Artificial Light Enhances Red Pigmentation, but Not Ripening, of Harvested 'Anna' Apples

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Additional index words. temperature, ethylene, *Malus domestica*

Abstract. Mature-green 'Anna' apples (*Malus domestica* Borkh.) reddened after harvest as a result of exposure to continuous cool-white fluorescent light. Color development was most rapid at 20°C but most intense at 13°C. At 2°C, although the induction of red pigmentation was the slowest, a 72-hr exposure rendered color not significantly different from that of red, commercially harvested fruit. The development of color was light-intensity dependent, approaching saturation at 14.5 W·m⁻² (at 13°C). No differences in fruit ripening were found between fruit that developed color under artificial light and red fruit from the commercial harvest, in spite of some stimulation of ethylene production during illumination.

One of the characteristics that determines the marketability of apples is fruit color (Walter, 1967). The highest quality apples have traditionally been grown in the northern, temperate zone, where color development is not a problem. However, apples are increasingly being grown in warmer regions of the world, where they are often deficient in satisfactory color (Blankenship, 1987). A high level of ethylene has been associated with the development of red pigmentation. Spraying with ethephon, an ethylene-releasing chemical, is a treatment adopted by some growers to improve fruit color (Blanpied et al., 1975) that, however, also leads to more-rapid fruit softening (Blanpied et al., 1975; Chalmers et al., 1973).

Light and temperature, which are known to be of major importance in anthocyanin accumulation in the fruit on the tree (Blankenship, 1987; Diener and Neumann, 1981; Walter, 1967) and after harvest (Arakawa et al., 1985; Faragher and Brohier, 1984; Siegelman and Hendricks, 1957; Walter, 1967), have been suggested as possible means for improving red coloration without increasing fruit ripening (Looney, 1975). In spite of the results noted, almost no attention has been paid to the influence of conditions conducive to red coloration on other characteristics relating to fruit ripening. If the use of artificial illumination for improving the red pigmentation of apples is to become a commercial practice, then it will be of paramount importance to ascertain its effect on fruit ripening and senescence.

Received for publication 28 Dec. 1988. This is contribution no. 2551-E, 1988 series, from the Agricultural Research Organization, The Volcani Center, Bet Dagan, Israel. We thank Ezri Levy for his dedicated technical assistance. We also thank J.D. Klien for reading the manuscript and for his constructive comments. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

The objectives of the present study were to: 1) verify the efficacy of postharvest illumination with cool-white light in inducing the red coloration of mature-green 'Anna' apples; 2) assess the influence of effective illumination treatments on fruit ripening; and 3) determine the optimum conditions for treatment, taking both previous considerations into account.

'Anna', an Israeli cultivar, is suitable for a subtropical climate because of its low chilling requirement. However, it is character-

ized by nonuniform (in time and coverage) color development, which, in very hot seasons, may be so delayed as to lead to fruit being harvested when it is overripe. The possibility of improving fruit color after harvest might lead to a greater uniformity in both fruit appearance and maturity.

Mature-green and red 'Anna' fruits, grown on the coastal plain of Israel, were harvested at the beginning of the commercial harvest (end of June). The green and red fruit were at a similar state of maturity at harvest, as judged by soluble solids content (SSC), flesh firmness, starch content, and the rate of ethylene evolution (see footnotes to Table 2). The green fruit was harvested mature to avoid the degradation of illumination-induced anthocyanin in subsequent darkness (Creasy, 1968). The harvested fruit was stored at 0°C for 5 weeks in darkness and removed to higher temperatures when needed. Continuous cool-white fluorescent light (Sylvania, 40-w tubes), as recommended by Bishop and Klein (1975), were used at three light intensities (7.5, 14.5, and 17.5 W·m⁻²) for illumination in chambers held at 2, 13, and 20 ± 0.5°C. Twenty-five fruits were arranged in a box so that only one side of the fruit was illuminated in each treatment. Color development on both sides of the fruit was followed daily with a Gardner calorimeter (Gardner Instruments XL20 Calorimeter) to determine the increase in red (parameter "a") pigmentation, in parallel with the rate of ethylene emission. Ethylene emission was determined by enclosing a pair of apples in

Fig. 1. Change in red pigmentation of 'Anna' apples during 3 days of illumination with cool-white fluorescent light at 14.5 W·m⁻², at 2, 13, or 20°C.

Table 1. Effect of illumination with cool-white light for 3 days at two temperatures on red pigment development and ethylene evolution on 'Anna' apples harvested green ($\pm$ SE)^a.

Illumination conditions		Hunter color		Ethylene production ^b ($\mu\text{l}\cdot\text{kg}^{-1}\cdot\text{hr}^{-1}$)
Intensity ($\text{W}\cdot\text{m}^{-2}$)	Temp. ($^{\circ}\text{C}$)	Initial fruit color	Nonilluminated cheek (Hunter a)	
14.5	2	Green	-8 ± 1.2	52 ± 9
	13	Green	-7 ± 2.1	153 ± 35
	20	Green	-8 ± 1.0	78 ± 18
0	0	Red	-6 ± 2.1	29 ± 20
	0	Green	-8 ± 1.2	47 ± 11

^aData shown are means of 25 replicates.

^bMeasured after 5 hr at 20C.

^cSun-exposed cheek.

Table 2. Effect of 3 days of illumination with cool-white light at various temperatures on subsequent ripening of 'Anna' apple fruit during 3 days in darkness at 20C ($\pm$ SE)^a.

Illumination conditions		Initial fruit color	Firmness (N)	SSC (%)	Starch index (1-5) ^b	Ethylene production ($\mu\text{l}\cdot\text{kg}^{-1}\cdot\text{hr}^{-1}$)
Intensity ($\text{W}\cdot\text{m}^{-2}$)	Temp. ($^{\circ}\text{C}$)					
14.5	2	Green	71 ± 11	11 ± 1	4 ± 0.5	280 ± 45
	13	Green	46 ± 9	11 ± 1	5 ± 0.2	298 ± 27
	20	Green	53 ± 9	11 ± 0.5	5 ± 0.4	309 ± 44
0	0	Red	55 ± 9	13 ± 0.5	4 ± 0.5	243 ± 40
	0	Green	68 ± 8	11 ± 0.6	4 ± 0.4	246 ± 28

^aData shown are means of 25 replicate.

^bRed mature fruit at harvest was characterized by 'a' + 15, firmness 74 N, SSC 12%, starch index 2.5, and ethylene emission $25 \mu\text{l}\cdot\text{kg}^{-1}\cdot\text{hr}^{-1}$. Green mature fruit at harvest was characterized by "a" -9, firmness 87N, SSC 10%, starch index 1.9, and ethylene emission $8 \mu\text{l}\cdot\text{kg}^{-1}\cdot\text{hr}^{-1}$.

^c1 = high starch content, 5 = low starch content.

Fig. 2. Change in red pigmentation of 'Anna' apples following 3 days of illumination with cool-white fluorescent light at various intensities at 2 or 13C.

hermetically sealed 1200 ± 15 -ml containers for 1 hr following 5 hr of equilibration at 20C. At the end of this period 1 ml of the headspace was sampled for ethylene quantification with a gas chromatography. Illumination was followed by 3 days in darkness at 20C, at the end of which the rate of ethylene evolution, the change in redness, and fruit ripeness on both sides of the fruit were determined. All fruit manipulations necessary to measure fruit color and the rate of ethylene emission were performed at minimal light intensity ($0.5 \text{ W}\cdot\text{m}^{-2}$), so as not to affect the color of the dark controls. This light intensity would not alter the effect of

illumination even at the lowest light intensity treatment ($7.5 \text{ W}\cdot\text{m}^{-2}$). For color determination, all fruit of a single treatment were removed from the illumination chamber for only 20 min and immediately thereafter returned to light. To measure the rate of ethylene evolution, fruit of all treatments were handled parallel and the effect of the temporarily altered conditions on this measurement, if any, were therefore similar in all treatments. A penetrometer was used to determine flesh firmness (1 l-mm tip); changes in starch content were determined by the IKI test; and SSC was measured with a hand refractometer. Two controls were held in the darkness at 20C for appropriate times: green-mature fruit to characterize the changes caused by illumination; and red commercially harvested fruit to assess differences in ripeness between treated green fruit and the red harvested fruit after shelf life.

The reported results are averages of measurements made in 25 fruits. The same apples were checked each time and, consequently, the samples were not independent. Therefore, no statistical analyses were performed and only the averages and their SE are presented.

Red pigment developed in the green fruit exposed to light under all tested conditions. In agreement with the results reported by others (Chalmers et al., 1973) no change in color could be detected for up to 20 hr of illumination. Exposure to light intensity of $14 \text{ W}\cdot\text{m}^{-2}$ at 13C for 3 days allowed the most intense color to develop (Fig. 1). This advantage of illumination at 13C for color intensity was already significant after 2 days, but the fastest response was measured at 20C after 1 day of illumination. Redness devel-

oped most slowly at 2C, with a minimum of 40 hr being required for measurable changes. In spite of the slow start, 3 days of illumination at 13C and $14.5 \text{ W}\cdot\text{m}^{-2}$ resulted in a degree of redness that did not differ significantly from that of the fruit illuminated at 20C or from the commercially harvested fruit. The fruit response to illumination was light-intensity dependent regardless of temperature until it reached an "a" value of ≈ 15 , close to that recorded for the red fruit on the tree (Fig. 2). At 13C, the red intensity was the highest at $14.5 \text{ W}\cdot\text{m}^{-2}$; greater illumination did not provide any additional benefits. Of particular interest are the results obtained for illumination at 2C, considering the fact that in other reports illumination at low temperatures promoted red pigmentation only when interrupted by illumination at higher temperatures (Faragher, 1983).

Under all tested conditions, each treated fruit showed 100% red coverage on the side exposed to light. No color developed on the nonilluminated side of the fruit (Table 1 negative values). This result implies that by applying illumination, not only is it possible to avoid marketing of green 'Anna' fruit, but also to assure fruit that is uniformly red on $\approx 50\%$ of its surface, whereas with present practice, red pigmentation covers from $\approx 10\%$ to 50% .

Under all tested conditions, fruit illumination followed by 3 days at 20C did not accelerate the ripening beyond that of commercially harvested fruit held in darkness for 3 days at 20C, as judged by the values for fruit firmness, SSC, starch content, and the rate of ethylene evolution (Table 2).

The high rate of ethylene evolution measured after illumination followed by 3 days in darkness at 20C was due mainly to the advance in ripening during storage at 20C (Tables 1, 2). Even the high value obtained for ethylene evolution at 13C after illumination only (Table 1) was substantially lower after 5 hr at 20C than that obtained for the commercially harvested fruit after 3 days at 20C (Table 2).

Considering the possibility that the slight increase in ethylene evolution during illumination might contribute to accelerated fruit ripening during post-illumination storage, an experiment was carried out to examine the storability of illuminated fruit. The fruit was illuminated at 13C for 2 days at a light intensity of $14.5 \text{ W}\cdot\text{m}^{-2}$, after which the ethylene evolution rate was $127 \mu\text{l}\cdot\text{kg}^{-1}\cdot\text{hr}^{-1}$. The fruit was then transferred to 0C and ethylene evolution dropped to $29 \mu\text{l}\cdot\text{kg}^{-1}\cdot\text{hr}^{-1}$. After 1 month in storage at 0C, it remained at the same level and increased to $267 \mu\text{l}\cdot\text{kg}^{-1}\cdot\text{hr}^{-1}$ after 3 additional days at 20C. The values for the green nonilluminated fruit were 46, 26, and $247 \mu\text{l}\cdot\text{kg}^{-1}\cdot\text{hr}^{-1}$, respectively, for the above three dates of measurements.

We conclude that 'Anna' apples can reach satisfactory red pigmentation without detriment to ripening with 2 days of illumination at 13C or 3 days at 2C under cool-white fluorescent light at $14.5 \text{ W}\cdot\text{m}^{-2}$. Effectiveness at 2C has significance for the possibility

of illuminating fruit in storage.

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HORTSCIENCE 25(5):549-552. 1990.

Pathogenicity, Growth, and Sporulation of *Mucor mucedo* and *Botrytis cinerea* in Cold or CA Storage

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Additional index words. postharvest diseases, mucor rot, gray mold, vegetables

Abstract. The virulence of *Mucor mucedo* (L.) Fr. (the cause of mucor rot) and *Botrytis cinerea* Pers. (gray mold) on vegetables stored at 13C for 7 days or 1C for 70 days varied with the host and controlled atmosphere (CA). *M. mucedo* was severely pathogenic at 13C to cucumber (*Cucumis sativus* L.), eggplant (*Solanum melongena* L. var. *esculentum* Nees), pepper (*Capsicum annuum* L.), and tomato (*Lycopersicon esculentum* Mill.), but not to bean (*Phaseolus vulgaris* L.). The fungus did not infect carrot (*Daucus carota* L. var. *sativa* DC.), celery (*Apium graveolens* L. var. *dulce* DC.), onion (*Allium cepa* L.), or parsnip (*Pastinaca sativa* L.) at 1C. *B. cinerea* was virulent on all of these crops at 13 or 1C. The severity of mucor rot and gray mold on eggplant stored at 13C for 14 days was suppressed most in a CA of 7.5% CO₂ + 1.5% O₂ and least in 1.5% O₂, in comparison with the air control. Similarly, the growth and sporulation of each pathogen on eggplant-extract agar maintained at 13C for 4 or 14 days were suppressed most in 7.5% CO₂ + 1.5% O₂; suppression was least in 1.5% O₂. The suppression of diseases on eggplant was highly correlated with the suppression of mycelial growth and sporulation of pathogens on agar.

Of the numerous reports of *Mucor* spp. causing decay of vegetables in cold storage, *Mucor mucedo* has not been listed as a pathogen in North America (Weimer and Harter, 1921; Butler, 1959; Smith et al., 1979). In 1981, in the United States, Moline and Miller (1981) first observed that *M. mucedo* caused a severe decay (hereafter referred to as mucor rot) of tomato fruit within 3 to 4 days after inoculation at 20C. There is little information regarding the suppression of mucor rot in controlled atmosphere (CA). In

contrast, *Botrytis cinerea* has been reported frequently to cause gray mold on stored vegetables in Europe or North America (Smith

et al., 1966; Adair, 1971; Geeson and Browne, 1980; Geeson et al., 1988). Gray mold was found to cause decay of vegetables shipped to the New York markets (Cappellini et al., 1987; Ceponis et al., 1985, 1986, 1987a, 1987b, 1988). In Ontario, Canada, Reyes and Smith (1986) have shown that *B. cinerea* caused severe gray mold on stored celery and that the disease was suppressed by CA storage at 0 to 1C. Other studies have indicated that CA suppresses gray mold on cabbage (Adair, 1971; Geeson and Browne, 1980). The objectives of the present study were to 1) compare the pathogenicity of *M. mucedo* with that of *B. cinerea* on vegetables in storage, and 2) determine if CA suppresses these diseases on eggplant and reduces growth and sporulation of the pathogens on agar.

The vegetables used in this study were 2-week-old (from anthesis), 10-cm-long, green bean pods (*Phaseolus vulgaris* L. c.w. Speculator); 8-week-old (from seeding), 4-cm-diameter carrot roots (*Daucus carota* L. var. *sativa* DC. cv. Spartan); 15-week-old (from seeding), 30-cm-long celery petioles (*Apium graveolens* L. var. *dulce* DC. cv. Tendercrisp); 2-week-old (from anthesis), 5-cm-diameter, green cucumber fruits (*Cucumis sativus* L. long type cv. Corona); 2-week-old (from anthesis), 5-cm-diameter eggplant fruits (*Solanum melongena* L. var. *esculentum* Nees narrow type cv. Tycoon); field-

Table 1. Pathogenicity of *Mucor mucedo* and *Botrytis cinerea* as indicated by average diameter of 10 replicate lesions on various vegetables stored at 1 or 13C for 70 and 7 days, respectively.

Vegetable	Lesion diam (cm) ^a			
	1C		13C	
	<i>Mucor mucedo</i>	<i>Botrytis cinerea</i>	<i>Mucor mucedo</i>	<i>Botrytis cinerea</i>
Bean	---	---	0.0 f	4.0 cd
Carrot	0.0 b	4.0 a	0.0 f	1.2 e
Celery	0.0 b	3.4 a	0.0 f	5.7 b
Cucumber	---	---	5.0 bc	5.4 b
Eggplant	---	---	8.5 a	5.8 b
Onion	0.0 b	3.0 a	0.0 f	1.2 e
Parsnip	0.0 b	3.6 a	---	---
Pepper	---	---	4.5 c	3.1 d
Tomato	---	---	8.8 a	3.6 d

^aMeans within each column followed by the same letter are not significantly different (Duncan's multiple range test, *P* = 0.05).

^bDashes = no data collected.

Received for publication 15 May 1989. I acknowledge with thanks Diane M.L. Beaulieu-Aruvee (of my laboratory) for technical assistance and William A. Straver (Hort. Res. Inst. Ont.) for supplying the cucumber and tomato fruits. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

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