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Silicic acid and potassium bicarbonate application affect fruit quality of strawberry cultivated in a rhizosphere cooling system at tropical lowland conditions

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ORIGINAL ARTICLE

Abstract

The effect of silicic acid (H_4SiO_4), potassium bicarbonate ($KHCO_3$), and their equal volume combination on strawberry fruit quality was determined on cultivars Festival and Fortuna when grown in a rhizosphere cooling system (RCS) in a completely randomized design. The RCS kept the plants' rhizosphere temperature at 18°C while the shoots were exposed to ambient tropical weather conditions. The treatments were applied either by foliar spraying or root drenching; and were selected due to limited evidence on how they affect strawberry fruit quality in the tropics. Analyzing the effects of the treatments using ANOVA showed that the root application of H_4SiO_4 and foliar application of $KHCO_3$ improved fruit size, mass, and shape of both strawberry cultivars, resulting in better fruit grading under the European Union's standards for fresh market strawberries. Fruit firmness, sweetness index, sugar content, and total soluble solid contents were also improved when treatments containing H_4SiO_4 were applied as foliar spray. Conversely, the root application of $KHCO_3$ adversely affected most of the parameters assessed. Our findings suggest that applying H_4SiO_4 could improve strawberry fruit quality, and root drenching is the most effective method. We therefore recommend root drenching with H_4SiO_4, or foliar application of $KHCO_3$, for improved strawberry fruit quality.

Keywords: cooling system; silicic acid; strawberry; rhizosphere

Introduction

Strawberry (*Fragaria* x *ananassa* Duch) fruit lovers consider various quality parameters before making a purchase. These include fruit freshness, berry size, color, taste, and fruit firmness (Fan *et al*., 2021; Rahman *et al*., 2021). In addition to these physical characteristics, physiochemical qualities, such as fruit sugar content, total soluble solids (TSS) content, phenolic compounds content, juice pH, and shelf life are also important to consumers, and the strawberry processing industry (Ebrahimi *et al*., 2012; Fan *et al*., 2021; Tohidloo *et al*., 2018). The main factors responsible for variations in strawberry fruit quality traits are plant nutrition, cultivar (cv.) type, pollination, and environmental/rhizosphere temperature (Paparozzi *et al*., 2018;

Tohidloo *et al*., 2018). Rhizosphere temperature affects growth and development by influencing root development, nutrient uptake, water absorption, and microbial activity (Khan *et al*., 2021; Zhou *et al*., 2024). Studies in the tropics have subsequently proved that growth and development of lettuce and tomato improved when the rhizosphere temperature was lower but within the optimal range (Ilahi *et al*., 2017; Mohammud *et al*., 2016). This suggests that the use of rhizosphere cooling systems (RCS) can improve the production of strawberry and other temperate crops in the tropics. It can further be hypothesized that at the correct rhizosphere temperature, strawberries could be produced in tropical lowland conditions when the shoots are exposed to ambient weather conditions. However, the ambient weather conditions of the tropics can have adverse effects on strawberry plants if the shoots are exposed directly to such conditions. These adverse effects could be reduced by applying silicon (Si), because Si has the potential to improve plant development under stress (Moradtalab *et al*., 2019).

Silicon has not been categorized universally as essential for plant growth; but in 2013, the Association of American Plant Food Control recognized Si as an essential element. The acceptance was premised on the studies that confirmed that silicon nutrients improved the growth and development of an array of crops. These include reducing the effects of salt stress on tomato (Stamatakis *et al*., 2003), increasing rice yield (Nagula *et al.,* 2015; Prakash *et al.,* 2011), improving sugar synthesis in fruits and tubers (Artyszak *et al*., 2016; Realpe and Laane 2008), and controlling fungal diseases, such as powdery mildew on strawberry plants (Jin *et al.,* 2014).

A study conducted by Dodgson *et al.* (2008) reported that some strawberry growers combine Si nutrients with $KHCO_3$ and apply it on their strawberry plants, as they believed it helped to control fungal diseases. This combined application may have additional effects on the growth and development of the strawberry plants; and that is worth studying. Application of silicon fertilizers has also been proven to improve important physical parameters of strawberry fruit (Miyake and Takahashi 1986; Yaghubi *et al*., 2019), although strawberry plants are conventionally classified as silicon non-accumulating plants (Epstein 1999). These studies, nonetheless, were carried out in environments known to be suitable for strawberry cultivation, and mostly involved the use of conventional silicon fertilizers (silica and silicates). These conventional silicon fertilizers may not be readily available for uptake by non-silicon-accumulating plants (Peris-Felipo *et al*., 2020). Hence, to have the maximum effect of Si on Si non-accumulating plants, such as strawberry, using the bio-available form (silicic acid) could be an ideal option.

Generally, root application of conventional silicon nutrients has been proven to have the best impact on the overall performance of strawberry plants (Dehghanipoodeh *et al*. 2016; Peris-Felipo *et al*., 2020), while root application of bicarbonates has been reported to have adverse effects on crops (Jelali *et al*., 2011; Lee *et al*., 2014). Notwithstanding these findings, identifying the best mode of applying silicic acid (H_4SiO_4) and bicarbonates for improved strawberry growth and development is important, especially when bicarbonates are used to produce lighter strawberry fruits (Abd-El-Kareem *et al*., 2020). The extent to which the root application of $KHCO_3$ affects the quality of strawberry fruit is also limited, although it is often used in organic and ecological farming systems. The current study thus aimed to determine how foliar application or root drenching with H_4SiO_4, potassium bicarbonate ($KHCO_3$), and their equal volume combination affect fruit quality of strawberry cultivars Festival and Fortuna, grown in an RCS at tropical lowland weather conditions of Malaysia. This approach was employed because most studies on Si nutrients used in strawberry production were carried out in cold climates and involved the use of silica and silicates, which may not be readily available for uptake by strawberry plants.

Materials and Methods

Experimental plot location and rhizosphere cooling system

The study was undertaken at a plant nursery of Universiti Malaysia Terengganu (UMT), Kuala Terengganu, Malaysia. Malaysia lies within latitude 2°30'–7°30' N and longitude 99°30'–119.30' E with Kuala Terengganu lying between latitude 5°19′48″ N and longitude 103°08′26″ E. The climate in Malaysia is equatorial with hot and humid weather throughout the year. The average annual rainfall in Malaysia is 250 cm, while the average annual temperature is 27°C. Temperature in Kuala Terengganu may rise to as high as 35°C during day time in the drier months (March–August), and may be as low as 23°C at night during monsoon months (October–February). The annual mean temperature of Kuala Terengganu is, however, estimated as 28°C.

The RCS built to grow the strawberry plants was placed under a polythene tunnel at the study location. The polythene tunnel measured 30 m × 15 m and had a mesh on two sides to improve air circulation. The RCS was designed to keep the rhizosphere of strawberry plants at a mean temperature of 18°C and was a modification of the RCS designed by Osei *et al.* (2023). The key components of RCS were a cooling unit and a trough system. The cooling unit had a water tank that held water kept at 9°C, and water pumps that pumped chilled water from the tank to circulate through polyvinyl chloride (PVC) pipes arranged in a loop in the troughs. The troughs were lined with linoleum, with coir and perlite as growth media. The troughs were covered with a white plastic sheet and the strawberry plants were planted in holes created in the plastic cover.

Planting materials and growth conditions

Runner plants of strawberry cultivars Festival and Fortuna (Florida Radiance) were obtained from Cameron Highlands, Malaysia, and grown in the RCS at a spacing of 15 cm between plants for a period of 6 months (22 February 2022 to 22 August 2022). The daughter plants selected had three leaves and visually looked healthy. Depending on the plants' phenology, standard strawberry fertilizer (CH-Fertilizer, prepared by the Malaysian Agricultural Research and Development Institute) was applied at a 3-day interval through the roots at an electrical conductivity of 1.3–5 deciSiemens per meter (dS/m) throughout the study period. The CH-fertilizer was applied at 1.3 dS/m in the first 3 weeks after transplanting and increased to 3.5 dS/m after the third week until the appearance of flower buds. At the reproductive phase, the conductivity of the CH-fertilizer applied was increased to 5 dS/m until the end of the study.

Experimental design and plant management

The study was designed in such a manner that plants of both cultivars were offered foliar spray or root applications of H_4SiO_4 (72%; Siben Co. Ltd., Taiwan) and $KHCO_3$ (M&M Chemicals, UK), or their equal volume combination, at H_4SiO_4 0.25% (v/v) and $KHCO_3$ 0.5% (s/v), as recommended by Jin *et al.* (2014). The treatments were randomly applied to the plots with five plants in three replications and started 21 days after transplanting. The treatments were applied on weekly basis for 5 weeks. For the root, and spray applications, only 45 mL of each treatment was applied.

Fruit size, mass, and shape

Fruit size, mass, and shape measurements were taken for 40 randomly picked strawberries from each treatment and control group. The fruit length and diameter across the equatorial region were measured using a CFC digital calliper whereas the shape was visually categorized based on the degree of malformation (nubbin). The categorization was done as 'no nubbins,' 'moderate nubbins,' and 'severe nubbins.' The mass of fruits, on the other hand, was taken by weighing each fruit on a digital scale, and the treatment mean values were determined. Based on fruit mass, diameter, and degree of malformation, the fruits were classified according to the European Union (EU) Marketing Standards for Fresh Fruits and Vegetables (EC No. 543/2011, June 2011). Fruits grouped in the 'extra class' conformed to all the physical requirements of strawberries stipulated in the EU regulation and had a fruit diameter >25 mm. Those placed in 'class I' conformed to the visual requirements and had a fruit diameter ranging from 25 mm to 18 mm. Fruits in 'class II' had allowable defects and a diameter of 25–18 mm. The fruits that did not meet the EU standards were classified as rejected. All fruits used for assessments were fruits that set within the first 5 weeks after treatment application ended; and were picked at harvest maturity (90% ripeness).

Fruit color

In all, 40 fruits were sampled for physical quality assessment and had their color measured with a chroma meter (CR-400, Konica Minolta Sensing Inc., Japan). The CIELAB color space $L^*a^*b^*$ values for each fruit were measured from the side of the fruit, and the mean $L^*a^*b^*$ values were obtained. The mean $L^*a^*b^*$ values were used to compute fruits' chroma as $C^* = (a^{*2} + b^{*2})^{1/2}$ and hue angle as h(°) = arctangent $[b^*/a^*]$, as described by McGuire (1992).

Fruit firmness

The firmness of 40 fruits of similar sizes from all the treatments was determined over a 6-week period at harvest maturity. Fruits selected for the assessment were placed on a firm surface, and their firmness was tested with a penetrometer (Qa Supplies, Italy). The treatment mean value of each cultivar was determined.

Total soluble solids and pH of fruit juice

The TSS content in degree Brix (°Bx) of the 40 fruits used for physical quality assessment was also determined. The fruits were hand-squeezed using cheesecloth into a beaker, and their individual TSS was determined with a hand-held refractometer (Atago Co. Ltd., Japan). The juice from 10 fruits of each treatment, and the control group replication was composited, and the pH of the juice was determined with a Hannah pH meter.

Fruit sugar content and sweetness index (SI)

In all, 15 fully ripened fruits of similar size from each treatment and the control group were randomly sampled and grouped into three replications of five fruits each. Fruits from each replication were cut into smaller pieces and then blended with a blender for 2 minutes at maximum speed. The homogenate was filtered through Whatman No. 1 filter paper after being squeezed through cheesecloth. Each of the three replications had 5 mL of its filtrate diluted with 10 mL of distilled water, and a syringe filter was used to filter 2 mL of the filtrate into a high-performance liquid chromatography (HPLC) vial for analysis.

A Shimadzu (Shimadzu Cooperation, Japan) HPLC machine with an RI-detector (RID-20A) thermostated at 30°C and a temperature-regulated column oven at 30°C integrator were used for sugar analysis. The technique used for sample preparation was a modification of the procedure described by Bogdanov and Baumann (1988). Standard solutions of 0.5%, 1%, and 2% of fructose, glucose, sucrose, and maltose (Merck, Sigma-Aldrich) were prepared with distilled water and acetonitrile (HPLC grade, J.T. Baker Inc., USA) at 50:50 (v/v), while the mobile phase used was water and acetonitrile at 20:80 (v/v). The mass of fructose, glucose, sucrose, and maltose (in g/100 g) of samples was determined as described by Bogdanov *et al.* (2002).

The total sugar content of the two strawberry cultivars was also computed, and the sweetness index determined as described by Keutgen and Pawelzik (2007). The sweetness perception was calculated based on the assertion that fructose is 2.3, and sucrose is 1.35 times sweeter than glucose.

Data analysis

Microsoft Excel 2010 was used for data processing and graphs construction. All data are presented as mean values. A one-way ANOVA was used to evaluate the difference between treatments whereas Tukey's test was used for multiple comparisons. Stata 14 statistical software was used for analysis of all statistical data.

Results

Fruit size, mass, and shape

The treatment application had different effects on fruit size, mass, and shape, with significant differences ($P < 0.05$) noted in the fruit mass of cv. Fortuna (Table 1). The root application of H_4SiO_4 resulted in the highest fruit length in both cultivars (Festival [27.15 mm], and Fortuna [32.12 mm]) and the highest fruit diameter (32.12 mm) in cv. Fortuna. The root application of $KHCO_3$, on the other hand, produced the smallest fruit length in both cultivars (Festival [24.88 mm] and Fortuna [28.36 mm]) (Table 1).

On fruit mass, foliar application of H_4SiO_4 + $KHCO_3$ led to the highest fruit mass in cv. Festival (7.34 g), with no significant differences ($P > 0.05$) observed among the treatments. Conversely, root application of H_4SiO_4 alone resulted in the highest fruit mass in cv. Fortuna (12.2 g). This was significantly different ($P < 0.05$) when compared to the lowest value (7.87 g); which was recorded when $KHCO_3$ was applied to cv. Fortuna via the roots (Table 1).

Smaller fruits were produced when treatments containing $KHCO_3$ were applied through root applications; but fewer nubbins were noticed. Thus, no or moderate nubbins were found in 87.5% of the harvested fruits of cv. Festival when the roots were drenched with $KHCO_3$. Less severe nubbins were also noticed in cv. Fortuna, with 87.5% of strawberries from plants treated with H_4SiO_4 alone or in combination with $KHCO_3$ having no signs of nubbins. When compared to the treatment values, the control plants of cv. Festival recorded a high percentage (27.5%) of the fruits classified as having severe nubbins (Table 1).

Fruit classification

The application of H_4SiO_4 through the roots and the foliar application of $KHCO_3$ led to most of the harvested fruits from these treatments being classified in the top two EU classes for fresh market strawberries (extra class and class I). In both cultivars, significant differences ($P < 0.05$) were observed in the extra class, with the root application of H_4SiO_4 resulting in the highest proportions (cv. Festival [52.5%], and cv. Fortuna [95%]) (Figure 1). The root application of H_4SiO_4 resulted in 100% of the harvested fruits of cv. Fortuna being classified in the top two classes, while foliar application of $KHCO_3$ led to 87.5% of the fruits in the top two classes. Contrarily, the root application of treatments containing $KHCO_3$ led to poor classification in both cultivars (Figures 1A and 1B).

Fruit firmness

Applying $KHCO_3$ either through foliar spraying or root drenching led to less firm fruits being produced in both cultivars (Figure 2). Conversely, the root application of H_4SiO_4 resulted in the firmest fruits in both cultivars. The firmest strawberries of cultivar Festival (1.36 kg/cm^2) was significantly different ($P < 0.05$) from that recorded when $KHCO_3$ was applied as a root drench (0.91 kg/cm^2) or as foliar spray (0.96 kg/cm^2). In cultivar Fortuna, the root application of H_4SiO_4, which led to the firmest fruits (0.81 kg/cm^2), was only significantly different ($P < 0.05$)

Table 1. Fruit quality assessment of strawberry cultivars Festival and Fortuna after application of silicic acid (H_4SiO_4) and potassium bicarbonate ($KHCO_3$) on the plants.

Cultivar	Treatment	Fruit size (mm)			Fruit shape (nubbin %)		
		Mass (g)	Length	Diameter	No	Moderate	Severe
Festival	Control	6.50±0.6**	26.85±2.7	22.36±0.6	47.50±4.7	25.50±5.0	27.50±4.7^{a}
	H_4SiO_4 (root)	7.08±0.4	27.15±1.9	22.91±1.0	50.00±7.0	35.00±9.5	15.00±2.8^{a,b}
	H_4SiO_4 (foliar)	6.40±0.6	26.43±1.1	23.08±0.5	47.50±4.7	37.50±6.2	15.00±2.9^{a,b}
	$KHCO_3$ (root)	5.81±0.9	24.88±2.6	21.94±1.1	65.81±6.4	22.50±4.7	12.50±2.5^{b}
	$KHCO_3$ (foliar)	7.21±0.4	27.06±5.4	23.04±0.6	47.50±8.5	40.00±8.1	12.50±2.5^{b}
	H_4SiO_4 + $KHCO_3$ (root)	6.99±0.2	25.96±2.2	20.93±0.3	52.5±0.2	30.00±7.0	17.50±2.5^{a,b}
	H_4SiO_4 + $KHCO_3$ (foliar)	7.34±0.3	26.56±2.6	22.73±0.2	50.00±4.0	32.50±2.5	17.50±2.5^{a,b}
Fortuna	Control	9.58±1.1^{a,b}	28.93±0.7	27.36±0.4	80.00±4.0	17.50±6.3	2.50±1.0^{b}
	H_4SiO_4 (root)	12.20±0.7^{a}	32.12±0.8	29.18±1.1	87.50±2.5	12.50±2.5	–
	H_4SiO_4 (foliar)	10.98±0.4^{a,b}	30.61±0.9	28.05±0.9	82.50±2.5	17.50±2.5	–
	$KHCO_3$ (root)	7.87±0.2^{b}	28.36±0.7	26.44±0.9	77.50±2.5	20.00±1.5	2.50±1.0^{b}
	$KHCO_3$ (foliar)	10.69±0.6^{a,b}	29.64±0.9	25.73±1.3	82.50±2.5	12.50±2.5	5.00±0.1^{a}
	H_4SiO_4 + $KHCO_3$ (root)	10.24±0.6^{a,b}	30.22±0.8	27.73±0.5	87.50±2.5	12.50±2.5	–
	H_4SiO_4 + $KHCO_3$ (foliar)	10.38±0.7^{a,b}	29.89±1.2	27.23±1.5	77.50±4.7	22.50±4.7	–

**Data show mean ± standard error (SE; n = 40).
Different superscripted letters indicate significant differences among treatments for that cultivar (Tukey's test; $P < 0.05$).

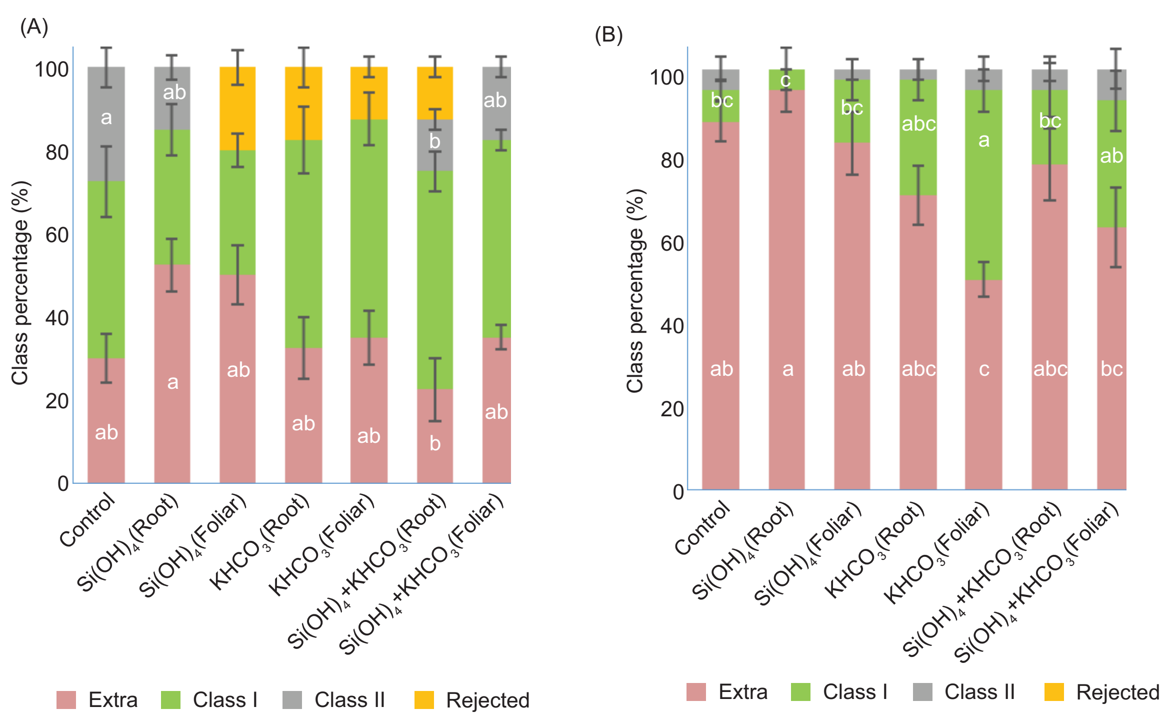

Figure 1. Fruit classification based on the European Union (EU) standards for fresh market strawberries for cultivars (A) Festival and (B) Fortuna after applying H_4SiO_4, $KHCO_3$, and their equal volume combination on the plants. Bars indicate standard error (SE; n = 40). Different letters indicate statistical differences by Tukey's test at $P < 0.05$.

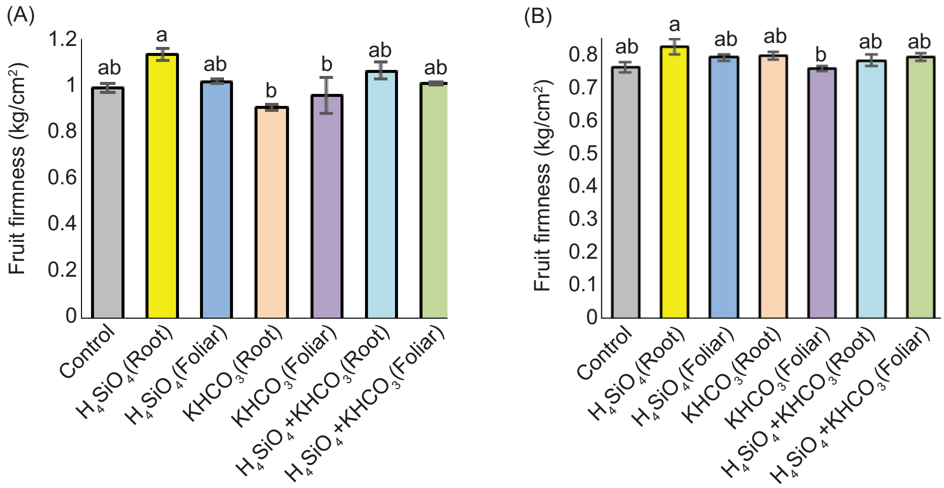

Figure 2. Fruit firmness of strawberry cultivars (A) Festival and (B) Fortuna after applying H_4SiO_4, $KHCO_3$, and their equal volume combination on the plants. Bars indicate standard error (SE; n = 40). Different letters indicate statistical differences by Tukey's test at $P < 0.05$.

from fruit of plants that received $KHCO_3$ as a foliar spray (Figures 2A and 2B).

Fruit color

The mode of applying the treatments influenced fruit color differently; as the root application of $KHCO_3$ and the control plants produced lighter red strawberries, treatments of H_4SiO_4 enhanced the redness of the strawberries (Table 2). The lightest fruits in both cultivars (Festival [45.69], and Fortuna [42.79]) were produced in plants administered the root application of $KHCO_3$, while the fruits with the top two chroma values (cv. Festival [40.15, 39.8], and cv. Fortuna [40.25, 39.84]) were from strawberry plants that received root or foliar application of H_4SiO_4. These values were significantly different ($P < 0.05$) from the other treatment mean values; with the exception of cv. Fortuna plants given root or foliar application of H_4SiO_4 + $KHCO_3$. High hue angles were also recorded in the control plants and plants treated with $KHCO_3$ via the roots (Table 2).

Table 2. Fruit color assessment of strawberry cultivars Festival and Fortuna after application of silicic acid (H_4SiO_4) and potassium bicarbonate ($KHCO_3$) on the plants.

Cultivar	Treatment	*L**	*a**	*b**	*a*/b**	Chroma	Hue angle
Festival	Control	40.71±1.2^{b}	29.59±0.2^{b}	20.26±0.5^{a,b}	1.46±0.05^{d}	35.87±0.3^{b}	34.39±0.9^{a}
	H_4SiO_4 (root)	40.68±0.4^{b}	34.28±0.6^{a}	20.90±0.2^{a,b}	1.64±0.03^{b,c}	40.15±0.6^{a}	31.39±0.5^{b,c}
	H_4SiO_4 (foliar)	40.49±0.1^{b}	33.06±0.2^{a}	22.15±0.1^{a}	1.49±0.02^{c,d}	39.80±0.2^{a}	33.82±0.4^{a,b}
	$KHCO_3$ (root)	45.69±0.1^{a}	28.64±0.3^{b}	18.88±0.1^{b,c}	1.52±0.02^{c,d}	34.30±0.3^{b,c}	33.40±0.3^{a,b}
	$KHCO_3$ (foliar)	41.11±0.6^{b}	29.99±0.2^{b}	17.21±0.3^{c,d}	1.74±0.04^{a,b}	34.58±0.3^{b,c}	29.84±0.5^{c,d}
	H_4SiO_4 + $KHCO_3$ (root)	41.41±0.5^{b}	29.51±0.6^{b}	16.89±0.7^{c,d}	1.75±0.04^{a,b}	34.00±0.9^{b,c}	29.75±0.6^{c,d}
	H_4SiO_4 + $KHCO_3$ (foliar)	41.33±0.5^{b}	29.15±0.6^{b}	15.99±0.6^{d}	1.83±0.05^{a}	33.26±0.8^{c}	28.73±0.6^{d}
Fortuna	Control	40.92±0.79**	30.67±0.8^{d,e}	19.98±0.5	1.54±0.05	36.62±0.7^{c}	33.10±0.9^{a,b}
	H_4SiO_4 (root)	40.98±0.83	35.02±0.3^{a}	19.82±0.6	1.77±0.06	40.25±0.3^{a}	29.50±0.8^{b}
	H_4SiO_4 (foliar)	40.83±0.39	34.18±0.4^{a,b}	20.45±0.5	1.67±0.04	39.84±0.5^{a,b}	30.89±0.6^{a,b}
	$KHCO_3$ (root)	42.79±0.94	29.70±0.7^{e}	19.95±0.6	1.49±0.04	35.78±0.8^{c}	33.88±0.7^{a}
	$KHCO_3$ (foliar)	40.30±0.14	31.72±0.2$^{c–e}$	19.76±0.6	1.61±0.05	37.38±0.4^{c}	31.90±0.7^{a,b}
	H_4SiO_4 + $KHCO_3$ (root)	41.28±0.45	32.84±0.2^{b,c}	19.01±1.3	1.76±0.14	38.01±0.6$^{a–c}$	29.99±1.8^{a,b}
	H_4SiO_4 + $KHCO_3$ (foliar)	41.30±0.40	32.11±0.1^{c,d}	19.73±0.2	1.63±0.01	37.69±0.2^{b,c}	31.57±0.2^{a,b}

**Data show mean ± standard error (SE; n = 40).
Different superscripted letters indicate significant differences among treatments for that cultivar (Tukey's test; $P < 0.05$).

Fruit pH

The application of the treatments reduced the pH of strawberry fruit juice. Thus, the highest pH in both cultivars (Festival [3.81], and Fortuna [3.82]) was recorded in the control plants. However, significant difference ($P < 0.05$) was only observed when the values determined in cv. Fortuna were compared to its lowest pH value (3.41). In cv. Fortuna, the lowest value was observed when foliar application of $KHCO_3$ was applied to the plants (Table 3).

Total soluble solids

Applying H_4SiO_4 increased the TSS of strawberry fruits. In cv. Festival, supplying H_4SiO_4 alone through the roots led to the highest fruit TSS (8.52 °Bx) whereas combining H_4SiO_4 and $KHCO_3$ as a foliar spray resulted in the highest TSS in the fruits of cv. Fortuna (6.88 °Bx). Both values, however, were significantly different ($P < 0.05$) from the lowest values (cv. Festival [6.76 °Bx], and cv. Fortuna [5.55 °Bx]), which were determined in the fruits of plants that received root application of $KHCO_3$. Combining H_4SiO_4 and $KHCO_3$ as a foliar spray also resulted in the second highest TSS in cv. Festival, an indication that foliar application of the combination was suitable for pigment synthesis in both cultivars (Table 3).

Fruit sugar content and sweetness index

There were no significant differences ($P > 0.05$) in the sugar content of fruits of cv. Festival treated plants. However, root drenching with H_4SiO_4 led to the highest fructose (2.83 g/100 g) and glucose content (2.84 g/100 g), while the root application of $KHCO_3$ resulted in the highest sucrose content (0.15 g/100 g). In cv. Fortuna, significant differences ($P < 0.05$) were observed in the fruits' glucose content, with the root application of H_4SiO_4 leading to the highest value (1.90 g/100 g). This was significantly different ($P < 0.05$) from the lowest value, which was recorded when H_4SiO_4 was combined with $KHCO_3$ and applied via the roots. Root or foliar application of H_4SiO_4 also led to the highest fructose content (1.64 g/100 g), while the foliar application of H_4SiO_4 produced the highest sucrose content in the cv. Fortuna fruits (Table 3).

In both cultivars, the highest total sugar content (cv. Festival [6.2 g/100 g], and cv. Fortuna [4.0 g/100 g]) was determined when H_4SiO_4 was applied. In cv. Fortuna, there were significant differences ($P < 0.05$) between the highest total sugar content, which was recorded when the plants were provided foliar application of H_4SiO_4, and the lowest (2.06 g/100 g), which was observed in plants given root application of $KHCO_3$ combined with H_4SiO_4. The highest total sugar content in cv. Festival was however observed when H_4SiO_4 was applied as a root drench; but there was no significant difference ($P > 0.05$) when it was compared to other treatment mean values (Table 3).

Root or foliar application of H_4SiO_4 improved fruit sweetness index of both strawberry cultivars. The highest sweetness index in cv. Festival (9.43) was observed when H_4SiO_4 was applied via the roots, while the highest sweetness index was recorded in cv. Fortuna (5.98) when H_4SiO_4 was applied via foliar spraying. Both values were only significantly different ($P < 0.05$) from the lowest mean values (cv. Festival [3.22], and cv. Fortuna [3.58]), which were determined when $KHCO_3$ was applied as a root drench in cv. Festival, or in combination with H_4SiO_4 in the case of cv. Fortuna (Table 3).

Discussion

Fruit size, mass, and shape

The strawberry fruit data analyzed demonstrated that applying H_4SiO_4 improved fruit size in the RCS, with root application being the most effective method for both cultivars. Similarly, applying 50-ppm potassium silicate improved fruit size of strawberry cultivar Camerosa in an outdoor hydroponic study (Ghasemi *et al.*, 2020). Strawberry cultivars Kurdistan and Paros also recorded increase in fruit size under NaCl stress after applying potassium silicate (Yaghubi *et al.*, 2019). This confirms that silicates which may not be readily available for uptake by silicon non-accumulating plants such as strawberries, improved strawberry fruit size. Therefore, the increased fruit size observed when H_4SiO_4 was applied in the RCS could be attributed to the treatment. A contrary view suggests that the nature of growth media influences silicon's effect on strawberry fruit size, thus concluding that Si application improves strawberry fruit size should be done with care (Peris-Felipo *et al.*, 2020).

On fruit mass, applying H_4SiO_4 via the roots had the greatest impact in the RCS, while root application of $KHCO_3$ was counterproductive. Similarly, potassium silicate and other silicon nutrients are reported to have improved individual strawberry fruit mass in organic farming, field trials, and growing tunnels (Ouellette *et al.*, 2017; Weber *et al.*, 2018). Silicic acid as a root drench on cv. Fortuna also resulted in a significant increase in individual fruit mass either under iron or without iron deficiency (Peris-Felipo *et al.*, 2020). The control plants and plants given root application of $KHCO_3$ having fruits of lesser mass in the RCS is likewise in line with the findings of Ouellette *et al.* (2017), who recorded lower strawberry fruit mass in the control plants when Si nutrients were applied.

Table 3. **Fruit sugar content (g/100 g), physiochemical properties, and sweetness index (SI) of strawberry cultivars Festival and Fortuna after application of silicic acid (H_4SiO_4) and potassium bicarbonate ($KHCO_3$) on the plants.**

Cultivar	Treatment	pH	TSS (°Bx)	Fructose	Glucose	Sucrose	Maltose	Total Sugar	SI
Festival	Control	3.81±0.1**	7.87±0.1^{a,b}	2.53±0.2	2.65±0.4	0.06±0.04	0.47±0.2	5.72±0.7	8.55±0.7^{a,b}
	H_4SiO_4 (root)	3.76±0.1	8.52±0.3^{a}	2.83±0.4	2.84±0.4	0.07±0.02	0.47±0.2	6.20±0.9	9.43±1.2^{a}
	H_4SiO_4 (foliar)	3.71±0.1	7.78±0.1^{a,b}	1.54±0.1	2.34±0.2	0.07±0.03	0.57±0.1	4.52±0.2	5.98±0.4^{a,b}
	$KHCO_3$ (root)	3.58±0.2	6.76±0.7^{b}	0.98±0.6	0.76±0.6	0.15±0.01	0.28±0.2	2.18±1.3	3.22±1.8^{b}
	$KHCO_3$ (foliar)	3.75±0.1	7.52±0.2^{a,b}	1.59±0.4	2.1±0.1	0.03±0.02	0.83±0.2	4.61±0.6	5.86±1.1^{a,b}
	H_4SiO_4 + $KHCO_3$ (root)	3.76±0.1	8.43±0.2^{a}	1.70±0.2	1.29±0.6	0.07±0.02	0.37±0.1	3.44±0.6	5.70±0.2^{a,b}
	H_4SiO_4 + $KHCO_3$ (foliar)	3.69±0.1	7.95±0.1^{a,b}	2.25±0.7	2.19±0.6	0.09±0.02	0.57±0.2	5.09±1.5	7.47±2.1^{a,b}
Fortuna	Control	3.82±0.1^{a}	5.93±0.1^{a,b}	1.38±0.1	1.57±0.1^{a,b}	0.17±0.04	0.16±0.01^{a,b}	3.27±0.1^{a,b}	4.96±0.2^{a,b}
	H_4SiO_4 (root)	3.77±0.1^{a}	6.58±0.2^{a}	1.64±0.1	1.90±0.1^{a}	0.14±0.01	0.20±0.05^{a,b}	3.87±0.3^{a}	5.85±0.4^{a,b}
	H_4SiO_4 (foliar)	3.77±0.1^{a}	6.85±0.2^{a}	1.64±0.2	1.89±0.3^{a}	0.23±0.03	0.24±0.07^{a}	4.00±0.5^{a}	5.98±0.8^{a}
	$KHCO_3$ (root)	3.41±0.1^{b}	5.55±0.4^{b}	1.10±0.1	1.21±0.1^{a,b}	0.06±0.01	0.14±0.02^{a,b}	2.50±0.2^{a,b}	3.81±0.4^{a,b}
	$KHCO_3$ (foliar)	3.81±0.1^{a}	6.30±0.1^{a,b}	1.50±0.3	1.66±0.3^{a,b}	0.12±0.08	0.14±0.02^{a,b}	3.42±0.5^{a,b}	5.27±0.8^{a,b}
	H_4SiO_4 + $KHCO_3$ (root)	3.78±0.1^{a}	6.11±0.1^{a,b}	0.90±0.2	1.01±0.2^{b}	0.07±0.02	0.07±0.01^{b}	2.06±0.3^{b}	3.58±0.2^{b}
	H_4SiO_4 + $KHCO_3$ (foliar)	3.80±0.1^{a}	6.88±0.2^{a}	1.37±0.1	1.59±0.1^{a,b}	0.09±0.02	0.17±0.01^{a,b}	3.22±0.2^{a,b}	4.87±0.3^{a,b}

**Data show mean ± standard error (SE; n = 15).
Different superscripted letters indicate significant differences among treatments for that cultivar (Tukey's test; $P < 0.05$).

In a study on peas, yield was adversely affected by high media bicarbonate levels (Jelali *et al.*, 2011). The authors concluded that high bicarbonate levels increased the growth medium's pH, leading to poor nutrient uptake by the plants, thereby resulting in poor yield. Therefore, the lesser mass observed in the fruits of the strawberry plants treated with $KHCO_3$ through the roots in this study was in line with the work of Jelali *et al.* (2011), and Souri and Hatamian (2019); and could have resulted from the poor uptake of nutrients by the strawberry plants.

The H_4SiO_4 treatment and foliar application of $KHCO_3$ improved the fruit shape of both cultivars in the RCS. Factors, such as pollen viability, genotype, flower position within the inflorescence, effects of the environment, and pollination, account for the shape of strawberry fruits (Darrow 1966; Pipattanawong *et al.*, 2009). It has also been reported that SiO_2 and H_4SiO_4 significantly improved strawberry pollen viability (Miyake and Takahashi, 1986; Wileman *et al.*, 2019). Thus, the root application of the treatments containing H_4SiO_4 producing fruits with fever nubbins in this study could be due to H_4SiO_4 increasing strawberry pollen viability, thereby resulting in fruits with fewer nubbins. The improved fruit shape in the $KHCO_3$-treated plants could also be ascribed to the role its K content plays in improving pollen viability. However, this cannot be a definitive cause, as other factors also account for the shape of strawberry fruits.

Fruit classification

Grading of the harvested strawberry fruits demonstrated that applying H_4SiO_4, especially through the roots, and foliar applications of $KHCO_3$, increased the percentage of fruits classified in the top two classes of the EU's standard for fresh market strawberries (extra class and class I). It has been proved in earlier studies that application of Si nutrients improved the factors used in the EU's strawberry fruits grading system. Si nutrients also reduce the adverse effects of temperature stress, improve flower production, and increase nutrient uptake (Dehghanipoodeh *et al.*, 2018). These factors also directly influence the parameters (size and shape) used in the EU's strawberry fruit grading system (Munaretto *et al.*, 2018). Applying potassium silicate was shown to improve the fruit size of strawberry cultivar Camerosa, while the fruit sizes of cultivars Kurdistan and Paros also improved under salt stress (Ghasemi *et al.*, 2020; Yaghubi *et al.*, 2019). However, the effect of Si on the strawberry fruit quality parameters used in the EU's grading system may be insignificant under field conditions (Ouellette *et al.*, 2017). The root applications of $KHCO_3$, on the other hand, led to poor fruit grading in both cultivars. This could be attributed to the root application of bicarbonates blocking iron absorption, which results in poor crop performances (Lee *et al.*, 2014). Abd-El-Kareem *et al.* (2020) observed that foliar application of $KHCO_3$ had an opposite effect, compared to root drenching. The researchers observed that foliar application of $KHCO_3$ improved strawberry fruit size. This is similar to what was observed when $KHCO_3$ was applied as a foliar spray in the RCS.

Fruit firmness

Applying $KHCO_3$ either as foliar spray or as root drench in the RCS resulted in the production of less firm fruits. Contrarily, the root application of H_4SiO_4 resulted in the firmest fruits. Fruit firmness varies extremely, but is useful in evaluating quality, ripening, resistance to injury, and differentiating between cultivars. Supplementing the growing media of strawberry plants with Si nutrients improves fruit firmness of harvested strawberry fruits as proven in earlier studies (Dehghanipoodeh *et al.*, 2016; Munaretto *et al.*, 2018); and this current study confirms that claim. However, firmness of strawberry fruit is not expected to increase if Si nutrients are applied under field conditions (Ouellette *et al.*, 2017). The less firm fruits harvested from plants given root application of $KHCO_3$ in the RCS is also similar to the findings of Jelali *et al.* (2011), who reported poor fruit formation after the application of bicarbonates. This suggests that growers who use $KHCO_3$ as a foliar spray on their strawberry farms have to be careful to avoid runoff, as that could be counterproductive.

Fruit color

The root application of $KHCO_3$ and the control plants produced light colored strawberry fruits whereas treatment with H_4SiO_4 enhanced the redness of fruits in the RCS. Strawberry fruit color is sometimes used as an indirect measure of the fruit's anthocyanin content. Therefore, it has been hypothesized that the lighter the color of a strawberry fruit, the lower the anthocyanin content and *vice versa* (Pathare *et al.*, 2013). Application of Si nutrients and seaweed extract on strawberry cultivar Clery was thus reported to have increased the anthocyanin content of the fruits, resulting in a more reddish harvest (Weber *et al.*, 2018). Other studies (Hajiboland *et al.*, 2018; Munaretto *et al.*, 2018) also arrived at similar observations and that confirms the findings of our study. Weber *et al.* (2018), however, suggested that the application of Si lowered the synthesis of some phenolic compounds in strawberry fruits, which could affect fruit color.

The application of treatments containing H_4SiO_4 in the current study led to lower hue angles in the fruits whereas fruits from the control plants and plants offered root application of $KHCO_3$ had high hue angles. This indicates that fruits of the H_4SiO_4-treated plants leaned toward the scarlet-red color spectrum, which is desirable, whereas the $KHCO_3$-treated plants leaned toward the orange red color spectrum. Root application of bicarbonates results in poor fruit formation (Shamsabad *et al.*, 2021), thus resulting in lower anthocyanin contents. This may have resulted in the high hue angles recorded in the fruits of plants that received $KHCO_3$ via the roots.

Total soluble solids content and pH of fruit juice

Although sugars are the major soluble solids in strawberry fruit juice, other soluble materials may be present (Fan *et al.*, 2021; Pineli *et al.*, 2011). The sugar component of strawberry fruits TSS is thus estimated to be 80%; but this depends on the nutrient status of the plant's growth media. This explains why root application of $KHCO_3$ adversely affected the TSS content of fruits of both cultivars in the RCS whereas applying H_4SiO_4 increased TSS of the fruits. Similarly, Si bio-fortification significantly increased the TSS of strawberry cultivar Elsanta, while the application of potassium silicate as a root drench on cultivars Kurdistan and Paros under NaCl stress significantly improved the fruits' TSS (Valentinuzzi *et al.*, 2018; Yaghubi *et al.*, 2019). Other studies (Munaretto *et al.*, 2018; Soppelsa *et al.*, 2019) also reported increase in strawberry fruit's TSS after application of Si fertilizer but the increase was not significant. Contrarily, Weber *et al.* (2018) observed a decrease in the sugar content of strawberry fruits when Si was applied. The findings by Weber *et al.* (2018) therefore did not align with what was observed in the RCS. The low TSS observed in the fruits of the plants given $KHCO_3$ through the roots in the RCS is however similar to the findings of Shamsabad *et al.* (2021), who proved that applying bicarbonates alone via roots significantly lowered the TSS of strawberries.

The treatments applied also decreased the pH of fruit juice in both cultivars. In a related study (Shamsabad *et al.*, 2021), the application of bicarbonates via the roots significantly lowered the fruit pH of other strawberry cultivars, similar to what was observed in cv. Fortuna in the RCS. Application of Si nutrient also reduced the juice pH of cultivar Fortuna; however, no significant differences were observed (Peris-Felipo *et al.*, 2020). This finding is not in line with what was observed in the RCS.

Fruit sugar content and sweetness index

Fruits of both strawberry cultivars treated with H_4SiO_4 in the RCS had higher sugar contents. This could be due to improved nutrient uptake, which is a characteristic of Si application (Ouellette *et al.*, 2017). In a previous study, the application of H_4SiO_4 through the roots of strawberry cultivar Fortuna resulted in the highest concentration of the major sugars found in strawberry fruits (Peris-Felipo *et al.*, 2020). Again, the application of sodium silicate significantly improved the sugar content of the fruits of strawberry cultivar Paros under varying soil and water conditions (Hajiboland *et al.*, 2018; Moradtalab *et al.*, 2019).

The current study proved that root or foliar application of H_4SiO_4 improved strawberry fruit sweetness index. The sweetness index of fruits is largely influenced by its fructose content, because fructose is regarded as the sweetest of all individual sugars in fruits. Similarly, a previous study showed that strawberry cultivar Fortuna had the highest fructose content when the plants were applied root treatment of H_4SiO_4 (Peris-Felipo *et al.*, 2020). The current study also confirmed that the H_4SiO_4 treatment increased the fructose content of strawberry fruits in the RCS, subsequently resulting in improved sweetness index of the fruits of the treated plants. The lower sweetness index of fruits from plants that were given $KHCO_3$ through the roots could be compared to earlier studies findings which concluded that the root application of bicarbonates resulted in poor nutrient uptake, which led to poor fruit sugar synthesis (Msilini *et al.,* 2009; Wang *et al.*, 2020).

Conclusions

In this study, we determined the effect of foliar or root application of H_4SiO_4 and $KHCO_3$ on the fruit quality of strawberry cultivars Festival and Fortuna, grown in RCS at lowland conditions in Malaysia. We discovered that applying H_4SiO_4 at 0.25% (v/v) improved strawberry fruit size, color, shape, firmness, TSS, sugar content, and sweetness if grown in the RCS. However, the root application of H_4SiO_4 is suggested to be the best mode of application, compared to its foliar application; and the root or foliar application of the other treatments. Foliar application of $KHCO_3$ at 0.5% (s/v) improved some strawberry quality parameters whereas its root applications adversely affected fruit quality. Applying an equal volume mix of H_4SiO_4 and $KHCO_3$ as a foliar spray on strawberry plants also improved fruit size, mass, and sweetness, depending on the cultivar that received it. This study therefore proved that H_4SiO_4 has the potential to be used by farmers to improve the physical and physiochemical quality of strawberry fruits under tropical lowland conditions; however, root application of $KHCO_3$ at 0.5% should be avoided.

Data Availability Statement

The datasets generated and analyzed in this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declared no conflict of interest.

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