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Storage Temperature and Ethylene Influence on Ripening of Papaya Fruit

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Abstract. **The temperature and ethylene response of ripening papaya fruit *(Carica papaya* L. CV. Sunset) was determined with and without 14 days of storage at 10C. Temperatures at or higher than 30C adversely affected the quality of the ripe papaya. Papayas held at 32.5C for 10 days failed to ripen normally, as evidenced by poor color development, abnormal softening, surface pitting, and an occasional off-flavor. Skin yellowing, fruit softening, and flesh color of papayas exhibited a quadratic response to ripening time within the temperature range of 22.5 to 27.5C. Flesh color development of nonstored fruit did not change significantly during the first 6 days at ripening temperatures, then rapidly increased. Fruit stored for 14 days at 10C exhibited faster ripening rates (e.g., degreening and softening and no delay in flesh color development) than nonstored fruit when removed to other ripening temperatures (17.5 to 32.5 C). Problems of weight loss and development of external abnormalities were more significant at temperatures higher than 27.5C. The optimal temperature range was found to be between 22.5 and 27.5C, with fruit taking 10 to 18 days to reach full skin yellowing from color break, whether or not fruit was stored at 10C. Exogenously applied ethylene (=100 μl·liter^{-1}) stimulated the rate of fruit ripening, as measured by more uniform skin yellowing and rate of flesh softening whether or not the fruit were stored for 14 days at 10C. Ethylene did not ripen immature papayas completely in terms of skin and flesh color development. The outer portion of the flesh of ethylene-treated fruit had a faster rate of ripening, as indicated by carotenoid development and softening rate, while the same area of the flesh was still pale white in nonethylene-treated fruit. Ethylene reduced the coefficient of variation for skin color, softening rate, and flesh color development in treated fruit. Ethylene increased the rate of skin degreening and hastened the rate of carotenoid development and softening in the outer mesocarp, while having little effect on the inner mesocarp.**

The papaya is a major economic crop' of Hawaii (Hawaii Dept. Agr., 1988). Surface transportation of fruit to the U.S. mainland may take up "to 2 weeks at 10 to 12C, followed by a period in the wholesale and retail system at various temperatures. Papayas are reported to ripen satisfactorily between 20 and 25C (Akamine, 1966; Broughton et al., 1977) and not to ripen at 10 and 15C (Nazeeb and Broughton, 1978). The tolerance of papayas to temperatures below 10C varies with the maturity of the fruit and the duration and temperature of exposure (Chen and Paull, 1986). Temperatures above 32.2C cause delayed coloring and ripening, rubbery pulp texture, copious latex oozing, and fruit surface bronzing (Akamine, 1977).

Exogenous C_2H_4 results in more rapid and uniform ripening in mangoes, tomatoes, bananas, and avocados (Barmore, 1974; Fuchs et al., 1975; Ke and Ke, 1980; Pratt and Workman, 1962; Proctor and Caygill, 1985). Papaya fruit ripening rate was hastened by a 24-hr treatment with 100 to 1000 ppm C_2H_4 at ambient temperatures (Akamine, 1977). How C_2H_4 affected the rate of ripening or whether storage affects this response is unclear. Uneven cohort ripening of papaya packed with the same initial skin colors in the same carton is a common problem. The research reported here addresses these problems by determining the optimum ripening temperature and the effect of C_2H_4 treatment with and without a period of storage at 10C.

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Materials and Methods

General. 'Sunset' papayas were obtained from the Poamoho Experimental Station on the island of Oahu, Hawaii. The fruit were harvested and sorted visually for skin color. Fruit for one test were all harvested on the same day. Color break to 10% yellow fruit were used in all the tests. After a double hot-water treatment of 30 min at 42C, followed by 20 min at 49C (Couey and Hayes, 1986), the fruit were dipped in a thiabendazole solution (650 ppm a.i.) for 5 sec to provide additional control of fungal decay (Couey and Farias, 1979). We stored the fruit 14 days at 10C to simulate surface transportation and holding.

All experiments were repeated at least once. A randomized complete-block design was used in all experiments. A treatment, with eight or 10 fruit in various experiments, was divided into two ripeness groups as blocks, color break, and 10% skin yellowing. Results were analyzed using the SAS-GLM statistical program (SAS Institute, 1985).

Fruit evaluation. Fruit ripening rate and quality were assessed, as needed, for a) initial and final surface color expressed as a percentage of skin yellowing compared to the total surface area; b) flesh color estimated as a percentage of full-ripened color, with normal color development expressed as 0 to 100%, and overripe areas showing water-soaked tissue expressed as > 100%; c) flesh color, also determined objectively by use of a Minolta (Ramsey, N. J.) chromameter with a 7-mm port in terms of the Commission International de L'Eclairage (CIE) 'L', 'a', 'b' values for the equatorial outer and inner flesh zones after the fruit were cut longitudinally; d) deformation force in newtons, i.e., the force required to push a 1.5-cm plunger 2 mm into the flesh; e) external and internal abnormalities were divided into six grades based on the percentage of area affected (0 = 0%> 1 = 1% to 10%, 2 = 11% to 35%, 3 = 36% to 65%, 4 = 66% to 90%, 5 = 91% to 100%); and f) flavor as evaluated by us (1 = underripe, 2 = ripe and normal, 3 to 5 = overripe, with increasing severity degrees of off-flavor).

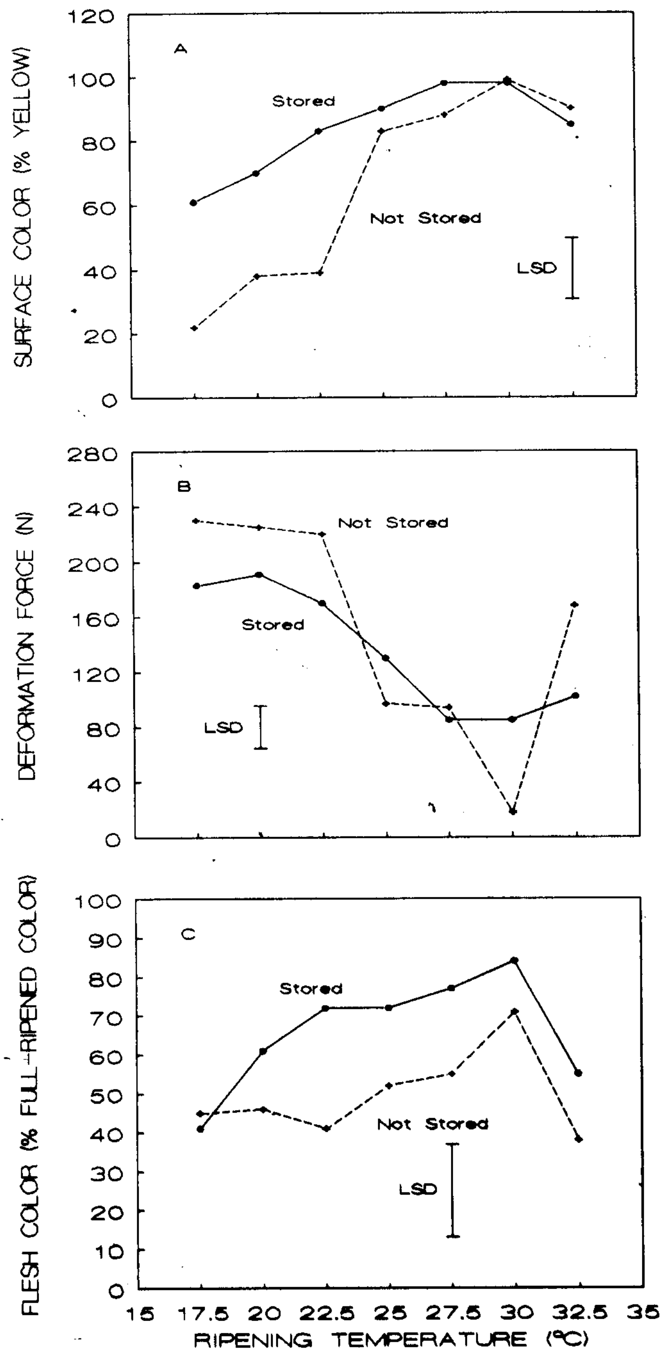

Fig. 1. Effect of temperature on **(A)** skin color (% yellow), **(B)** deformation force (in Newtons), and (C) flesh color (percent of full-ripened color) of papayas 10 days after harvest or after storage for 14 days at 10C. Statistical analysis: skin color, not stored, $r^2 =$ 0.233, L***, skin color = 510.1 – 70.9 temperature; stored, r^2 = 0.155, L*** Q***, skin color = – 93.9 + 7.75 temperature + 0.11 temperature analysis of variance (ANOVA) temperature*** storage* ** temperature **x** storage"'. Deformation force, not stored, $r^2 =$ 0.261, L*** Q*"* C***, N = –2857.4 + 409.8 temperature – 17.63 temperature + 0.24 temperature stored, $r^2 =$ 0.139, L** Q**C**, N = –2229.7 + 312.6 temperature – 13.1 temperature + 0.2 temperature ANOVA temperature** storage* temperature × storage[ns]. Flesh color, not stored, $r^2 =$ *0.100,* L*Q**C*, % = 546.2 – 68.1 temperature + 3.0 temperature' – 0.04 temperature3 stored, $r^2 =$ 0.107, L* Q*, % = 120.5 – 16.8 temperature + temperature ANOVA temperature*** storage*** temperature × storage[ns].

Table 1. Effect of various ripening temperatures on external abnormalities and weight loss of papaya fruit. Fruit were either not stored or stored for 14 days at 10C before ripening at various temperatures for 10 days.

Ripening temp (°C)	External abnormalities[z]		Wt loss (% initial)	
	Not stored	Stored	Not stored	Stored
17.5	0	1.0	5.9	9.1
20	0.1	1.0	3.3	4.7
22.5	0.5	1.0	4.8	5.8
25	1.0	1.1	7.9	9.1
27.5	1.6	2.1	9.8	13.3
30	1.8	2.4	10.5	13.0
32.5	3.1	2.5	11.2	15.3
Significance	L***Q***	L***Q**	L***Q**	L***Q***
r^2	0.583	0.428	0.543	0.496
Storage (S)	***		***	
Temperature (T)	***		***	
S × T	NS		NS	

'Coefficient of determination (r^2) for best-fit model. L, Q, and C represent significance of linear, quadratic, or cubic components, respectively, at $P < 0.01$.

NS, **,***Nonsignificant or significant at P = 0.01 or 0.001, respectively.

Temperature conditions. Fruit were ripened at 17.5,20,22.5, 25, 27.5, 30, or 32.5C for 5 or 10 days with and without prior storage at 10C for 14 days. Based on the initial experiments, the temperature range of 22.5 to 27.5C was selected for subsequent tests and where fruit was ripened for 4 to 10 days (non-cold-stored) or for 4 to 12 days after storage for 14 days at 10C.

Ethylene application. Ethylene was applied using a continuous flow system to maintain a concentration of =100 µl·liter^{-1}. Fruit were treated for either 24 or 48 hr at 25C. Observations were made immediately after harvest and at 2-day intervals during ripening or following storage at 10C for 14 days.

Results

Time-temperature response for ripening. The rate of skin yellowing showed a linear relationship to the ripening temperature from 17.5 to 30C (Fig. 1A). The skin was entirely (100%) yellow after 10 days at 30C and 60% RH, with weight losses of 10% to 13% (Table 1). Skin yellowing was retarded above 30C with or without prior storage of fruit for 14 days at 10C (Fig. 1A). Serious external abnormalities (irregular brown spots) occurred after 10 days at 32.5C and 60% RH, with weight losses of 11% to 15% (Table 1). Internal abnormalities were not detected in these tests. The skin yellowing rate for papayas ripened at 17.5 and 22.5C without cold storage was slower than for fruit stored for 14 days at 10C (Fig. 1A). After 10 days at 20C, fruit not stored were =40% yellow, while fruit stored for 14 days at 10C, then ripened at 20C were =70% yellow.

Fruit stored for 14 days at 10C softened more slowly for the first 4 days after removal to ripening temperatures than fruit receiving no storage (Fig. 2 C and D). Ten days after removal from 10C storage, fruit ripened at higher temperatures (25 and 27.5C) were softer than those ripened at 22.5C (Fig. lB). There was no significant change in the deformation force of fruit ripened between 17.5 and 22.5C for 10 days with or without storage (Fig. lB). Fruit ripened between 22.5 and 30C had a similar rate of fruit softening, irrespective of whether or not the fruit was previously stored for 14 days at 10C. The rate of softening was retarded above 30C.

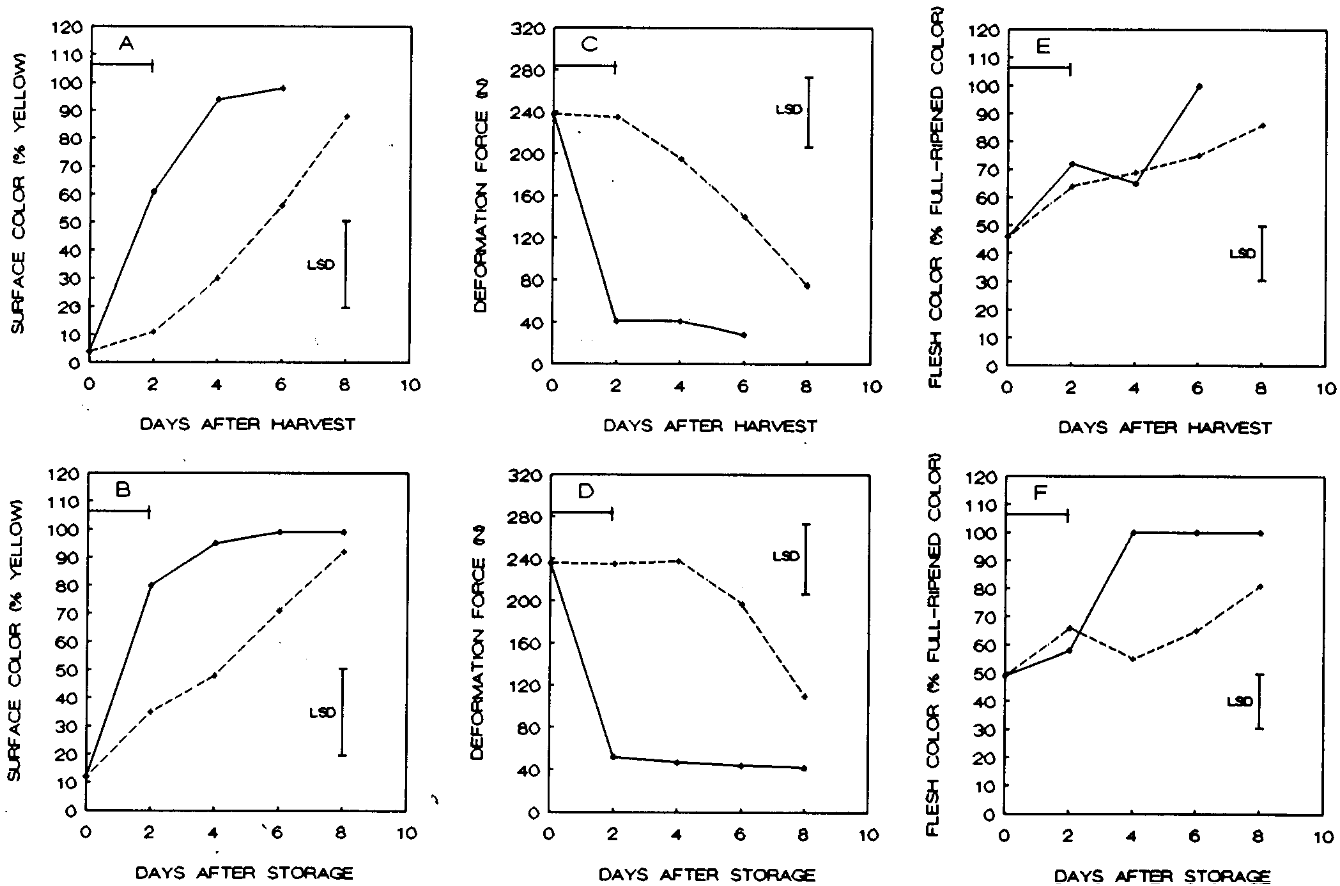

Fig. 2. Effect of exogenous C_2H_4, application (=100 µl·liter[1], 48 hr) on **(A, B)** skin color (% yellow), **(C, D)** deformation force (N), and **(E, F)** flesh color (percent of full-ripened color) of papayas ripened at 25C. **(A, C, E)** Days after harvest with no storage. **(B, D, F)** Days after removal from 14 days of storage at 10C with (—) and without (---) C_2H_4 treatment (n = 8). Horizontal bars represent 48 hr of C_2H_4 treatment.

Fruit first stored for 14 days at 10C had a significantly higher rate of flesh color development than fruit ripened below 27.5C (Fig. 1C). Flesh color development of nonstored fruit ripened below 27.5C was less than that of fruit first stored for 14 days at 10C. For fruit ripened below 30C for 10 days, there was an inverse quadratic relationship to flesh color development, while a converse relationship was found for stored fruit. Fruit ripened at 32.5C for 10 days showed less flesh color development than that ripened at most lower temperatures.

In the first 4 days after removal from storage, flesh color development was similar for fruit held from 22.5 through 27.5C (data not shown). Significant differences in flesh color development among different ripening temperatures occurred ≈ 6 days after removal from cold storage. Ten days after cold storage, flesh color reached ≈ 76% of maximum, regardless of ripening temperatures (Fig. lC). Cold-stored papayas ripened at the higher temperatures (25 and 27.5C) for 12 days were overripe. Off-flavor also occasionally developed in fruit ripened at 32.5C for 10 days (data not shown).

Ethylene effect on papaya ripening. Papayas treated with =100 µl C_2H_4/liter for 24 to 48 hr ripened faster and more uniformly in terms of the rate of skin yellowing (Fig. 2 A and B), softening (Fig. 2 C and D), and flesh color development (Fig. 2 E and F). The visually determined flesh color of C_2H_4-treated papayas was not significantly increased until 1 to 3 days after C_2H_4 treatment when skin degreening reached ≈ 80% and 95% yellow, irrespective of whether or not the fruit had been stored at 10C for 14 days (Fig. 2A vs. 2E and 2B vs. 2F).

Ethylene had a greater effect on fruit stored previously at 10C than fruit not stored in terms of surface color development immediately after C_2H_4 treatment, but eventually, the fruit developed the same percentage of yellow surface (Fig. 2A vs. 2B). The flesh color development rate was increased by C_2H_4, irrespective of whether the fruit was stored at 10C (Fig. 2 E and F). Visually determined flesh color development in fruit previously stored at 10C then ripened at 25C was shortened from =3 days to 1 day by C_2H_4 treatment.

When 85% of the skin was yellow, the outer portion of the flesh in C_2H_4-treated fruit was orange-pink before the same portion of nontreated fruit, which was still a pale white. The CIE ‘a’ (green to red) (Fig. 3) and ‘b’ (data not shown) values for the inner and outer portions of the flesh from C_2H_4-treated papayas were higher in the outer flesh than in that part of untreated control fruit.

The coefficient of variation (CV) for skin yellowing of fruit treated with C_2H_4 was 2.6% vs. 13.9% for nontreated fruit. Deformation force CV was 20.7 N vs. 33.5 N for fruit treated and not treated with C_2H_4, respectively.

Ethylene did not ripen immature papaya completely. Ethylene-treated immature fruit had softer flesh, 65 N vs. 29 N for treated color-break fruit 6 days after C_2H_4 treatment. Such fruit, however, had little yellow skin (8% yellow) and no flesh color

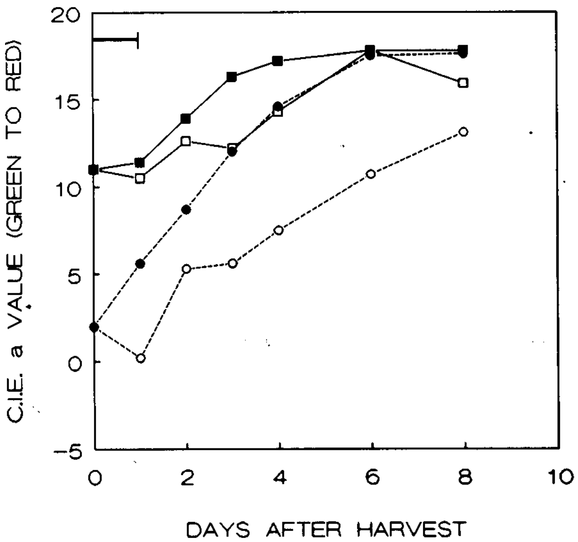

Fig. 3. Effect of C_2H_4 treatment on papaya outer and inner mesocarp flesh color at the fruit equator, in terms of CIE ‘a’ values (green to red). The fruit were ripened at 25C. All points are means of 10 fruit. (●– – –●) Outer mesocarp with C_2H_4, (○– – –○) outer mesocarp without C_2H_4, (■—■) inner mesocarp with C_2H_4, and (□—□) inner mesocarp without C_2H_4. Analysis of variance: inner mesocarp, ethylene^{ns} days*** ethylene × days^{ns}; no C_2H_4 ‘a’ = 11.75 − 1.61 days, L***Q^{ns}C^{ns}; C_2H_4 ‘a’ = 707 + 4.91 days − 0.74 days^2, L***Q^{ns}C^{ns}. Outer mesocarp, ethylene*** days*** ethylene × days^{ns}; no C_2H_4 ‘a’ = −3.73 + 5.16 days, L**Q^{ns}C^{ns}, C_2H_4 ‘a’ = 1.70 + 3.91 days − 0.12 days^2 L**Q**. Horizontal bar represents 24 hr of C_2H_4 treatment.

development. Immature fruit were defined as fruit having white seeds remaining in the seed cavity.

Discussion

Surface color (Fig. 1A), softening (Fig. 1B), and flesh color (Fig. 1C) developed faster in cold-stored fruit within temperature range 17.5 to 30C. The rate of yellowing in C_2H_4-treated papayas was faster in fruit held for 10 days at 10C than in nonstored fruit (Fig. 2A vs. 2B and 2E vs. 2F). Hobson (1987) reported that an increase in tomato softening due to cold storage could result from the release of C_2H_4 during storage, which then stimulates softening upon removal from storage. The stimulation of C_2H_4 production (< 0.1 µl·liter^{-1}) in papaya during 14 days storage at 10C (Chan et al., 1985) could explain the faster ripening rate of the stored papayas in these tests. Altered tissue sensitivity to C_2H_4 (Knee, 1985) via changes in the C_2H_4-binding affinity to the receptors and/or the number of receptors (Yang, 1985) could have increased during the 14 days storage at 10 Canal could have made the fruit more sensitive to the ripening temperatures and exogenous C_2H_4. Seasonal variation was another possibility, as the slight softening related to storage at 10C seemed to appear in summer fruit, but not in winter-harvested fruit.

High temperatures affect red color development and softening in tomatoes (Hall, 1964). Mature-green tomatoes do not soften, and polygalacturonase (PGase) did not appear when fruit were stored at 33C for 15 days. However, PGase increased after a delay of 6 days upon transfer to 22C (Yoshida et al., 1984). Ogura et al. (1976) reported that a 15-day storage at 33C suppresses C_2H_4 production in mature-green tomatoes. Akamine (1977) reported that papaya fruit ripened abnormally at temperatures above 32.2C. The present study confirms these findings in that fruit ripened at 32.5C had abnormal delayed softening (Fig. 1B), poor internal color development (Fig. 1C), surface pitting, and an occasional off-flavor. A delay in papaya softening due to high temperatures (46C for 65 rein) is explained by a decrease in PGase amount and/or activity (Chan et al., 1981). Abnormal papaya softening caused by 32.5C (Fig. 1B) may have resulted from a failure to produce adequate C_2H_4 for papaya ripening, from a decrease in sensitivity in response to C_2H_4, or from damage to the PGase system (Chan and Tam, 1982; Chan, 1986).

Papayas ripened at 32.5C had poor red flesh color development (Fig. 1C). The highest weight loss occurred at 32.5C, where relative humidity was lower than at the lower temperatures (Table 1). Papaya red flesh color is due to lycopene development (Yamamoto, 1964). This finding was similar to the inhibition of tomato lycopene synthesis above 30C (Goodwin and Jamikorn, 1952). Flesh color development of papaya ripening at 30C was normal, but marketability was adversely affected by skin browning (Table 1). Excessive weight loss at higher temperatures with lower relative humidity (Table 1) led to skin wrinkling. A loss of 7% of initial weight is necessary to induce noticeable loss in papaya skin gloss and appearance (Paull and Chen, 1989).

Ethylene-treated papayas ripened faster and more uniformly, individually and as a cohort, in terms of degreening rate (Fig. 2 A and B), softening (Fig. 2 C and D), and flesh color development (Fig. 2 E and F) with or without storage at 10C. Fruit softness (Fig. 2C) reached the edible condition (≈ 50 N of deformation force) immediately after the C_2H_4 treatment, although the skin was only 60% yellow (Fig. 2A). The effect of C_2H_4 was to accelerate the rate of ripening of the mesocarp tissue nearer the skin (Fig. 3). Ethylene had no significant effect on the rate of ripening of the mesocarp near the seed cavity. The mesocarp tissue near the seed cavity had already developed a desirable flesh color and had begun to soften when the fruit were treated with exogenous C_2H_4. These results are similar to those reported for other climacteric fruits, such as mangoes that ripen from the inside out (Barmore, 1974; Fuchs et al., 1975; Lazan et al., 1986).

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