Impact of Temperatures During Fruit Development on Fruit Growth Rate and Qualities of 'KU-PP2' Peach

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In protected agriculture, optimum temperature management is crucial for enhancing fruit productivity and maintaining cost-effective production. The aim of the present study was to investigate the effects of temperature on peach fruit development and quality. Container-grown 'KU-PP2' peach trees grafted on low-chill peach rootstocks were cultivated under controlled conditions at different temperatures (20, 25, and 30°C) during fruit development for two years (2020 and 2021). Fruit growth rates were calculated by measuring fruit diameter every 3 d from fruit setting to first harvest; fruit quality and phytochemistry were analyzed at harvest. Growing temperature markedly affected fruit growth, maturation, and fruit quality. The development of fruit in all treatments exhibited double sigmoid growth curves that included three stages (S1, S2, and S3). Fruit growth rate during S1 and S2 stages was increased, and fruit development period was significantly shortened with an increase in temperature. Contrary to the duration of S3, which was longer at higher temperatures, fruit grown at a high temperature (30°C) ripened by 12–18 days earlier than those grown at low-temperature regimes. In addition, high-temperature conditions were also associated with reduced fruit quality (size, weight, and sweetness), but enhanced development of red coloration. Therefore, even though high-temperature conditions can accelerate early fruit expansion and hasten fruit maturity, such conditions also have negative effects on important agronomic fruit traits.

Key Words: forcing culture, low-chill peach, protected agriculture, *Prunus persica*.

Introduction

Temperature is considered the most influential of the environmental factors that affect fruit development (Menzel, 2019). In warm conditions, the fruit development period was short, with accelerated progress from flowering to fruit maturation. Warrington et al. (1999) reported a strong positive relationship between temperature and fruit expansion rate in apple, with fruits growing almost 10 times faster at 20°C than at 6°C. Similar results were reported by Dela Bruna (2007), who studied the development of peach fruits in a subtropical region of Brazil. Even though temperature is clearly associated with fruit development, the effects of high temperature on fruit growth seem to depend on the timing and duration of exposure (Warrington et al., 1999).

Temperature was also reported to affect the maturity

and phytochemistry of fruit crops, including apple (Austin et al., 1999; Sugiura et al., 2013), apricot (Brown, 1952), and peach (Weinberg, 1948). In spring 2004, for example, high temperatures in California were associated with small and early peach crops (DeJong, 2005). Mackenzie et al. (2011) reported that high temperatures negatively affect important agronomic fruit traits (size and weight) by disrupting normal plant functions and by reducing sugar accumulation. Similar results were reported for strawberry, in which fruit weight decreased as mean greenhouse temperature increased from 15 to 25°C (Kumakura and Shishido, 1994). Even though many studies have investigated the association between temperature and fruit productivity, few have investigated the influence of temperature on low-chill peaches under forcing conditions.

When growing fruit trees under forcing conditions, proper temperatures, during any plant development period are crucial for maximizing yield and preventing excessive energy use. 'KU-PP2' is a new yellow flesh peach cultivar with a low chilling requirement and early ripening that has been bred and released by Kagawa University, Japan, for use in forcing culture systems to

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produce very early season fresh peaches when the open field grown fruits are limited or not yet available. 'KU-PP2' requires approximately 400 chilling hours to flower and grow normally. Under natural conditions in Kagawa Prefecture, Japan, this cultivar blooms in mid to late March and ripens in mid to late June (Manabe et al., 2015). To maximize fruit productivity and minimize production cost, the responses of 'KU-PP2' peach trees to temperature must be established and considered during each development period. The effects of forcing temperature on the budburst, flowering, and carbon assimilation of 'KU-PP2' were reported previously (Sikhandakasmitta et al., 2021a, b). However, the effects of temperature on fruit growth have yet to be fully explored. Therefore, the aim of the present study was to quantify the effects of temperature, during fruit development of 'KU-PP2' peach on fruit growth rate and qualities under controlled conditions.

Materials and Methods

Plant materials

The controlled conditions were conducted within three phytotrons located at the Faculty of Agriculture, Kagawa University, Japan (34° 15' N, 134° 07' E). The air temperature in each phytotron was fixed at 20, 25, and 30°C. 'KU-PP2' peach trees grafted on 'Tsukuba 1 Gou' peach rootstock were grown in 56 L containers. Six vigorous and uniform seven-year-old trees were used as plant materials and exposed to natural conditions prior to the temperature treatments. All 'KU-PP2' flowers were hand-pollinated in late March of both years using fresh pollen to synchronize fruit setting. After fruit set, two plants were moved into each phytotron, and the fruits thinned to 6–7 fruits per tree. All plants were maintained using the same cultural practices.

Fruit development observation

In both 2020 and 2021, five fruits were tagged on each tree, and the cheek diameter of each fruit was measured every 3 d using a digital vernier caliper. Absolute fruit growth rates ($\text{mm} \cdot \text{d}^{-1}$) were calculated from fruit setting until fruit harvest. Fruit development period was computed as the number of days from flower blooming to fruit harvest.

Fruit quality evaluation

Fruits were harvested when fruit began softening and was easily detached. The dimensions (fruit length, cheek diameter, and suture diameter), fresh weight, and phytochemical components of fruit were measured immediately after harvesting. Total soluble solids concentration (TSS) was quantified on the cheeks of opposite sides of each fruit using PR-101 α , a digital refractometer (Atago Co., Ltd., Japan), as well as flesh firmness. Fruit skins on the two opposite sides were removed before flesh firmness measurement. Firmness

was determined with a KM-1 fruit hardness tester (Fujiwara Scientific Co., Ltd., Japan) equipped with a 5-mm cylindrical flat probe, which was injected 10 mm into the flesh. The titratable acid (TA) content (% malic acid) of each fruit was measured by extracting juice from the fruit pulp and titrating the juice using NaOH and an acidity titrator (TA-72; DKK-TOA Corporation, Japan). Finally, fruit skin coloration was scored visually as the percentage of skin with red coloration, according to the European cooperative programme for plant genetic resources (ECPGR) priority descriptors for peach (Giovannini et al., 2013).

Data analysis

Mean values were calculated for the quality data from each tree, and analysis of variance (ANOVA) of the quality data was performed using the Statistical Analysis System (SAS) University Edition (SAS Institute Inc., USA). Tukey's honestly significant difference (HSD) test was then used to identify significant differences among treatment means ($P < 0.05$). Within each treatment regime, mean values were also calculated for the fruit growth rates of each developmental stage, log-transformed, and then examined using a general linear model (GLM).

Results and Discussion

Effect of temperature on fruit development and fruit maturation

Growth temperature significantly affected the period of fruit development and timing of maturity. However, the fruit development pattern as a double sigmoid curve, which was partitioned into three stages (S1, S2, and S3), was observed in all temperatures (Fig. 1). Each fruit development stage was determined by fruit growth rate. During the S1 stage, 'KU-PP2' peach fruits exhibited rapid fruit expansion, whereas the S2 stage was characterized by limited fruit expansion, and the S3 stage was characterized by another period of rapid fruit expansion (Fig. 1).

Even though the double sigmoid growth pattern was observed in all the temperature regimes, the duration and growth rate for each stage varied. At higher temperature conditions (25°C and 30°C), both the S1 and S2 stages were shorter, as was the duration of fruit maturation (Table 1). The S1 stage was shortest at 30°C (18–24 d), followed by 25°C (24–30 d) and 20°C (30–36 d; Table 1). However, the S3 stage was the longest at 25°C and 30°C. Similar results in Japanese apricot (Yamamoto et al., 1990; Suzuki et al., 1995) and grape (Hale and Buttrick, 1974) showed that, even though high temperatures shorten the duration of fruit development in early-stages (S1 and S2), the conditions prolong the S3 stage.

There was a positive relationship between temperature and fruit growth rate during early fruit development (S1 and S2; Fig. 2). However, the relationship

between fruit growth rate and temperature was greater during the S1 stage ($R = 0.8722$; $P < 0.001$) than during the S2 stage ($R = 0.4504$; $P = 0.017$). Higher temperatures accelerated early fruit growth but also retarded late fruit expansion. There was a strong negative relationship ($R = 0.809$; $P < 0.001$) between temperature and fruit growth rate during the S3 stage (Fig. 2; Table 1). Furthermore, the elevated temperature shortened the S1 and S2 stages, thereby reducing the fruit develop-

ment period (Table 1). The shortest time span of the early fruit growth stage (S1) occurred at 30°C treatment, as did the shortest fruit development period (78 d; Table 1).

In the present study, the fruit development period of the ‘KU-PP2’ peach was shortened by high-temperature conditions. This corroborates the findings of Dela Bruna (2007), who reported that peaches cultivated in subtropical areas also respond to high-temperature con-

Fig. 1. Effect of temperature on the fruit growth of ‘KU-PP2’ peach. Fruit growth was measured from flower blooming to fruit harvest. All curves were divided into 3 stages: S1, S2, and S3, by 2 vertical lines.

Fig. 2. Effect of growth temperature (GT) on the fruit expansion rate (FER) of ‘KU-PP2’ peach. Regressions for the S1, S2, and S3 fruit development stages were $FER_{S1} = (0.0436 \times GT) - 0.191$ ($R = 0.8722$; $n = 30$; $P < 0.001$), $FER_{S2} = (0.0108 \times GT) + 0.148$ ($R = 0.4504$; $n = 30$; $P = 0.017$), and $FER_{S3} = (-0.0586 \times GT) + 2.366$ ($R = 0.809$; $n = 30$; $P < 0.001$), respectively.

Table 1. Effect of temperature on the phenology of fruit development in ‘KU-PP2’ peach.

Temperatures	Development stage duration (d) ^z				Harvest date ^y	
	S1	S2	S3	Total	2020	2021
20°C	36 a	30 a	30 b	96 a	9 Jun (161)	21 June (172)
25°C	30 b	24 b	36 a	90 b	31 May (152)	14 June (165)
30°C	24 c	18 c	36 a	78 c	24 May (145)	4 June (155)
P-value	<0.001	<0.001	0.006	0.002	—	—

Data was log transformed before statistical analysis.

^z Data are expressed as mean values $\pm$ standard errors ($n = 20$). Different lowercase letters within the same row denote significant differences ($P \leq 0.05$; Tukey’s test).

^y Harvest date was defined as the date of first harvest. Values in parentheses indicate Julian calendar harvest dates.

ditions by exhibiting accelerated growth during the fruit development period, resulting in early fruit ripening and small fruit size. Sugiura et al. (2003) and Hayama et al. (2007) reported that temperature was related to fruit growth and maturity in high-chill peaches and apples. Previous studies of peaches have reported that final fruit size is a function of cell division during the S1 stage and cell expansion during the S3 stage. Scorza et al. (1991) confirmed that cell number and size are directly related to final peach fruit size, since peach cultivar with small fruit exhibit shorter S1 and S3 stages. Furthermore, Yamaguchi et al. (2004) showed that cell division, cell enlargement and the final fruit size were influenced by genetic and environmental factors during fruit development. Sugiura et al. (2003) and Giovannelli et al. (2014) found positive relationships between the fruit size, weight, and fruit development period of apples and peaches, respectively. Therefore, long-term exposure to high temperatures during fruit development might reduce fruit size by hastening fruit growth during early fruit growth and by shortening the overall development period.

Effect of temperature on fruit characteristics and phytochemical components

A previous study with the 'KU-PP2' peach reported that exposure to high-temperature conditions negatively affected fruit productivity and quality (Sikhandakasmitta et al., 2021b), and the present study confirms that fruit weight, fruit dimensions, and TSS were lowest at 30°C and greatest at 20°C (Table 2). The smaller size and TSS of 'KU-PP2' fruits grown under high-temperature conditions may be associated with the negative effects of high temperature on photosynthesis ability. Most of the raw materials and energy used for fruit growth are produced *via* photosynthesis. Sikhandakasmitta et al. (2021b) reported that long-term exposure to high-temperature conditions reduced the photosynthesis ability of 'KU-PP2' peach trees by changing leaf characteristics, breaking photosynthetic pigments, and disrupting gas exchange and that this, ultimately,

reduced fruit size and fruit quality. Lopez and DeJong (2007) confirmed that the occurrence of elevated temperature during fruit growth increases the risk of insufficient nutritional resources, resulting in poor fruit quality. However, in the present study, the temperature regime had no significant effect on fruit shape, flesh firmness, or titratable acidity (TA).

Regarding the effect of high temperatures on fruit development, high-temperature conditions significantly decreased not only the duration of the S1 stage and overall fruit development but also the final fruit size. Conversely, the conditions extended the period of the S3 stage. A longer period S3 stage due to high-temperature conditions did not increase final fruit size. These results suggest that the final fruit size was affected more greatly by cell division during the S1 stage than cell elongation during the S3 stage.

Even though exposure to high-temperature conditions during fruit development negatively affected the fruit quality of 'KU-PP2' peach, the elevated temperature also stimulated the development of red coloration on the fruits' skin (Table 2). Fruit grown at 30°C had more red coloration than fruit grown at lower temperature regimes. Many studies have reported that extent of red coloration on peach skin is positively related to light exposure (Corelli-Grappadelli and Coston, 1991; Kataoka and Beppu, 2004). Therefore, peach fruits ripened under shade or low-light conditions possess less red coloration than fruit ripened under full sunlight. Furthermore, a previous study of 'KU-PP2' peach reported that 'KU-PP2' trees grown at 30°C had smaller leaves, which reduced the level of canopy shade. As a result, peach fruit grown under high-temperature conditions were probably exposed to higher light intensities, which may be associated with greater red skin coloration (Sikhandakasmitta et al., 2021b).

Conclusions

In the present study, growing temperatures significantly affected the development period, agronomic

Table 2. Effect of temperature on the fruit characteristics of 'KU-PP2' peach.

Fruit trait	Temperatures ^z			P-value
	20°C	25°C	30°C	
Fruit weight (g)	137.5±4.9 a	124.5±3.1 b	98.0±2.5 c	<0.001
Fruit cheek diameter (mm)	55.7±2.6 a	50.3±1.4 b	47.4±2.2 c	<0.001
Fruit suture diameter (mm)	58.1±2.4 a	52.2±1.1 b	51.7±2.7 b	0.015
Fruit length (mm)	56.5±2.2 a	54.8±1.2 ab	51.6±3.3 b	0.021
Total soluble solids (°Brix)	15.8±0.4 a	12.0±0.3 b	11.7±0.5 b	0.038
Titratable acidity (%)	0.23±0.05	0.19±0.02	0.22±0.06	0.434
Flesh firmness (N)	3.34±0.11	3.63±0.08	3.53±0.13	0.365
Red coloration (% surface)	10–15 b	10–15 b	60–75 a	<0.001

^z Data were expressed as mean±standard errors (n=20). Different lowercase letters within the same row denote significant differences ($P\leq 0.05$; Tukey's test).

characteristics, and phytochemical components of ‘KU-PP2’ peach fruit. High-temperature conditions can accelerate early fruit growth and fruit maturity and can stimulate the development of red skin coloration in ‘KU-PP2’ peach; however, such conditions can also retard late fruit development and negatively affect aspects of fruit quality. Thus, identifying the proper temperature for each fruit development phase is crucial to maximizing fruit productivity and maintaining the economic value of peach fruit produced by protected agriculture.

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