22 to 53% less carotenoids (Thomas, 1975), and poor pulp color appeared after 15 days at 17°C, although fruit soften and degreen to an acceptable level (Medlicott *et al.*, 1986).
4. *To study changes in respiration rate, ethylene production and PGase in papayas stored at low temperature to see whether the slight softening of cold-stored summer fruit is related to cold storage or the physiological conditions.*
5. *To determine whether the climacteric rise is affected by exogenous ethylene and ethylene production of propylene-treated ones.* The time to the climacteric and softening after harvest is shortened in response to ethylene in tomatoes, avocados, cantaloupes, Japanese persimmons (Pratt and Workman, 1962; Ogura *et al.*, 1976; Eaks, 1980; McGlasson and Pratt, 1964; Takata, 1982).
6. *A taste panel is suggested to determine whether fruit flavor is affected by ripening temperatures and ethylene.*

## Appendix

TABLE 4 Heterogeneity of the surface color/temperature relationship for fruit with or without cold storage 10 days after harvest or cold storage (i.e. cold storage effects) within the temperature range from 17.5° to 30°C.

Variable	Source	Df	F <sup>x</sup>
Surface color (visual, %yellow)	Temp.	1	97.11 ***
	Storage	1	32.24 ***
	Temp. x Storage	1	18.25 ***
C.I.E. <i>L</i>	Temp.	1	125.67 ***
	Storage	1	38.85 ***
	Temp. x Storage	1	10.85 ***
C.I.E. <i>a</i>	Temp.	1	157.58 ***
	Storage	1	22.94 ***
	Temp. x Storage	1	3.14 ns
C.I.E. <i>b</i>	Temp.	1	115.84 ***
	Storage	1	45.47 ***
	Temp. x Storage	1	12.63 ***

<sup>x</sup> ns Non-significant at 5% level (n=8).  
 \*\*\* Significant at 0.1% level.

## Appendix

TABLE 5 Effect of temperature on surface color development (% yellow) of ripening papayas 10 days after harvest or cold storage (10°C for 14 days).

Ripening Temperature (°C)	Surface color (% yellow) <sup>x</sup>	
	Not stored	Stored
At harvest	4 ± 3	
After cold storage		7 ± 3
17.5	24 ± 13	62 ± 21
20	39 ± 9	71 ± 16
22.5	41 ± 17	85 ± 10
25	87 ± 17	91 ± 13
27.5	92 ± 10	96 ± 7
30	100 ± 0	97 ± 5
32.5	90 ± 14	84 ± 41

<sup>x</sup> Mean ±  $t_{.05} s_y$  is the 95% confidence limits of each mean, n=8 except that for 32.5°C (stored), n=6.

## Appendix

TABLE 6 Effect of temperature on deformation force (kg) of ripening papayas 10 days after harvest or cold storage (10°C for 14 days).

Ripening Temperature (°C)	Deformation force (kg) <sup>x</sup>	
	Not stored	Stored
At harvest	23.0 ± 0.2	
After cold storage		22.7 ± 0.2
17.5	22.7 ± 0.1	18.3 ± 3.3
20	22.7 ± 0.2	18.9 ± 3.3
22.5	22.4 ± 0.2	17.4 ± 4.1
25	9.9 ± 5.5	13.5 ± 5.3
27.5	9.3 ± 5.4	8.2 ± 2.3
30	2.4 ± 0.8	8.2 ± 5.4
32.5	17.0 ± 5.0	10.7 ± 8.1

<sup>x</sup> Mean ±  $t_{.05} s_{\bar{y}}$  is the 95% confidence limit of each mean, n=8 except that for 32.5°C (stored), n=6.

## Appendix

TABLE 7 Effect of temperature on flesh color (% full-ripened color) of ripening papayas 10 days after harvest or cold storage (10°C for 14 days).

Ripening Temperature (°C)	Flesh color (% full-ripened color) <sup>x</sup>	
	Not stored	Stored
At harvest	44 ± 8	
After cold storage		32 ± 13
17.5	46 ± 16	43 ± 15
20	47 ± 14	61 ± 10
22.5	43 ± 17	73 ± 11
25	53 ± 8	73 ± 20
27.5	56 ± 12	79 ± 26
30	74 ± 14	84 ± 24
32.5	39 ± 10	60 ± 44

<sup>x</sup> Mean ±  $t_{.05} s_{\bar{y}}$  is the 95% confidence limits of each mean, n=8 except that for 32.5°C (stored), n=6.

## Appendix

TABLE 8 Effect of temperature on surface color development (% yellow) of ripening papayas 5 days after harvest or cold storage (10°C for 14 days).

Ripening Temperature (°C)	Surface color (% yellow) <sup>x</sup>	
	Not stored	Stored
At harvest	4 ± 3	
After cold storage		7 ± 3
17.5	14 ± 7	23 ± 12
20	16 ± 9	43 ± 13
22.5	18 ± 13	54 ± 17
25	26 ± 8	51 ± 24
27.5	29 ± 11	56 ± 18
30	22 ± 13	59 ± 19
32.5	24 ± 12	52 ± 27

<sup>x</sup> Mean ±  $t_{.05} s_{\bar{y}}$  is the 95% confidence limits of each mean (n=8).

## Appendix

Table 9 Effect of ripening temperature and relative humidity (RH) on the weight loss (%).

Temperature (°C)	RH	Equation line for the best fit	R <sup>2</sup>	Root MSE
Non-cold-stored				
22.5	52-74	$Y = 0.28 + 0.82X$	0.911 ****x	0.743
25	60-72	$Y = 0.22 + 1.09X$	0.896 ***	1.074
27.5	49-65	$Y = 1.67 + 1.12X$	0.323 ***	4.698
Cold-stored				
22.5	56-62	$Y = 3.91 + 0.44X$	0.609 ***	1.411
25	79-81	$Y = 2.01 + 1.21X$	0.621 ***	2.259
27.5	77-84	$Y = 2.03 + 0.86X$	0.889 ***	1.224

x \*\*\* Significant at 0.1% level.

## Appendix

Table 10 Effect of ethylene treatment (200 ppm, 24 hrs) on papaya flesh color (outer portion of equatorial mesocarp) in terms of C.I.E. *a* values (-*a*=green, +*a*=red). The fruit were ripened at 25°C.

Days after harvest	C.I.E. <i>a</i> value <sup>x</sup>	
	Without C <sub>2</sub> H <sub>4</sub>	With C <sub>2</sub> H <sub>4</sub>
At harvest	2.0 ± 3.4	
1	0.2 ± 3.0	5.6 ± 2.8
2	5.3 ± 2.6	8.7 ± 2.8
3	5.6 ± 3.5	12.0 ± 2.8
4	7.5 ± 5.1	14.6 ± 1.5
6	10.7 ± 3.0	17.5 ± 1.2
8	13.1 ± 4.3	17.6 ± 1.5

<sup>x</sup> Mean ±  $t_{0.05} s_y$  is the 95% confidence limits of each mean (n=10).

## Appendix

### Abbreviation

ACC	1-aminocyclopropane-1-carboxylic acid
EDB	ethylene dibromide
EFE	ethylene forming enzyme
GA <sub>3</sub>	gibberellin A <sub>3</sub>
HREFE	heat resistance ethylene forming enzyme
HSEFE	heat susceptible ethylene forming enzyme
PGase	polygalacturonase (E.C. 3.2.1.15)
RH	relative humidity
TBZ	thiabendazole
TSS	total soluble solids

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