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Silicon-Mediated Tomato Resistance Against *Ralstonia solanacearum* is Associated with Modification of Soil Microbial Community Structure and Activity

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Abstract Bacterial wilt caused by *Ralstonia solanacearum* is a serious soil-borne disease of Solanaceae crops. In this study, the soil microbial effects of silicon-induced tomato resistance against *R. solanacearum* were investigated through pot experiment. The results showed that exogenous 2.0 mM Si treatment reduced the disease index of bacterial wilt by 19.18 % to 52.7 % compared with non-Si-treated plants. The uptake of Si was significantly increased in the Si-treated tomato plants, where the Si content was higher in the roots than that in the shoots. *R. solanacearum* inoculation resulted in a significant increase of soil urease activity and reduction of soil sucrase activity, but had no effects on soil acid phosphatase activity. Si supply significantly increased soil urease and soil acid phosphatase activity under pathogen-inoculated conditions. Compared with the non-inoculated treatment, *R. solanacearum* infection significantly reduced the amount of soil bacteria and actinomycetes by 52.5 % and 16.5 %, respectively, but increased the ratio of soil fungi/soil bacteria by 93.6 %. After *R. solanacearum* inoculation, Si amendments significantly increased the amount of soil bacteria and actinomycetes and reduced soil fungi/soil bacteria ratio by 53.6 %. The results suggested that Si amendment is an effective approach to control *R. solanacearum*. Moreover, Si-mediated resistance in tomato against *R. solanacearum* is associated with the changes of soil microorganism amount and soil enzyme activity.

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Bacterial wilt caused by *Ralstonia solanacearum* is a serious soil-borne disease widely distributed in tropical, subtropical, and some warm temperate regions of the world [28]. The pathogen generally enters a plant through the roots, penetrates the xylem, systemically colonizes the stem, and causes wilt symptoms [33]. Traditional controlling methods including resistant varieties, chemical agents, and crop rotation were used to control this pathogen. However, host resistance is easy to lose because of the rapid variation of pathogenic bacteria. Chemical application has limited effects on this pathogen, and may cause negative effects on food safety and the environment. Rational organic amendments may provide a practical, environmentally sound, and economical control strategy [12, 15, 52, 59]. However, some organic composts, such as city compost and livestock and poultry organic fertilizer, may contain heavy metal, antibiotics, and hormone, which restrict their practical applications.

Silicon is the second most abundant mineral element in the earth's crust [17]. A number of studies have indicated that Si can enhance the resistance of plants to various diseases [7, 12, 15, 20, 39]. Si-treated plants show higher resistance to pathogen penetration of host tissue because of the specific accumulation and polymerization of $Si(OH)_4$ in the cell walls [8, 29]. Si may also activate a series of biochemical defense responses to increase host resistance, including the increased antioxidant enzyme activities and the production of antifungal compounds such as phenolic metabolism product and phytoalexins, etc. [7, 20]. In tomato, the beneficial effects of silicon in prohibiting *R. solanacearum* development were also studied [12, 15]. Recent studies showed that Si could induce the production of resistance signal molecules, defense, signal transduction, and

resistance-related genes and housekeeping genes in *R. solanacearum*-infected treatments [22, 23].

Pathogen infection may alter soil microbial community structure and influence the component and amount of soil microorganisms, transferring the soil from high-fertility "bacteria type" to low-fertility "fungi type" [34, 55]. The sensitivity of soil microorganisms to changes in soil conditions can reflect soil health status and act as indicators of soil quality [32]. Previous studies of Si-mediated pathogen resistance have mostly concentrated on aboveground-induced resistance [12, 15, 22, 23]. To our knowledge, no related studies focusing on the soil microbial effects of Si supply on bacterial wilt resistance have been reported. The objectives of this study were to investigate the impacts of Si amendment on soil microbial population densities and microbial activity in *R. solanacearum*-infected treatments in tomato.

Materials and Methods

Plant Materials and Growth Conditions

Tomato genotype Taiwan Red cherry (susceptible to *R. solanacearum*) was used throughout the experiment. Tomato seeds were surface-sterilized in water at 50 °C for 15 min, germinated on moist filter paper for 2 days in Petri dishes, and then sown in nursery soil (with nutrition soil and organic fertilizer ratio of 3:1). Tomato seedlings were grown in a growth chamber at 30 °C/25 °C (day/night) with a photoperiod of 14 h and a light intensity of 200 μmol m^{-2} s^{-1}. After 5 weeks of germination, the seedlings were transplanted to a polyethylene plastic pot (170 mm diameter×165 mm height) filled with 2 kg of soil. The soil was collected from a field with continuous cropping cultivation of tomato in Zhucun village, Zengcheng city, Guangdong province, China. The content of soil organic matter and soil-available N, P, K, and Si were 16.04 g kg^{-1}, 67.24 mg kg^{-1}, 110.8 mg kg^{-1}, 49.94 mg kg^{-1}, and 31.02 mg kg^{-1}, respectively. Approximately 95.7 mg of urea, 235.7 mg of superphosphate, and 48 mg of potassium chloride were added per kilogram of soil before transplanting to meet the nutrient demand for tomato plant growth.

Experimental Design

The following four treatments were used in this experiment: no Si addition and no *R. solanacearum* inoculation (CK), Si addition (Si), *R. solanacearum* inoculation (Rs), and Si addition and *R. solanacearum* inoculation (Rs+Si). The experiment was arranged in a completely randomized design with 10 replications. Our preliminary experiment using different Si concentrations showed that 2.0 mM of Si exhibited the best effects in inhibiting bacterial wilt. Thus, 2.0 mM of Si was used in this experiment. Si was added as potassium silicate (K_2SiO_3) to the soil before seedling transplantation. In the Si-deficient treatment, potassium chloride (KCl) was used to replenish potassium. After 15 days of *R. solanacearum* inoculation, all treated plants were harvested, and then divided into shoots and roots to measure Si content. Soil from different treatments were also collected to determine soil-available Si content, soil urease activity, soil acid phosphatase activity, soil sucrase activity, soil microbial population densities including soil bacteria, fungi, and actinomycetes, as well as the *R. solanacearum* content in soil.

R. solanacearum Inoculation

A highly aggressive strain of *R. solanacearum*, which was kept in our laboratory and has been determined to be race 1 biovar 3, was used to inoculate tomato plants. The bacteria were grown on CPG medium [33] for 48 h at 30 °C. The cells were harvested from agar plates by water flushing [15] and adjusted to OD_{600}=0.3 (about 3×10^8 CFU mL^{-1}). Tomato plants were inoculated with *R. solanacearum* by cutting their roots and injecting the inoculum suspension (about 3×10^8 CFU mL^{-1}, 15 mL per pot). The non-inoculated plant roots were also cut and injected with the same volume of distilled water.

Pathogen Symptom Evaluation

Disease development was evaluated every 2 days after pathogen infection using a disease score based on 10 plants per treatment according to the method [18]. The evaluation started when the first symptoms appeared on the leaves, and was continued until the symptoms were stable. The following scoring was used: 0=no symptom, 1=one leaf wilted, 3=two or three leaves wilted, 5=all except the top leaves wilted, 7=all leaves wilted, and 9=stems collapsed or plants died.

$$\text{Disease index}(\%) = \left[\sum (r \times N_r)/(R \times n)\right] \times 100\%$$

where r is the mean disease severity, N_r is the number of infected plants with a rating of r, R is the value of the most serious disease severity in each treatment, and n is the total number of plants tested.

Determination of Si Content in Roots, Leaves, and Soil

Si content in tomato roots and leaves was determined according to the method described by van der Vorm [53]. Briefly, 0.1 g of leaf (or root) samples was ashed in porcelain crucibles for 3 h at 550 °C. The ash was dissolved in 1.3 % hydrogen fluoride, and the Si content in the solutions

was measured through colorimetric molybdenum blue method at 811 nm with a spectrophotometer (PGENERAL TU-1901 UV–VIS, Beijing, China).

Soil-available Si was extracted by citric acid with minor modifications [2]. About 10 g of air-dried, finely sifted soil (passed through a 2-mm sieve) was added to a plastic bottle with a volume of 250 mL. Approximately 100 mL citric acid was added, and then the plastic bottle was shaken and incubated (GXZ Intelligent; JiangNan Instrument Plant, China) at 30±0.1 °C for 5 h. Afterward, 5 mL of filtered fluid was taken to determine the Si concentration in the solutions by colorimetric molybdenum blue method at 811 nm with a spectrophotometer [UV-2501(pc)s 220 V; Shimadzu, China].

Determination of Soil Enzyme Activity

Soil urease, soil phosphatase enzyme, and soil sucrase activities were selected to determine soil microbial activity.

Soil urease activity was determined using the method described by Yao and Huang [57], with minor modification. About 5 g of air-dried, finely sifted soil (passed through a 1-mm sieve) was added to a 25-mL volumetric flask. Approximately 1 mL of toluene was added to the flask after 15 min, and then 10 mL of 10 % urea solution and 10 mL of citrate buffer (pH6.7) were added. The flask was shaken and then placed in an incubator (GXZ Intelligent; JiangNan Instrument Plant) at 37±0.1 °C for 24 h. After incubation, the sample was filtered through a quantitative filter paper. Subsequently, 3 mL of filtrate, 17 mL of deionized water, 4 mL of sodium phenate solution, and 3 mL of sodium hypochlorite solution were added to a 50-mL volumetric flask. After 20 min, deionized water was added to the flask to reach 50 mL volume in the test tube. Finally, soil urease activity was colorimetrically determined at 578 nm with a UV spectrophotometer [UV-2501(pc)s 220 V; Shimadzu] within 1 h.

Only acid phosphatase enzyme activity was measured in this study because the soil used was acidic, and acid phosphatase is the main phosphatase enzyme [16]. The activities of soil acid phosphatase were assayed on 1 g of oven-dry equivalents of buffered soil solutions incubated for 1 h at 37 °C after the addition of the enzyme-specific substrate solution. The product of all reactions, *p*-nitrophenyl phosphate, was colorimetrically measured at 412 nm on a UV spectrophotometer [51].

Soil sucrase activity was assayed according the method described by Guan et al. [26]. Briefly, 5 g of air-dried soil (sieved to <1 mm), 15 mL of 8 % glucose solution, 5 mL of 0.2 M phosphate buffer (pH5.5), and five drops of toluene were added to a 25-mL volumetric flask. After incubation for 24 h at 37 °C, the soil solution was filtered and a 1-mL aliquot was transferred to a volumetric flask with 3 mL of 3, 5-dinitrylsalicylate, and then heated for 5 min. After the solution reached room temperature, the product was colorimetrically quantified at 508 nm using a spectrophotometer [UV-2501(pc)s 220 V; Shimadzu].

Determination of the Densities of Soil Microbial Population

The amount of soil bacteria, fungi, and actinomycetes were determined via dilution plate method [25, 41], with minor modification. The media for soil bacteria, fungi, and actinomycetes were beef-protein medium, potato sucrose agar medium, and Gause 1 culture medium, respectively. About 5 g of air-dried soil was added to a flask with 50 mL of sterile water, and then the flask was shaken using a shaking table (ASH-202P shaker; Abbot Corporation, USA) for 20 min. About 0.5 mL of supernatant fluid was added to a tube equipped with 4.5 mL of sterile water. The solution was diluted to 10^{-6}, and 0.1 mL of the diluted solution was taken and coated in the corresponding medium, which was then placed in an incubator (GXZ Intelligent; JiangNan Instrument Plant) at 28 ± 0.1 °C. The bacteria, fungi, and actinomycetes were cultured for 2, 4, and 6 days, respectively. After incubation, the colony number was recorded to count the densities of different microbial populations.

The amount of *R. solanacearum* in the soil was determined using the plate method, with some modifications [38]. About 5 g of soil was collected at 15 days after pathogen inoculation, and then diluted to 10^{-4} using 1:10 gradient dilution method. The soil-suspending liquid was coated by 100 μL TTC, and then incubated for 48 h at 30± 0.1 °C using thermostatic cultivation (GXZ Intelligent; JiangNan Instrument Plant). The method of plate culture count is used to record the amount of soil bacterial wilt.

Statistical Analysis

All the data in the figures were expressed as the means± standard error of four replicates and analyzed by ANOVA using SPSS13.0 (Statistical Analysis Systems Institute, version 13.0; SPSS Inc., Chicago, IL, USA). Statistical differences among treatments were determined by Duncan's test ($P<0.05$) and *t* test ($P\leq0.05$).

Result

Disease Index

Bacterial wilt symptoms developed fast and were observed at 5 to 6 days post-inoculation (dpi). Tomato plants treated with 2 mM Si had significantly lower disease indexes compared with the no-Si-treated control (Pi-1) lines (Fig. 1). Si application reduced the disease index of bacterial wilt by 52.7 %, 19.18 %, 32.10 %, and 39.2 % at 7, 9, 11, and 13 days post-inoculation, respectively.

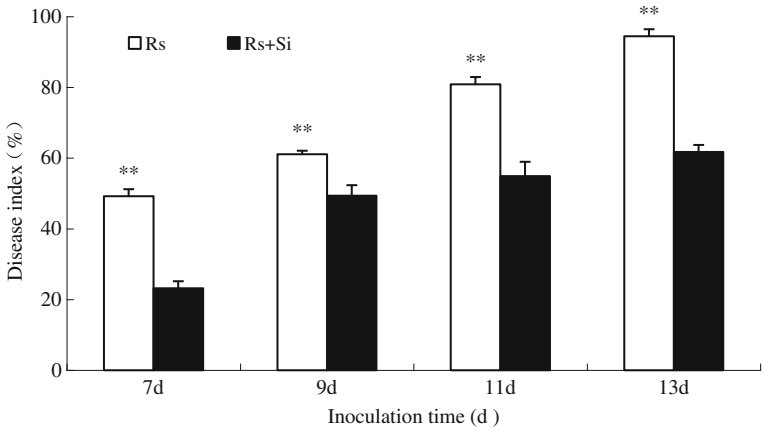

Fig. 1 Effects of silicon supply and *R. solanacearum* inoculation on the disease index (%) of bacterial wilt in tomato plants. *Rs*: *R. solanacearum* inoculation only, *Rs+Si*: *R. solanacearum* inoculation and Si 2.0 mM application. The values are means±standard error with four replicates. Two *asterisks* on a column denote a significant difference at $P<0.01$ by using *t* test

Silicon Concentration in Soil, Roots, and Shoots

Soil-available Si content in Si-treated tomato plants was significantly higher regardless of pathogen inoculation (Fig. 2). Si treatment increased soil available Si content by 15.18 % in the non-inoculated treatments and by 18.0 % in the inoculated treatments. Si concentration in tomato roots and shoots were also significantly increased in the Si-treated treatments. Si application increased the Si content by 23.87 % and 199.62 % in the roots and shoots of the non-inoculated treatments, and by 9.58 % and 344.82 % in roots and shoots of the inoculated treatments (Fig. 3). Si content was about five to 15 times higher in roots than that in shoots, regardless of Si supply. However, *R. solanacearum* did not have impacts in silicon uptake or distribution.

Soil Enzyme Activity

Soil sucrase activity was significantly inhibited by *R. solanacearum* infection. Compared with the non-inoculated treatment, *R. solanacearum* inoculation dramatically decreased soil sucrase activity by 76.8 %. Si supply had no effects on soil sucrase activity regardless of pathogen inoculation (Fig. 4a).

In the non-inoculated treatments, Si amendment did not influence soil acid phosphatase activity (Fig. 4b). However, Si application significantly increased acid phosphatase activity by 15.3 % in *R. solanacearum*-inoculated treatments.

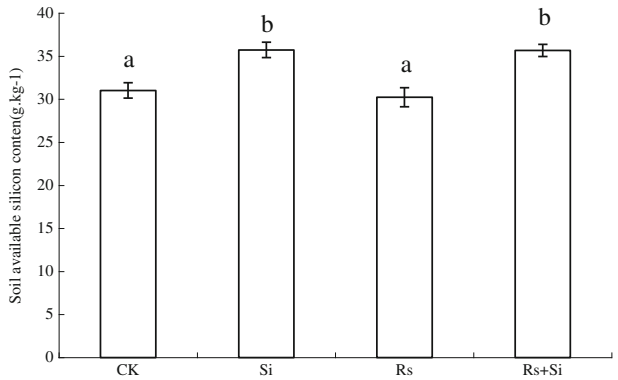

Fig. 2 Effects of Si and *R. solanacearum* inoculation on soil available Si content. *CK*, *Si*, *Rs*, and *Rs+Si* indicate no Si and no inoculation, Si application only, *R. solanacearum* inoculation only, and *R. solanacearum* inoculation and Si application, respectively. The values are the means±standard error with four replicates. Significant differences ($P<0.05$, using Duncan's new multiple range tests) among all treatments are indicated by different *letters* above the bars

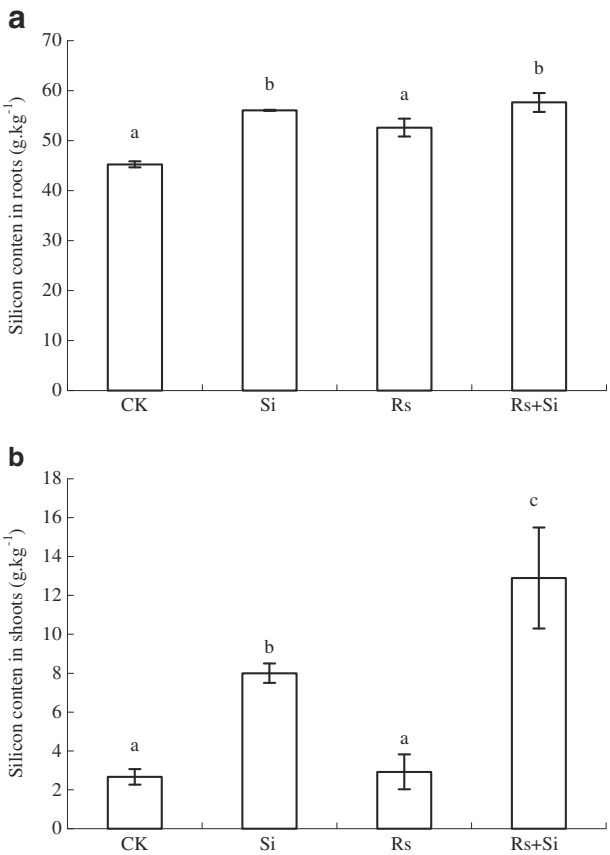

Fig. 3 Effects of Si and *R. solanacearum* inoculation on Si content in roots (**a**) and shoots (**b**). *CK*, *Si*, *Rs*, and *Rs+Si* indicate no Si and no inoculation, Si application only, *R. solanacearum* inoculation only, and *R. solanacearum* inoculation and Si application, respectively. The values are the means±standard error with four replicates. Significant differences ($P<0.05$, using Duncan's new multiple range tests) among all treatments are indicated by different *letters* above the bars

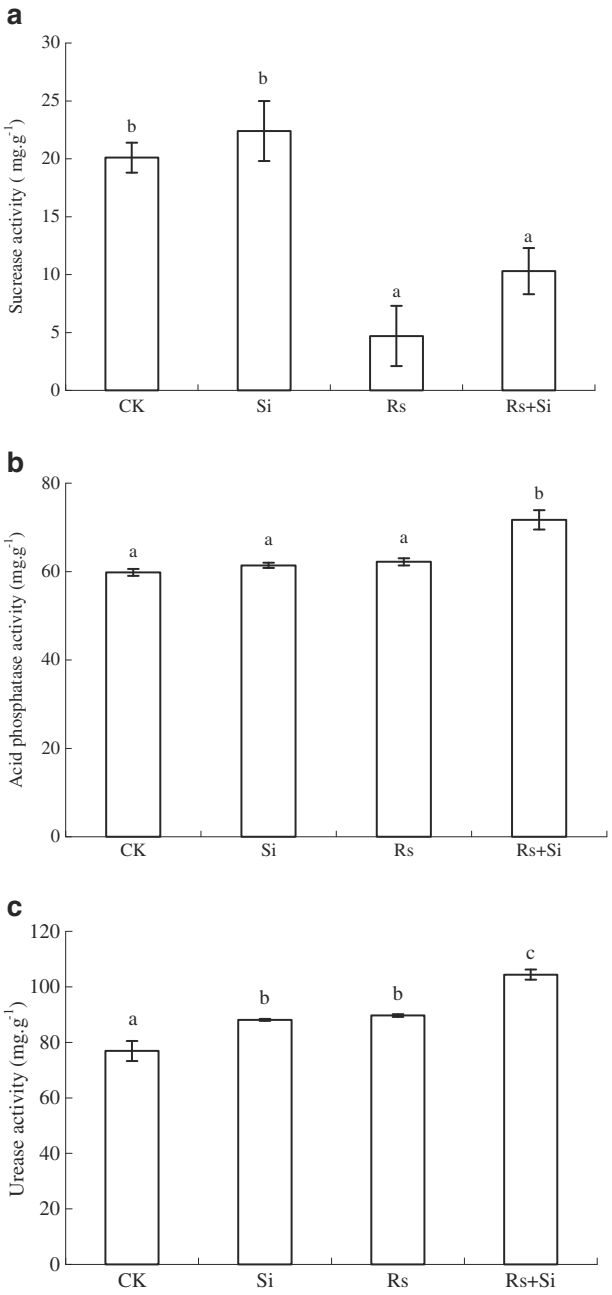

Fig. 4 Effects of Si and *R. solanacearum* inoculation on the activity of soil sucrase (**a**), acid phosphatase (**b**), and urease (**c**). *CK*, *Si*, *Rs*, and *Rs+Si* indicate no Si and no inoculation, Si application only, *R. solanacearum* inoculation only, and *R. solanacearum* inoculation and Si application, respectively. The values are the means±standard error with four replicates. Significant differences ($P<0.05$, using Duncan's new multiple range tests) among all treatments are indicated by different *letters* above the bars

Compared with non-inoculated treatment, *R. solanacearum* infection significantly increased soil urease activity by 16.6 % (Fig. 4c). Si supply resulted in a significant increase of soil urease activity, which increased by 14.6 % and 18.5 % under non-inoculated and inoculated treatments, respectively.

Amount of *R. solanacearum* in Soil

R. solanacearum infection significantly increased the amount of *R. solanacearum* in soil by 51.41 % (Fig. 5). However, the soil treated with 2 mM Si had significantly lower amount of *R. solanacearum* compared with the non-Si-treated control. The amount of *R. solanacearum* in soil was decreased by 23.2 % because of Si application, which was a value close to the control level.

The Densities of Soil Microbial Population

Si supply and *R. solanacearum* inoculation significantly influenced the amount of soil microbial population (Fig. 6a–c). Compared with non-infected soil, the amounts of soil bacteria, fungi, and actinomycetes in *R. solanacearum*-infected treatments significantly were decreased by 52.5 %, 8.5 %, and 16.5 %, respectively. Soil bacteria had the highest reduced amplitude. However, simultaneous Si application and *R. solanacearum* increased the amount of soil bacteria and actinomycetes by 124.9 % and 22.4 %, respectively, compared with the non-Si-treated but inoculated soil. Soil fungi/bacteria ratio in the inoculated treatments was greatly increased by 93.6 %. However, Si application significantly reduced soil fungi/bacteria ratio by 53.8 % in the infected soil (Fig. 7).

Discussion

Si-mediated plant resistance against different pathogens has been broadly studied in several pathosystems such as blast

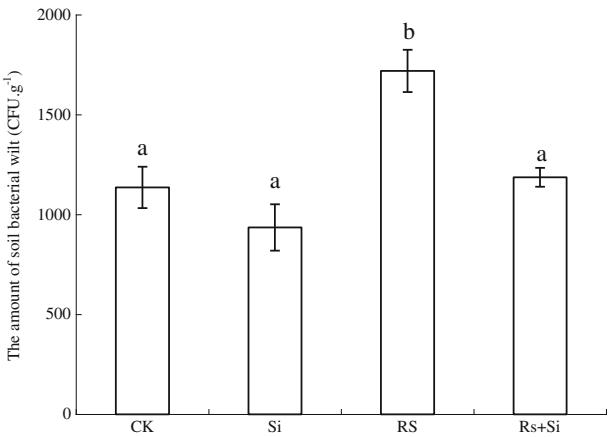

Fig. 5 Effects of Si and *R. solanacearum* inoculation on the population of *R. Solanacearum* in soil. *CK*, *Si*, *Rs*, and *Rs+Si* indicate no Si and no inoculation, Si application only, *R. solanacearum* inoculation only, and *R. solanacearum* inoculation and Si application, respectively. The values are the means±standard error with four replicates. Significant differences ($P<0.05$, using Duncan's new multiple range tests) among all treatments are indicated by different *letters* above the bars

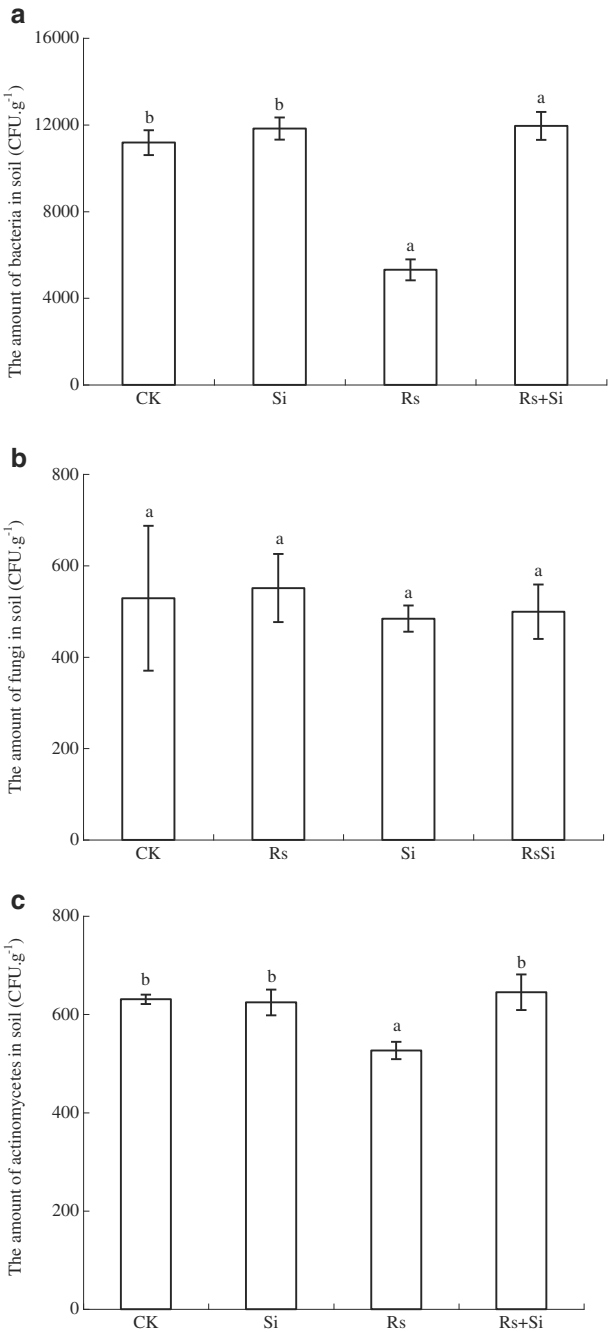

Fig. 6 Effects of Si and *R. solanacearum* inoculation on the amount of soil bacteria (**a**), fungi (**b**), and actinomycetes (**c**). *CK*, *Si*, *Rs*, and *Rs+ Si* indicate no Si and no inoculation, Si application only, *R. solanacearum* inoculation only, and *R. solanacearum* inoculation and Si application, respectively. The values are the means±standard error with four replicates. Significant differences ($P<0.05$, using Duncan's new multiple range tests) among all treatments are indicated by different *letters* above the bars

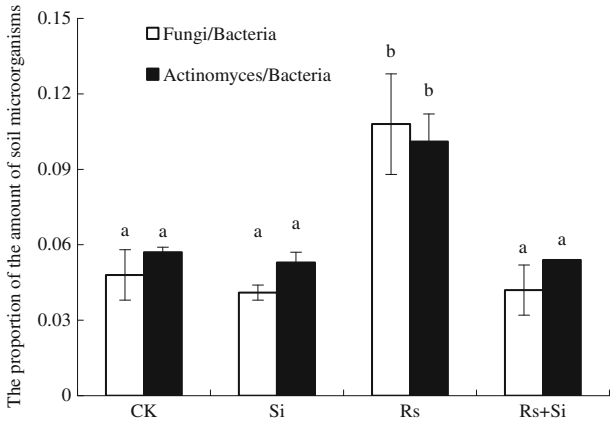

Fig. 7 Effects of Si and *R. solanacearum* inoculation on component ratio of soil microorganisms. *CK*, *Si*, *Rs*, and *Rs+ Si* indicate no Si and no inoculation, Si application only, *R. solanacearum* inoculation only, and *R. solanacearum* inoculation and Si application, respectively. The values are the means±standard error with four replicates. Significant differences ($P<0.05$, using Duncan's new multiple range tests) among all treatments are indicated by different *letters* above the bars

and sheath blight in rice [13, 46], powdery mildew in wheat, cucumber, and *Arabidopsis*, and rust in cowpea [3, 21, 29, 36]. In the current study, the application of 2.0 mM Si significantly reduced the *R. solanacearum* development of tomato plant (Fig. 1). This inhibited effect has also been reported by other studies [12, 15]. The mechanism by which Si reduces the incidence of *R. solanacearum* is still unclear. The current study also found that the lower disease severity in Si-treated tomato plants was in line with the lower amount of *R. solanacearum* in soil and higher Si content in tomato roots and shoots (Figs. 3 and 5). Therefore, Si uptake and accumulation in roots possibly have an important role in enhancing plant resistance to pathogen. Evidence showed that Si-mediated resistance to pathogen was associated with higher deposition of Si in plants which acted as a mechanical role [5, 27, 48]. More studies have shown that Si can induce host defense response by increasing the level of antifungal phenolic compounds (such as lignin, phytoalexins, chlorogenic acid, and rutin) [19, 45, 46, 49] and the activity of protective enzymes (such as peroxidase, polyphenol oxidase, and phenylalanine ammonia-lyase) [7, 10, 36]. Limited information about possible resistance mechanisms in tomato to *R. solanacearum* mediated by Si is available. Earlier studies suggested that Si had an indirect effect on wilt bacterial growth through induced resistance interacting with resistance factors of the plants [12, 15]. Recent studies have shown that Si-enhanced resistance to *R. solanacearum* in tomato was associated with the up-regulated expression of defense marker genes (such as jasmonic acid/ethylene marker genes) and housekeeping genes, including phosphoglycerate kinase genes, alpha-tubulin, and actin [22, 23].

However, all these explanations on Si-mediated pathogen resistance mechanism mostly focus on the inducing resistance of aboveground parts. Unlike blast or power mildew, bacterial wilt caused by *R. solanacearum* is a soil-borne disease. The pathogen generally enters a plant through the roots from the soil. Soil is the key issue to be considered in

this problem. To our knowledge, no reports have investigated the inhibited function of Si to pathogen from the soil microbial perspective.

Soil microbial activity has an important function in quantifying soil function, such as the C and N cycle and organic matter decomposition [14, 40, 43]. As an integral part of nutrient cycling in soil, soil-specific enzyme activity including dehydrogenase and phosphatase can also be used to estimate soil microbial activity and evaluate soil health [1, 24, 31]. Our study provides evidence that the application of 2.0 mM Si significantly increases soil urease and soil acid phosphatase activity in response to *R. solanacearum* infection (Fig. 4). An essential aspect of soil health is the ability of the soil to resist soil-borne plant pathogens. This phenomenon is known as general disease suppression and is attributed to the total microbial activity [4, 58]. Hydrolytic enzymes including soil sucrase, urease, and phosphatase can characterize soil carbon, nitrogen, phosphorus, and nutrient cycle condition [54]. Sucrase activity has a good relationship with soil organic matter, nitrogen, phosphorus, microorganism quantity, and soil respiration intensity. The higher the fertility of the soil is, the stronger the sucrase activity [25]. Rasmussen et al. [44] found that activities of β-glucosidase and cellobiohydrolase were positively correlated with soil pathogen suppressiveness to *Fusarium culmorum* in barley seedling. Similarly, Leon et al. [35] found that arylsulfatase activity had good correlation with the suppression of common root rot of snap bean. Organic amendments are often used to improve soil quality, notably by contributing to general suppressiveness through enhanced soil microbial biomass and activity [31]. Ros et al. [47] found that compost-induced defense response to fusarium wilt resistance led to an increase of soil phosphatase and urease activity. Compost prepared from waste onion peelings is more effective in reducing the viability of the sclerotia of *Sclerotium cepivorum* than that prepared from *Brassica* or carrot wastes [11]. Our study indicated that Si is a beneficial supplement that increases tomato resistance against *R. solanacearum* through increasing soil-specific enzyme activities (Figs. 1 and 4a, b).

A good relation exists between soil fertility and soil microorganism. The plant, soil, and soil microbes all work together to mediate and influence the various exchanges that contribute to plant health and productivity [9]. Beneficial microbiota can compete with pathogens for space and nutrients, or produce microbial agents, thereby improving plant health [37]. Our study found that the amounts of soil bacteria, fungi, and actinomycetes were significantly reduced, whereas soil fungi/bacteria ratio greatly increased, transforming the soil from "bacteria type" into "fungi type" after pathogen inoculation (Figs. 6 and 7). These results are similar to those of other studies regarding the change of soil microbial population resulted from pathogen infection [6, 38]. However, Si treatment significantly increased soil bacteria, actinomycetes, and the total amount of soil microorganism in *R. solanacearum*-infected soil; soil fungi/bacteria ratio greatly decreased (Figs. 6 and 7). Larkin [34] reported that continuous potato cropping resulted in the decline of the amount of soil bacteria and actinomycetes and increases the amount of soil fungi. Evidence showed that increased bacterial densities were associated with increased suppressiveness of amended soils toward southern blight (*Sclerotium rolfsii*) of processing tomatoes, the phytophthora root rot of alfalfa, and potato scab [6, 56]. Compost can increase the soil microbial quantity and improve soil quality, thereby reducing pathogen incidence [30, 42]. Sun et al. [50] suggested that soil bacteria and soil actinomycetes could improve the soil alkaline phosphatase, sucrose, and urease activity. Our study found that Si and *R. solanacearum* inoculation significantly reversed the reduction of the amount of soil bacteria and actinomycetes that resulted from pathogen infection (Fig. 6). Our results suggested that Si could improve soil fertility, increase the amount of soil antagonistic bacteria, and suppress *R. solanacearum* expansion to maintain a healthy soil ecosystem.

In conclusion, our study found that Si supply had an important role in suppressing bacterial wilt caused by *R. solanacearum*. The pathogen resistance mediated by Si was associated with the alteration of soil microbial activity and soil microbial community structure. However, further studies from molecular and proteome aspects are needed to elucidate the soil microbial mechanism, which will be helpful to provide a theoretical basis for Si fertilizer applications in vegetable production.

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