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# Effect of Storage Temperature on Fruit Ripening in Three Kiwifruit Cultivars

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**The responses of three kiwifruit cultivars, *Actinidia chinensis* 'Sanuki Gold', *A. chinensis* 'Rainbow Red', and *A. deliciosa* 'Hayward' to various storage temperatures (0, 5, 10, 15 and 20°C) for 8 weeks were investigated. The rate of fruit which initiated ethylene production due to rot development increased with increases in storage temperature. Early-maturing cultivars, 'Rainbow Red' and 'Sanuki Gold' fruit stored at 5, 10, and 15°C showed drastic softening and a decrease in titratable acidity (TA) to an edible level within 4 weeks without detectable ethylene production, whereas fruit stored at 0 and 20°C maintained high firmness and TA even after 8 weeks unless they were infected with rot. A late-maturing cultivar, 'Hayward' fruit stored at 5 and 10°C softened more rapidly than when stored at 0, 15, or 20°C. Treatment with 1-Methylcyclopropene (1-MCP) did not suppress the low temperature modulated fruit ripening in any cultivars, indicating its independence from ethylene. These results suggest that 'Sanuki Gold' and 'Rainbow Red' are more sensitive to low temperatures compared to 'Hayward' and the sensitivity is involved in the determination of storage life and how early the fruit matures on the vine.**

**Key Words:** early-maturing cultivar, late-maturing cultivar, low-temperature storage, rot incidence.

## Introduction

The plant hormone ethylene initiates ripening-associated events in kiwifruit, such as increased respiration, softening, reduction in acidity, conversion of starch to sugar, and aroma development as it is a climacteric fruit (Antunes et al., 2000; Mworia et al., 2010). Kiwifruit has been believed to be extremely sensitive to ethylene, which accelerates ripening (Ritenour et al., 1999; Yin et al., 2010). The presence of ethylene in the storage room shortens kiwifruit storage life and hence, it is a major challenge during long-term storage (Pranamornkith et al., 2012). Thus, the main areas of investigation into how to extend kiwifruit storage life are ethylene elimination and low temperature control (Koukounaras and Sfakiotakis, 2007).

In kiwifruit, major postharvest diseases are soft rot caused by *Botryoshaeria* spp. and *Phomopsis* spp. and stem-end rot by *Diaporthe actinidia*, which are epiphytic at harvest, and penetrate inside the fruit during storage (Kinugawa, 2000). Once the pathogenic fungus invades a single fruit, it induces ethylene biosynthesis that affects other surrounding fruit (Yano and Hasegawa, 1993). Therefore, in order to understand the ripening physiology and evaluate the storage potential of kiwifruit, especially at room temperature, we have to eliminate the effects of disease-induced ethylene.

1-Methylcyclopropene (1-MCP), a synthetic cyclic olefin that is used to extend storage life in many climacteric fruit, inhibits ethylene action through interaction with ethylene receptors (Sisler and Serek, 1997). Pre-storage treatment with 1-MCP significantly delays the increase in ethylene production and softening of 'Hayward' fruit during their shelf life at room temperature, after short- and medium-term cold storage (Koukounaras and Sfakiotakis, 2007). In kiwifruit, 'Bartlett' pears and 'Charantais' melons, fruit treated with 1-MCP exhibited significant extension of storage and shelf life (Asiche et al., 2016; Nishiyama et al., 2007; Villalobos-acuña et al., 2011). In this study, we used 1-MCP treatment and spatial isolation to eliminate the effects of ethylene produced by adjoining diseased fruit.

Storage temperature plays a pivotal role in fruit metabolism during long-term storage, causing changes in

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physical and chemical attributes and in the aroma composition of various fruits (Antunes and Sfakiotakis, 2002; Antunes et al., 2000; Ritenour et al., 1999). The kiwifruit industry utilizes a cold storage temperature of 0–4°C to slow down the ripening process and extend fruit life (Arpaia et al., 1987; Pranamornkith et al., 2012). Low temperatures generally inhibit microbial growth and suppress metabolic changes, thus maintaining fruit quality during storage (Wang and Wang, 2009).

The genus *Actinidia* consists of 55 species and 76 taxa native to Asia, including a wide array of cultivars (Kim et al., 2009; Thompson et al., 2000; Wang and Gleave, 2012). *Actinidia deliciosa* 'Hayward' and *A. chinensis* 'Hort16A' are widely commercialized kiwifruit cultivars, and many other novel cultivars have been introduced and grown commercially worldwide (Kim et al., 2009). In Japan, *A. chinensis* 'Sanuki Gold' and *A. chinensis* 'Rainbow Red' are new cultivars gaining commercial prominence with the most notable fruit attributes being smooth skin and a high soluble solids content (SSC). However, these cultivars have a relatively short storage life compared to *A. deliciosa* 'Hayward'. 'Sanuki Gold', bred in Kagawa, Japan, is a tetraploid (4n) with large fruit size (200 g), brown skin, golden yellow flesh, and high SSC (16%), whereas 'Rainbow Red' (2n) has green, smooth skin with red concentric rings, weighs 100 g, and has an extremely high SSC (18%) (Mworia et al., 2010; Nishiyama et al., 2008). 'Hayward' is medium-sized (120 g) and has hairy skin and a lower SSC (14%) than the other two cultivars. 'Sanuki Gold' and 'Rainbow Red' are early-maturing types harvested in early October and late September, respectively, in contrast to 'Hayward', which is a late-maturing type harvested in early November. The most important postharvest disparity between the cultivars is storage life; 'Hayward' can be stored for up to 6 months (Arpaia et al., 1987), whereas 'Sanuki Gold' and 'Rainbow Red' can be stored for only 1 or 2 months even at low temperature. Thus, it will be useful to study 'Sanuki Gold' and 'Rainbow Red' in order to determine the physiological differences among cultivars and to develop appropriate methods for long-term storage.

Our previous research on the kiwifruit *A. chinensis* 'Sanuki Gold' showed that fruit stored at 5°C ripened faster than fruit stored at room temperature, accompanied by elevated expression of specific ripening-associated genes, encoding cell wall-modifying enzymes, carbohydrate metabolism, and transcription factors in an ethylene-independent manner when effects of disease-induced ethylene was eliminated (Mworia et al., 2012). Furthermore, during low-temperature storage, repeated application of 1-MCP failed to suppress changes in firmness and titratable acidity. It was concluded that exposure to low temperature accelerated ripening of 'Sanuki Gold' kiwifruit. There is little information on the impact of prolonged storage under various storage temperature regimes in different kiwifruit cultivars. The objectives of our study were to assess the effect of different storage temperatures (0, 5, 10, 15, and 20°C) on development of ripening rot and ripening characteristics in ethylene-free conditions using three kiwifruit cultivars 'Sanuki Gold', 'Rainbow Red', and 'Hayward'.

## Materials and Methods

*Plant materials*

*A. chinensis* 'Sanuki Gold' and *A. chinensis* 'Rainbow Red' fruit were obtained from a commercial orchard in Kagawa, Japan. 'Sanuki Gold' fruit were harvested on October 5, 2011 while 'Rainbow Red' fruit were harvested on September 27, 2011. *A. deliciosa* 'Hayward' fruit were harvested from the experimental orchard at Okayama University, Japan on November 7, 2011. Kiwifruit were immediately transported to a postharvest laboratory at Okayama University, Japan where they were sorted to obtain fruit of uniform size and without defects or blemishes.

*Ethylene and fruit rot screening*

To monitor for disease infections, ethylene production of all fruit was measured individually at harvest and a few fruit were found to be producing ethylene. These fruit were set aside and monitored at room temperature for a few days. Shortly thereafter, rot symptoms developed, indicating that the initiation of ethylene production was due to fruit rot. Therefore, we decided to conduct strict ethylene and fruit rot screening (twice a week) to remove the effects of disease-induced ethylene during the entire experimental period. Once ethylene production $>0.02\ nL \cdot g^{-1} \cdot h^{-1}$ was detected, the fruit were transferred to a separate room and monitored at room temperature. Ethylene measurements were conducted by incubating individual fruit in a 0.4 L container. After 1 h, 1 mL of headspace gas was withdrawn and injected into a gas chromatograph (Model-GC8 CMPF; Shimadzu, Kyoto, Japan) equipped with a flame ionization detector (set at 200°C) and an activated alumina column ($\phi$ 4 mm × 1 m) set at 80°C (Mworia et al., 2010).

*Treatments and storage conditions*

Fruit at the commercial harvesting stage were stored spatially separated (5 cm apart) in order to avoid effects of disease-induced ethylene. The experimental design consisted of control fruit (CON), 1-MCP, and five temperature regimes (0, 5, 10, 15, and 20°C). Treatment with 1-MCP was conducted twice a week throughout the duration of storage by exposing fruit to $5\ \mu L \cdot L^{-1}$ of 1-MCP (SmartFresh™, Rohm and Hass, Philadelphia, PA, USA) for 12 h, according to Mworia et al. (2010, 2012).

*Evaluation of fruit quality indices*

Fruit firmness (outer pericarp and core), SSC, and TA were determined at week 0, 2, 4, 6, and 8 using 5 biological replications. Fruit were exposed to room temperature for 2 h before assessment. Fruit skin was sliced off from two opposite cheeks along the equatorial region and outer pericarp firmness was subsequently measured using a penetrometer (model SMT-T-50; Toyo Baldwin, Tokyo, Japan) fitted with a 5-mm plunger (Asiche et al., 2016). The SSC of the fruit juice was determined using a digital Atago PR-1 refractometer (Atago Co. Ltd, Tokyo, Japan) and expressed as Brix (%). TA was determined by titrating the extract against 0.1N NaOH and then expressed as percentage citric acid equivalents.

## Results

*Fruit rot incidence at different storage temperatures*

For all three cultivars and storage temperatures, fruit that initiated ethylene production were isolated and monitored in a separate room as described in the previous section. These fruit increased ethylene production and developed visible rot symptoms within a few days. As shown in Figure 1, the highest percentage of ethylene-producing fruit was observed during storage at 20°C. In fact, 'Rainbow Red' CON fruit and 'Sanuki Gold' 1-MCP fruit at 20°C could only be stored for 4 and 6 weeks respectively since most of the fruit produced ethylene (Fig. 1A, B). Notably, storage of fruit at lower temperatures (0 and 5°C) significantly reduced fruit rot incidence in all the three cultivars with rot incidence being virtually absent at 0 and 5°C. Nevertheless, fruit without ethylene production did not develop rot symptoms throughout the experimental period and were considered healthy fruit. These fruit were used for further analysis of ripening characteristics.

*Changes in fruit firmness*

Figure 2 shows the outer pericarp firmness of the three kiwifruit cultivars for the CON and 1-MCP fruit. The outer pericarp firmness of 'Rainbow Red' CON and 1-MCP fruit stored at 5, 10, and 15°C drastically decreased from 37 N at harvest to 2–6 N at 4 weeks (Fig. 2A, B). However, fruit stored at 0 and 20°C maintained high firmness of approximately 35 N and 20 N, respectively for both the CON and 1-MCP groups after 4 weeks. 'Sanuki Gold' CON and 1-MCP fruit at 5, 10, and 15°C also showed a sharp decrease in outer pericarp firmness from ~30 N at harvest to ~4 N at 4 weeks (Fig. 2C, D). At this time point, however, both 'Sanuki Gold' CON and 1-MCP fruit at 0 and 20°C still had a higher firmness of approximately 25 N. Conversely, 'Hayward' fruit exhibited slower softening of the outer pericarp compared to the other cultivars. As shown in Figure 2E and F, both 'Hayward' CON and 1-MCP fruit at 5 and 10°C decreased in terms of outer pericarp firmness at a faster rate (after 4 weeks) than fruit at 0, 15, and 20°C. However, the firmness of 'Hayward' fruit at 5 and 10°C even after 8 weeks was higher than that of 'Rainbow Red' and 'Sanuki Gold' at 4 weeks.

*Changes in SSC and TA*

Figure 3 shows the changes in SSC in the three kiwifruit cultivars during storage. 'Rainbow Red' fruit stored at 5, 10, 15, and 20°C in both the CON and 1-MCP groups showed a more rapid increase in SSC, achieving >15% by 4 weeks (Fig. 3A, B). However, the SSC of both CON and 1-MCP fruit at 0°C showed a slower increase in SSC, achieving <15% by 8 weeks. Conversely, 'Sanuki Gold' CON and 1-MCP fruit at 0 and 20°C showed the least increase in SSC, to 13% after 4 weeks, whereas fruit at 5, 10, and 15°C showed a consistent increase in SSC reaching a maximum of approximately

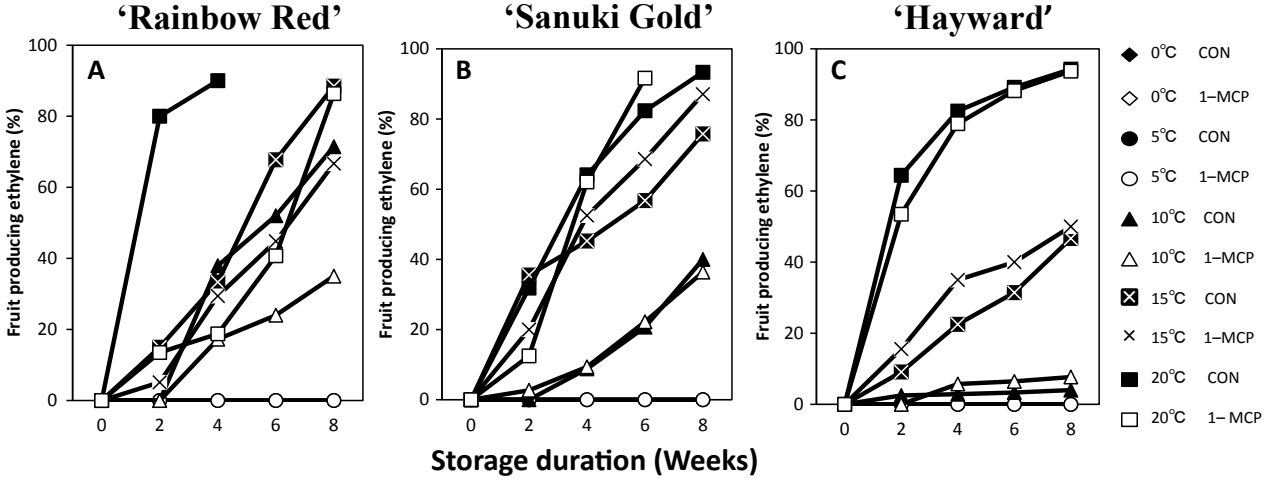


**Fig. 1.** Effect of storage temperature and 1-MCP treatment on percentage of ethylene-producing fruit (rot incidence) in 'Rainbow Red', 'Sanuki Gold', and 'Hayward'. All fruit that initiated ethylene production developed rot symptoms within a few days after transfer to a separate room. Therefore, the percentage of ethylene-producing fruit is identical to fruit rot incidence. Treatment with 1-MCP was performed twice a week during the experimental period.

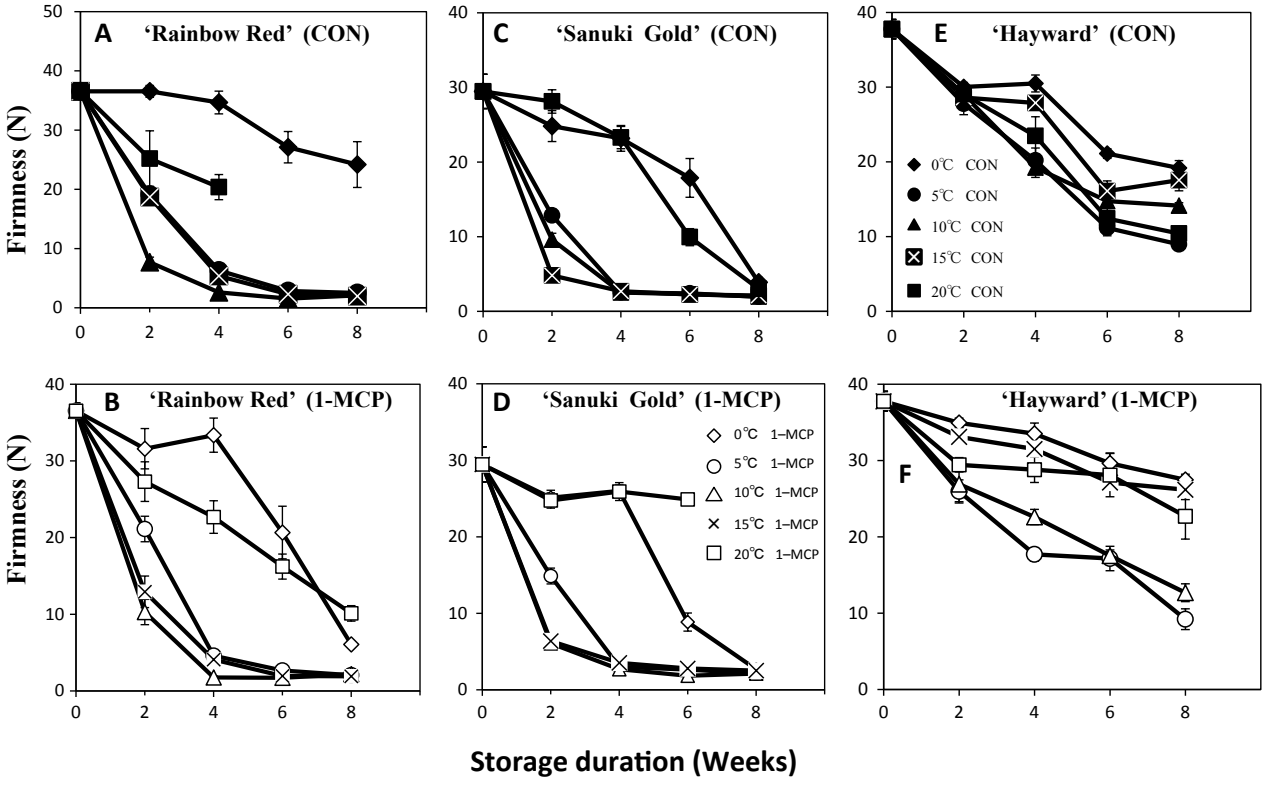


**Fig. 2.** Effect of storage temperature and 1-MCP treatment on outer pericarp firmness of 'Rainbow Red', 'Sanuki Gold', and 'Hayward' fruit. Treatment with 1-MCP was performed twice a week during the experimental period. Each data point is composed of 5 fruit with SE bars.

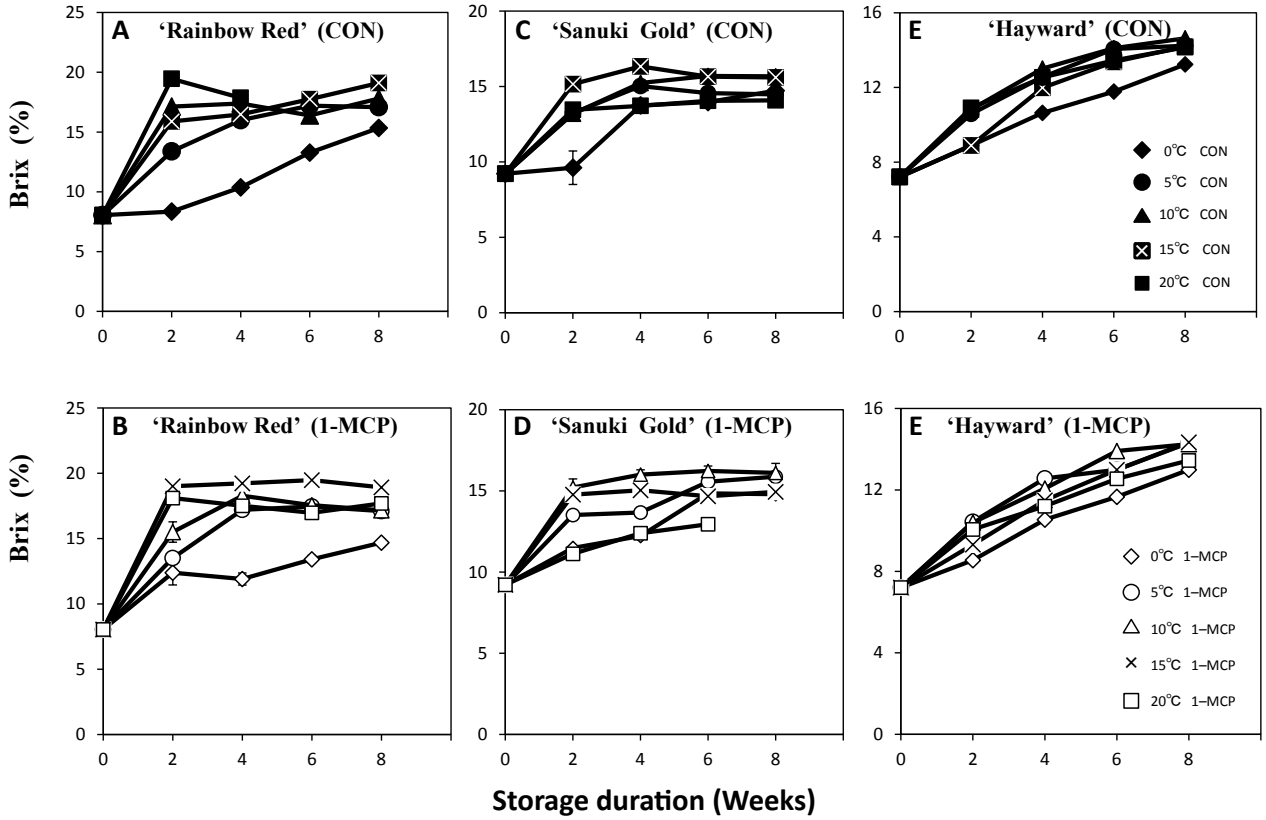


**Fig. 3.** Effect of storage temperature and 1-MCP on SSC of 'Rainbow Red', 'Sanuki Gold', and 'Hayward' fruit. Treatment with 1-MCP was performed twice a week during the entire experimental period. Each data point is composed of 5 fruit with SE bars.

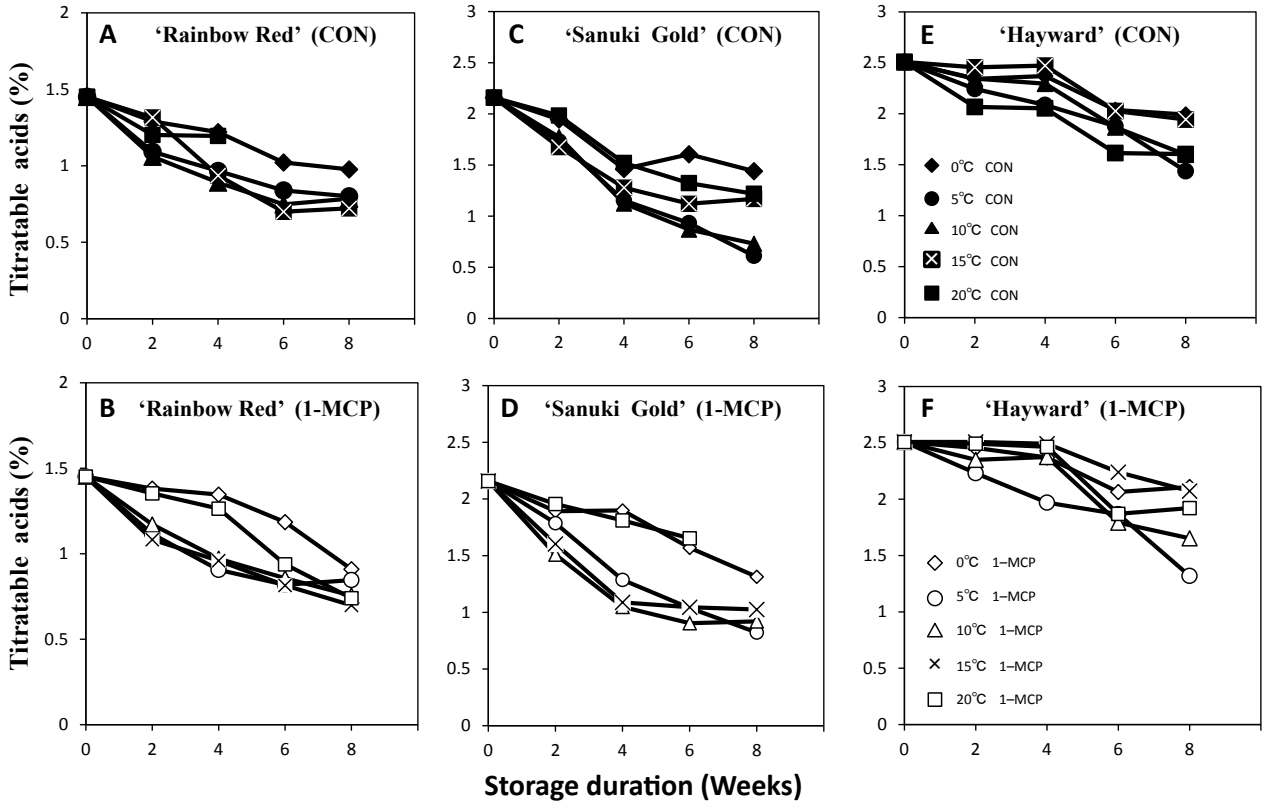


**Fig. 4.** Effect of storage temperature and 1-MCP on TA of 'Rainbow Red', 'Sanuki Gold', and 'Hayward' fruit. Treatment with 1-MCP was performed twice a week during the experimental period. Each data point is composed of 5 fruit with SE bars.

15% after 6 weeks (Fig. 3C, D). For 'Hayward' CON and 1-MCP fruit, the SSC increased gradually in all temperature regimes, attaining a maximum of approximately 14% within 8 weeks, although the rate was slower in fruit at 0°C (Fig. 3E, F).

The TA of 'Rainbow Red' CON and 1-MCP fruit at 5, 10, and 15°C decreased more rapidly than that of fruit at 0 and 20°C to below 1% within 4 weeks (Fig. 4A, B). A similar trend was observed in the TA of both 'Sanuki Gold' CON and 1-MCP fruit, with TA rates decreasing more rapidly in fruit at 5 and 10°C than in fruit at 0 and 20°C (Fig. 4C, D). 'Hayward' fruit showed a higher TA level than the other two cultivars both at harvest and after 8 weeks, as well as a slower rate of decrease in TA during storage (Fig. 4E, F). After 8 weeks of storage, the TA level of 'Hayward' 1-MCP fruit was lower at 5 and 10°C than at 15 and 20°C.

## Discussion

*Ethylene-dependent and -independent fruit ripening in kiwifruit*

The plant hormone ethylene is responsible for ripening in climacteric fruit, causing changes in fruit attributes such as softening, increases in SSC, and reduction in TA (Mworia et al., 2010; Tacken et al., 2010). Exogenous application of ethylene or propylene, an ethylene analogue, accelerated kiwifruit ripening to within 5 days at room temperature, accompanied by endogenous ethylene production (Antunes et al., 2000; Mworia et al., 2010). Conversely, application of 1-MCP, an ethylene perception inhibitor, suppressed ethylene-controlled ripening in kiwifruit even after initiation of ripening, as also observed in melons, pears, apples, and tomatoes (Boquete et al., 2004; Ergun et al., 2005; Nakatsuka et al., 1997; Nishiyama et al., 2007; Pre-Aymard et al., 2003). It is believed that kiwifruit are highly sensitive to exogenous ethylene (Arpaia et al., 1987; Michell, 1990). Thus, in the present study, we conducted frequent screening to remove ethylene-producing fruit. These fruit developed rot symptoms within a few days, so ethylene was attributed to disease stress (Fig. 1). Fruit rot in kiwifruit is mainly caused by *Botryoshaeria* sp. and *Phomopsis* sp. (Kinugawa, 2000), which infect fruit on the vine and are manifested during storage especially at high temperatures and under moist conditions. According to Sfakiotakis et al. (1997), kiwifruit do not start autocatalytic ethylene production at harvest unless the fruit sustain mechanical damage or pathogen attack. The present results agree with this finding since healthy 'Rainbow Red', 'Sanuki Gold', and 'Hayward' kiwifruit did not produce ethylene throughout the storage period at the various temperatures. As previously reported by Yano and Hasegawa (1993), ethylene evolution in healthy kiwifruit is stimulated by ethylene stemming from diseased fruit packed in the same container or by exogenous ethylene gas.

Based on this, fruit producing ethylene as a result of disease infection were isolated through strict and frequent screening to avoid contamination and ensure that fruit sampled at various temperatures were completely ethylene-free. This procedure resulted in a storage life of more than 4 weeks for fruit stored at 20°C, which is much longer than that previously observed in other studies (Kim et al., 1999; Schotsmans et al., 2008; Taglienti et al., 2009).

According to our previous study, 'Sanuki Gold' kiwifruit with undetectable ethylene production exhibited low temperature-modulated ripening whereby fruit stored at 5°C ripened faster than fruit at 25°C (Mworia et al., 2012). Treatment of fruit stored at 5°C with 1-MCP did not inhibit the ripening process indicating that 'Sanuki Gold' fruit ripened in response to low temperature independent of ethylene. In the present study, healthy 'Rainbow Red' and 'Sanuki Gold' fruit with undetectable ethylene production ripened faster during storage at 5, 10, and 15°C compared to fruit at 0 and 20°C (Figs. 2 and 4). Similarly, 'Hayward' fruit with undetectable ethylene production ripened faster at 5 and 10°C than fruit at 0, 15, and 20°C. Repeated 1-MCP treatment did not suppress ripening since both CON and 1-MCP groups depicted a similar ripening pattern at the respective storage temperatures. Therefore, the present results suggest that kiwifruit ripening is modulated by temperature independent of ethylene and the effect of temperature on kiwifruit ripening is manifested in all cultivars. In the absence of ethylene, the rate of ripening in healthy kiwifruit is mainly dependent on the storage temperature. Low-temperature-induced ripening has also been reported in other fruit species such as pears, apples, and plums, but this is assumed to be facilitated by ethylene biosynthesis due to cold stress, contrary to what we observed in kiwifruit (Candan et al., 2008; El-Sharkawy et al., 2003; Kim et al., 1999; Tacken et al., 2010). Furthermore, some fruit attributes are still manifested even when ethylene biosynthesis is suppressed. Experiments on transgenic apple fruit with suppressed 1-aminocyclopropane-1-carboxylic acid synthase (ACS) and 1-aminocyclopropane-1-carboxylic acid oxidase (ACO) genes showed that sugar and acid composition/accumulation are not exclusively under the control of ethylene (Dandekar et al., 2004). In banana fruit, accumulation of sugar after propylene treatment was not inhibited by 1-MCP once the ripening process had been initiated (Golding et al., 1998), and in the cantaloupe melon, suppression of the ACO gene did not inhibit sugar accumulation and loss of acidity, indicating that both ethylene-dependent and -independent regulation coexist during climacteric fruit ripening (Pech et al., 2008).

*Sensitivity to low temperature reflects cultivar differences in kiwifruit*

In previous studies, it has been demonstrated that different kiwifruit cultivars exhibit varying storability during low temperature storage. 'Sanuki Gold' and 'Rainbow Red' kiwifruit are known to be highly perishable with a storage potential of only 1–2 months even at low temperature (Mworia et al., 2012; Nishiyama, 2007). Conversely, 'Hayward' kiwifruit are renowned for their longer storage potential of about 4–6 months (Pranamornkith et al., 2012). In the present study, 'Rainbow Red', 'Sanuki Gold', and 'Hayward' kiwifruit exhibited cultivar differences in ripening pattern during storage at 0, 5, 10, 15, and 20°C. 'Rainbow Red' and 'Sanuki Gold' fruit exhibited a faster reduction in firmness without any ethylene production during storage at 5, 10, and 15°C reaching the lowest firmness within 4 weeks compared to fruit at 0 and 20°C (Fig. 2). On the other hand, 'Hayward' fruit softening was faster at 5 and 10°C compared to fruit at 0, 15, and 20°C. Thus, our results suggest that the major difference between the highly perishable cultivars ('Rainbow Red' and 'Sanuki Gold') and the more hardy cultivar ('Hayward') is the response to a 15°C storage temperature. 'Rainbow Red' and 'Sanuki Gold' fruit stored at 15°C ripened faster than fruit stored at 20°C, whereas 'Hayward' fruit stored at 15°C showed a delayed ripening pattern similar to that of fruit stored at 20°C. Furthermore, the softening of 'Hayward' fruit at 5 and 10°C took a longer time of 8 weeks compared to only 4 weeks exhibited by 'Rainbow Red' and 'Sanuki Gold' at 5, 10, and 15°C (Figs. 2 and 3). In commercial production, kiwifruit is harvested at the pre-climacteric stage when fruit softening has not commenced. In Japan, 'Sanuki Gold' and 'Rainbow Red' fruit are harvested in early October and late September, respectively, when the minimum field temperature is approximately 15°C. 'Hayward' fruit are harvested in early November when the minimum field temperature is approximately 10°C. Thus, the present study suggests that the differences in maturity dates between 'Rainbow Red'/'Sanuki Gold' fruit and 'Hayward' fruit can be attributed to different sensitivities to temperature.

*Implications of storage temperature in kiwifruit cultivars*

Commercially, harvested kiwifruit are usually stored at low temperatures of about 0–4°C to prolong their storage life (Arpaia et al., 1987). However, our present study shows that kiwifruit ripening occurred faster at lower storage temperatures (5, 10, and 15°C for 'Rainbow Red' and Sanuki Gold' kiwifruit, and 5 and 10°C for 'Hayward' kiwifruit) compared to higher storage temperatures. However, it was peculiar that for all cultivars, fruit ripening was suppressed at 0°C in a similar manner to 20°C. The delayed fruit ripening at 0°C can be attributed to a slowness of response, indicating that in as much as 0°C provides physiological stimuli to induce ripening, it also strongly suppresses the metabolic processes of ripening. Arpaia et al. (1986) showed

that in 'Hayward', temperature ranging from 0°C to 10°C is a crucial factor that leads to softening in ethylene-free conditions. Similar conclusions were echoed by Marsh et al. (2004), who showed that 'Hayward' fruit stored at 4 and 10°C softened faster than fruit stored at 0°C. Our present study shows that for long-term storage, a temperature of either 0°C or 20°C is most effective in extending storage life with a reduced ripening rate. However, the high prevalence of fruit rot at 20°C makes it unsuitable for long-term storage of kiwifruit. Therefore, storage at 0°C seems to be most effective in delaying ripening and fruit rot, providing a marked extension of storage life.

Storage at 5 and 10°C provided ripe, edible fruit within 4 and 8 weeks in 'Rainbow Red' and 'Sanuki Gold' respectively without ethylene production. 'Hayward' fruit can be stored for more than 8 weeks at low temperature since the fruit were firmer with high acidity even after 8 weeks at 5 and 10°C. Since consumer preference for kiwifruit is based on fruit firmness, SSC, and acidity, ethylene treatment is usually performed after storage to ensure fruit show uniform ripening characteristics before being brought to market (Boquete et al., 2004; MacRae et al., 1990). The present study shows that for 'Rainbow Red' and 'Sanuki Gold' fruit, 5 or 10°C can be recommended for storage periods of 4 or 8 weeks without ethylene treatment before shipping.

In conclusion, our results show that the ripening rates of kiwifruit cultivars are modulated by storage temperature. Furthermore, kiwifruit sensitivity/response to low temperature is closely related to differences in the storage potential of the cultivars at low temperature and how early or late the fruit matures on the vine.

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