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Full Length Research Paper

The effects of silicon level in nutrient solution on the uptake and distribution of silicon in zucchini and zinnia, and its interaction with the uptake of selected elements

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The beneficial role of silicon (Si) in the growth of some plants is linked to its uptake and accumulation inside their tissue. However, the optimum level of Si in the nutrient solution that can provide maximum benefits and its interaction with other elements is less understood. A study was conducted to evaluate the impact of different levels of soluble Si in nutrient solutions on the uptake and distribution of Si and other elements into different parts of zucchini and zinnia, and its effects on the growth of these two plants. Increasing the concentrations of Si in the nutrient solution increased the accumulation of Si (in leaves and roots) and potassium (in stem and petiole) and reduced calcium without affecting the levels of magnesium and phosphorus in different organs of both plants. Application of Si at 50 mg L^{-1} resulted in maximal accumulations of P, Ca and Mg in both plants and increased their growth. However, the application of higher levels of Si caused stunting. For optimal benefits, application of Si at 50 to 100 mg L^{-1} is recommended for these plants.

Key words: Accumulation, distribution, growth, silicon, uptake, zinnia, zucchini.

INTRODUCTION

Silicon (Si) is known as the second most abundant element in the earth's crust and among the major inorganic constituents of higher plants (Epstein, 1999; Ma and Takahashi, 2002). Some researchers believe that the essentiality of this element to plant growth has been difficult to demonstrate due to its high abundance in nature (Gali and Smith, 1992). However, when crops with a high Si demand are repeatedly grown in soils with low levels of plant-available Si, then symptoms of Si deficiency are manifested by low productivity and susceptibility of these crops to biotic and abiotic stresses (Epstein, 1994, 2001; Ma and Takahashi, 2002). Recently, the beneficial roles of Si on plant growth and resistance to biotic and abiotic stresses have received considerable attention (Datnoff et al., 1997; Iwasaki and Matsumura, 1999; Ma, 2004; Meyer and Keeping, 2005; Ma and Yamaji, 2006).

The mechanisms of uptake, translocation and accumulation of Si on several plants have been well documented (Raven, 2001; Tamai and Ma, 2003; Liang et al., 2005; Kaya et al., 2006; Rains et al., 2006). The level of Si accumulated in plants and its beneficial effects on growth of these crops have been linearly related to the level of Si supply (Bélanger et al., 1998; Ma and Takahashi, 2002; Ma, 2004). However, excessive application of Si may result in poor fruit quality (Samuels et al., 1993; Lieten et al., 2002). Therefore, with increased application of Si to plants, careful investigation of the relationship between the level of Si application and growth and nutritional composition of plants is needed. The objectives of this research were to investigate the effects of Si supply on:

1. The uptake and distribution of Si, Ca, K, Mg and P to different parts of zucchini and zinnia;
2. Growth of these plants; and
3. Characteristics of the fruits of zucchini and the flowers

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of zinnia.

MATERIALS AND METHODS

Preparation of plants

Seeds of zucchini (*Cucurbita pepo* L. F1-Hybrid Partenon) and zinnia (*Zinnia elegans* Jacq. cv. Jakobrekop Sunbow), obtained from Starke Ayres (South Africa), were sown in seedling® trays containing composted pine bark. The trays were kept in a greenhouse (26 to 28°C and relative humidity of 75 to 85%) and irrigated with 0.5 g NPK 3:1:3 (38) + 0.5 g $Ca(NO_3)_2$ L^{-1} (Ocean Agriculture (Pty) Ltd, South Africa). Seedlings of zucchini and zinnia were transplanted to pots after two and four weeks, respectively, and kept in a nutrient re-circulating system containing 0.5 g NPK plus soluble Si, in the form of K_2SiO_3, at 11 different concentrations (0, 50, 100, 150, 200, 250, 300, 400, 500, 750 and 1000 mg L^{-1}). After six weeks of growth, visual observation was made on the growth of these plants and quality of their produce.

Energy dispersive X-ray fluorescence (EDX) analysis

Leaf samples taken from different positions of each plant were washed thoroughly with distilled water, cut into pieces of approximately 10 mm diameter and fixed overnight in 3% glutaraldehyde in cacodylate buffer (0.1 M; pH 7). Samples were then dehydrated in a graded alcohol series, critical point dried in a Hitachi HCP-2 using carbon dioxide as the transfusion fluid, and mounted onto copper stubs using double-sided carbon tape. Then samples were coated with gold-palladium in a Polaron E500 Sputter Coater. Finally, the accumulation of Si and other elements (C, Ca, Mg, K, O and P) in the samples was assayed using an environmental scanning electron microscope with an energy dispersive X-ray analysis system (ESEM-EDX) and calculated using the fundamental parameter method of the EDX program as used by Marguí et al. (2005).

Inductively coupled plasma-optical emission spectrometers (ICP-OES) analysis of plant tissues for elemental compositions

Preparation of samples

Plants were washed thoroughly using tap water, rinsed in distilled water, and cut into four parts: leaves, roots, flower/fruits, and stem + petioles. Samples were then oven-dried at 70°C for 72 h, and ground into particles less than 1 mm in diameter using a blender. A sample of 0.5 g of each plant material was put into a crucible, kept overnight in a furnace (650°C) and then processed using microwave digestion.

Microwave digestion

All sample digestions were carried with the CEM microwave digester (CEM MARS5™ Microwave) using tarred 100 mL Teflon® PFA digestion vessels. Ash, 5 ml of 65% HNO_3 and 0.1 ml HF (for stem + petioles and fruit/flower) or 1 mL hydrogen fluoride (HF) (for roots and leaves) were put into each vessel. Thirteen (13) vessels, including a reagent blank vessel, were arranged in a scrubber and digestion was performed using the following procedures. The temperature was ramped to 165°C within 10 min with the application of 1200 W power, followed by a dwell time of 20 min at 165°C. The temperature and pressure limits were set to 175°C and 15.2 bar (220 psi), respectively. Once the internal temperature of the microwave was cooled to < 65°C, the vessels were vented in a fume exhaust system to release the residual pressure. Digested samples were diluted to 100 ml with de-ionized distilled water (DDW) to make a dilution factor of 100 (v/v) and transferred into high-density polyethylene bottles.

Preparation of standards

A 100 ml reagent blank was prepared by mixing DDW with 5 mL of HNO_3 and 0.1 or 1 ml of HF. Two sets of five standard solutions (that is, 2, 15, 50, 100 and 200 mg L^{-1}) were prepared to avoid formation of Si precipitates, with the first set containing only Si and the second set containing Ca, K, Mg and P.

ICP-OES system

All measurements were made using an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) (Varian Model 720-ES). To avoid instrument damage and contamination from the free HF of the solution, a V-groove nebulizer, a Sturman-Masters Spray Chamber, and a Radial Torch were used instead of the glassy materials of the machine. Samples were taken automatically at a rate of 1 ml min^{-1} using an SPS3 AutoSampler. The plasma forward power was 1000 W, with plasma and auxiliary gas flow rates of 15 and 1.5 L min^{-1}, and a pump rate of 15 rpm was used to aspire the sample solutions. The ICP system was calibrated using ICP Expert II software, with each calibration curve being constructed linearly through zero after subtraction of the reagent blank, as used by Feng et al. (1999).

RESULTS

When Si was added into the nutrient solution at 50 to 100 mg L^{-1}, the growth of both plants appeared to be improved (Figure 1). However, as the level of Si supply was increased, both plants looked stunted. At 500 to 1000 mg L^{-1}, both plants showed increased breakage and appeared yellowish. Regardless of the level of Si used in the nutrient solution, the colour and texture of the fruits of zucchini remained unaffected. However, the size and numbers of fruits were reduced when the Si level was more than 500 mg L^{-1} (Figure 2). In contrast, the flowers of zinnia appeared dull and dry when the plant was supplied at high rates (>300 mg L^{-1}). The results of the EDX analysis and elemental mapping show that the leaves of both plants accumulated high levels of Si. Even in the control, where Si was not added into the nutrient solution, the leaves of both plants accumulated some levels of Si (Figure 3). As the concentration of Si in the nutrient solution was increased, the leaves of both plants accumulated more Si. In some cases, this level was even higher than that of C and O.

Application of Si at 50 mg L^{-1} doubled the total amount of Si accumulated in different parts of zucchini, with leaves accumulating more than six times as much. At 400 mg L^{-1}, the level of Si reached maximum level (that is, 68.8 mg g^{-1} dry weight (dw)). Similarly, the level of Si accumulated by the roots of the same plant was almost doubled when the concentration of Si in the solution was kept between 50 to 200 mg L^{-1}. The impacts of Si supply

Figure 1. Effects of Si concentration (in mg L^{-1}) on growth of zucchini (left) and zinnia (right) in nutrient recirculating system.

Figure 2. Effects of Si concentration on fruits of zucchini grown in nutrient recirculating system.

on the accumulation of this element by zinnia were similar to that in the case of zucchini. As much as 92.6 mg g^{-1} dw of Si was accumulated by the leaves of zinnia, with 250 mg L^{-1} of Si considered to be the optimum. The roots of this plant also accumulated the maximum level of Si (24.2 mg g^{-1} dw) when supplied with Si at 150 mg L^{-1}. The level of Si in the flowers of zinnia was doubled when the plant was supplied with 50 mg L^{-1}. However, subsequent increases in Si supply did not result in increased deposition of this element in the same tissue. Regardless of Si levels in the nutrient solution, the accumulation of Si in the fruits of zucchini and the stem and petioles of both plants was not affected.

Increasing the level of Si in the nutrient solution resulted in increased accumulations of K (in stems and petioles) and Mg (in leaves) by both plants. Accumulation of Ca by both plants reached a maximum when these plants were fed with 50 mg L^{-1} of Si. However, extra application of Si resulted in reduced accumulations of Ca, especially in the roots, flowers and fruits of both plant species. The level of P in the fruits of zucchini and the flowers of zinnia were increased slightly with increased levels of Si supply. Overall observation on the levels of Ca, Mg and P showed that both plants accumulated the highest levels of these elements when they were fed with Si at 50 mg L^{-1} (Figure 4).

DISCUSSION

To our knowledge, this is the first investigation to assess the effects of Si in the nutrient solution on the uptake and distribution of Si, K, Ca, P and Mg to different parts of zinnia and zucchini and the growth of these plants. When conducting plant tissue analysis, most researchers consider leaves as the main organ (Adatia and Besford, 1986; Samuels et al., 1991; Ranganathan et al., 2006). However, such observations often provide inconclusive results because elements are distributed to different organs of each plant species at different levels (Ma and Takahashi, 2002; Mitani and Ma, 2005; Ma and Yamaji, 2006). Even when samples are being taken from the

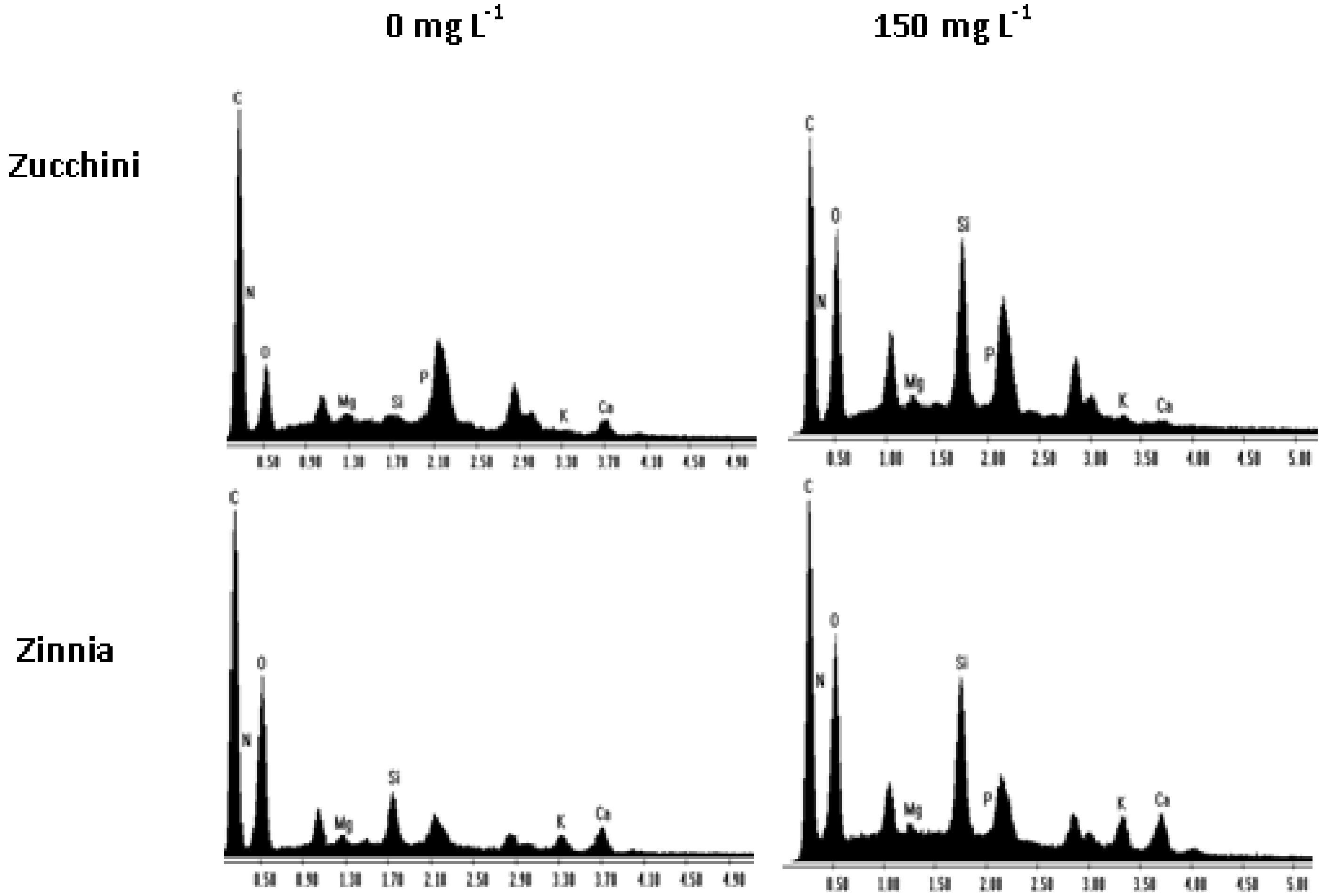

Figure 3. Energy dispersive x-ray (EDX) spectrums of silicon and other elements on leaves of zucchini and zinnia plants that received Si treatments of 0 (control) and 150 mg L^{-1}.

leaves only, their orientation (Adatia and Besford, 1986) and age or proximity to the source of Si (Ma and Yamaji, 2006) may affect the outcome. In the young leaves of wheat, Si is mainly concentrated in the abaxial (lower) epidermal cells, whereas in old leaves both abaxial and adaxial (upper) epidermal cells have the same levels of Si (Hodson and Sangster, 1988). Moreover, the distribution of Si in different parts of the root and reproductive parts is often variable (Epstein, 1994; Mitani and Ma, 2005). In this study, such variables were avoided by taking representative samples of each organ from the entire plant and blending them thoroughly after drying.

Accumulation of Si by some plant species may be equal to or higher than some macronutrients such as P, K, Mg, Ca and S (Epstein, 1994, 1999). Even where no Si was added into the nutrient solution, the levels of Si in the roots and leaves of zinnia and zucchini were higher than those of Ca, P, K and Mg. Since Si is ubiquitous in nature (Epstein, 1994, 1999; Mitani and Ma, 2005), it was believed that composted pine bark and water, which were used in the growing system, were the source of this element.

Growth of both plants was optimum at low levels of Si (that is, 50 to 100 mg L^{-1}), because uptake of most of the elements that were considered in this study was maximal in both. In contrast, high levels of Si supply resulted in nutrient imbalance in the solution, which was manifested by stunted growth. Adding Si into the nutrient solution did not affect the quality of zucchini fruits, as proven by the visual assessment and elemental composition of this organ. In agreement with our findings, Bélanger et al. (1998) reported that the application of Si at 100 mg L^{-1} increased the yield of cucumber. However, beyond that level, they observed hardening of the fruit, resulting in poor fruit quality. Samuels et al. (1993) found that cucumber plants produced unusual, dull-appearing fruits when they were grown in hydroponics supplied with Si. Observation by Ago et al. (2008) showed that the response of cucurbits to Si treatment may vary among species or even the cultivar level. Hence, no generaliza-

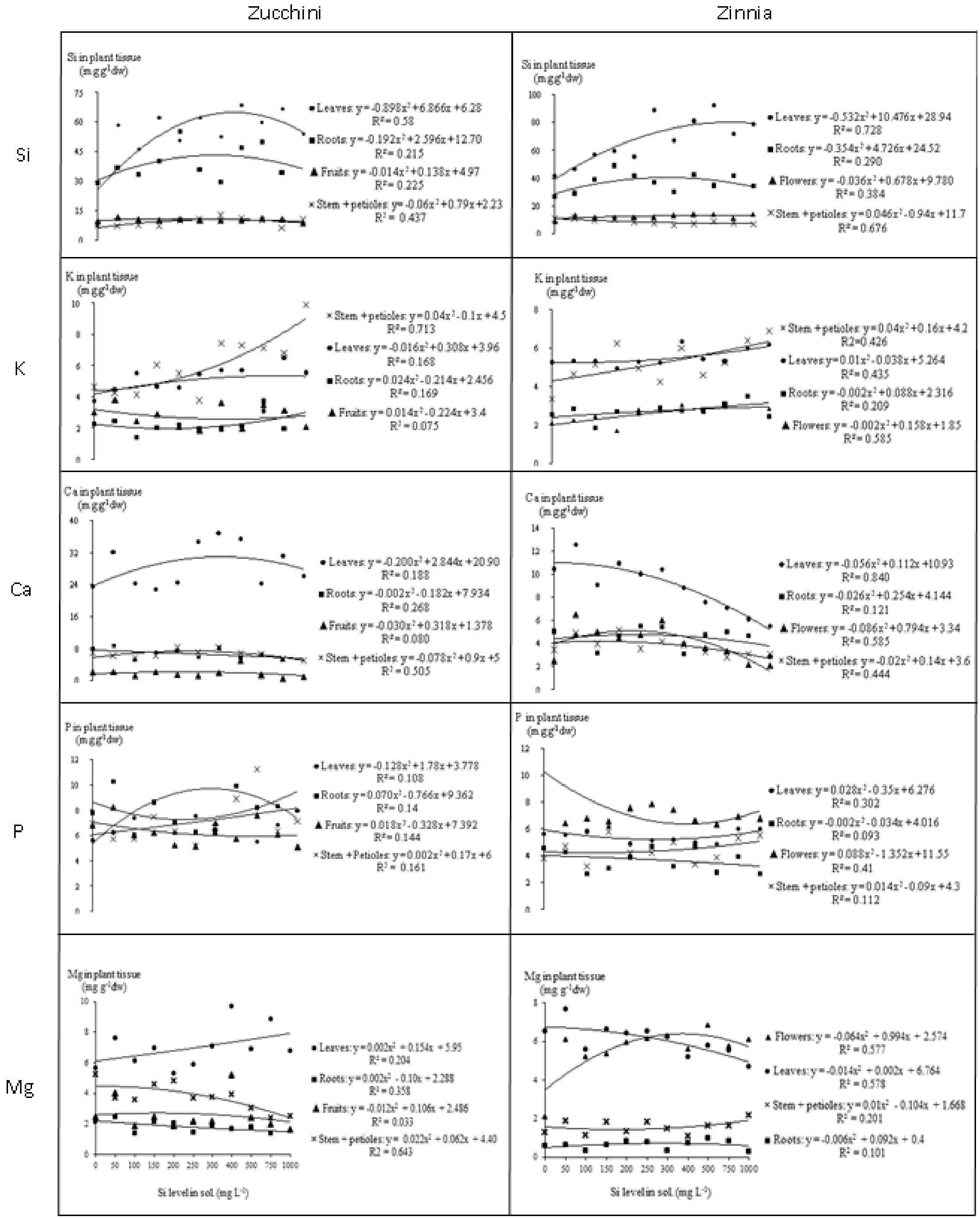

Figure 4. Effects of concentration of Si applied in nutrient solution on accumulations of Si, K, P, Ca and Mg in different parts of zucchini and zinnia after six weeks of growth in a nutrient re-circulating system.

tion can be made on each plant species and cultivar without proper testing.

Elemental analysis of the whole plant showed that the application of 50 to 100 mg L^{-1} Si was optimal for maximal accumulation of most of the elements considered in this study and optimum growth of both plants. In addition to increasing the growth of both plants, application of Si at lower concentrations can avoid risk of infection by some pathogens such as powdery mildew fungi (Miyake and Takahashi, 1982a, b; Bélanger et al., 1998; Fauteux et al., 2005; Re´mus-Borel et al., 2005; Moyer et al., 2008; Shetty et al., 2012). The relationship between the application of Si and the uptake of Ca, Mn, Fe, P and other elements and its impact on the growth of plants have been well documented by several researchers (Ma and Takahashi1990, 1993; Marschner et al.,1990; Savvas et al., 2002).

Previous research on the effects of Si on the uptake and accumulation of P in various plants provided contradictory results (Islam and Saha, 1969; Ma and Takahashi, 1990). This was because Si is possibly involved in the metabolic or physiological changes in the plants by promoting or suppressing the uptake and transportation of selected elements, depending on the stress conditions (Liang, 1999). Islam and Saha (1969) discovered that the application of Si resulted in increased levels of P, Ca and Mg in rice. Interestingly, Ma and Takahashi (1990) found that the concentration of Si in the shoots of cucumber was slightly reduced with increased level of P in the same organ, although the uptake of Si was not significantly affected by the presence of P in the nutrient solution. They concluded that Si could increase the availability of P when Si is deficient or reduce the uptake of P when the levels of Si are high, reflecting that Si plays a major role in balancing P uptake.

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