Full Paper

Effect of Plant Growth-promoting Rhizobacteria (PGPRs) on plant growth, yield, and quality of tomato (*Lycopersicon esculentum* Mill.) under simulated seawater irrigation

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To determine the effects of three PGPRs on plant growth, yield, and quality of tomato under simulated seawater irrigation, a two consecutive seasons' field experiment was conducted in Yancheng Teachers University plot from April to June and August to October, 2011. The results showed that *Erwinia persicinus* RA2 containing ACC deaminase exhibited the best ability compared with *Bacillus pumilus* WP8 and *Pseudomonas putida* RBP1 which had no ACC deaminase activity to enhance marketable yields of fresh and dried fruits in tomato under simulated seawater irrigation especially under HS condition. *B. pumilus* WP8 had significant effects on improving tomato fruit quality under the conditions of irrigating with 1.0% NaCl solution (MS) and with 2.0% NaCl solution (HS). Na⁺ contents were generally accumulated much more in tomato plant mid-shoot leaves than in fruits whatever the salt concentration. More sodium accumulation in leaves of *E. persicinus* RA2 and *B. pumilus* WP8 treatments under HS condition were found than in control. *E. persicinus* RA2 and *B. pumilus* WP8 can promote tomato growth, improve fruit quality more firmly than *P. putida* RBP1 during two consecutive seasons. Our study suggested that *E. persicinus* RA2 and *B. pumilus* WP8 are considered to be promising PGPR strains which are suited for application in salt marsh planting, ACC deaminase activity was not unique index on screening for PGPRs with the aim of salt stress tolerance, and plant growth promoting activities may be relevant to different growth indices and different stress conditions.

Key Words—ACC deaminase activity; *Bacillus pumilus* WP8; *Erwinia persicinus* RA2; plant growth-promoting rhizobacteria (PGPR); *Pseudomonas putida* RBP1; simulated seawater irrigation; yield and quality

Introduction

Tomato (*Lycopersicon esculentum* Mill.) is generally known to be a moderately salt-sensitive plant (Katerji et al., 2003). More than a 50% reduction in tomato pro-

duction occurred with growth in saline media with an electrical conductivity (EC) of 7.5 dS/m (Caro et al., 1991). Many studies have shown that salt stress could affect tomato plant growth and/or fruit yield through multiple mechanisms, including salt-induced osmotic stress (Sam et al., 2003), nutrient imbalance (Al-Karaki, 2000), excess Na⁺ and Cl⁻ ions toxicity (Epstein, 1979), abscisic acid (ABA) and ethylene explosion (Godoy et al., 1990; Mayak et al., 2004), systemic metabolic derangement (Hasegawa et al., 2000), and inhibition of photosynthetic activity (Dernetriou et al.,

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2007). In consideration of the increasing prevalence of salinity world-wide due to the amount of alluvial mud-flats, protected cultivations and wastewater irrigation, enhancing salt tolerance in tomato is becoming more and more important. In recent decades, there have been many effective methods devised to ameliorate this problem, namely, application of transgenic technology (Zhang and Blumwald, 2001), breeding for increasing salt tolerance, cultural techniques (Cuartero et al., 2006), and introduction of some beneficial bacteria termed plant growth-promoting rhizobacteria (PGPR) with different action types.

The use of PGPR and/or PGPR formulations to improve salt tolerance in tomato is considered to be an environment, and eco-friendly approach; however, growth promotion has been mostly attributed to 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity of selected PGPR strains for the ability to reduce precursor for synthesizing ethylene, whose explosion lead to slow growth or death under salt stress (Mayak et al., 2004), and whether there exist other pathways to confer resistance in tomato plants to salt stress is still unknown. It is undoubtedly a meaningful strategy to screen PGPR strains if there actually exist PGPR strains having no ACC-deaminase activity which can also induce salt stress tolerance. Furthermore, there is also little understanding of the effect of PGPR on the yield and quality of tomato under salt stress conditions.

Thus, the aims of this study were to determine: (1) whether PGPR without ACC deaminase activity can still promote tomato plant growth or not under simulated seawater irrigation; (2) whether PGPR improve tomato fruit quality as yield increases under simulated seawater irrigation.

Materials and Methods

PGPR strains and inoculum preparation. The three PGPR strains, namely *Erwinia persicinus* RA2, *Bacillus*

pumilus WP8 and *Pseudomonas putida* RBP1 were, isolated from rhizosphere soil of rape, wheat and reed in Jiangsu Province of China (Kang et al., 2010). All three strains were identified by phenotype and 16S rRNA gene sequencing, and have been deposited in GenBank; the accession numbers were GU979220, GU979232 and GU979226, respectively. Each PGPR inoculum was prepared by harvesting bacterial cells by centrifugation at $5,000 \times g$ for 10 min from 24 h cultures in nutrient broth (NB) at 28°C , 180 r min^{-1} , followed by repeated washing with sterile distilled water, and each cell suspension was finally diluted with sterile distilled water to 10^8 cfu ml^{-1} as determined by plate count on NB solid medium.

ACC deaminase activity assay. ACC deaminase activity was assayed according to the method of Penrose and Glick (2003) by measuring the amount of α -ketobutyrate produced when the enzyme ACC deaminase cleaves ACC, and the production of α -ketobutyrate during this reaction was determined by comparing the absorbance at 540 nm of a sample to a standard curve of pure α -ketobutyrate. Briefly, a stock solution of 100 mmol L^{-1} α -ketobutyrate (Sigma-Aldrich Co., U.S.A.) was prepared in 0.1 M Tris-HCl (pH 8.5) and stored at 4°C . The quantity of α -ketobutyrate (μmmol) produced by this reaction was determined by comparing the absorbance of a sample to a standard curve of α -ketobutyrate ranging from 0.1 to 1.0 nmol at 540 nm . To measure specific activity of the cultures, protein estimation was carried out according to Lowry (1951). The in vitro ACC deaminase activities of the three PGPR strains are displayed in Table 1, RA2 shows the highest value, whereas in RBP1 and WP8 it was not detected.

Plant material and method of inoculation. A popular tomato cultivar in China, 'jingdan No. 1', was used for the experiment. More than 200 1-month-old uniform seedlings were purchased from Biancang Town, Yancheng City, China. Before transplantation, seedling roots of each treatment were submerged in the PGPR

Table 1. In vitro ACC deaminase activity of three PGPR strains.

PGPR strains	ACC deaminase activity ($\mu\text{mol } \alpha\text{-ketobutyrate mg}^{-1} \text{ protein h}^{-1}$)
RA2	4.71 ± 1.02
RBP1	ND
WP8	ND

ND means not detected.

inoculum as described above for 20 min; controls were treated identically to treated seedlings but submerged only in sterile distilled water instead of inoculum.

Field experiment. Replicated field experiments were laid out in randomized block designs with three replications per treatment at Yancheng Teachers University, Yancheng, China, from April to June and August to October, 2011. The average monthly temperatures and rainfall during above-mentioned two periods in tested districts were respectively 18.3°C, 101.5 mm and 21.8°C, 93.7 mm based on data provided by the Bureau of Meteorology. Characteristics of two replicated (not the same place) sandy loam soil were pH 7.6 and 7.9 (1 : 1, soil : water), organic matter 3.83 g kg⁻¹ and 3.61 g kg⁻¹, total nitrogen (N) 1.49 g kg⁻¹ and 1.32 g kg⁻¹, available N 19.44 mg kg⁻¹ and 17.35 mg kg⁻¹, P 4.62 mg kg⁻¹ and 5.12 mg kg⁻¹, as well as K 2.25 mg kg⁻¹ and 2.31 mg kg⁻¹. Three seedlings with the same treatment were transplanted in each replicated plot (1 × 2 m) separated by 1 m, and there was no other inoculation or any fertilizer application during the following growth period. Main plot treatments were: (1) plants without PGPR treatment irrigated with tap water (400 ml each time) per plant every 3 days throughout the entire life (briefly, 'OS', same below); (2) plants without PGPR treatment irrigated with 1.0% NaCl solution (simulated 30% of the salt concentration of sea water) at the same rate (MS); (3) plants without PGPR treatment irrigated with 2.0% NaCl solution (simulated 60% of the salt concentration of sea water) at the same rate (HS); (4) plants inoculated with *E. persicinus* RA2 irrigated with tap water at the same rate (OS+RA2); (5) plants inoculated with *B. pumilus* WP8 irrigated with tap water at the same rate (OS+WP8); (6) plants inoculated with *P. putida* RBP1 irrigated with tap water at the same rate (OS+RBP1); (7) plants inoculated with *E. persicinus* RA2 irrigated with 1.0% NaCl solution at the same rate (MS+RA2); (8) plants inoculated with *B. pumilus* WP8 irrigated with 1.0% NaCl solution at the same rate (OS+WP8); (9) plants inoculated with *P. putida* RBP1 irrigated with 1.0% NaCl solution at the same rate (OS+RBP1); (10) plants inoculated with *E. persicinus* RA2 irrigated with 2.0% NaCl solution at the same rate (MS+RA2); (11) plants inoculated with *B. pumilus* WP8 irrigated with 2.0% NaCl solution at the same rate (OS+WP8); (12) plants inoculated with *P. putida* RBP1 irrigated with 2.0% NaCl solution at the same rate (OS+RBP1). After 2 months of growth, three plants were chosen randomly

within the three replicates in each treatment in order to estimate the following parameters as described in detail below.

Marketable yield of tomato. The marketable yield of tomato (fresh weight) per treatment was calculated from the sum of all selected tomatoes which were not less than 60 g and the dry weight yield was obtained after drying to constant weight at 80°C. Average marketable fruit weight and dry fruit weight were determined by calculating the average of all selected marketable tomatoes and dry marketable tomatoes.

Plant growth indices. Plants above-ground fresh biomass was determined by weighing and height was measured from ground level to the terminal bud, under-ground biomass and root depth were obtained using the same method except that the root system was washed with tap water before weighing. The dry biomass of plants was investigated after drying to constant weight.

Leaf and fruit chemical analysis. Chemical analysis here mentioned was performed from 3-month-old plants. Three random expanded mature leaves and fruits were collected from mid-shoot of each plant and dried at 70°C for 24 h followed by grinding to fine powders. Pink tomatoes were harvested and were allowed about 2 days of further maturation at room temperature before analysis. Water soluble sugars were determined by the method of phenol sulfuric acid (DuBois et al., 1956) after the pre-preparation of resuspension of each sample (100 mg) in 2 ml of water, sonication, and centrifugation at 2,500 × *g* for 10 min. Vitamin C (VC) content was determined using the spectrophotometer method described by Qi (2011). The concentrations (mg 100 mg⁻¹ DW) of Na⁺ content in tomato plant mid-shoot leaves were measured with flame photometry (Shanghai, Model FP6410) (Overman and Davis, 1947) and quantified based on a standard curve of pure Na⁺. Water content was calculated as (FW – DW)/FW, where FW and DW are the fresh and dry weight, respectively. Dry weight was obtained by drying the material at 80°C until a constant weight.

Statistical analysis. The analysis of variance (ANOVA) was performed using the software SPSS 15.0 for Windows (SPSS, Chicago, IL) and treatment means were compared by Duncan's test at a 5% level of probability.

Results

Effect of PGPR on tomato plants growth under simulated seawater irrigation

The increased salt stress decreased all the growth indices except root length. Three PGPR strains exhibit varying degrees of growth promotion, and play a more significant role in plant biomass than shoot height or root length (Table 2). During the Spring period (from April to June), within the 3 PGPR strains, aboveground fresh and dry weight of the RA2 treatment under MS conditions were increased by 119.95% and 147.41% as compared with the MS control, whereas underground fresh and dry weight of the RA2 treatment under MS conditions were increased by 132.51% and 114.62%. By contrast, RA2 highlighted its growth-promoting ability under MS conditions rather than under the other two conditions, while RBP1 showed the greatest activity under OS conditions. The indices related to biomass of the WP8 treatments were not so outstanding in comparison with the other two PGPR strains. However, during Autumn period (from August to October), RA2 exerts great influence on aboveground-related indices under OS condition, WP8 highlights its growth promoting ability in MS condition rather than in the other two conditions, while the behavior of RBP1 is not as good as the preceding period.

Effect of PGPR on marketable tomato fruit yield under simulated seawater irrigation

Marketable tomato fruit yields were increased significantly under MS conditions and decreased significantly while under HS conditions ($p < 0.05$); however, the average marketable fruit weight was decreased significantly only under HS conditions (Table 3). Under all the testing conditions, growth-promoting actions of the three PGPR strains were not embodied in enhancing the average marketable fruit weight but in enhancing marketable fruit yield significantly ($p < 0.05$). For example, during Spring period, the marketable fruit yields of RA2, WP8 and RBP1 treatments were increased by 174.92%, 45.10% and 49.54% respectively as compared with controls under OS conditions; however, the average marketable fruit weights were not only increased significantly but even slightly decreased in comparison with the control, which means the positive effects of the three PGPRs on the fruit yield are not decided by the average fruit weight but the number of

fruits.

RA2 exhibited the best ability compared with other PGPR strains to enhance yields of fresh and dried fruits in tomato under simulated seawater irrigation, especially under HS conditions. Furthermore, significant yield enhancement of tomato does not depend on the average marketable fruit weight except under HS conditions. The ability to increase yields of RBP1 treatment in the Autumn period is not so distinct as in the Spring period.

Effect of PGPR on tomato fruit quality under simulated seawater irrigation

As shown in Table 4, there were no significant differences in the water soluble sugar (WSS) or VC content between the MS control and OS control except in WSS during the Autumn period the however, the HS control had the highest values of 4.24% and 18.54 mg 100 g⁻¹ DW in Spring period, MS and HS control have the highest values of 5.07% and 17.26 mg 100 g⁻¹ DW respectively in Autumn period and showed a significant increase compared to OS control ($p < 0.05$).

The three PGPR strains showed varying degrees of improvement of tomato fruit quality. Under the WP8 treatment, RA2 and RBP1 did not significantly increase WSS or VC contents under OS conditions in Spring period, however, in Autumn period, both RA2 and WP8 improve tomato fruit quality significantly compared with OS control ($p < 0.05$). With increasing salt concentrations, the enhancements of WSS and VC contents by PGPR strains compared to control are exhibited more significantly except RBP1. WP8 had the most significant effect on improving tomato fruit quality among the three strains which plays the best role in WSS and VC promotion under MS conditions and HS conditions respectively.

Effect of PGPR on Na⁺ contents in tomato plant mid-shoot leaves and fruits

As illustrated in Table 5, greater Na⁺ contents were generally accumulated in tomato plant mid-shoot leaves than in fruits whatever the salt concentration. When the salt concentration was increased, sodium was accumulated significantly in both leaves and fruits ($p < 0.05$). There was no significant Na⁺ accumulation ($p > 0.05$) for PGPR strain treatments in comparison with controls either in leaves or in fruits under OS or MS conditions; however, in Spring period, sodium contents in leaves of the RA2 and WP8 treatments in-

Table 2. Effect of PGPRs on tomato-growing indices 2 months after transplanting.

Treatment	The period from April to June, 2011					The period from August to October, 2011						
	Aboveground-related indices ^b			Underground-related indices ^b		Aboveground-related indices ^b			Underground-related indices ^b			
	Height (cm)	Fresh weight (g)	Dry weight (g)	Length (cm)	Fresh weight (g)	Dry weight (g)	Height (cm)	Fresh weight (g)	Dry weight (g)	Length (cm)	Fresh weight (g)	Dry weight (g)
OS ^a	85.06 ef	350.53 f	51.57 g	3.93 cd	9.75 e	2.54 b	80.00 cd	318.77 d	46.78 d	3.30 d	8.57 e	2.64 cd
OS+RA2	108.17 c	527.32 c	68.69 cd	5.60 a	14.33 b	3.49 a	102.88 a	496.17 a	74.68 a	5.00 bc	14.24 b	4.57 ab
OS+WP8	85.70 ef	412.67 e	54.89 f	4.20 bcd	11.53 c	2.49 b	86.13 c	410.03 b	61.94 b	5.23 b	14.03 b	4.51 b
OS+RBP1	116.67 b	672.00 a	90.54 b	3.03 e	10.93 d	2.70 b	96.01 b	398.07 b	52.69 c	2.73 e	8.27 e	2.99 cd
MS ^a	82.33 fg	282.66 h	41.26 i	4.53 bc	7.72 g	1.71 e	75.57 de	251.00 f	38.07 e	4.57 c	12.57 c	3.14 c
MS+RA2	104.79 c	621.71 b	102.08 a	3.70 d	17.95 a	3.67 a	94.77 b	506.57 a	75.03 a	4.50 c	13.97 b	5.07 ab
MS+WP8	95.35 d	496.87 d	66.37 d	4.83 b	9.97 e	2.60 b	84.23 c	494.70 a	74.59 a	5.93 a	17.80 a	5.18 a
MS+RBP1	143.67 a	513.14 cd	70.24 c	3.04 e	9.55 e	2.39 bc	75.00 de	360.53 c	54.08 c	2.67 e	8.20 e	2.75 cd
HS ^a	48.23 i	204.10 i	35.70 j	4.57 bc	8.83 f	1.42 f	40.73 g	179.80 g	24.94 f	3.77 d	10.40 d	2.47 d
HS+RA2	70.20 h	302.13 h	42.71 hi	3.83 d	11.01 cd	2.57 b	70.03 ef	324.97 d	51.67 c	3.67 d	11.00 d	4.53 b
HS+WP8	74.57 gh	287.55 h	45.27 h	3.80 d	10.74 d	2.17 cd	76.67 de	307.73 d	44.67 d	4.57 c	14.23 b	4.74 ab
HS+RBP1	92.64 de	324.38 g	59.68 e	2.77 e	7.84 g	2.08 d	67.80 f	280.30 e	40.17 e	3.33 d	7.90 e	2.48 d

For each experiment, values within a column followed by the same letter are not significantly different according to Duncan's test ($p < 0.05$).

^a OS, MS and HS represent plants irrigated with non-NaCl solution (tap water), 1.0% NaCl solution (simulated 30% of the salt concentration of sea water) and 2.0% NaCl solution (simulated 60% of the salt concentration of sea water).

^b Each value represents the mean of 4 plant replicates.

Table 3. Effect of PGPRs on marketable tomato fruit yield per plant and fruit weight per treatment 2 months after transplanting.

Treatment	The period from April to June, 2011				The period from August to October, 2011			
	Marketable fruit yield (g/plant) ^b		Average marketable fruit weight (g/fruit) ^c		Marketable fruit yield (g/plant) ^b		Average marketable fruit weight (g/fruit) ^c	
	Fresh weight	Dry weight	Fresh weight	Dry weight	Fresh weight	Dry weight	Fresh weight	Dry weight
OS ^a	435.05±30.06 f	26.73±2.87 e	108.76±18.23 ab	6.68±1.29 abc	395.81±6.86 fg	24.63±1.25 h	103.68±6.80 bc	6.52±0.58 ab
OS+RA2	1,196.02±120.61 b	68.63±8.78 b	108.73±32.40 ab	6.24±1.78 abc	1,049.21±68.44 b	54.28±3.33 bc	115.51±5.64 a	6.88±1.05 ab
OS+WP8	631.24±25.76 de	40.96±2.29 d	90.18±22.05 bc	5.85±1.62 abc	707.10±33.22 d	45.39±3.50 d	98.14±1.61 cd	7.21±1.49 a
OS+RBP1	650.56±41.98 de	40.42±3.24 d	86.74±30.68 bc	5.39±1.86 bc	459.33±32.19 f	30.43±1.91 fg	89.33±3.47 e	5.47±1.02 bc
MS ^a	571.71±30.76 e	37.60±2.67 d	107.20±23.29 ab	7.05±1.35 ab	460.80±27.23 f	28.55±0.71 gh	101.93±3.96 bc	6.14±0.92 abc
MS+RA2	1,327.53±61.40 a	76.73±3.85 a	109.41±35.71 ab	6.32±1.98 abc	1,244.48±74.23 a	67.34±2.68 a	107.36±3.11 b	6.77±0.62 ab
MS+WP8	624.38±26.16 e	37.92±1.84 d	106.43±28.82 ab	6.46±1.86 abc	794.00±46.49 c	57.07±2.61 b	93.53±1.00 de	7.73±0.89 a
MS+RBP1	1,023.23±93.97 c	63.70±6.24 b	109.63±41.50 ab	6.83±2.70 ab	549.55±38.78 e	38.53±2.50 e	91.41±2.59 de	5.49±0.74 bc
HS ^a	250.01±33.52 g	15.84±2.13 f	71.43±13.91 c	4.52±1.21 c	231.78±38.75 h	14.22±2.19 i	72.65±2.86 f	4.50±0.70 c
HS+RA2	728.69±27.14 d	50.38±3.34 c	94.63±33.76 bc	6.54±2.07 abc	812.58±68.08 c	50.58±1.37 c	90.21±2.99 e	5.33±0.81 bc
HS+WP8	341.64±35.74 fg	19.57±2.23 f	97.61±28.61 abc	5.59±1.75 bc	460.45±27.26 f	33.49±2.76 f	91.26±2.60 de	6.81±0.82 ab
HS+RBP1	631.39±45.46 de	38.21±3.82 d	131.54±40.79 a	7.96±2.33 a	342.18±22.41 g	25.52±1.83 h	74.02±5.55 f	4.80±0.32 c

For each experiment, values within a column followed by the same letter are not significantly different according to Duncan's test ($p < 0.05$).

^a OS, MS and HS represent plants irrigated with non-NaCl solution (tap water), 1.0% NaCl solution (simulated 30% of the salt concentration of sea water) and 2.0% NaCl solution (simulated 60% of the salt concentration of sea water). ^b Each value represents the mean of marketable tomato fruit yield per plant of 4 plants replicates.

^c Each value represents the mean of marketable tomato fruit weight per treatment with above 4 plant replicates respectively.

Table 4. Effect of PGPRs on tomato fruit quality as Indicated by water soluble sugar and fruit VC content.

Treatment	The period from April to June, 2011		The period from August to October, 2011	
	Water soluble sugar content (%) ^b	Fruit VC content (mg 100 g ⁻¹ DW) ^b	Water soluble sugar content (%) ^b	Fruit VC content (mg 100 g ⁻¹ DW) ^b
OS ^a	2.83±0.36 e	13.45±1.10 ef	4.40±0.21 f	12.20±0.65 gh
OS+RA2	3.36±0.52 de	16.32±1.14 de	5.13±0.11 de	15.62±0.93 ef
OS+WP8	4.77±0.21 b	17.54±1.71 bcd	5.93±0.48 c	18.19±0.55 cd
OS+RBP1	2.92±0.38 e	12.49±1.60 f	4.65±0.32 ef	11.54±0.95 h
MS ^a	3.04±0.27 e	15.53±0.63 de	5.01±0.29 e	13.95±0.36 fg
MS+RA2	4.62±0.33 b	16.36±2.05 de	5.64±0.26 cd	16.75±0.62 de
MS+WP8	5.89±0.30 a	19.85±1.48 b	7.59±0.26 a	22.44±1.80 b
MS+RBP1	3.78±0.25 cd	16.62±2.37 cde	5.11±0.33 de	15.78±0.51 ef
HS ^a	4.24±0.42 bc	18.54±1.12 bcd	5.07±0.14 e	17.26±0.36 cde
HS+RA2	5.61±0.36 a	20.42±2.14 b	6.61±0.23 b	20.77±0.60 b
HS+WP8	6.22±0.28 a	26.76±1.05 a	7.73±0.25 a	27.62±1.95 a
HS+RBP1	4.35±0.37 bc	19.47±1.44 bc	5.91±0.59 c	18.78±1.58 c

For each experiment, values within a column followed by the same letter are not significantly different according to Duncan's test ($p < 0.05$).

^a OS, MS and HS represent plants irrigated with non-NaCl solution (tap water), 1.0% NaCl solution (simulated 30% of the salt concentration of sea water) and 2.0% NaCl solution (simulated 60% of the salt concentration of sea water).

^b Each value represents the mean of 8 fruits replicates randomly picked from 4 plants.

Table 5. Effect of PGPRs on Na⁺ contents in tomato plant mid-shoot leaves and fruits 2 months after transplanting.

Treatment	The period from April to June, 2011		The period from August to October, 2011	
	Na ⁺ contents in leaves (mg/100 mg DW) ^b	Na ⁺ contents in fruit (mg/100 mg DW) ^b	Na ⁺ contents in leaves (mg/100 mg DW) ^b	Na ⁺ contents in fruit (mg/100 mg DW) ^b
OS ^a	0.053±0.006 e	0.039±0.004 d	0.030±0.006 e	0.029±0.008 e
OS+RA2	0.051±0.003 e	0.037±0.001 d	0.034±0.002 e	0.027±0.004 e
OS+WP8	0.049±0.005 e	0.036±0.004 d	0.032±0.004 e	0.030±0.005 e
OS+RBP1	0.049±0.004 e	0.037±0.006 d	0.035±0.006 e	0.028±0.005 e
MS ^a	0.70±0.03 d	0.058±0.006 c	0.620±0.05 d	0.049±0.003 d
MS+RA2	0.78±0.01 d	0.064±0.005 bc	0.670±0.04 d	0.052±0.004 d
MS+WP8	0.89±0.05 d	0.069±0.006 b	0.777±0.04 d	0.062±0.004 c
MS+RBP1	0.74±0.07 d	0.065±0.005 bc	0.630±0.05 d	0.049±0.005 d
HS ^a	1.54±0.18 c	0.086±0.010 a	1.49±0.06 bc	0.078±0.003 b
HS+RA2	1.78±0.12 b	0.093±0.003 a	1.62±0.17 b	0.089±0.005 a
HS+WP8	2.23±0.25 a	0.094±0.005 a	1.92±0.21 a	0.091±0.007 a
HS+RBP1	1.62±0.19 bc	0.065±0.004 bc	1.45±0.09 c	0.080±0.005 b

For each experiment, values within a column followed by the same letter are not significantly different according to Duncan's test ($p < 0.05$).

^a OS, MS and HS represent plants irrigated with non-NaCl solution (tap water), 1.0% NaCl solution (simulated 30% of the salt concentration of sea water) and 2.0% NaCl solution (simulated 60% of the salt concentration of sea water).

^b Each value represents the mean of 4 plant replicates.

creased by 15.58% and 44.80% ($p < 0.05$) respectively as compared with the HS control. Sodium contents in fruits of RBP1 treatment is decreased by 24.42% ($p < 0.05$) as compared with the HS control. In Autumn, RA2 and WP8 under HS conditions showed significant enhancement of sodium accumulation ($p < 0.05$) in both leaves and fruits except RBP1 treatment.

Discussion

The use of PGPR strains to alleviate salt stress is considered to be a promising new channel that can help to improve plant growth without environmental disruption. While the present study gives another salt stress condition of simulated seawater irrigation on account of the expansive salt marshes around the Yellow Sea in China. The National Coastal Development Plan is in dire need of workable agricultural biotechnology against salt stress.

Yield indices are selected to indicate growth-promotion activity in most studies (Abbaspoor et al., 2009; Barriuso et al., 2008; Chakraborty et al., 2011; Kausar and Shahzad 2006), however, quality indices are equally important in vegetable and fruit plants which are rarely discussed. The three PGPR strains can all promote tomato growth, increase fruit yield and/or improve fruit quality; however, biomass enhancement and quality improvement are often not entirely exhibited by any one of the three strains in Spring period except WP8 in Autumn period, which is considered a promising PGPR strain for further application especially under salt stress conditions. As shown in Table 6, strain RA2 and RBP1 had the ability to promote tomato plants growth under all test conditions, whereas WP8 plays a similar role only under MS and HS conditions in Spring period. The contrary results of correlation between tomato plant growth and marketable yield are excited in RA2, RBP1 and WP8 treatment, which implied that good plant growth does not always mean high fruit production. In contrast, plant growth promotion by RA2 and RBP1 have not reappeared in tomato quality improvement, whereas desired effects on fruit quality were obtained from WP8 treatments. Accumulation of solution sugar can be attributed to balance protection for plant cells (Greenway and Munns, 1980) or attributed to the reduction in utilization of carbohydrates for the formation of new cells and tissues (Alfocea et al., 1993). Anyway, this information reflects the diverse pathways in growth promotion by PGPR

Table 6. Effect of PGPR strains on different growth indices.

Salt stress	The period from April to June, 2011						The period from August to October, 2011					
	Growth promotion ^a			Quality improvement ^{ac}			Growth promotion ^{ae}			Yield increment ^{ab}		
	RA2	WP8	RBP1	RA2	WP8	RBP1	RA2	WP8	RBP1	RA2	WP8	RBP1
OS	+	-	+	-	+	+	+	+	+	+	-	-
MS	+	+	+	+	+	+	+	+	+	+	+	+
HS	+	+	+	+	+	+	+	+	+	+	+	+

^a "+" and "-" represent that PGPR strains had significant and slight effects on different biological indices.

^b Transverse lines in parentheses represent slight effects on average marketable fruit weight.

^c Transverse lines in parentheses represent slight effects on fruit VC content.

^d "+" and "-" represent that PGPR strains can and can't significantly enhance accumulation of sodium in leaves.

^e Transverse lines in parentheses represent slight effects on underground-related indices.

strains. Based on this, we can reasonably select PGPR strains according to different objectives. For example, we may use RA2 and WP8 when high quality fruits are needed, and select RBP1 when high non-fruit products are needed. Thus, some potential combinations might be more useful than applications of single PGPR strains, which will be proven in further work.

Our results also suggest that some PGPR strains exhibit growth-promoting actions only under several specific conditions, which not mean non-stress conditions. In some cases, like WP8, PGPR strains seem to be more effective under salt stress than non-stress conditions, because they are competitive against other relatively simple indigenous soil microorganisms under salt stress condition (Foti et al., 2008; Liu et al., 2010). Further more, efficiency in growth promotion of some PGPR strains like RBP1 are often unstable in different seasons and maybe in different locations, which is expressed in a slight effect on tomato growth in Autumn period compared with the Spring period.

The action mechanism of salinity tolerance induced by PGPR strains was attributed to the ACC deaminase activity of selected strains (Mayak et al., 2004), which is considered the principle of screening strategy. However, this study shows clearly that reduction in ethylene production by ACC deaminase-producing PGPR strains is not necessary for salt tolerance. WP8 and RBP1 without ACC deaminase activity can also show growth promotion through quality improvement and yield increment. ACC deaminase-producing strain RA2 can steadily promote tomato growth under testing salt stress conditions in comparison with WP8 and RBP1, and this may be a reason for using ACC deaminase activity as an index for screening.

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