Establishing an Efficient Fruit Ripening Method for Sweet Pepper (\textit{Capsicum annuum} L.) through Light Irradiation and Dark Processing

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A light irradiation method was found to promote coloring in sweet pepper fruit (\textit{Capsicum annuum} L.) harvested at the breaker stage of mature green fruit. In summer and autumn culture, heating systems are not usually used, and a large amount of uncolored fruit remains after harvest because of low temperatures and/or insufficient sunlight. We investigated the use of light irradiation to enhance the color of the fruit post-harvest and found that light intensities between 50 \( \mu \text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \) and 200 \( \mu \text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \) made no difference to the coloring rate; however, higher intensities resulted in an increase in the carotenoid content, which is responsible for the color in red sweet pepper fruit. Although temperatures of 15–25°C with light irradiation are considered to be appropriate for fruit coloring, the transpiration rate was found to increase in proportion to temperature rises, and the fruit wilted at 25°C. We also confirmed that fruit colored more than 50% by light irradiation continued getting colored in the dark at temperatures above 15°C. This combination of light irradiation and dark processing may potentially improve the ripening process efficiency and preserve the market value of fruit.

Key Words: coloring, lighting, paprika, post-harvest.

Introduction

The consumption of sweet pepper fruit (\textit{Capsicum annuum} L.) has been increasing in recent years. Sweet pepper fruit can be found in different colors, such as red, and is widely used to enhance the taste and color of fresh salads, as well as cooked foods. The increasing popularity of this fruit is evident from the 2014 data indicating an increase in the planted area for sweet peppers to 57 ha along with an increase in greenhouse horticulture facilities in Japan (Ministry of Agriculture, Forestry and Fisheries, 2014, http://www.maff.go.jp/j/tokei/kouhyou/tokusan_yasai/). Sweet peppers are sensitive to the surrounding environment, specifically temperature and sunlight levels; therefore, environmental control technologies and advanced cultivation techniques are needed. There are some large-scale agricultural production corporations in Miyagi Prefecture which produce sweet pepper fruit all year round. As the production of sweet peppers in large greenhouse facilities continues to increase, stable production of this fruit will become increasingly important. In summer and autumn culture, heating systems are not usually used, and red sweet pepper fruit are generally harvested from June until the end of November. However, because of low temperatures and solar radiation in late autumn, approximately 15% of the fruit are not harvested, because they are insufficiently pigmented, which leads to a low market value. Thus, the post-harvest ripening of these unripened fruit is of economic value since colored red fruit can be shipped to market.

Capsanthin is the red carotenoid pigment responsible for the color of the ripe fruit of red pepper cultivars (Hornero-Mendez et al., 2000; Minguez-Mosquera and Hornero-Mendez, 1993). Both green and red peppers also contain yellow carotenoid pigments, but these are usually masked by chlorophyll in the green fruit and by red carotenoids in the red fruit (Nagle et al., 1979). During ripening of red sweet pepper fruit, the chlorophyll and lutein contents decrease, whereas the \( \beta \)-carotene,
antheraxanthin, and violaxanthin content increase. Subsequently, pigment constituents such as zeaxanthin, β-cryptoxanthin, capsanthin, and capsorubin are compounded (Hornero-Mendez et al., 2000). Moreover, the biosynthesis mechanism of these pigments is known to be different from that in tomatoes. The carotenoid content of tomatoes increases by ten-fold or more during maturation, mainly because of the presence of lycopene, which shows an increase of 500-fold or more (Fraser et al., 1994). In addition, the decrease in chlorophyll production and lycopene biosynthesis during tomato maturation is promoted by ethylene (Alexander and Grierson, 2002); however we were unable to confirm that ethylene promotes the coloring of sweet pepper fruit (Yoshida et al., 2014). Thus, the pigmentation process in sweet peppers is different from that in tomatoes, and the mechanism is not yet completely understood. However, we recently reported that light irradiation contributes greatly to the pigmentation of sweet pepper fruit (Yoshida et al., 2014), and fluorescent lamps can be used to promote coloring post-harvest. This is a low-cost method for improving the coloring of sweet pepper fruit post-harvest, resulting in an improved production of sweet pepper fruit with increased market value. In this study, we investigated the light intensities and temperatures required for the post-harvest pigmentation of sweet pepper fruit. Moreover, we aimed to establish an optional method to accelerate fruit coloring through a combination of light irradiation and dark processing.

### Materials and Methods

#### Plant materials

Fruit of sweet peppers (*Capsicum annuum* L. ‘Special’) were obtained from VEGI-Dream Kurihara Corporation, Takashimizu, Kurihara, Miyagi Prefecture, Japan (latitude 33°64'N, 141°02'E). Sweet peppers were grown in rockwool medium and fertilized with nutrient solution in a large scale greenhouse. The green mature fruit were harvested at the breaker stage, when the red color in the green fruit was less than 5%. They were picked during the low temperature period from October–May in 2012 and 2013.

The effect of different light irradiation intensities and dark processing (EXP. 1)

We performed light irradiation and dark processing at 20°C for green mature sweet pepper fruit at the breaker stage (Table 1). The entire surface of the fruit, except for its underside, was irradiated using fluorescent light (FL15SS·ENW, FL20SS·ENV, and FL40SS·ENW; Panasonic CO., Ltd., Osaka, Japan). Fruit were irradiated at 3 different intensities: 50 μmol·m⁻²·s⁻¹, 100 μmol·m⁻²·s⁻¹, and 200 μmol·m⁻²·s⁻¹. We also performed dark processing of the fruit as a control experiment. During both light irradiation and dark processing, the fruit was placed into a polyethylene bag to prevent drying. The fruit was removed from the bag every 1–2 days to check the color that time and then packaged again. The Color CIELAB parameter (a*: redness) was determined using a spectrophotometer (CR-200; Konica Minolta, INC, Osaka, Japan). A minimum of three inde-

| Experiment | Treatment | Light intensity (μmol·m⁻²·s⁻¹) | Temperature (°C) | Light irradiation (days) | Dark processing (days) |
|------------|-----------|--------------------------------|-----------------|-------------------------|-----------------------|
| EXP. 1     | 50        | 20                            | 5               | —                       | —                     |
|            | 100       | 20                            | 5               | —                       | —                     |
|            | 200       | 20                            | 5               | —                       | —                     |
|            | Dark      | 0                             | —               | —                       | 5                     |
| EXP. 2     | 10°C      | 10                            | 10              | —                       | —                     |
|            | 15°C      | 15                            | —               | —                       | —                     |
|            | 20°C      | 100                           | 20              | 5                       | —                     |
|            | 25°C      | 25                            | 5               | —                       | —                     |
|            | 30°C      | 30                            | 5               | —                       | —                     |
| EXP. 3     | 30%       | 100                           | 20              | 2–4                     | 0–4                   |
|            | 50%       | 100                           | 20              | 2–4                     | 0–4                   |
|            | 70%       | 100                           | 20              | 2–4                     | 0–4                   |
|            | 90%       | 100                           | 20              | 2–4                     | 0–4                   |
| EXP. 3, 4  | 15°C (L7) | 15                            | 7               | —                       | —                     |
|            | 15°C (L5+D4) | 15              | 5               | 4                       | —                     |
|            | 20°C (L6) | 20                            | 6               | —                       | —                     |
|            | 20°C (L3+D4) | 20              | 3               | 4                       | —                     |
|            | 25°C (L4) | 25                            | 4               | —                       | —                     |
|            | 25°C (L3+D4) | 25              | 3               | 4                       | —                     |

Table 1. Light intensity and temperature in the experiments.
pendent experiments with three fruit on each test were performed, and data were given by the mean ± SE. Differences in mean value measurements were analyzed using the Tukey-Kramer test.

Carotenoids were analyzed by using HPLC (High-Performance Liquid Chromatography) equipped with a photodiode array detector (HPLC-DAD). At the beginning of carotenoid analysis, each fruit was diced and the sample (2.0 g) was homogenized in an acetone/n-hexane = 4/6 solution, followed by centrifugation (4000 rpm, 4°C, 4 min). The supernatant was concentrated under reduced pressure. The residue was redissolved in 2 mL of the acetone/n-hexane = 4/6 solution for the HPLC analysis. We used an HPLC-DAD system (pump: L-2130; Hitachi, Tokyo, Japan; DAD detector: L-2455; Hitachi) and a YMC carotenoid column (4.6 mm ID × 250 mm; YMC, Kyoto, Japan) for carotenoid quantification. The carotenoids were identified on the basis of their retention times and UV/VIS absorption (200–600 nm) measured against a standard carotenoid peak. The concentration of each carotenoid was calculated from a standard calibration curve. The wavelengths used for the quantification of zeaxanthin, β-cryptoxanthin, β-carotene, and capsanthin were 452 nm, 452 nm, 474 nm, and 474 nm, respectively. The flow rate was set to 1 mL·min$^{-1}$ and the solvent gradient based on solvent A (Methanol) and solvent B (Methanol/tert-butyl methyl ether/H$_2$O = 8/90/3, by volume) was set as follows: 1% B (0 min), 10% B (10 min), 30% B (20 min), and 100% B (30–35 min). To analyze the carotenoid contents, three independent experiments with at least three fruit on each test were performed and the results were averaged. Differences in mean value measurements were analyzed using Tukey’s test.

Change in the coloration and carotenoid content of the fruit at different temperature conditions with light irradiation (EXP. 2)

We kept the light intensity constant at 100 μmol·m$^{-2}$·s$^{-1}$ and varied the incubation temperatures using 10°C, 15°C, 20°C, 25°C, and 30°C (Table 1). Similar to EXP. 1, the fruit were stored in a polyethylene bag to prevent drying. The color and carotenoid contents of the fruit were determined in the same way as described in EXP. 1. To analyze the $a^*$ value and carotenoid contents, three independent experiments with at least three fruit on each test were performed and the results were averaged. Differences in mean value measurements were analyzed using Tukey’s test.

Efficient coloring methods by the combination of light irradiation and dark processing (EXP. 3)

Using the same method as described in EXP. 1, we irradiated the fruit with light at 100 μmol·m$^{-2}$·s$^{-1}$ at 20°C until varying degrees of color were obtained (30%, 50%, 70%, and 90%, Table 1). Then, the fruit was subjected to dark processing to determine whether the coloration process would continue in the absence of light. This phenomenon was studied at temperatures of 15°C, 20°C, and 25°C. Fruit were irradiated (100 μmol·m$^{-2}$·s$^{-1}$) for 3–5 days at temperatures of 15°C, 20°C, and 25°C. The color was adjusted to approximately 50% by light irradiation, and this was followed by dark processing for 4 days at the same temperature as that used during the light irradiation. The coloration and the carotenoid content of the irradiated fruit were examined using the same methods as described in EXP. 1. Three independent experiments with at least three fruit in each test were performed and the results were averaged. Statistical analysis was performed by the same method as described in EXP. 2.

Weight changes in the fruit treated by a combination of light irradiation and dark processing (EXP. 4)

We investigated the decrease in the weight of the fruit (calculated from the weight of the fruit after light irradiation or a combination of light irradiation and dark processing relative to the weight measured immediately after sampling the fruit) that was colored through a combination of light irradiation and dark processing. Three independent experiments with at least three fruit in each test were performed and the results were averaged. These data were evaluated by two-way ANOVA. Before the analysis, Arcsine transformations were used for the percentage data.

Results

Effects of different light intensities and dark processing on the color of the fruit (EXP. 1)

Mature green sweet pepper fruit at breaker stage were irradiated using fluorescent light at 20°C for 5 days at 3 different light intensities: 50 μmol·m$^{-2}$·s$^{-1}$, 100 μmol·m$^{-2}$·s$^{-1}$, and 200 μmol·m$^{-2}$·s$^{-1}$. In addition, fruit were subjected to dark processing for 5 days at 20°C. We investigated the color of the fruit, as quantified by the $a^*$ value. The $a^*$ value of mature red fruit that could be sold exceeded approximately 25, and on average about 30 (Table 2). Therefore, it was determined that the fruit with $a^*$ value above 25 had marketable value. By day 3, the $a^*$ value of fruit irradiated at 200 μmol·m$^{-2}$·s$^{-1}$ intensity was different compared with that of the fruit treated through dark processing (Fig. 1). Furthermore, on day 5, the $a^*$ values of the fruit irradiated at 50 μmol·m$^{-2}$·s$^{-1}$, 100 μmol·m$^{-2}$·s$^{-1}$, and 200 μmol·m$^{-2}$·s$^{-1}$, were higher than those of the fruit subjected to dark processing. Therefore, this data confirmed that light irradiation at intensities greater than 50 μmol·m$^{-2}$·s$^{-1}$ promotes the coloring of fruit. Next, we examined the carotenoid content in the fruit after each treatment (Table 2). We found that the content of β-carotene and capsanthin in the fruit irradiated at light intensities of 100 μmol·m$^{-2}$·s$^{-1}$ and 200 μmol·m$^{-2}$·s$^{-1}$ for 5 days was greater compared with those in the fruit
Table 2. Effect of light irradiation and dark processing on each carotenoid content in the sweet pepper.

| Treatments          | a* value | Carotenoids content (mg·kg⁻¹) |
|---------------------|----------|-----------------------------|
|                     |          | β-carotene | β-cryptoxanthin | Zeaxanthin | Capsanthin |
| 50 μmol·m⁻²·s⁻¹     | 15.9 b*  | 2.5 c       | 0.7 c          | 3.8 a      | 4.7 bc     |
| 100 μmol·m⁻²·s⁻¹    | 20.9 b   | 7.6 b       | 1.1 bc         | 2.3 b      | 9.8 a      |
| 200 μmol·m⁻²·s⁻¹    | 24.8 ab  | 17.8 a      | 2.2 a          | 3.3 a      | 9.2 ab     |
| Dark processing     | 9.3 c    | 1.4 c       | 0.7 bc         | 3.4 a      | 3.4 c      |
| Fruit at breaker stage | -13.3 d | 1.3 c       | N.D.x          | 5.1 a      | 0.5 c      |
| Mature red fruit    | 30.2 a   | 11.8 ab     | 1.3 b          | 2.4 b      | 13.3 a     |

* Light irradiation and dark processing were carried out for 5 days using mature green fruit at the breaker stage at 20°C.

Efficient coloring methods by the combination of light irradiation and dark processing (EXP. 3)

We determined that the coloring of sweet pepper fruit is promoted by light irradiation and also identified the optimal temperature for the coloring to occur. In contrast, other studies have indicated that the coloring can progress in the dark if the temperature is maintained at approximately 20°C (Kono, 2002). Therefore, we examined the coloring condition of fruit which had suffi-

cient market value even with dark processing. To do this, the fruit was irradiated at 100 μmol·m⁻²·s⁻¹ and 20°C until various stages of coloration (30%, 50%, 70%, and 90%) were attained, at which point they were dark processed at 20°C. We found that the coloring con-
Continued throughout the dark processing, and that the fruit that was colored more than 50% prior to dark processing exceeded a* value of 25 and reached a marketable value after approximately 3–4 days (Table 4). After 4 days, the fruit that was colored approximately 30% prior to dark processing also continued to gain color, achieving a* value of 20; however, the fruit had a light red color, which is associated with a low market value. Next, we examined the effect of temperature on the coloring that occurs during dark processing. Fruit were irradiated with light at 15°C, 20°C, and 25°C until they were colored approximately 50%, followed by dark processing at the same temperature. This treatment produced fruit with a* values above 25 at all temperatures, and the coloring reached a marketable level visually (Table 5). In addition, the capsanthin content in the fruit treated at 25°C was greater than that in the fruit treated at 15°C and 20°C.

**Table 4.** The color changes of fruit which were colored by light irradiation and dark processing at 20°C.

| The ratio of red color in fruit after light irradiation | a* value of pericarp under dark processing (days) |
|--------------------------------------------------------|-------------------------------------------------|
| 30%                                                    | 4.0 c 11.7 c 14.0 b 16.4 b 20.3 b               |
| 50%                                                    | 10.4 b 20.0 b 23.5 a 24.7 a 26.1 a               |
| 70%                                                    | 19.2 a 22.4 b 25.8 a 28.1 a 28.4 a               |
| 90%                                                    | 25.6 a 29.0 a 29.3 a 30.1 a 29.4 a               |

* Light irradiation at 100 μmol·m⁻²·s⁻¹ was carried out using mature green fruit at the breaker stage at 20°C until various stages of coloration (30%, 50%, 70%, and 90%).

**Table 5.** a* value and carotenoid content of the fruit, which were ripened by dark processing after light irradiation.

| Temperature (°C) | Light irradiation (days) | Dark processing (days) | a* value | Carotenoids content (mg·kg⁻¹) |
|------------------|--------------------------|------------------------|----------|------------------------------|
|                  |                          |                        |          | β-carotene                   |
| 15               | 5                        | 4                      | 25.9     | 3.3 a 6.4 b                  |
| 20               | 3                        | 4                      | 26.1     | 4.8 a 6.0 b                  |
| 25               | 3                        | 4                      | 30.2     | 2.4 a 10.3 a                 |

* Light irradiation at 100 μmol·m⁻²·s⁻¹ was carried out using mature green fruit at the breaker stage in 15°C, 20°C, and 25°C, and dark processing was carried out for 4 days at the same temperature immediately.

**Discussion**

The coloring of the green mature sweet pepper fruit harvested at the breaker stage was promoted by irradiation of the fruit with light having intensities of 50 μmol·m⁻²·s⁻¹, 100 μmol·m⁻²·s⁻¹, and 200 μmol·m⁻²·s⁻¹ (Fig. 1). In addition, the capsanthin and β-carotene content in the fruits with light irradiation increased compared to dark processing (Table 2). These results are consistent with a study that reported that the carotenoid content in cultivated sweet pepper fruit was affected by light exposure during growth and development (Russo and Howard, 2002) and with another study that found an increase in carotenoid content in the fruit irradiated using sunlight throughout ripening compared with fruit that experienced interrupted light irradiation (Lopez et al., 1986). Carotenoids are useful for the elimination of the active oxygen that is generated by excess light irradiation, and in the prevention of photo-chemistry system II inhibition (Nishiyama et al., 2006,
In addition, the inoculation of reactive oxygen species on the surface of sweet pepper fruit has been found to induce the expression of several genes connected to carotenoid synthesis, including python synthase (PSY) (Bouvier et al., 1998). PSY is known to contribute to carotenoid biosynthesis during fruit ripening and during stress (Fray and Grierson, 1993; Giorio et al., 2008; Saito et al., 2008). In sweet pepper fruit, it has been shown that light irradiation can be used to induce this enzyme (Nagata et al., 2015). This increase in the expression level of PSY may be due to light-stress. In contrast, earlier studies have demonstrated that the gene expression of PSY is controlled by the phytochrome in sinapis alba and arabidopsis (Von Lintig et al., 1997). The mechanism for light-driven carotenoid synthesis in sweet pepper fruit is still somewhat unclear and further research is required to better address this topic.

We found that the contents of β-carotene and capsanthin in the fruit irradiated at light intensities of 100 μmol·m⁻²·s⁻¹ and 200 μmol·m⁻²·s⁻¹ were greater compared with those in the fruit that had undergone dark processing (Table 2). In addition, when light intensities of 100 μmol·m⁻²·s⁻¹ and 200 μmol·m⁻²·s⁻¹ were used for 5 days, there was no significant difference in the coloring level, so a light intensity of 100 μmol·m⁻²·s⁻¹ is better than 200 μmol·m⁻²·s⁻¹ when considering use at production sites. Therefore, in EXPs. 2, 3, and 4, the light intensity was set to 100 μmol·m⁻²·s⁻¹. The coloring of fruit was strongly promoted at temperatures of 20°C and 25°C (Table 3). The content of capsanthin, the main red pigment in irradiated fruit, also significantly increased at temperatures of 20°C and 25°C (Table 3). Coloring of the fruit occurred even at 15°C, but 7 days were needed to bring the fruit from the breaker stage to a marketable stage. Previous studies indicated that a minimum temperature of 10°C was needed to color the fruit, and that the most suitable temperature range was 20–25°C, regardless of the presence/absence of light (Kono, 2002; Yoshida et al., 2014). In addition, when treated at 30°C, the β-carotene content in many processed fruit increased, resulting in an orange color. For instance, in tomatoes, while the lycopene content decreases at temperatures above 30°C, the β-carotene content increases (Hamauzu et al., 1998). The importance of temperature control was clearly demonstrated from EXPs. 2–3, and the temperature range most appropriate for the coloring of fruit by light irradiation was 15–25°C; however, results from the weight loss studies indicated increased transpiration at 25°C (Table 6). Fruit that experienced a weight loss of 3% or more was softened by light irradiation at 25°C after 3–4 days, and as such it is preferable to perform light irradiation in the temperature range of 15–20°C. To efficiently introduce this method to production sites, it will be necessary to optimize the space needed for light irradiation and minimize the irradiation time. Fruit that is colored to 50% or more by light irradiation can achieve market levels of coloring in approximately 4 days by maintaining the fruit at 20°C and using dark processing (Table 4). Bouvier et al. (1998) reported that reactive oxygen species induced gene expression for carotenoid synthesis with passing time. As shown in Figure 1, the a* value of the pericarp did not change after 1 day of light irradiation, but the difference in the a* value in light irradiated fruit and dark processed fruit began to appear from 3 days later. Therefore, if the fruit is kept at a temperature that is suitable for gene expression and carotenoid synthesis, capsanthin can be synthesized for several days after light irradiation, including under dark processing conditions. Provided there is access to a temperature-controlled space at the production site, dark processing can be used for coloring fruit. On the other hand, most fruit colored about

Table 6. The influence treatment under different temperature conditions had on the pace of fruit weight decrease.

| Temperature (°C) | Treatments* | Light irradiation (days) | Dark processing (days) | Weight reduction rate (%) |
|------------------|-------------|-------------------------|-----------------------|--------------------------|
| 15               |             | 7                       | 0                     | 2.5                      |
|                  |             | 5                       | 4                     | 1.5                      |
| 20               |             | 6                       | 0                     | 2.3                      |
|                  |             | 3                       | 4                     | 1.7                      |
| 25               |             | 4                       | 0                     | 4.6                      |
|                  |             | 3                       | 4                     | 3.2                      |

* Light irradiation at 100 μmol·m⁻²·s⁻¹ was carried out using mature green fruit at the breaker stage at 15°C, 20°C, and 25°C, and dark processing was carried out for 4 days at the same temperature immediately. Following these treatments, the a* value of the green mature fruit exceeded 25.

** NS, *, and ** indicate not significant, or significant differences at P < 0.05, and 0.01, respectively, by two-way ANOVA (n=3). Before the analysis, Arcsine transformations were used for the percentage data.
30% became a light red color with dark processing at 20°C for 4 days, and coloring did not proceed stably after even more days (data not shown). Therefore, we suggest restricting the use of dark processing to fruit that are more than 50% colored.

In previous studies on coloring of sweet pepper, there were some issues regarding use in the production site, so we aimed to establish an efficient method that is easy to utilize. Kono (2002) reported that sweet pepper fruit colored more than 50% even in dark processing, and the fruit reached market value. However, at production sites, fruit of various coloring levels remain in late autumn, and it is difficult to harvest only fruit colored more than 50%. In addition, we developed a technology that can promote coloring by light irradiation even at the breaker stage of the mature green fruit (Yoshida et al., 2014), but a large space for light irradiation is needed. The combination of light irradiation and dark processing used in this study will make it possible to ship fruit at the breaker stage or when partially colored and mainly harvested in the late autumn, and this method is beneficial in terms of shortening the time for lighting and efficiency in terms of irradiation space. Moreover, this combination can color the fruit earlier than using dark processing and reduce the loss of fruit weight compared with only light irradiation. Therefore, this process may potentially improve the ripening process efficiency and preserve the market value of fruit.

In 2014, approximately 14% of the sweet pepper yield was unmarketable due to insufficient color, and since approximately 90% of uncolored fruit can be made marketable by light irradiation, an overall increase in yield of 12.6% can be achieved. In large-scale greenhouses, an enormous quantity of sweet pepper fruit at the breaker stage remain at the end of the cultivation period, making the results presented in this work regarding the efficiency of light irradiation to color fruit very relevant. Further research is currently underway to study the wavelengths most effective in coloring fruit.

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