Alleviation of Fruit Decay During the Export and Domestic Storage of Satsuma Mandarin Fruit Through Temperature Treatment and Ultraviolet-C Irradiation via Phytoalexin Production

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To prevent the decay of satsuma mandarin fruit during the distribution process, we investigated the effect of ultraviolet-C (UV-C) irradiation and temperature treatment (TT) on scoparone (a phytoalexin) production in fruits. To this end, the fruits were maintained at 20°C for 24 h following irradiation, and then the scoparone content was measured after export to Singapore by sea freight or after domestic storage. The scoparone content in the flavedo of TT fruits significantly increased for 24 h after UV-C irradiation, compared with that in the flavedo of non-TT fruits. In fruits exported in reefer containers (0°C), the scoparone content in the TT fruits was 59.1 μg·g⁻¹FW, whereas that in non-TT fruits was 15.1 μg·g⁻¹FW. The domestically stored fruits showed similar trends to those of the exported fruits. The scoparone content in domestically stored fruits was higher than that in the exported fruits because the storage temperature was higher than the temperature in the reefer container used for export. There was a significant difference in the decay rate between UV-C-irradiated and non-irradiated fruits. These results showed that UV-C irradiation was effective in reducing the decay of fruits exported by sea, and TT before storage induced scoparone production in the flavedo, even under cold storage.

Key Words: citrus, mixed cargo, scoparone, storage, 6,7-dimethoxycoumarin.

Introduction

Citrus fruits are prone to decay during harvest, storage, packing, and transit (Kuniga et al., 2015). The postharvest decay of fruits is caused by Penicillium italicum, Penicillium digitatum, Botrytis cinerea, and other fungi, and it leads to severe economic losses (Lai et al., 2012; Luo et al., 2012; Moscoso-Ramírez et al., 2013). Treatment of fruits with sodium hypochlorite has been carried out at the request of importing countries to minimize decay (Fukazaki, 2014). However, immersing large volumes of mandarin fruits in sodium hypochlorite and air-drying them is time consuming. Therefore, a technology to rapidly treat large volumes of fruits in packing facilities before shipping is required.

Several studies have demonstrated that ultraviolet C (UV-C) radiation directly inhibits fungal growth and induces antifungal responses in Citrus species (Chalutz and Droby, 1992; Yamaga et al., 2017). UV-C radiation increases the production of phytoalexins such as scoparone (6,7-dimethoxycoumarin) and scopoletin (7-hydroxy-6-methoxycoumarin) in citrus peel, and the responses are associated with resistance to postharvest decay (D’hallewin et al., 1999; Rodov et al., 1992). Phytoalexin levels vary among species and are influenced by the number of days post irradiation or inoculation (Kuniga et al., 2005, 2015; Ortuño et al., 2011). Kuniga et al. (2015) examined scoparone accumulation in UV-C-irradiated and non-irradiated fruits of Kiyomi tangor, Hyuganatsu, Eureka lemon, and satsuma mandarin inoculated with gray mold for up to seven days post-inoculation. They reported that scoparone accumulated more rapidly and reached higher levels in the UV-C treated fruits, especially in the fruits of Kiyomi tangor and Hyuganatsu.
Some studies have reported the effect of temperature on scoparone production. Arimoto and Homma (1988) reported that a high scoparone content was produced in inoculated leaves or incised shoots of citrus plants maintained at 25°C in the light, and the content decreased with a decrease in temperature to 15°C. In addition, we previously reported that scoparone production in satsuma mandarin fruits irradiated with UV and stored at 5°C for 13 days was very low (Yamaga et al., 2019). However, there are no studies on scoparone accumulation and decay in UV-C irradiated citrus fruits following a two-week distribution process, including export under low temperatures.

Satsuma mandarins, which are produced in Shizuoka Prefecture in Japan, are exported to Canada, New Zealand, and other countries, and there are plans to expand the export to Southeast Asian countries, including Singapore (Shizuoka Prefectural Government Office Agriculture Bureau, 2020). Singapore has a relatively small land area and is becoming increasingly urbanized. In addition, the food self-sufficiency rate is only 10% because there are only a few agricultural production sites in the country. Singapore is also a base for activity in Singapore has been increasing, providing Singaporeans an opportunity to become familiar with Japanese food products.

Agricultural products are generally shipped from the place of origin via a wholesale market to an importer in the export destination country, or directly to the exporter, and then exported to the local business partners (Shimowatari, 2013). Satsuma mandarin fruits produced in Shizuoka are often exported from the production areas through exporters and sold to local department stores, supermarkets, restaurants, and others. Fruits and vegetables with short shelf lives are transported by air, and those that can be stored for extended periods are transported by sea. It takes approximately three weeks to export cargo from Japan to Southeast Asia by sea, including customs clearance activities in both countries.

In the present study, we evaluated the scoparone content in the flavedo tissues of satsuma mandarin fruits. We also evaluated the decay of fruits subjected to UV-C irradiation and temperature treatment (TT) after export by sea under low temperatures, rather than under optimum conditions due to mixed cargo conditions, and under domestic storage conditions. To assess fruit appearance and rind injury by cold temperature or UV irradiation, the rind color of the exported fruits and domestically stored fruit was measured. In addition, the internal fruit qualities (e.g., soluble solid content and titratable acidity) of domestically stored fruits were investigated.

Materials and Methods

UV-C irradiation and temperature treatment of harvested fruits

Satsuma mandarin fruits were harvested from an orchard in Shimizu, Shizuoka City, in mid-December 2019. The harvested fruits were transported to a laboratory in the Fruit Tree Research Center at the Shizuoka Prefectural Agriculture and Forestry Research Institute on December 17, 2019. L-2L (diameter: 67.0–79.9 mm) size fruits were selected for the experiments. We irradiated the fruits with UV-C at a dose of 6.0 kJ·m−2 (irradiation time: 5 min) as described by Yamaga and Nakamura (2019). The fruits were placed 18 cm from the irradiation source, with the pedicels facing up. The fruits were then turned upside down and irradiated for another 5 min. Two UV-C lamps with peak emissions at 254 nm (GL-15; TOSHIBA Corporation, Tokyo, Japan) were used, and UV-C irradiance was measured using a UV radiometer (RS-13L; ESPEC MIC Corporation, Aichi, Japan). Approximately 80–90 irradiated or non-irradiated fruits were placed in a cardboard box (outer dimensions: 360 mm [L] × 310 mm [W] × 190 mm [H]). The TT groups of fruits were maintained in a room at 20°C for 24 h following UV-C irradiation, and maintained in a room without temperature control (average temperature: 12°C) for 15 h (Fig. 1). The non-TT groups of fruits were maintained in a room without temperature control for 39 h following UV-C irradiation.

Satsuma mandarin fruit export by sea and domestic storage

The export schedules by sea and domestic storage conditions are presented in Figure 1. The examined fruits for export to Singapore, except those for domestic storage, were placed in cold storage in Shizuoka on December 19, 2019. They were stacked on pallets and transported to a cold storage warehouse near Shimizu Port for customs clearance. On December 20, 2019, the cargo that passed customs clearance was placed in a high-standard reefer container (Fresh keeping device “futecc”; Denso Corp., Aichi, Japan), and the temperature was set at 0°C; thereafter, the container was loaded onto a cargo ship (NYK VENUS) on December 24, 2019, which departed from Shimizu Port on the same day. The packing conditions of satsuma mandarin fruits in the cardboard box and the loading situation in terms of mixing with other cargo are illustrated in Figure 2. The temperature during transport and domestic storage was measured using temperature and shock recorders (G-MEN20; SRIC Corp., Nagano, Japan) every 1 h. The recorders were placed inside the cardboard boxes. The ship arrived in Singapore on January 5, 2020. The fruits to be examined were taken out of the container after clearing customs on the following day and transferred to a local cold storage warehouse. The fruits
were then immediately transported to Mitsui Chemicals Singapore R & D Center (50 Science Park Road, #06-08 The Kendall Singapore Science Park II, Singapore 117406, Singapore) in a refrigerated vehicle. The examined fruits placed in cardboard boxes for domestic storage were stored for 17 days in a storage room (30 m³) at 7°C and in a room without temperature control at the Fruit Tree Research Center of the Shizuoka Prefectural Agriculture and Forestry Research Institute. The temperature was measured using the above-mentioned methods.

**Survey of the decay rate of fruits**

In both exported and domestically stored fruits, the decayed fruits under each treatment were counted at 19 days after the beginning of storage based on the dates of the exported fruits. The fruits that decayed due to natural fungal infection (as shown by water-soaked, soft rot spots) were counted (Fig. 3). The total decay rate was calculated using the following formula: decay rate = (total number of decayed fruits/total number of examined fruits) × 100. The TT and non-TT had two replicates for each treatment: UV or non-UV treatment in each storage room, with approximately 90 fruits per replicate (box).
**Scoparone production analysis**

Scoparone was extracted as described by Kuniga et al. (2005). The flavedo tissue (0.8 g) of fruits under each treatment was excised with a knife and extracted using 80% ethanol. Subsequently, the tissue was homogenized in a blender and centrifuged at 3000 rpm for 20 min. The aqueous phase of the extract was evaporated and partitioned against dichloromethane. The dichloromethane fraction was dried and dissolved in 4 mL of 25% methanol, and then filtered. The solutions (20 μL) were injected into an HPLC system (FP-2020; JASCO Corporation, Tokyo, Japan) equipped with a C18 column (Inertsil ODS2 4.6 mm × 150 mm; GL Science, Tokyo, Japan) and an auto injection system. The column was eluted with a gradient of 20%−70% methanol for 26 min at 40°C. The flow rate was 1.2 mL·min⁻¹. Each treatment had four replicates, with one fruit per replicate.

**Relationship between decay rate and temperature summation, and relationship between scoparone content and temperature summation for export or domestic storage**

We developed a scatter plot to show the relationship between the decay rate under each treatment and the temperature at every 1 h during storage using the obtained data for all examinations for export by sea and two domestic storage facilities. Hourly temperature data were used for analysis because the examination period was less than a month, sampling time was not at the beginning of the day, and considering previous studies on scoparone accumulation. The temperature data from December 17 (at the start of TT) to January 7 (sampling) were used. Similarly, the relationship between scoparone content before averaging and the temperature summation was illustrated.

**Internal fruit quality after domestic storage and rind color after export and domestic storage**

After domestic storage, the internal fruit quality and rind color were examined. Specific gravity was determined by weighing the fruit in air and water. Percentage of flesh was the ratio of flesh weight to whole fruit weight. Soluble solid content (SSC) and titratable acidity (TA) were determined using freshly extracted juice. The SSC was determined using a digital refractometer (DBX-55A; Atago Co., Ltd., Tokyo, Japan). The TA was determined by titrating 5 mL of the juice to a pH of 8.1, using 0.156 mol·L⁻¹ NaOH. The acidity of the juice is expressed as grams of citric acid per 100 mL of juice. Rind color was measured using a color analyzer (CR-13; Konica Minolta Japan, Inc., Tokyo, Japan). The CIELAB (L* = lightness, a* = bluish-green/red purple hue component, b* = yellow-blue hue component) properties of the rinds were measured. Three fruits constituted a replicate, and each treatment had four replicates. After export from Japan to Singapore by sea, only rind color was examined. In the exported fruits, other qualities (e.g., soluble solid content and titratable acidity) were not surveyed due to a lack of analytical equipment.

**Statistical analysis**

Statistical analyses were performed using the statistical computing program R v 3.6.2. The fruit decay rate, rind color, and internal fruit quality data were analyzed using a three-way analysis of variance (ANOVA). The scoparone production data were analyzed using Tukey’s multiple range test, with the significance level set at P < 0.05. The difference in scoparone production between TT and non-TT was evaluated using the Student’s t-test. Also, the relationship between scoparone content and temperature summation during storage in TT and non-TT were analyzed using Student’s t-test.

**Results**

**Temperatures for exports by sea and in domestic storage**

Temperatures inside cardboard boxes during transport by sea or domestic storage are presented in Figure 4. The temperature in the boxes for export dropped below 1°C three days after they were placed in reefer containers. The temperature during transportation by sea was around 0°C−1°C until the container arrived at the Singapore Port. Conversely, the average cold storage temperature in domestic storage was 7.0°C, and the average normal storage temperature was 8.8°C. In December particularly, the temperatures were relatively high because the surrounding temperatures were high. In addition, the degrees of impact were low except during loading and unloading, and the cargo being transported was relatively stable during transportation to Singapore (data not shown).

![Fig. 4. Temperatures during export to Singapore by sea and domestic storage.](image-url)
Effect of UV-C and TT on the decay rate in fruits exported by sea and stored domestically

The effect of UV-C irradiation and TT before storage on fruit decay and the three-way ANOVA results are illustrated in Figure 5 and Table 1, respectively. The decay rate of UV-C-irradiated fruits transported to Singapore was 0%, and that of the non-irradiated fruits was 2.6%–9.1%, with a significant difference. The decay rate increased significantly as the storage temperature rose. The TT tended to increase the decay rate in non-irradiated fruits; however, such a trend was not observed in the UV-C-irradiated fruits. The decay rate of TT fruits under normal storage was the highest in all treatments. The relationships between decay rate and temperature summation in export or storage including the TT period (24 h) are presented in Figure 6. Overall, the decay rate tended to increase as the temperature summation increased. The decay rates of non-UV treated fruits with TT for export (temperature summation: 1492) and normal storage (temperature summation: 4657) were higher than other sample groups. In contrast, that of UV-treated fruits did not increase even with TT.

Effect of UV-C and TT on scoparone production in the flavedo

The results of scoparone production in the flavedo are illustrated in Figure 7. The scoparone content in the TT fruits at 24 h after UV-C irradiation was significantly higher than that in the non-TT fruits. In fruits exported in reefer containers (setting 0°C), the scoparone content in TT fruits was 59.1 μg·g⁻¹FW. In contrast, the content in non-TT fruits was lower than that in TT fruits (15.1 μg·g⁻¹FW). The fruits subjected to domestic cold storage showed trends similar to those of the exported fruits. The scoparone content was higher in the domestically stored fruits than in the export fruits. At cold temperatures (setting 7°C), the scoparone content in TT fruits was significantly higher than that in non-TT fruits; however, there was no significant difference between TT and the non-TT fruits under normal storage. The relationship between scoparone content and temperature summation for export or storage including the TT period (24 h) is illustrated in Figure 8. A significant positive correlation was found between the temperature summation and scoparone content under both treatments (TT and non-TT). A stronger correlation was observed under TT than under non-TT.

Although the temperature summation of TT fruits during export (0°C) was low, these fruits had similar

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**Table 1. Three-way ANOVA of effect of UV-C irradiation and temperature treatment before storage on fruit decay.**

| Source               | P-value |
|----------------------|---------|
| Storage temperature  | <0.05   |
| UV                   | <0.05   |
| TT                   | 0.098   |
| (a)*(b)              | 0.11    |
| (a)*(c)              | 0.26    |
| (b)*(c)              | 0.076   |

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**Fig. 5. Effect of UV-C irradiation and temperature treatment before storage on the decay of satsuma mandarin fruits.**

**Fig. 6. Relationship between decay rate and temperature summation during export by sea or domestic storage, including the TT period (24 h).** Each temperature summation (1293, 1492, 3694, 3893, 4458, 4657) indicates that TT(−) in export, TT(+) in export, TT(−) in cold storage, TT(+) in cold storage, TT(−) in normal storage and TT(+) in normal storage, respectively.

**Fig. 7. Scoparone accumulation in satsuma mandarin fruits after UV-C irradiation and temperature treatment.** Data are expressed as mean ± SE (n = 4). Different letters indicate significant differences at P < 0.05 by Tukey’s multiple range test. Lowercase letters are related to comparisons of storage environments (including 24 h after irradiation), within TT(−). Uppercase letters are related to comparisons of storage environments (including 24 h after irradiation), within TT(+) . NS and ** indicate nonsignificant and significant difference at P < 0.01, respectively, by t-test.
Scoparone content to non-TT fruits in domestic cold storage (7°C).

**Influence of UV-C, TT, and storage temperature on rind color and fruit quality after storage**

The influence of UV-C irradiation and TT before storage on rind color after export by sea and domestic storage, and internal fruit quality in domestic storage are shown in Tables 2 and 3, respectively. The L* value of exported fruits was lower than that of domestically stored fruits. The a* value showed interaction with the storage temperature and TT. Rind browning was observed in some UV-irradiated fruits, with an incidence rate of 0%–8.5% (data not shown). Chilling injury (pitting) at low temperatures was not observed in exported fruits. In domestically stored fruits, the percentage of flesh, specific gravity, rind puffing, and SSC were not significantly different between cold temperature and normal temperature treatments. The TA of UV-C irradiated fruits was higher than that of non-irradiated fruits. Fruits stored at cold temperatures tended to have a higher TA than those stored at normal temperatures.

**Discussion**

In the present study, UV-C irradiation was found to be effective at reducing the decay of fruits exported by sea. Scoparone production by non-irradiated fruits was not detected in previous studies (Yamaga and Nakamura, 2018, 2019; Yamaga et al., 2016). The dose (ED_{50}) at which the antifungal properties of scoparone is the most effective against elongation of the germ tube of P. digitatum is 29 μg·mL^{-1} (Kim et al., 1991). Our results suggest that the scoparone content (59.1 μg·g^{-1}FW) in the fruits exported by sea with UV-irradiation was sufficient to inhibit the infection of fungi that cause diseases during storage.

![Fig. 8. Relationship between individual scoparone content and temperature summation during export by sea or domestic storage, including the TT period (24 h). ** and *** indicate significant difference at P < 0.01 and 0.001, respectively, by t-test. Each temperature summation (278, 431, 1293, 1492, 3694, 3893, 4458, 4657) indicates that TT(−) in 24 h after irradiation, TT(+) in 24 h after irradiation, TT(−) in export, TT(+) in export, TT(−) in cold storage, TT(+) in cold storage, TT(−) in normal storage and TT(+) in normal storage, respectively.

| Treatment (Temperature) | UV-C irradiation | TT | L*  | a*  | b*  |
|-------------------------|------------------|----|-----|-----|-----|
| Export (0°C)            | UV(+) (+)        | 58.5 | 36.4 | 56.6 |
|                         | UV(+) (−)        | 57.0 | 36.2 | 54.6 |
|                         | UV(−) (+)        | 60.7 | 35.8 | 57.6 |
|                         | UV(−) (−)        | 60.3 | 35.8 | 59.3 |
| Domestic 1 (7°C)        | UV(+) (+)        | 60.6 | 24.5 | 58.7 |
|                         | UV(+) (−)        | 62.8 | 25.2 | 62.6 |
|                         | UV(−) (+)        | 62.8 | 25.2 | 62.6 |
|                         | UV(−) (−)        | 65.0 | 24.8 | 63.8 |
| Domestic 2 (9°C)        | UV(+) (+)        | 60.7 | 26.4 | 60.3 |
|                         | UV(+) (−)        | 62.2 | 24.1 | 59.6 |
|                         | UV(−) (+)        | 63.3 | 25.7 | 64.5 |
|                         | UV(−) (−)        | 64.3 | 22.8 | 63.1 |

Table 2. Influence of UV-C and TT on rind color after export by sea and domestic storage.

- **Temperature treatment before storage.**
- **NS, *, and ** indicate nonsignificant and significant differences at P<0.05 and P<0.01, respectively, by three-way ANOVA.
- Data are expressed as the mean of 4 replicates.
We previously showed that scoparone production was significantly higher in satsuma mandarin fruits stored at high temperatures (Yamaga et al., 2019). Furthermore, the scoparone content in fruits stored at 20°C for at least three days was similar to that in fruits stored at 20°C for ten days, even when they were stored at low temperatures. In contrast, the scoparone content in fruits stored at 5°C was relatively low. The TT (stored at 20°C for 24 h) fruit already accumulated 13.4 μg·g⁻¹ FW scoparone after 24 h irradiation. Furthermore, an additional 45.7 μg·g⁻¹ FW scoparone was accumulated after low temperature (0°C) transportation. In contrast, non-TT fruits hardly produced any scoparone in the same period. These results support a previous study and indicate that temperature treatment before export affects scoparone accumulation, even at low temperatures.

With normal temperature storage, there was no significant difference in the scoparone content between TT and non-TT fruits. The normal temperature was 10°C over the first half of the storage period due to the influence of external air temperature, and scoparone accumulated even in the non-TT fruits. The effect of TT was potentially masked. On the other hand, there was a positive correlation between scoparone content and temperature summation during export by sea and domestic storage. This is probably the first study to indicate a relationship between scoparone accumulation in Citrus and temperature summation, although the effect of temperature on scoparone production has previously been reported (Arimoto and Homma, 1988; Yamaga et al., 2019).

The decay rate of non-UV and TT fruits under normal storage showed an increasing trend compared with non-TT fruits. In contrast, the UV-irradiated fruits did not decay even when the fruits were temporarily exposed to high temperature environments. This result may indicate that phytoalexins induced by UV-C and TT contributed to the low decay rate. In the present study, we did not observe a direct relationship between fruit decay suppression and scoparone content increase. This relationship can be verified if experiments are conducted at the same temperature. For storage at various temperatures, it should be remembered that the activity of fungi (e.g., Penicillium) becomes stronger as the temperature increases (Tsubaki, 1990). Under both treatments (UV and non-UV), the decay rate was higher due to fungi activated with normal temperature treatment than that when the storage period was at a higher temperature. Therefore, temperature treatment without UV irradiation is likely to be counterproductive due to fungi increase. On the other hand, UV-irradiated fruits exported at 0°C did not decay; however, the decay rate of non-irradiated fruits with TT was 9.1%. This fruit decay could be due to cold stress on the peel. It is well known that plants subjected to cold stress accumulate phenolic substances. An increase in phenolic substances is associated with increased phenylalanine ammonia-lyase (PAL) activity (Engelsma, 1974; Nagai et al., 1988), that is, enhanced PAL activity results in an increase in phytoalexin from coumarin formation (Hino et al., 1982). Thus, scoparone accumulation may have enhanced cold stress tolerance.

UV-C irradiation did not influence the SSC, degree of rind puffing, specific gravity, percentage of flesh, or rind color of heat-treated fruit stored domestically for

| Table 3. Influence of UV-C and TT on internal fruit quality after domestic storage. |
|---------------------------------|---------------------------------|---------------------------------|------------------|------------------|------------------|
| Treatment (Temperature)         | UV-C irradiation                | TT                             | Fruit weight (g) | Specific gravity | Percentage of flesh (°Brix) | SSC (°Brix) | TA (g/100 mL as citric acid) | SSC/TA |
| Domestic 1 (7°C)                | UV(+)                           | (+)                            | 123              | 0.83             | 77.1              | 11.3              | 0.65                      | 17.4   |
|                                 | UV(-)                           | (+)                            | 116              | 0.85             | 75.8              | 11.8              | 0.73                      | 16.1   |
|                                 |                                  | (-)                            | 129              | 0.82             | 75.5              | 10.8              | 0.69                      | 15.7   |
|                                 |                                  | (-)                            | 117              | 0.85             | 76.7              | 10.9              | 0.65                      | 16.7   |
| Domestic 2 (9°C)                | UV(+)                           | (+)                            | 131              | 0.86             | 76.8              | 12.1              | 0.75                      | 16.1   |
|                                 | UV(-)                           | (+)                            | 129              | 0.86             | 77.5              | 11.4              | 0.73                      | 15.6   |
|                                 |                                  | (-)                            | 119              | 0.85             | 73.9              | 11.0              | 0.61                      | 18.0   |
|                                 |                                  | (-)                            | 124              | 0.84             | 76.1              | 10.4              | 0.48                      | 21.5   |

Significance: Storage temperature (a) — NS NS NS * NS

UV (b) — NS NS NS * NS

TT (c) — NS NS NS NS NS

(a)*(b) — NS NS NS * NS

(a)*(c) — NS NS NS NS NS

(b)*(c) — NS NS NS * NS

z Temperature treatment before storage.
y NS and * indicate nonsignificant and significant difference at P<0.05, respectively, by three-way ANOVA. — indicates that the analysis was not performed.

Data are expressed as the mean of four replicates.
19 days. In contrast, the TA of UV-C-irradiated fruits was higher than that of the non-irradiated ones. However, in our previous studies, we examined the influence of UV irradiation on the internal quality of satsuma mandarin fruits and found that UV-C or UV-B irradiation did not influence TA (Yamaga et al., 2016, 2017). In addition, D’hallewin et al. (1999) reported no differences in internal quality characteristics between UV-C-treated and untreated fruits of various citrus cultivars (e.g., Washington Navel, Tarocco, and Valencia Late). Conversely, Kaewsuskaeng et al. (2011) reported that the citric acid content of UV-B-treated lime fruit (Citrus latifolia Tan.) increased continuously up to 20 days of storage, and they indicated that citric acid could be maintained due to the suppression of respiration and senescence caused by UV treatment. Further research is needed to elucidate the effect of UV-C irradiation on citric acid content.

Pre-storage conditioning for curing of rind in citrus is a strategy used to prevent a temporary high-humidity environment at the beginning of storage and to facilitate humidity management during storage (Fujisawa et al., 2001). Furthermore, a high postharvest TT affects controls chilling injury, suppresses fruit weight loss, and reduces citric acid content (Hasegawa and Iba, 1984; Hamada and Taniguchi, 1989; Murata and Yamawaki, 1992; Niikawa et al., 2008). The general method of TT for satsuma mandarin in production sites is storage under 20°C and 80% relative humidity for five to seven days; however, the treatment periods and conditions are different from those adopted in the present study. Therefore, in this study, it is suggested that the temperature treatment before export did not significantly affect internal the fruit quality.

The optimum storage temperature for citrus fruits has been reported to be 5°C–8°C (Fujisawa et al., 2001). In the present study, the fruits were stored and exported at temperatures lower than the optimal storage temperature because they were transported in a container with other vegetables. Generally, it is essential to maintain temperature as low as possible within a range at which fruit damage does not occur to maintain fruit freshness for prolonged periods. Most Citrus species are tropical or subtropical, and they have a poor tolerance to low temperatures. However, the symptoms of chilling injury (pitting) were not observed during transportation in the present study. In the present study, uneven temperatures were not likely to have occurred in containers, and supercooling did not occur because the containers used had two compressors and two inverters that minimized internal temperature variations; the difference in temperature was ±0.5°C, as in a previous report (Ikegaya et al., 2019).

Ikegaya et al. (2019) showed that loading satsuma mandarin Aoshima unshu (late maturing cultivar) in a container with other vegetables exported to Singapore by sea for 19 days using a reefer container under low temperatures (0°C) conditions similar to those adopted in the present study did not alter fruit taste based on sensory evaluation. In this study, we could not investigate the quality of exported fruits, such as SSC and TA. In the future, detailed surveys of fruit quality after export are required.

Diverse foods and ingredients are being imported and exported worldwide, and people’s eating habits are becoming equally diverse. In Europe, strategies that take advantage of the characteristics of respective regions have been more successful than national approaches. Similarly, in Japan, multiple regions (prefectures) should coordinate and combine their farming activities and export processes. If fruits and vegetables from multiple areas could be mixed, then the probability of transporting fruits and vegetables outside the appropriate storage temperature ranges would increase. In the future, temperatures during export should be considered carefully so that various agricultural products can be exported under similar shipping conditions. Once a mixed loading method for fruits and vegetables is established, the technology could be applicable to relatively small quantities of exports across the globe. The results of the present study may serve as a reference for transport tests on other horticultural produce.

To the best of our knowledge, the present study is the first to report scoparone production in the flavedo tissue and decay of satsuma mandarin fruits after UV-C irradiation and TT before export from Japan to Singapore by sea. In this case, it was considered that 0°C transport by mixed cargo was suitable for UV-C irradiated fruits. Therefore, a better method for reducing fruit decay would be to maintain these fruits under an environment of 20°C for 24 h after UV irradiation, and transport them at a low temperature of 0°C. A challenge associated with the commercial application of UV light on fruits is ensuring dose uniformity at the packing lines (Tanaka et al., 2016). For practical application of UV irradiation at such lines, a strategy of irradiating fruits on all sides is recommended. A UV-C irradiation system for use in packing lines that addresses the challenge mentioned above has already been developed (Yamaga et al., 2019). In Japan, late cultivars of satsuma mandarin (e.g., Aoshima unshu) are harvested from autumn to winter, but cultivars of satsuma mandarin harvested very early (e.g., Miyamoto wase) or mandarins cultivated in greenhouses, and other medium–late ripening citrus cultivars (e.g., Harumi, Setoka, and Shiranui, called as Sumo mandarin in North America) can be cultivated even when the outside temperatures are high (spring, summer, and autumn). In actual export and domestic distribution activities, it is assumed that the goods are placed in a temporary high-temperature environment. Therefore, this study, which verified fruit decay at different temperatures after UV irradiation, may be useful even for fruit distribution in other seasons.

In conclusion, the present study demonstrated that...
UV-C irradiation could reduce decay of fruits exported by sea and that scoparone production in the flavedo of fruits treated at 20°C for 24 h can be induced even when the fruits are stored at near 0°C for export (18 days) after TT.

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