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Soluble solids content is positively correlated with phosphorus content in ripening strawberry fruits

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ABSTRACT

Soluble solids content (SSC) is one of the main parameters for evaluating the nutritive value of strawberry (*Fragaria × ananassa*), which is affected by a number of factors including genetics, environmental conditions and cultivation practices. In this study, we found that there was a positive correlation between SSC and phosphorus (P) content in fully ripened strawberry fruits. The positive correlation between SSC and P content was first verified among 24 strawberry cultivars with the correlation coefficient $r = 0.95$. Furthermore it was also verified among strawberry fruits harvested at different dates ($r = 0.96$) and among different parts (top, middle and bottom) of strawberry fruits ($r = 0.87$). To provide further confirmation, plants of strawberry cultivar 'Yanli' in solar greenhouse with the conventional cultivation management were irrigated with different concentrations of P fertilizer (phosphoric acid) once a week from the beginning of white stage and the result showed that P content and SSC in fruits from plants treated with 6.0 mM phosphoric acid increased 45.0% and 16.7%, respectively. Photosynthetic rate (Pn) and water use efficiency (WUE) of phosphoric acid treated plants increased 28.8% and 16.1% compared with the control plants. Our research lays the theoretical basis for improving the flavor of strawberry by applying P fertilizer.

1. Introduction

Strawberry (*Fragaria × ananassa*), one of the most economically important fresh and processed fruits, is cultivated in all arable regions of the globe from the Arctic to the Tropics. It is well known that consumers now pay much more attention to food quality. As a regular part of the diets of millions of people, strawberry is consumed for both its unique flavour and nutrient content throughout the world (Zorrilla-Fontanesi et al., 2011). Strawberry flavor is decided in part by the balance between soluble solids content (SSC) and titratable acid content in ripe fruits. Now, consumers usually prefer sweet strawberries, while sweetness is positively correlated to SSC. Decreasing SSC in strawberries results in lower consumer acceptance of fruits (Keutgen and Pawelzik, 2007), so the SSC value of strawberry fruits is demanded by both consumers and growers.

Genetic factors and environmental conditions affect fruit quality. There is a considerable variation in SSC among different cultivars, and usually the Japanese strawberry cultivars set fruits with a high SSC compared to European cultivars (Yashiro et al., 2002). SSC of strawberry fruits is quantitatively inherited, and it is greatly influenced by environmental conditions (Shaw, 1990). Culture system and cultural practices such as planting time, ground cover, manuring and irrigation have a great impact on variation of SSC in strawberries (Correia et al., 2011; Jouquand et al., 2008; Kirnak et al., 2003; Moshiur Rahman et al., 2014). Fertilizers are extremely important factors in determining strawberry yield and quality. Sufficient nitrogen (N) is essential for normal plant development of strawberry (Papadopoulos, 1987), but high N level can reduced SSC in strawberry fruits (Cantliffe et al., 2007). Potassium (K) is needed in relatively high amounts by strawberries, and high K treatments often increased significantly SSC in strawberry fruits (Ahmad et al., 2014; Hammad et al., 2014).

The effects of phosphorus (P) on quality of strawberry fruits have received little attention. Valentinuzzi et al. (2015) showed when P was deficient in strawberry plants, SSC in fruits significantly decreased. In our previous studies, we found that the fruit of white-flesh mutant of strawberry cultivar 'Sachinoka' was sweeter than the fruit of wild type, and the total soluble sugar content in mutant fruits was significantly higher than that in wild type fruits (Liang et al., 2012). And the content of P in mutant fruits at the color turning stage was 22% higher than that in wild type fruits (Li et al., 2013). So we speculate that there is a positive correlation of SSC with P content in strawberry fruits, and increasing P content in strawberries can result in sweeter strawberries. To verify

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this hypothesis, we measured P and SSC in different kinds of strawberry fruits and increased SSC in strawberry fruits by applying P fertilizer.

2. Materials and methods

2.1. Plant materials

Twenty-five strawberry (*Fragaria* × *ananassa*) cultivars were used in this study, including 6 Japanese cultivars (Sachinoka, White-Flesh Mutant of Sachinoka, Toyonoka, Tochiotome, Benihoppe, Akanekko), 5 American cultivars (Allstar, Honeoye, Totem, Albion, Sweet Charlie), 12 Chinese cultivars (Yanli, Hongxiutianxiang, Xiuli, Dongxiang, Yanxiang, Yongli, Jingchunxiang, Jingquanxiang, Shuxiang, 13–22, 11–5–16, 10–5–2), one Germany cultivar (Brandenburg) and one cultivar (Nuobinka) introduced from Russia. Among them, Sachinoka, Toyonoka, Yanli and Allstar were used for analysis of the ratio of sugar content to SSC, while, all of them were used for analyzing the correlation between SSC and P content except for Allstar. Sachinoka and Sweet Charlie were used for analyzing distribution of P in different parts of strawberry fruits. Yanli was used as the material for P fertilizer application trail. Strawberry plants grew in a plastic covered solar greenhouse of Shenyang Agricultural University under conventional cultivation management. Before planting, 5 m^3 of compost and 15 kg of NPK compound fertilizer (20–5–10) were incorporated into the loamy soil. The plastic mulched hill system was used and young runner plants were planted in soil for 7 inches spacing in early September. Drip irrigation was used and the drip tapes were under plastic film. Strawberry grew and developed under sunlight, and temperatures in the solar greenhouse were 20–25 °C and 5–10 °C for day and night, respectively.

For measuring SSC, P and total sugars contents, fruits at full-red stage were harvested with uniform size. To measure the distribution of P in different parts of fruits, strawberry fruits were transversely cut into three parts: top, middle and bottom. Three fruits were ground together in liquid nitrogen as a sample pool, and three biological replicates were included.

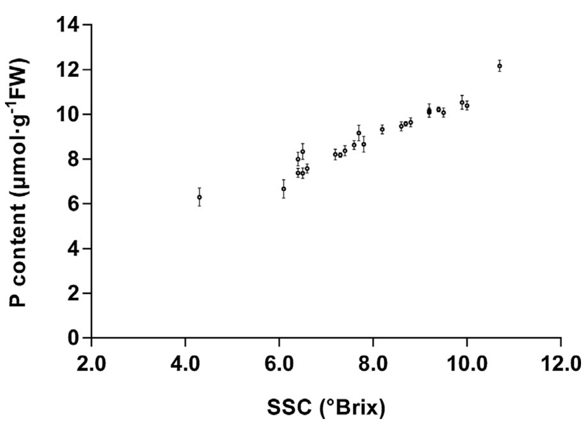

Fig. 1. The scatterplot of SSC compared to P content in fruits of different strawberry cultivars. Error bars represent standard deviation of three biological replicates.

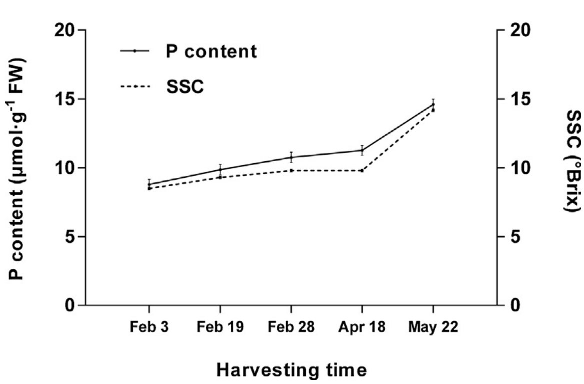

Fig. 2. Changes of SSC and P content of 'Sachinoka' fruit harvested from February to May. The dotted line indicating SSC levels corresponds to the right vertical axis. Error bars represent standard deviation of three biological replicates.

2.2. P measurement

Determination of P content in strawberry fruits was performed by the Mo-Sb colorimetric method (Ames, 1966). After the fruits were ground evenly into powder in liquid nitrogen, 1 g fruit powder was digested in the solution including 5 mL concentrated sulfuric acid at 400 °C for 10 min, subsequently when the solution was cold, 3 mL 30% hydrogen peroxide was added and then the solution was heated up to 400 °C for 30 min. The clear liquor was collected and the total amount of P was determined by the molybdate assay.

2.3. SSC quantity

Fruit powder ground in liquid nitrogen was collected into a 50 mL centrifuge tube and kept at room temperature for thawing. Juice was filtered and used for SSC measurement with a digital pocket refractometer ATAGO PAL-1 (Atago Co. Ltd., Tokyo, Japan). Results were expressed in °Brix.

2.4. Total sugars content quantity

The powder of strawberry fruit (0.2 g) was added into a graduated test tube with 10 mL distilled water and the solution was heated in an 80 °C water bath for 50 min. Then the solution was filtered through qualitative filter paper and the clear solution was used for total sugars content measurement by the anthrone-sulfuric acid assay (Dische, 1962).

2.5. Applying phosphoric acid fertilizer

'Yanli' strawberry plants were irrigated 4.0 mM, 6.0 mM or 8.0 mM phosphoric acid fertilizer once a week from the beginning of white stage. Each plant was irrigated 500 mL of phosphoric acid solution each time, and water as the blank control.

2.6. Photosynthetic efficiency measurement

Photosynthetic efficiency of 'Yanli' strawberry plants irrigated with P fertilizer was measured using a portable photosynthesis system (CIRAS-2, PP Systems, Massachusett, USA) at morning between 09:30 and 11:30 to avoid photoinhibition potentially resulting from high light stress at midday. Measurements were made under saturating photosynthetic photon flux densities (1000 μ mol m^{-2} s^{-1} PPFD) from a LED light source and data were recorded automatically at an interval of 2 min until the net photosynthetic rate (Pn) was stable. The determining parameters included: Pn, internal CO_2 concentration (Ci), stomatal conductance (Gs) and transpiration rate (Tr). And the photosynthetic water use efficiency (WUE) was calculated as the ratio of Pn and Tr, i.e., WUE = Pn/Tr. Responses were determined in ten leaves from different plants for each treatment.

2.7. Statistical analysis

SPSS 20.0 was used for analysis. Analysis of variance (ANOVA) was used to test the statistical significance of differences, and the significance of differences among means was carried out using Duncan's (1955) multiple-range test at the 5% level. The (Pearson)