Passion Fruit Quality under Acidic Soil Conditions

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The suitable soil pH for passion fruit growth has been well studied; however, the optimal soil pH for producing high-quality fruit has not been determined. In this study, the effects of soil acidity on fruit quality were determined. One-year-old passion fruit plants were grown in pots filled with soil adjusted to four pH levels (pH 3.5, 4.5, 5.5, and 6.5). The numbers of flowers and fruits were counted, and the external appearance and juice quality of the harvested fruits was evaluated. Vegetative growth, physiological responses, and leaf mineral contents were also measured. At pH 4.5 and 5.5, fruit were heavier and larger, with a better peel color than the fruit at pH 3.5 and 6.5. As indicators of taste, the titratable acid content was lower and total soluble solid content was higher at pH 4.5 and 5.5, indicating preferable palatability. The sugar/acid ratio was highest at pH 4.5. The numbers of flowers and fruits, vegetative growth, and photosynthetic rate were also higher at pH 4.5 and 5.5. Conversely, soil with a near-neutral pH of 6.5 yielded fruit with a pale peel color, severe peel wrinkles, and a low sugar/acid ratio. Vegetative growth was inhibited, and the photosynthetic rate and leaf water potential were lowest at pH 6.5. The leaf/fruit ratio was lower at pH 6.5. A shortage of photosynthate may have reduced fruit quality. Leaf nitrogen, manganese, and zinc contents, as well as the chlorophyll content (SPAD index), were lowest at pH 6.5. Deficiencies in these minerals may have led to a low photosynthetic rate and SPAD index under the higher pH condition. With excessive acidic soil (pH 3.5), vegetative growth, photosynthetic rate, and the number of flowers were as high as those at pH 4.5, although the fruit-set percentage and fruit quality were lower. Thus, strongly acidic soil around pH 4.5 is recommended for producing high-quality passion fruit.

Key Words: mineral contents, *Passiflora*, soil pH, vegetative growth.

Introduction

Soil pH 5.5–7.5 has been thought suitable for passion fruit cultivation; e.g. 5.5–6.0 (Gilmour, 1983), 5.5–6.5 (Deshmukh et al., 2017), 5.5–6.8 (Nakasone and Paull, 1998), and 6.5–7.5 (Morton, 1987). Kondo et al. (2017) cultivated passion fruit in soils with various pH values (pH 4.7, 5.4, 6.8, and 7.4), however, and noted that the photosynthetic rate, SPAD index, and leaf nitrogen (N) and phosphorus (P) contents increased in acidic soils (pH 4.7 and 5.4), and that vegetative growth decreased in alkaline soil (pH 7.4), concluding that passion fruit prefers acidic soils. Similarly, Niwayama and Higuchi (2018) reported that strongly acidic soil with pH 3.5

promoted the recovery of root growth after pruning roots in half, which may promote vegetative growth in passion fruit. Therefore, strongly acidic soil can be suitable for passion fruit vegetative growth.

In some species, fruit quality is affected by rhizospheric pH levels. For example, in the Valencia orange, the Brix sugar content increased as soil pH decreased, and acid content was highest at a soil pH of 4.0 (Anderson, 1971). Meanwhile, the sugar content of highbush blueberries grown in a solution culture with a pH of 3.5 was higher than that with a pH > 4.5 (Katakura and Yokomizo, 1995). Similarly, strongly acidic soil possibly increases passion fruit vegetative growth and photosynthate, and may improve fruit quality. An increase in photosynthate resulted in a low acid content in passion fruit juice (Kondo and Higuchi, 2011). However, the optimal soil pH for high quality fruit remains unknown.

In this study, to clarify the effects of soil acidity on passion fruit quality, passion fruit vines were transplanted into soils with different pH values (pH 3.5, 4.5,

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5.5, and 6.5), and the juice quality and external fruit appearance were evaluated. Vegetative growth, the numbers of flowers and fruits, and leaf mineral contents were also examined to assess the factors affecting fruit quality.

Materials and Methods

Plant materials

One-year-old hybrid passion fruit (*Passiflora edulis* Sims × *P. edulis* Sims f. *flavicarpa* Deg. ‘Summer Queen’) plants were grown in a greenhouse at Kyoto University (35.0°N, 135.8°E). Thirty-six plants propagated by cutting in September 2016 were grown in 1 L plastic pots filled with 50% weathered granite soil and 50% bark compost (v:v). The soil pH (H₂O) on 15 April, 2017 (before transplanting) was 5.25. The plants were transplanted into 10 L clay pots filled with soil that was adjusted to various pH levels on 15 April, 2017 using the method described below. At transplanting, the rhizosphere soil was not removed so as to not injure the roots. The plants were trimmed to a single stem, trained vertically to a height of 150 cm, and then trained horizontally. Immediately after transplanting, the horizontally trained vines were cut at 90 cm and the axillary buds were pinched, and three newly emerged axillary vines were allowed to grow downward. The pots were spaced with 30 cm between pots and 80 cm between rows. A 1000 mL nutrient solution (pH 6.2) containing 6.0 mM NH₄NO₃, 6.0 mM (NH₄)₂SO₄, 2.0 mM KNO₃, 1.0 mM Ca(NO₃)₂, 1.5 mM K₂HPO₄, 3.0 mM CaCl₂, 2.0 mM MgSO₄, and 1.0 mM K₂SO₄ was applied to each plant once a week, and the plants were irrigated daily. The side windows of the greenhouse were opened to allow air ventilation at temperatures above 30°C, and the minimum temperature in winter was maintained above 8°C by heating.

Soil pH treatment

The plants were transplanted to soil adjusted to four pH levels (pH 3.5, 4.5, 5.5, and 6.5) using sulfuric acid or calcium carbonate. The soil consisted of 50% weathered granite soil and 50% bark compost (v:v). The soil was sampled immediately after transplanting and air-dried for several days at room temperature. For 10 g of this air-dried soil, 25 mL of distilled water was added, and the mixture was shaken for 1 h. Then, it was left for 30 minutes before the pH was measured with a pH meter (IM-22P; DKK-TOA Co., Tokyo, Japan). The soil pH values were 3.58, 4.51, 5.39, and 6.73 for the target soil pH levels of 3.5, 4.5, 5.5, and 6.5, respectively (Table 1).

To monitor the soil pH change, one plant per treatment was exclusively used for continuous pH monitoring. The soil was sampled at a depth of 14–16 cm and 6–8 cm from the main vines twice a month until 3 July, and the soil pH was measured using the same method as above. According to the results of the pH monitoring,

Table 1. Soil pH on 15 April and 28 August.

Level	Soil pH	
	15 April ^z (at transplanting)	28 August ^y (after harvest)
3.5	3.58	4.09 b
4.5	4.51	4.39 b
5.5	5.39	4.90 a
6.5	6.73	5.09 a

^z: Soil was sampled once for each treatment (n=1).

^y: Different letters within a column indicate statistical differences by Tukey’s test at $P < 0.05$ (n=8).

sulfuric acid or calcium carbonate was added with irrigation water to maintain the pH at the target levels.

Measurements

The number of flowers per fruit-bearing vine was recorded from 14 May to 25 June, and artificial pollination was conducted at 12:00–13:00 h (3–4 hours after flowering) using a paint brush with fresh pollen. One week after pollination, the number of fruit per fruit-bearing vine was counted, and the number of fruit per vine was reduced to four by fruit thinning. To prevent fruit from dropping to the ground, each fruit peduncle was tied to the vine with thread. Mature fruit that had abscised from vines were harvested. Immediately after harvest, the fruit weight and dimensions were measured, peel color was estimated visually at five levels (1: pale green to 5: dark purple), and the number of days after pollination to harvest (DAP) was recorded. After 10 days of storage at 25°C, the peel color was estimated again, and the degree of wrinkling was estimated visually at five levels (1: no wrinkles to 5: severe wrinkles). Peel weight was recorded and the percentage of juice weight per fruit weight, titratable acidity (TA), and total soluble solid (TSS) content were measured using the methods described by Kondo and Higuchi (2013a). The sugar/acid ratio (TSS/TA) was calculated accordingly.

The vine length, numbers of nodes and leaves, and costa length of each leaf on one vine per plant were measured every two weeks until 24 June. The total leaf area was estimated based on the costa length using the calibration described by Kondo and Higuchi (2012). The leaf/fruit ratio, the leaf/flower ratio, and the leaf area per flower were calculated. The relative chlorophyll contents (SPAD index) of mature leaves at the tenth nodes from the base of the downward axillary vines were measured using a chlorophyll meter (SPAD-502Plus; Konica Minolta Sensing, Inc., Osaka, Japan) on 19 June and 21 July. On the same day, the maximum quantum yield of photosystem II (Fv/Fm) of the same mature leaves was measured using a chlorophyll fluorometer (OS-30p; Opti-Sciences, Hudson, NH, USA) at 10:00–14:00 h. The photosynthetic rate,

transpiration rate, and stomatal conductance of the above leaves were measured using a portable gas exchange system (LI-6400; LI-COR Inc., Lincoln, NE, USA) at 10:00–14:00 h on 21 July. The measurement conditions were $1200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPFD, 380 ppm CO_2 , 30°C block temperature, and $350 \mu\text{mol}\cdot\text{s}^{-1}$ flow rate. On the same day, leaf water potential was measured using a pressure chamber (Model 3000; Soilmoisture Equipment Corp., Santa Barbara, CA, USA) at 10:00–14:00 h. Roots were rinsed with water to remove soil on August 28, and the root dry weight was measured after oven-drying at 70°C for 3 days.

Leaves at the tenth nodes from the base of the downward axillary vines were sampled on August 16, and leaf N, P, potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), and zinc (Zn) contents were measured using the methods described by Kondo and Higuchi (2013b).

Statistical analysis

The four treatments were arranged in a randomized block design with eight replications. The data were analyzed by randomized block analysis of variance (ANOVA), and data exhibiting statistical differences among treatments were subjected to further analysis using Tukey's test ($P < 0.01$ or 0.05).

Results and Discussion

Soil pH

The soil pH values in the pH 3.5, 4.5, and 5.5 treatments did not fluctuate largely, although that at pH 5.5 was a little lower than the target level (Fig. 1). The mean values were 3.77 ± 0.05 , 4.44 ± 0.09 , and $5.14 \pm$

0.11 , respectively. The mean value for pH 6.5 treatment was 6.48 ± 0.17 and this was almost the same as the target level, while the soil pH fluctuated. The soil pH values sampled from all plants after harvest (on August 28) were 4.09 ± 0.13 , 4.39 ± 0.15 , 4.90 ± 0.28 , and 5.09 ± 0.58 , respectively (Table 1).

Vegetative growth & physiological responses

The vines elongated similarly in all pH treatments within the first four weeks (Fig. 2). However, after 27 May, the vines in the pH 6.5 treatment became shorter than those of the other treatments. The vine length at a pH of 4.5 tended to be longest. Leaf area and numbers

Fig. 1. Changes in soil pH after passion fruit transplantation. Soil pH mean values for the treatments were 3.77 ± 0.05 (circles), 4.44 ± 0.09 (squares), 5.14 ± 0.11 (diamonds), and 6.48 ± 0.17 (triangles).

Fig. 2. Changes in vine length, leaf area, and the numbers of nodes and leaves after transplanting of 'Summer Queen' passion fruit to different pH soils within 3.5–6.5. Different letters within the same date indicate statistical differences by Tukey's-test at $P < 0.05$ ($n = 8$). Vertical bars indicate SE. Source: Niwayama and Higuchi, 2017, Res. Trop. Agr. 10 [Ext. 2]: 9–10.

Table 2. Effects of soil pH on photosynthetic rate, transpiration rate, stomatal conductance, and leaf water potential of ‘Summer Queen’ passion fruit.

Soil pH treatment	Photosynthetic rate ($\mu\text{mol CO}_2 \text{ m}^{-2} \cdot \text{s}^{-1}$)	Transpiration rate ($\text{mmol H}_2\text{O m}^{-2} \cdot \text{s}^{-1}$)	Stomatal conductance ($\text{mol H}_2\text{O m}^{-2} \cdot \text{s}^{-1}$)	Leaf water potential	Root dry weight (g)
3.5	14.92 a	3.74 a	0.15 a	−0.48 a	9.04 a
4.5	12.99 ab	3.07 a	0.13 a	−0.49 a	11.38 a
5.5	12.42 ab	2.82 a	0.11 a	−0.57 a	10.52 a
6.5	8.76 b	1.97 a	0.07 a	−0.90 b	6.75 a

Different letters within a column indicate statistical differences by Tukey’s test at $P < 0.05$ ($n = 8$).

Fig. 3. Relationship between stomatal conductance and leaf water potential after transplanting of ‘Summer Queen’ passion fruit to different pH soils from 3.5–6.5. **: significance at $P < 0.01$.

of nodes and leaves were smallest at pH 6.5, at which the photosynthetic rate and leaf water potential were lowest, and transpiration rate and stomatal conductance also tended to be low (Table 2). In addition, the root dry weight tended to be lightest at pH 6.5. The inadequate root mass at pH 6.5 likely led to water deficiencies in the plants. Stomatal conductance was highly correlated with leaf water potential in all treatments (Fig. 3), and the photosynthetic rate and transpiration rate depended on stomatal conductance (Fig. 4). These results suggest that stomatal closure caused by water deficiency lowered the photosynthetic rate in the pH 6.5 treatment. A decrease in the photosynthetic rate may have inhibited vegetative growth at pH 6.5.

Vegetative growth was similar among the pH 3.5–5.5 treatments (Fig. 2). In general, acidic soil such as pH 3.5–5.5 generally inhibits plant growth (e.g. Doss and Lund, 1975). On the other hand, some plants are known to prefer acidic soil. For instance, tea plants grown in soils at pH 3.5 exhibited the highest dry weight (Fung and Wong, 2002). In the blueberry, the optimum range of soil pH has been reported to be 4.0–5.2 (Harmer, 1945). Passion fruit can also grow in soil with a pH of 3.5–5.5, and it prefers the acidic soil.

The SPAD index on 19 June was lowest at pH 6.5 (Table 3). On 21 July, the SPAD index tended to be lowest at pH 6.5, although Fv/Fm was not affected by soil pH. Therefore, the reduction in the SPAD index at

Fig. 4. Relationships of photosynthetic rate and transpiration rate to stomatal conductance after transplanting of ‘Summer Queen’ passion fruit to different pH soils from 3.5–6.5. **: significance at $P < 0.01$.**Table 3.** Effects of soil pH on the SPAD index and Fv/Fm of ‘Summer Queen’ passion fruit.

Soil pH treatment	19 June		21 July	
	SPAD index	Fv/Fm	SPAD index	Fv/Fm
3.5	58.1 a	0.79 a	63.2 a	0.80 a
4.5	55.5 ab	0.77 a	63.5 a	0.81 a
5.5	55.2 ab	0.77 a	60.6 a	0.81 a
6.5	52.2 b	0.75 a	55.6 a	0.80 a

Different letters within a column indicate statistical differences by Tukey’s test at $P < 0.05$ ($n = 8$).

pH 6.5 was unlikely to be caused by photoinhibition, but may have been related to mineral absorption. Kondo et al. (2017) reported that the SPAD index decreased as soil pH increased in passion fruit. Deficiencies in chlorophyll content could partially explain the decrease in the photosynthetic rate at pH 6.5.

Niwayama and Higuchi (2018) reported that strongly acidic soil (pH 3.5) promoted the recovery of passion fruit root growth. However, in this study, dry root weight did not differ significantly between pH 3.5–5.5 (Table 2).

Numbers of flowers and fruits

The number of flowers was not affected by soil pH from 14 May to 15 June (Table 4). After 16 June, the number of flowers increased as soil pH decreased. The number of fruits was smallest at pH 6.5 after 1 June, although that was not affected by soil pH from 14 May to 31 May (Table 5). The fruit-set percentage from 14 May to 15 June was lowest at pH 6.5, while that after 16 June was lowest at pH 3.5 (Table 6). The total numbers of flowers and fruits during the flowering period were lower at pH 6.5 (Table 7). The total fruit-set percentage was lower at pH 3.5 and 6.5. The leaf/flower ratio was not affected by soil pH. Conversely, the leaf area per flower was smallest at pH 6.5. At pH 6.5, and the decrease in vegetative growth (Fig. 2) and photosynthetic rate (Table 2) may have reduced the leaf area per flower. The small leaf area per flower at pH 6.5 may have lowered the numbers of flowers and fruits, as well as the fruit-set percentage. At pH 3.5, the number of flowers was highest after 16 June (Table 4), and leaf area was similar among the pH 3.5–5.5 treatments (Fig. 2). Therefore, the relative increase in the number of flowers at pH 3.5 may have caused the small leaf area per flower (Table 7), resulting in a reduction in the fruit-set percentage after 16 June (Table 6).

The percentage of upright style flowers, which are incapable of fruit-set (e.g., Ishihata, 1981), increased at pH 3.5 after 16 June (Table 8), suggesting that the higher frequency of upright style flowers was another reason for the low fruit-set percentage after 16 June.

Fruit quality

Fruit in the pH 4.5 and 5.5 treatments were heavier and larger than the fruit in the other treatments (Table 9). Peel color after ripening was better at a pH of 4.5 and 5.5, although the peel color immediately after harvesting was not affected by soil pH. TA was lower and TSS was higher at pH 4.5 and 5.5 than the other treatments, and the sugar/acid ratio was highest at pH 4.5

(Table 10). Conversely, at pH 6.5, the peel color after ripening was worse and peel wrinkling was more severe, and peel weight was the lightest among the treatments. The juice percentage increased as the soil pH increased. The leaf/fruit ratio was higher at pH 3.5 and 4.5. In a previous report (Kondo and Higuchi, 2011), passion fruit weight and dimensions, as well as the sugar/acid ratio, increased and peel color improved as

Table 4. Changes in the number of flowers per fruit bearing vine of ‘Summer Queen’ passion fruit.

Soil pH treatment	The number of flowers		
	14 May–31 May	1 June–15 June	16 June–25 June
3.5	5.25 a	6.54 a	2.71 a
4.5	4.75 a	6.79 a	2.00 ab
5.5	5.04 a	6.46 a	1.58 bc
6.5	4.71 a	6.04 a	1.13 c

Different letters within a column indicate statistical differences by Tukey’s test at $P < 0.05$ ($n = 24$).

Table 5. Changes in the number of fruits per fruit bearing vine of ‘Summer Queen’ passion fruit.

Soil pH treatment	The number of fruits		
	14 May–31 May	1 June–15 June	16 June–25 June
3.5	4.88 a	4.79 ab	1.88 a
4.5	4.54 a	5.33 a	1.75 a
5.5	4.79 a	4.92 ab	1.46 ab
6.5	4.17 a	4.00 b	0.88 b

Different letters within a column indicate statistical differences by Tukey’s test at $P < 0.05$ ($n = 24$).

Table 6. Changes in the fruit-set percentage of ‘Summer Queen’ passion fruit.

Soil pH treatment	Fruit-set percentage (%)		
	14 May–31 May	1 June–15 June	16 June–25 June
3.5	93.6 ab	73.2 bc	70.3 b
4.5	97.3 a	80.0 a	93.3 a
5.5	95.8 ab	77.1 ab	94.6 a
6.5	90.9 b	67.1 c	80.8 ab

Different letters within a column indicate statistical differences by Fisher’s exact test $P < 0.05$.

Table 7. Effects of soil pH on the total numbers of flowers and fruits per fruit bearing vine, total fruit-set percentage, leaf/flower ratio, and leaf area per flower of ‘Summer Queen’ passion fruit.

Soil pH treatment	Number of flowers	Number of fruits	Fruit-set (%)	Leaf/flower ratio	Leaf area per flower (m ²)
3.5	14.46 a	11.50 a	80.00 b	1.74 a	0.022 bc
4.5	13.50 a	11.58 a	87.97 a	1.85 a	0.027 a
5.5	13.25 a	11.33 a	86.62 a	1.88 a	0.026 ab
6.5	11.54 b	8.79 b	77.57 b	1.75 a	0.021 c

Different letters within a column indicate statistical differences by Tukey’s test at $P < 0.05$ (number of flowers and fruits: $n = 24$, leaf area per flower and leaf/flower ratio: $n = 8$) and by Fisher’s exact test (fruit-set).

the leaf/fruit ratio increased, and an increase in photosynthate per fruit may improve fruit quality. The plants grown in soil with a pH of 4.5 grew well (Fig. 2) and the leaf/fruit ratio was higher, suggesting that high assimilation may improve fruit weight and dimensions, peel color, and the sugar/acid ratio. The fruit quality at pH 5.5 was as high as that at pH 4.5. In the pH 5.5 treatment, the lower pH value than the target level (Fig. 1) was likely to positively affect fruit quality. Meanwhile,

fruit quality decreased at pH 3.5, although the leaf/fruit ratio at pH 3.5 was as high as that at pH 4.5. At pH 3.5, the number of flowers after 16 June was highest (Table 4) and the leaf area per flower was smaller (Table 7). These results suggest that relatively excess flowering at pH 3.5 caused the consumption of photosynthate and a relative reduction in matter distribution to the fruit, resulting in a deterioration in fruit quality.

It was reported that acid content decreased and TSS increased as DAP increased (Shiomi et al., 1996; Macha et al., 2006). In this study, however, TA was highest and TSS was lowest at pH 6.5, although DAP was longer at pH 3.5 and 6.5. The leaf/fruit ratio at pH 6.5 was lowest (Table 10) where the shortage of matter distribution into fruit was likely to delay ripening, resulting in a longer DAP.

Leaf mineral contents

Leaf N, Mn, and Zn contents decreased as soil pH increased (Table 11). Similarly, Kondo et al. (2017) reported that leaf Mn and Zn contents decreased as soil

Table 8. Changes in the percentage of upright style flower of ‘Summer Queen’ passion fruit.

Soil pH treatment	The percentage of upright style flowers (%)		
	14 May–31 May	1 June–15 June	16 June–25 June
3.5	0.00 a	0.00 a	21.54 a
4.5	0.00 a	0.00 a	2.08 b
5.5	0.00 a	0.00 a	2.63 b
6.5	0.00 a	0.00 a	0.00 b

Different letters within a column indicate statistical differences by Fisher’s exact test $P < 0.05$.

Table 9. Effects of soil pH on fruit weight, dimensions, peel color, wrinkle degree, and peel weight of ‘Summer Queen’ passion fruit.

Soil pH treatment	Weight (g)	Length (mm)	Diameter (mm)	Peel color ^z		Wrinkle degree ^y	Peel weight (g)
				At Harvest	After 10-day storage		
3.5	87.5 b	65.1 b	60.5 b	2.6 a	4.3 ab	1.5 b	41.7 b
4.5	94.6 a	67.9 a	63.0 a	2.9 a	4.6 a	1.3 b	44.5 a
5.5	95.1 a	67.6 a	62.7 a	2.8 a	4.6 a	1.5 b	43.7 ab
6.5	81.3 c	66.5 ab	60.0 b	2.5 a	4.2 b	2.0 a	35.5 c

Different letters within a column indicate statistical differences by Tukey’s test at $P < 0.01$ ($n = 90, 89, 84$, and 83 for soil pH 3.5, 4.5, 5.5, and 6.5 treatments, respectively).

^z: Peel color was estimated visually at 5 levels (1: pale green to 5: dark purple).

^y: Wrinkle degree was estimated visually at 5 levels (1: no wrinkles to 5: severe wrinkles).

Table 10. Effects of soil pH on titratable acidity (TA), total soluble solid content (TSS), sugar/acid ratio, juice percentage, leaf/fruit ratio, and days after pollination to harvest (DAP) of ‘Summer Queen’ passion fruit.

Soil pH treatment	TA (%)	TSS (°Brix)	Sugar/acid ratio	Juice percentage (%)	Leaf/fruit ratio	DAP
3.5	2.74 ab	14.3 b	5.3 bc	35.1 b	6.19 a	62.3 a
4.5	2.62 b	16.2 a	6.4 a	36.2 ab	6.19 a	59.9 b
5.5	2.72 b	15.7 a	5.9 ab	37.0 a	6.06 ab	59.8 b
6.5	2.93 a	13.5 b	4.7 c	37.7 a	5.16 b	62.4 a

Different letters within a column indicate statistical differences by Tukey’s test at $P < 0.01$ (Data excluding leaf/fruit ratio: $n = 90, 89, 84$, and 83 for soil pH 3.5, 4.5, 5.5, and 6.5 treatments, respectively; leaf/fruit ratio: $n = 8$).

Table 11. Effects of soil pH on the leaf mineral contents (dry weight basis) of ‘Summer Queen’ passion fruit.

Soil pH treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (ppm)	Mn (ppm)	Zn (ppm)
3.5	5.1 a	0.3 a	2.88 a	1.12 b	0.2 b	40.7 a	316 bc	54.4 a
4.5	4.7 a	0.3 a	2.13 b	2.35 a	0.2 ab	41.7 a	549 a	41.7 ab
5.5	4.2 b	0.3 a	2.23 b	2.88 a	0.25 a	26.4 a	369 b	27.5 bc
6.5	3.9 b	0.3 a	2.31 b	2.69 a	0.20 ab	32.8 a	228 c	20.9 c

Different letters within a column indicate statistical differences by Tukey’s test at $P < 0.05$ ($n = 6, 8, 8$, and 6 for soil pH 3.5, 4.5, 5.5, and 6.5 treatments, respectively).

pH increased in passion fruit. Leaf N, Mn, and Zn are closely related to chlorophyll biosynthesis and photosynthesis (Mae et al., 2001; Masuda, 1988). A deficiency in these minerals may have lowered the photosynthetic rate and SPAD index at a pH of 6.5 (Tables 2 and 3).

Leaf K content was highest at pH 3.5, while Ca and Mg contents were lowest. A previous study found that leaf K content and TA increased as K nutrient concentration increased in passion fruit (Kondo and Higuchi, 2013a). Kondo and Higuchi (2014) also reported that the leaf Ca content decreased and TA increased at high Ca concentrations in passion fruit. Similarly, our results indicated that TA increased when the leaf K content was high and Ca content was low at a soil pH of 3.5. Leaf P and Fe contents were not affected by soil pH.

Conclusion

Acidic soil with a pH of 4.5 is recommended for producing high-quality passion fruit, although fruit quality did not differ statistically between pH 4.5 and 5.5. Conversely, near-neutral soil (pH 6.5) resulted in decreased vegetative growth, fruit-set percentage, and fruit quality. Thus, recommendable soil for growing passion fruit should be acid such as pH 4.5. To lower the soil pH, the application of organic matter or acid fertilizer (e.g. ammonium sulfate) will be effective. Irrigation with rainwater is also acceptable because it is generally acid. However, extremely acidic soil (pH 3.5) will result in a decreased fruit-set percentage and fruit quality.

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