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原　著

The effect of light quality on harvested sweet corn by low intensity LED light irradiation at low temperature during short storage

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Summary

Sweet corn with husk (*Zea mays* L. *var. saccharata f.* Peter corn) was stored at 5 °C for 4 d under a photosynthetic photon flux density (PPFD) of 1 μmol $m^{-2}s^{-1}$ using red and blue LEDs. During storage, the sugar content (Brix) was measured consecutively for 4 d, and the amino acid content was analyzed after 4 d storage. Corn stored under blue LED light at 5 °C had higher sugar content than corn stored in a dark, cool condition. Similarly, the content of umami was increased by storage under the blue LED-cool condition, a result likely due to increases in aspartic acid and the major amino acid, glutamic acid. The red LED-cool condition was not as good as the blue LED-cool condition for preserving corn, but was much better than dark, room temperature storage. In contrast, the palatability of sweet corn kept at room temperature in the dark quickly declined. Blue LED-cool preservation appears to be a useful technique for storing sweet corn with husk.

Introduction

Harvested sweet corn quality deteriorates extremely fast in comparison with other vegetables due to a rapid decrease in sugar content from respiration and conversion to starch[1]. To prevent the deterioration of harvested vegetables, low temperatures are effective for suppressing respiration[2]. The respiration rate of sweet corn is higher than other vegetables, and the Q10 value, which is an index of the respiration dependency on temperature, is higher, too[2]. Cooling harvested sweet corn is very effective in preventing quality deterioration. As a result, it is possible to preserve sweet corn for two weeks at 0 °C and 95% humidity[3].

The effectiveness of low intensity light irradiation during the preservation of seedlings or harvested plant tissues has been reported previously[4)-8)]. By using red LED and supplying mineral nutrients in the form of a nutrient gel, harvested green leaves were kept fresh at low temperature for 27 days[9]. High quality harvested green leaves or grafted plug seedlings were maintained under optimized conditions of light irradiation in addition to CA (Controlled Atmosphere) storage[10]. A mixture of red and blue light irradiation at low temperature decreased the required light intensity to maintain the quality of green plants during long-term storage[11].

To date, the effectiveness of low intensity light irradiation on dehusked fruits is unknown. Since details about the mechanisms of amino-acid biosynthesis have been elucidated by biochemistry, molecular biology and genetics[12], we now know how to control the dynamics of amino-acid synthases by photonic conditions.

In this study, we discovered fundamental knowledge about the effect of low light irradiation on harvested, sweet corn with husk during low temperature storage. Because of the convenience of devices such as LEDs and refrigerator, our result may enjoy widespread practical use in the near future.

Materials and Methods

1. Plant Materials

Sweet corn (*Zea mays* L. *var. saccharata*) was picked from fields at Ashoro-shi in Hokkai-do or Mori-machi in Shizuoka Prefecture. We used sweet corn ear two days after harvest for this study. Corn was kept at 10 °C during transport from Hokkai-do to Shizuoka Prefecture or stored in a refrigerator. Upon receipt, corn with husk

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was placed into the light-irradiation boxes, and the temperature was maintained at 5 °C.

2. Light sources and storage conditions

Red LEDs (LXHL-LD3C, Lumileds Lighting LLC., San Jose, CA, USA) and blue LEDs (LXHL-LB3C, ditto) were used as light sources. Both LEDs had low, directional light diffusion patterns. Using The LEDs and light boxes were configured to work as pseudo Integrating Spheres. The LEDs were placed on top of the box, and the entire sweet corn ear surface was irradiated by LED light because light was reflected isotropically by the light box wall. Light power at the bottom of the box was adjusted to 1 μmol $m^{-2}s^{-1}$ in photosynthetic photon flux density (PPFD). PPFD was measured using a Photon flux meter (LI-190SA Quantum Sensor, LI-COR, Inc., Lincoln, NE, USA). We confirmed that the PPFD on the surface of sweet corn ears in such a box was approximately 1 μmol $m^{-2}s^{-1}$.

An ear of sweet corn was wrapped with PVC film and placed in a box standing up. The box was covered with aluminum foil to prevent irradiation from adjacent boxes, and the boxes were set in the refrigerator at 5 ± 1 °C. LED irradiation at low temperature was maintained for 4 days after which time sweet corn was dehusked and frozen at −40 °C.

3. Sensory Evaluation

Frozen corn ears were defrosted at room temperature for 2 hours. Defrosted corn ears were heated in a microwave oven for 5 minutes, the ear was cut into 20 pieces and evaluated for taste. Subjective measurement of sensory quality (sweetness, umami, visual appearance of kernels) was obtained by submitting samples to a 12-member taste panel using an 11-point scale (from +5 to −5). We determined a score of sensory quality for an objective corn in comparison with the corn stored under the Dark and Cool condition (control). When a panelist judged that a sample quality was better than control, the score of sensory quality stood at positive. Significant differences in the parameters were determined using the sensory quality evaluation method for rice[13]. The following abbreviations were used for the storage conditions: 'Red and Cool' (RC), 'Blue and Cool' (BC), 'and the control condition 'Dark and Cool' (DC).

4. Brix measurement

Placement of the corn ears into the boxes signaled the start (0 hr) of the experiment for Brix measurement. Almost daily, 3 g of corn kernels were harvested to measure the Brix of squeezed corn juice with a refractometer (Pocket Refractometer Model-PAL-1, Atago Co. Ltd, Tokyo, Japan).

5. Analysis of amino acids

Since there was a significant difference in 'umami' in the sensory evaluation, we analyzed quantitatively the amino acid content of stored corn kernels.

To identify which amino acid was changed by LED irradiation during low temperature storage, we ordered the analysis of 18 free amino acids by the Japan Food Research Laboratories (Japan). Free amino acid analysis was carried out using an Amino Acid Analyzer (JLC-500/V, JEOL, Tokyo, Japan; Column, LCR-6, JEOL).

Secondly, we focused on glutamic acid and aspartic acid, using a highly selective fluorimetric determination of acidic amino acids by high performance liquid chromatography (HPLC) after intramolecular eximer-forming derivatization with a pyrene-labeling reagent[14]. HPLC (LC-20AD, Shimadzu, Kyoto, Japan), with a fluorescence detector (RF-10AXL, Shimadzu), Column (ODS80Ts, Toso, Tokyo, Japan) was used for the amino acid analysis.

Results

1. Sensory evaluation

Scores of the sensory evaluation parameters that indicated significant difference are shown in Fig. 1. Subjective visual appearance revealed that Red irradiation and cool temperature (RC) and Blue irradiation and cool temperature (BC) was better than Dark (no irradiation) and cool temperature (DC), and also the visual appearance of corn stored under the RC condition was significantly better than for corn stored under BC condition. RC and BC were sweeter than DC, and RC and BC were equally sweet. The umami evaluation of corn stored under

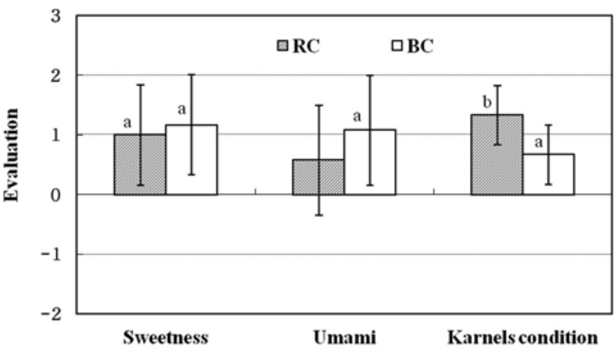

Fig. 1: Comparison of Sensory Evaluation Sore for sweet corn kernels preserved under different conditions and its 95% confidence interval (95% CI)

DC: Dark & Cool, RC: Red light & cool, BC: Blue light & Cool
Different letters 'a, b' indicate significances ($P < 0.05$). An error bar indicates the range of 95% CI. If an error bar crosses to 0, there is no significance with DC.

the BC condition was significantly better than for corn stored under the DC condition, but umami levels of RC stored corn did not differ from those of DC and BC stored corn.

2. Brix daily change

Fig. 2 shows the daily change in kernel sugar content (Brix). When corn was stored under the DC condition, Brix decreased with time. Brix deterioration at 3 d and 4 d was significant (Kruskal-Wallis test, $P < 0.05$). In RC or BC conditions, Brix deterioration was not significant until 4 d. The Brix measurement of corn stored 3 d and 4 d in RC and BC conditions differs significantly from the Brix measurement of of corn stored under the DC condition for 3–4 d. Brix did not change during 4 d storage under the RC and BC conditions.

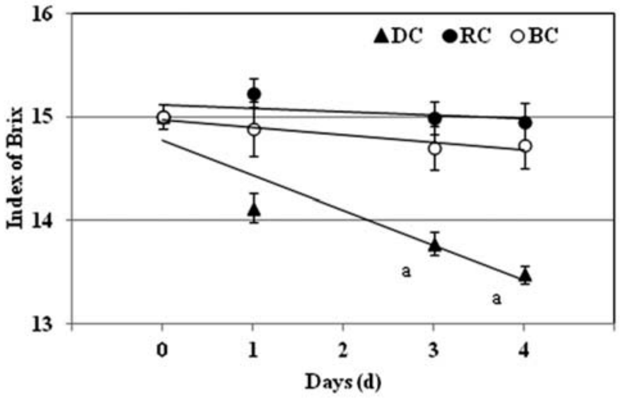

Fig. 2: Daily changes of Brix Index for sweet corn preserved under different conditions. Vertical bars represent standard errors of the means (n = 4) of each day.
Means with ‘a’ mark are significantly different at the 5% level.
DC: Dark & Cool, RC: Red light & cool, BC: Blue light & Cool

Also, we confirmed that the moisture content (%) of sweet corn did not change during whole period of storage and there was no dependency on the light irradiation condition.

3. Analysis of Amino Acids

The total amino acid content was high in BC-stored corn; glutamic acid, alanine, proline, serine, lysine, and aspartic acid were the major amino acids present in the samples with glutamic acid being the most abundant (Table 1). The glutamic acid content of DC- and BC-stored corn was higher than that of RC-stored corn. The glutamic acid content of RC-stored corn was 19% less than that of DC-stored corn. The aspartic acid content changed remarkably depending on the light irradiation condition. The aspartic acid of RC-stored corn was about 50% higher than that of DC-stored corn, and that of BC-stored corn was about 110% higher than that of DC-stored corn. The aspartic acid content of BC-stored corn was almost equal to the alanine content, which was the second most abundant amino acid in sweet corn.

Table 1 Ingredient contents of free amino acid for sweet corn under different preservation conditions [mg/100 g]

Free Amino Acid	DC	RC	BC
Glutamic acid	99	78	96
Alanine	61	57	55
Proline	44	37	42
Serine	33	37	41
Aspartic acid	27	41	56
Lysine	22	21	22
Tyrosine	11	11	9
Threonine	9	10	10
Leucine	6	7	6
Valine	6	6	7
Glycine	6	6	6
Arginine	6	5	6
Phenylalanine	4	5	6
Histidine	4	4	5
Isoleucine	3	4	4
Cysteine	1	2	1
Tryptophan	0	1	0
Methionine	0	0	0
Total	342	332	372

(n = 3) DC: Dark & Cool, RC: Red light & cool, BC: Blue light & Cool

Fig. 3 shows the changes in glutamic acid and aspartic acid contents in corn subjected to light irradiation conditions. The glutamic acid content of corn stored under the DC and BC conditions was significantly higher than corn stored under the RC condition (Tukey test, $P < 0.05$). The aspartic acid content of RC- and BC-stored corn was significantly higher than that of DC-stored

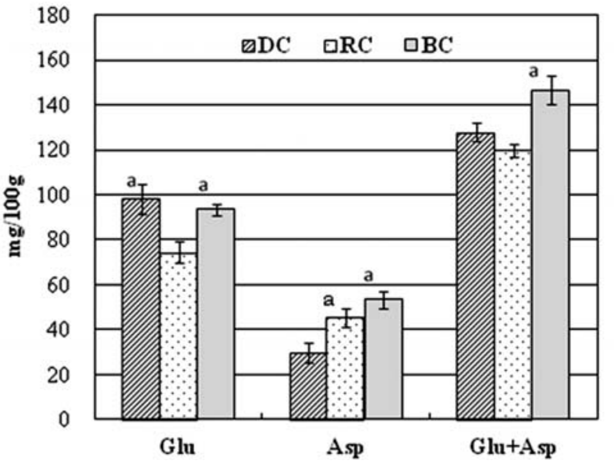

Fig. 3: Comparison of contents of glutamic acid, aspartic acid and total of those acids in sweet corn kept under the different preservation conditions. The value represents the average of 3 measurements. Means with ‘a’ mark are significantly different at the 5% level.
DC: Dark & Cool, RC: Red light & cool, BC: Blue light & Cool

corn. In addition the totals of glutamic acid content and aspartic acid content for each condition are indicated in Fig. 3. Total content of BC-stored corn was significantly higher than that of DC- and RC-stored corn.

Discussion

1. Effect of low light irradiation and low temperature storage

Subjective sensory evaluation revealed that Red light (RC) or Blue light (BC) irradiated cool conditions were effective for keeping sweet corn kernels looking fresh in appearance. The appearance of corn stored under the RC condition differed significantly from other conditions (BC, DC). Here, the appearance of sweet corn means visual freshness (color, glaze, etc). Therefore, we think that the RC storage method is effective for keeping freshly sweet corn in visually appealing.

Similarly, sensory evaluation revealed that the RC and BC conditions were effective in maintaining kernel sweetness. The daily change in sugar content deteriorated in the dark condition (DC), and RC and BC conditions reduced the deterioration of sweetness with time. There were no statistically significant differences in the sweetness sensory scores or in the Brix values for RC- and BC-stored corn.

We hypothesize that the Brix value did not decline due to a mixed effect coming from 1) the inhibition of sweet corn respiration caused by a nearly zero rate of CO_2 exchange when the light irradiation intensity is nearly equal to the light compensation point[15], and 2) a reduction in starch synthase enzyme activity at low temperature.

On the other hand, the sensory evaluation revealed that BC-stored corn significantly differed from DC-stored corn in umami. As a result from the analysis of amino acids (Fig. 3), the glutamic acid (glu) content of BC-stored corn was almost equal to DC-stored corn; however, the aspartic acid (asp) content of BC-stored corn was significantly higher than DC-stored corn. So, the effect of the BC condition on the glu content is equal to what happens under the DC condition, but the BC condition was more effective in increasing the asp content than the DC condition. Also, the glu content of corn stored under the RC condition was significantly less than for corn stored under the DC and BC conditions; however, the asp content of RC-stored corn was significantly higher than for corn stored under the DC condition. So, the RC condition was less effective than the DC condition in regulating the glu content, but the RC condition was more effective in increasing the asp content than the DC condition.

The taste of vegetables is changed by the glutamic and aspartic acid content[16]. But in this case, the valance of sour taste was changed by the composition of glu and asp. Then, we have a question, how does umami taste change when the content of glu and asp is changed?

Some studies for receptor of umami taste suggested that the psychophysical detection threshold values for glu or asp were estimated around 1 to 4 mM[17,18] (10–40 mg/100 g converted by author). In Fig. 3, all of the asp and glu contents were more than psychophysical detection threshold value, except the asp content of DC-stored corn which was nearly detection threshold. In addition, the receptors for umami of human or rat responded proportionally to the contents of glu (MSG: Mono Sodium Glutamate) and asp[18,19], and it was difficult to discriminate between the tastes of glu (MSG) and asp[19,20]. So we have recognized that the contribution of glu and asp to the umami taste is almost equal. So, shown in Fig. 3, we evaluated the total content of glu and asp as parameters for the umami taste. The total content of BC-stored corn was significantly more than those of DC- and RC-stored corn. This result is consistent with the result of the sensory evaluation (Fig. 1)

The composition and content of glu and asp were changed by the light irradiation condition. Corn stored in the BC condition had the best taste and glu and asp contents within the conditions examined in this study.

2. The dependency of amino acid content on light quality

We confirmed that the amino acid composition of sweet corn was changed by light irradiation during cool storage (Fig. 3). In comparison with dark storage (DC), the asp content increased but the glu content did not change in BC-stored corn whereas, the asp content increased and the glu content decreased in corn stored under the RC condition. The precise mechanism for these differences in amino acid metabolism in corn kernels depending on light wavelength is unknown at present. In higher plants, the assimilation of ammonia is dynamically controlled by the external environment[12] likely by light irradiation or by the internal environment likely by the sucrose content in plastids.

Suzuki et.al. (2001) reported that the amino acid content of maize seedlings changed depending on the light treatment during storage[21]. Seven-d-old dark grown maize seedlings were subjected to intermittent 5 min Red light (6 Wm^{-2}) treatment at 4 h intervals (R), continuous white light (300 $\mu mol\ m^{-2}s^{-1}$) (WL) or no light irradiation(D) for 72 hours. At the beginning, the total amino acid content was 759 nmol mg^{-1} {gln : glu : asn : asp = 16 : 29 : 323 : 31 (nmol mg^{-1})}. WL decreased the total amino acid by 80%; 145 nmol mg^{-1} {gln : glu : asn : asp = 2 : 12 : 22 : 4}, whereas the total amino acid content remained constant in the R condition at 855 nmol mg^{-1} {gln : glu : asn : asp = 2 : 13 : 448 : 32}, and the D treatment substantially increased the total amino acid content by 150% to 1087 nmol mg^{-1} {gln : glu : asn : asp = 8 : 17 : 600 : 27}. The asn content was also changed by the light treatment, and these actions were coupled with the activity of ferredoxin-dependent glutamate synthase (Fd-GOGAT).

The results reported by Suzuki et al. (2001) strongly indicate that plant amino acid in plant contents must change depending on the light quality during storage. We hypothesize that the light quality during storage highly relates to the activity of nitrogen assimilation enzymes as glutamate synthase (GS), ferredoxin-dependent glutamate synthase (Fd-GOGAT), aspirate aminotransferase (Asp-AT), asparagine synthetase (AS); however, there are some differences between our results and the Suzuki et al. (2001) report. In our study, Red irradiation (RC) decreased the glu and increased the asp contents in comparison with the dark (DC) control; that is, the change in the content of these two amino acids was different. We do not know whether these differences depend on environmental conditions such as light quality, light intensity, temperature or the sample's developmental state such as seedlings versus corn kernels.

Blue light is more effective than red light in the photosynthesis reaction. For example, photosynthetic performance of blue light irradiated birch plantlets *in vitro* was twice the effect of Red light because increasing both the chlorophyll content and translocation rate of carbohydrates from chloroplasts is dependent on light quality[22]. Also, the content of ribulose-1,5-bisphosphate carboxylase /oxygenase (Rubisco) of blue light grown pea seedlings was higher than seedlings grown in red light[23]. In addition to these reports, the dependency of the photosynthesis reaction and nitrogen assimilation on light quality affects our results indicating inhibition of Brix deterioration and differences in amino acid; however, at this time we do not know whether translocation could occur from the husk irradiated by low intensity light at low temperature into the corn kernels. This possibility merits further research.

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