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Foliar application of selenium (Se) at heading stage induces regulation of photosynthesis, yield formation, and quality characteristics in fragrant rice

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Abstract

In order to study the effect of foliar application of sodium selenate on fragrant rice performance at the heading stage, the present study was conducted with two fragrant rice cultivars, 'Meixiangzhan-2' and 'Xiangyaxiangzhan'. At the heading stage, six concentrations of sodium selenate solution (0, 10, 20, 30, 40, and 50 µmol L^{-1}) were sprinkled to plants. Our results showed that foliar application of sodium selenate increased chlorophyll contents in rice leaves and upregulated net photosynthetic rate at the grain-filling stage. The enhancement was observed in grain yield, seed-setting rate, and in 1,000-grain mass. The highest yield and net photosynthetic rate were both recorded at 40 µmol L^{-1} treatment for both cultivars. Furthermore, foliar application of sodium selenate also improved some grain quality attributes, such as head rice rate and crude protein content. The Se concentration in fragrant rice grain also increased due to sodium selenate application. In conclusion, sodium selenate has potential to be the exogenous plant growth regulator in fragrant rice production to increase yield and quality.

Additional key words: 1,000-grain mass; aromatic rice; gas exchange; microelement; photosynthetic capacity.

Introduction

As the curiosa in rice (*Oryza sativa* L.), fragrant rice is desired by people because of the taste and optimal flavour and other preferred features (Ren *et al*. 2017). In recent years, fragrant rice is fetching premium prices in international markets and the demand is increasing around the world (Mo *et al.* 2016). Thus, farmers and researchers begin to pay more attention to a problem how to increase fragrant rice yield and promote a grain quality. An exogenous plant growth regulator might become an effective way to improve fragrant rice yield.

Photosynthesis is an important physiological process and significantly affects the rice growth and development. A previous study showed that about 90% of the dry matter formed during the growth and development of crops came from photosynthetic assimilates (Petridis *et al.* 2018). The study of Thussagunpanit *et al*. (2015) also showed that photosynthetic rate is one of the limiting factors in the yield formation of rice. Furthermore, the research of Wu *et al*. (2008) revealed that the higher light intensity could enhance photosynthetic rate and increase the dry matter accumulation and finally improve the grain yield of rice. Therefore, photosynthesis is a key part in aroma rice production to improve fragrant rice yield and ensure the yield stability.

Selenium (Se), as a trace and non-metallic element, plays an essential role in physiological activities of plants. In 1982, an investigation evidenced that Se application could alleviate the stress of crops caused by toxic elements, such as arsenic, antimony, mercury, and copper (Gotsis 1982). The research of Hu *et al.* (2014) revealed that Se fertilizer could significantly decrease the accumulation of cadmium and lead in rice tissues and thus alleviate the damage caused by these elements. The study of Wang *et al.* (2012) also showed that foliar application of Se at low concentration could activate the antioxidant system and enhance photosynthesis while the higher Se concentration could damage the photosynthetic apparatus and inhibit photosynthesis. Hence, Se might have potential to be the exogenous regulator in rice production. However, the effects of selenate application on photosynthesis, yield

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Abbreviations: C_i – intercellular CO_2 concentration; E – transpiration rate; g_s – stomatal conductance; P_N – photosynthetic rate; WUE – water-use efficiency.
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formation and grain quality of fragrant rice were rarely studied. Therefore, in this study, we compared the rice photosynthesis, grain quality, and yield under five different concentrations of sodium selenate to explore effects of foliar application of Se on fragrant rice performance.

Materials and methods

Plant materials and growing conditions: Seeds of two fragrant rice cultivars, 'Xiangyaxiangzhan' and 'Meixiangzhan-2', widely grown aromatic rice in Guangdong Province, China, were provided by College of Agriculture, South China Agricultural University, Guangzhou, China. Before sowing, the seeds were soaked in water for 24 h, germinated in manual climatic boxes for another 12 h, then shade-dried, followed by sowing in polyvinyl chloride trays for nursery raising. Then, the 20-d-old seedlings were transplanted to the fields at the planting distance of 30 × 12 cm. Field experiment between July and November 2017 was conducted at Experimental Research Farm, College of Agriculture, South China Agricultural University, Guangzhou, China (23°16'N, 113°23'E, and 11 m from mean sea level). The experimental soil in Guangzhou was sandy loam containing 15.7% organic matter, 0.96% total N, 0.76% total P, and 12.46% total K. The experimental sites enjoyed a subtropical monsoon climate (Fig. 1).

Treatments and plant sampling: Six treatments were realized by overhead sprinkle with 0, 10, 20, 30, 40, and 50 µmol L^{-1} sodium selenate (Na_2SeO_4; *Shandong Xiya Chemical Co*., *Ltd.*, China) at the heading stage, marked further as CK, Se1, Se2, Se3, Se4, and Se5, respectively. The treatments were arranged in randomized complete block design (RCBD) in triplicates with net plot size of 21 m^2. Fifteen litres of corresponding liquid was applied to each plot, respectively. Fresh leaves were separated and collected from the rice plants at the grain-filling stage (after 15 d of the heading stage), washed with double distilled water, and stored at –80°C for biochemical analysis. At maturity, the rice plants were collected from thirty hills in each plot and the sampled plants were oven-dried at 80°C until constant mass to record total biomass.

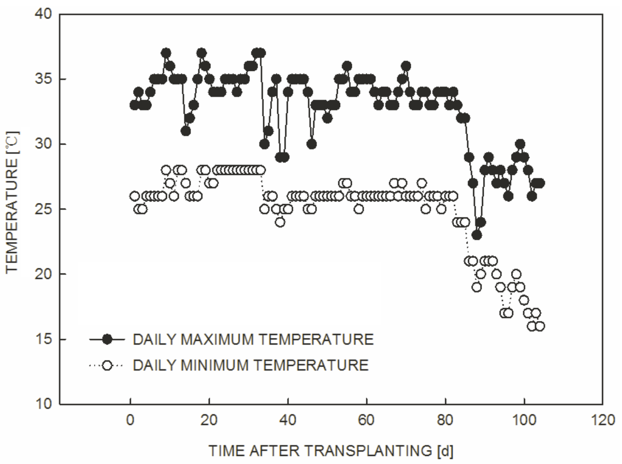

Fig. 1. Daily maximum and minimum temperatures during the experiment.

Photosynthetic parameters: During the grain-filling stage (after 15 d of heading stage), portable photosynthesis system (*LI-6400*, *LI-COR*, USA) was used to determine net photosynthetic rate (P_N), stomatal conductance (g_s), intercellular CO_2 concentration (C_i), transpiration rate (E), and water-use efficiency (WUE) at 09:00–10:30 h according to Kong *et al.* (2017) with the following adjustments: PAR at leaf surface was 1,100 and 1,200 µmol(photon) m^{-2} s^{-1}, ambient CO_2 concentration was 385 and 400 µmol mol^{-1}, air temperature was 31.5 ± 0.5°C with 60–80% relative air humidity. SPAD meter *SPAD-502* (*Konica Minolta*, Japan) was used for precise, rapid, and non-destructive estimation of leaf chlorophyll (Chl) content.

Chl and soluble protein content: The estimation of photosynthetic pigment and soluble protein were done using the methods described by He *et al.* (2019). The fresh leaf samples (0.1 g) were extracted with 95% alcohol and the absorbance was read at 665, 649, 652, and 470 nm (UV-VIS spectrophotometer *UV-2550*, *Shimadzu*, Japan). The soluble protein content was measured by using *Brilliant Blue G-250* (*Shanghai Aladdin Biochemical Technology Co.*, *Ltd*., China), the absorbance was read at 595 nm and expressed as µg g^{-1}(FM).

Se content in grains, leaves, and stems: For sample preparation, the mature grain and leaf from rice plants were dried in a fume hood at 50°C. Then, brans were separated and the seeds were ground into powder. Total Se content in polished grain was determined by using atomic absorption spectrophotometer (*Z2300*, *HITACHI*, Japan) with hydride generator (*HFS-3*, *HITACHI*, Japan). Before the estimation, 0.1-g samples were digested with 1.5 ml of concentrated HNO_3 and 0.5 ml 30% H_2O_2 in a digestive stove at 180°C for 1.5 h. The digested product was reconstituted to 10 ml with Milli-Q water and auto-sampled for total Se determination (Wang *et al.* 2013).

Yield and yield-related traits: At the maturity stage, the rice grains were harvested from five units of sampling area (1.75 m^2) in each plot and then threshed by machine. The harvested grains were sun-dried and weighted in order to determinate the grain yield. Twenty hills of rice from different locations in each plot were randomly collected for the estimation of effective panicles number per hill. Then, six hills of representative plants were taken for estimation of the yield-related traits including seed-setting rate and 1,000-grain mass.

Grain quality attributes: After sun-drying, grains were stored at room temperature for at least a month to determine grain quality components. Brown rice rate was estimated using a rice huller (Jiangsu, China) and milled rice and head rice recovery rates were calculated by using a *Jingmi* testing rice grader (Zhejiang, China). Grains with chalkiness and chalkiness degree were estimated by using an *SDE-A* light box (Guangzhou, China) while an *Infratec-1241* grain analyzer (*FOSS-TECATOR*) was used to determine the grain amylose and protein contents.

Statistical analysis: Data were analyzed on *Statistix 8.1* (*Analytical Software*, Tallahassee, FL, USA), while differences between means were separated by using least significant difference (LSD) test at 5% probability level. Graphical representation was conducted *via SigmaPlot 14.0* (*Systat Software Inc*., California, USA).

Results

Chl content: Foliar applications of sodium selenate significantly increased Chl contents (Fig. 2). Compared to CK, Se treatments increased the total Chl content by 4.2–15.0%. The trend of Chl *a* content was recorded as: Se4 > Se5 = Se3 > Se2 > Se1 > CK for both 'Meixiangzhan-2' and 'Xiangyaxiangzhan'. Similar trends were also observed in Chl *b* and carotenoid content.

Soluble protein content: As shown in Fig. 3, compared to CK, Se3 and Se4 treatments significantly increased the soluble protein content in leaves of both cultivars. For 'Meixiangzhan-2', compared with CK, Se3 and Se4 treatments increased soluble protein in leaves by 7.1 and 13.0%, respectively. For 'Xiangyaxiangzhan', 15.2 and 8.1% higher soluble protein contents were recorded under Se3 and Se4 compared with CK.

Photosynthesis and SPAD values: Foliar application of sodium selenate at the heading stage significantly affected photosynthesis during the grain-filling stage (Fig. 4). Compared with CK, all Se treatments (except Se1 in 'Meixiangzhan-2') enhanced P_N significantly. In Se2, Se3, Se4, and Se5, 13.6, 11.8, 24.5, and 11.7% higher P_N was recorded for 'Meixiangzhan-2', respectively. For 'Xiangyaxiangzhan', 12.7, 18.6, 27.7, 38.0, and 31.7% higher P_N in Se1, Se2, Se3, Se4, and Se5 were found,

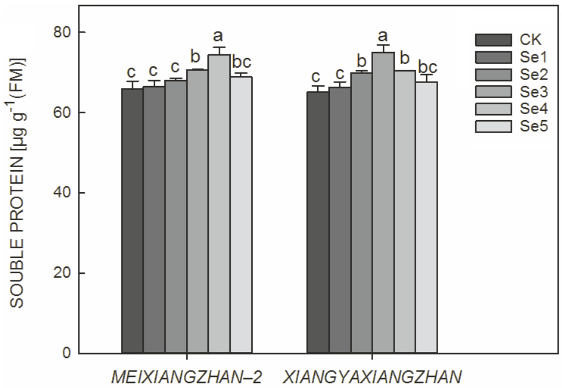

Fig. 3. Effect of sodium selenate on soluble protein in leaves of two fragrant rice cultivars. Bars represent SE of three replicates. Means sharing *the same letter* do not differ significantly at $P \leq 0.05$ according to least significant difference (LSD) test for both cultivars. CK, Se1, Se2, Se3, Se4, and Se5 – 0, 10, 20, 30, 40, and 50 μmol L^{-1} sodium selenate, respectively.

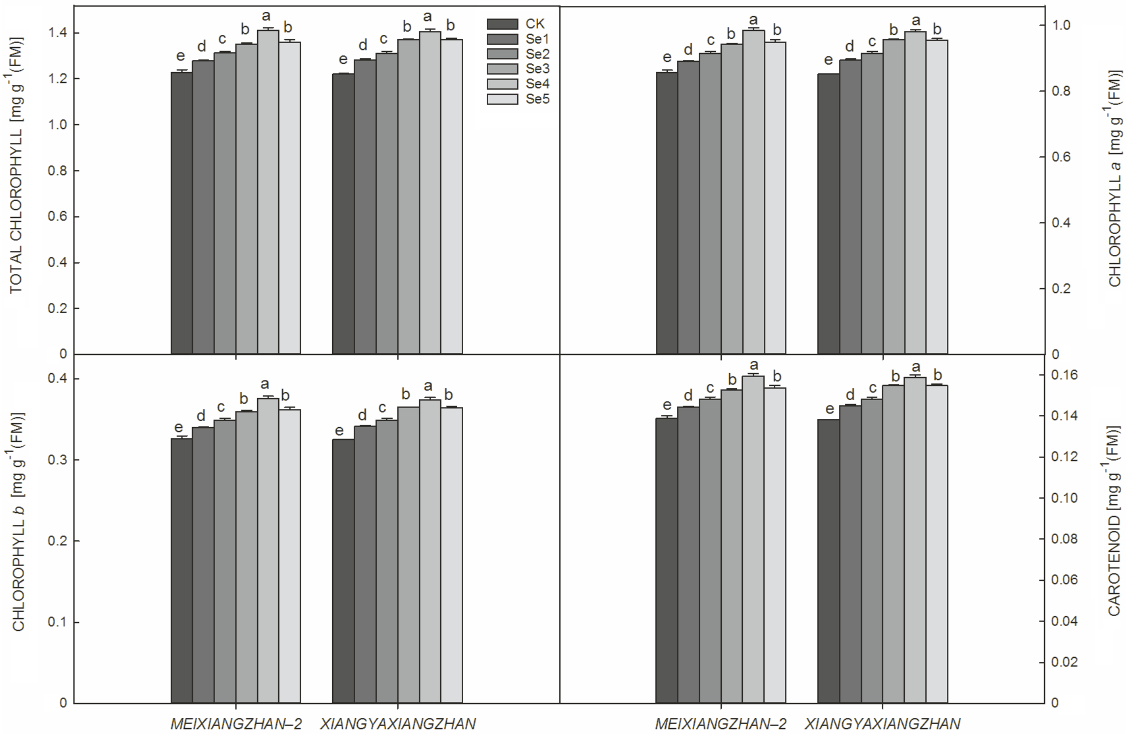

Fig. 2. Effect of sodium selenate on chlorophyll contents of two fragrant rice cultivars. Bars represent SE of three replicates. Means sharing *the same letter* do not differ significantly at $P \leq 0.05$ according to least significant difference (LSD) test for both cultivars. CK, Se1, Se2, Se3, Se4, and Se5 – 0, 10, 20, 30, 40, and 50 μmol L^{-1} sodium selenate, respectively.

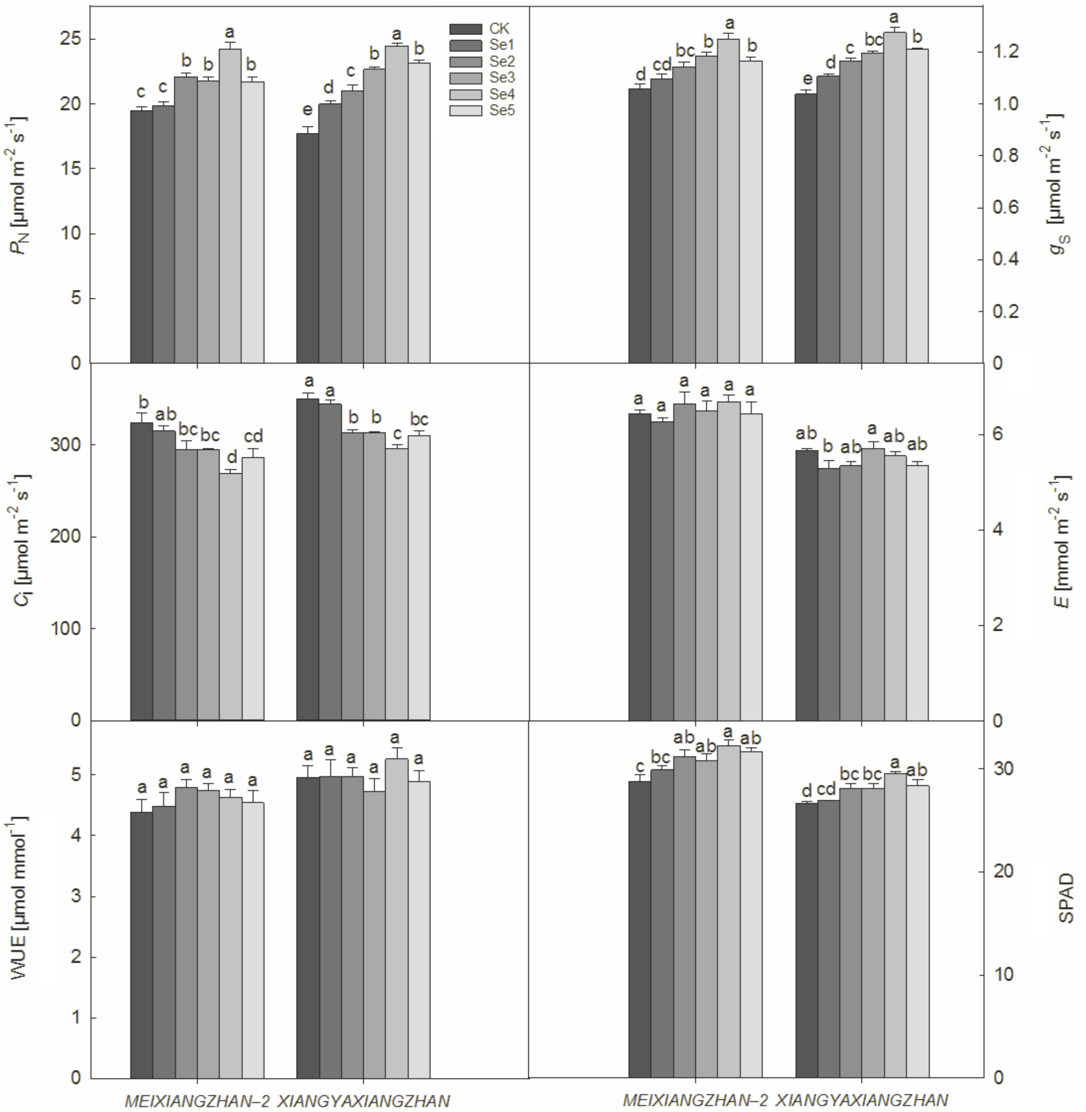

Fig. 4. Effect of sodium selenate on net photosynthesis, gas exchange, and SPAD values of two fragrant rice cultivars. Bars represent SE of three replicates. Means sharing *the same letter* do not differ significantly at $P \leq 0.05$ according to least significant difference (LSD) test for both cultivars. CK, Se1, Se2, Se3, Se4, and Se5 – 0, 10, 20, 30, 40, and 50 μmol L^{-1} sodium selenate, respectively.

respectively. The highest g_s was recorded in Se4 treatment for 'Meixiangzhan-2'. For 'Xiangyaxiangzhan', all Se treatments remarkably increased g_s. Compared with CK, values for C_i remained at a lower level under Se2, Se3, Se4, and Se5 treatments. Furthermore, compared with CK, Se2, Se3, Se4, and Se5 significantly increased SPAD values, while the highest value was recorded at Se4 for both cultivars. In addition, there was no significant difference in *E* and WUE between different treatments.

Dry matter accumulation at maturity: Foliar application of sodium selenate at the heading stage significantly affected the dry matter accumulation in fragrant rice (Fig. 5). For 'Meixiangzhan-2', dry matter masses higher by 7.3, 9.3, 13.4, 13.7, and 12.0% were recorded in Se1, Se2, Se3, Se4, and Se5, respectively, compared with CK at maturity. For 'Xiangyaxiangzhan', dry matter masses higher by 2.6, 8.7, 11.7, 11.9, and 10.7% compared with CK were observed in Se1, Se2, Se3, Se4, and Se5, respectively.

Se content: As shown in Fig. 6, foliar application of sodium selenate significantly increased the Se content in fragrant rice. Compared with CK, 1.58-, 1.11-, 1.36-, 1.50-, and 1.45-fold higher Se contents in grain were recorded in Se1, Se2, Se3, Se4, and Se5, respectively, for 'Meixiangzhan-2'. For 'Xiangyaxiangzhan', Se1, Se2, Se3, Se4, and Se5 treatments increased the Se content by 36.9, 80.3, 79.3, 117.3, and 113.5%, respectively. The similar trend was recorded in the Se content of leaves. Moreover, compared with CK, Se4 and Se5 also significantly increased the Se content in stems.

Yield and related attributes: Different Se treatments

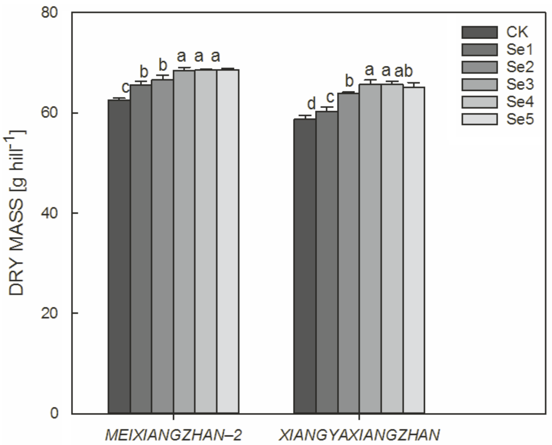

Fig. 5. Effect of sodium selenate on dry matter accumulation of two fragrant rice cultivars. Bars represent SE of three replicates. Means sharing *the same letter* do not differ significantly at $P \leq 0.05$ according to least significant difference (LSD) test for both cultivars. CK, Se1, Se2, Se3, Se4, and Se5 – 0, 10, 20, 30, 40, and 50 µmol L^{-1} sodium selenate, respectively.

affected rice yield and related attributes significantly (Table 1). For 'Meixiangzhan-2', the seed-setting rates of Se2, Se3, Se4, and Se5 were significantly higher than that of CK, *i.e.*, by 83.2, 81.9, 85.7, and 82.4%, respectively. Higher 1,000-grain masses were also observed in Se2 and Se4 than that of CK, 20.34 and 20.99 g, respectively. Furthermore, the highest yield was recorded in the Se4 treatment. For 'Xiangyaxiangzhan', compared with CK, Se2, Se3, and Se4 treatments remarkably improved the seed-setting rate, while the 1,000-grain masses of Se2, Se3, Se4, and Se5 were significantly higher than that of CK, *i.e.*, 20.09, 20.11, 21.11, and 20.53 g, respectively. Furthermore, Se2, Se3, Se4, and Se5 showed the higher yields than that of CK. In addition, there was no significant difference between different treatments in panicle number per hill and grain number per panicle for both cultivars.

Grain quality: As shown in Table 2, foliar application of sodium selenate improved grain quality of fragrant rice in terms of brown rice rate, milk rice rate, head rice rate, crude protein, and chalky rice rate. For 'Meixiangzhan-2', both Se3 and Se4 treatments significantly increased brown rice rate, milk rice rate, head rice rate, and crude protein content in grains compared with CK. Se3 also significantly decreased chalky rice rate and chalkiness. For 'Xiangyaxiangzhan', higher brown rice rates, milk rice rates, and head rice rates were recorded in Se4 and Se5 compared with CK, while all Se applications significantly increased crude protein content in grains.

Discussion

The photosynthesis of fragrant rice is affected by several agronomic and external climatic factors. Present study focused on the effect of exogenous sodium selenate application at the heading stage on photosynthesis, yield formation, and grain quality in fragrant rice. It

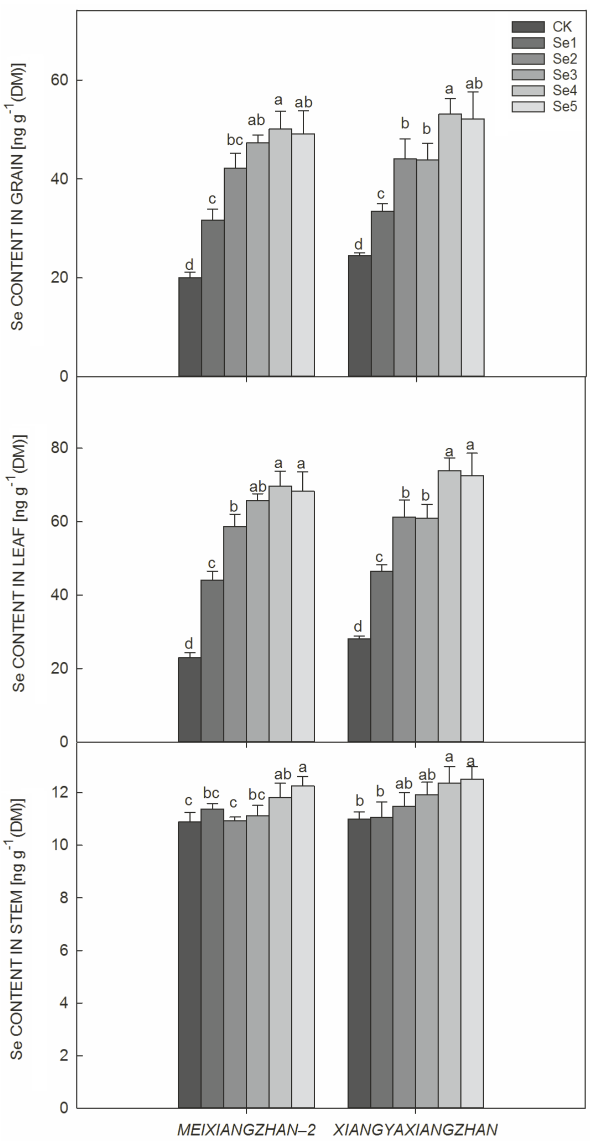

Fig. 6. Effect of sodium selenate on Se content in grains, leaves, and stems of two fragrant rice cultivars. Bars represent SE of three replicates. Means sharing *the same letter* do not differ significantly at $P \leq 0.05$ according to least significant difference (LSD) test for both cultivars. CK, Se1, Se2, Se3, Se4, and Se5 – 0, 10, 20, 30, 40, and 50 µmol L^{-1} sodium selenate, respectively.

was found that foliar application of sodium selenate significantly increased the P_N at the grain-filling stage for both 'Meixiangzhan-2' and 'Xiangyaxiangzhan'. Compared with control, Se applications increased the P_N by 2.2–24.6% and 12.7–37.6% for 'Meixiangzhan-2' and 'Xiangyaxiangzhan', respectively, while the highest P_N were both recorded in the Se4 treatment. The improvement was attributed to the increment in g_s, photosynthetic pigments, and soluble proteins. Compared with CK, foliar application of sodium selenate remarkably increased the g_s, Chl content, and soluble protein content, which corroborated with the previous reports of He *et al.* (2019)

Table 1. Effect of sodium selenate on rice yield and related attributes of two fragrant rice cultivars. Values sharing *the same letter* within a column do not differ significantly at $P \le 0.05$ according to least significant difference (LSD) test for both cultivars. *, ** – significant at $p<0.05$ and $p<0.01$, respectively, ns – insignificant. CK, Se1, Se2, Se3, Se4, and Se5 – 0, 10, 20, 30, 40, and 50 μmol L^{-1} sodium selenate, respectively.

Cultivar	Treatment	Panicle number per hill	Grain number per panicle	Seed-setting rate [%]	1,000-grain mass [g]	Yield [t ha^{-1}]
Meixiangzhan-2	CK	21.47^{a}	136.31^{a}	78.08^{d}	19.66^{c}	4.46^{b}
	Se1	21.52^{a}	134.39^{a}	79.68^{cd}	19.85^{bc}	4.45^{b}
	Se2	22.85^{a}	137.98^{a}	83.15^{ab}	20.34^{b}	4.46^{b}
	Se3	21.64^{a}	136.39^{a}	81.94^{bc}	20.27^{bc}	4.47^{b}
	Se4	20.99^{a}	136.52^{a}	85.67^{a}	20.99^{a}	4.63^{a}
	Se5	21.65^{a}	137.69^{a}	82.37^{bc}	19.97^{bc}	4.42^{b}
Xiangyaxiangzhan	CK	19.51^{a}	116.67^{a}	79.34^{d}	19.34^{d}	3.95^{c}
	Se1	19.44^{a}	113.89^{a}	80.48^{cd}	19.68^{cd}	4.14^{bc}
	Se2	19.04^{a}	117.96^{a}	82.64^{bc}	20.09^{bc}	4.24^{b}
	Se3	18.86^{a}	115.69^{a}	84.39^{ab}	20.11^{bc}	4.18^{b}
	Se4	19.01^{a}	117.85^{a}	86.19^{a}	21.11^{a}	4.50^{a}
	Se5	19.32^{a}	116.42^{a}	81.80^{bcd}	20.53^{b}	4.30^{b}
Analysis of variance						
Cultivar (C)		*	**	ns	ns	*
Selenium (Se)		ns	ns	**	**	**
Se × C		ns	ns	ns	ns	*

Table 2. Effect of sodium selenate on grain quality attributes of two fragrant rice cultivars. Values sharing *the same letter* within a column do not differ significantly at $P \le 0.05$ according to least significant difference (LSD) test for both cultivars. *, ** – significant at $p<0.05$ and $p<0.01$, respectively, ns – insignificant. CK, Se1, Se2, Se3, Se4, and Se5 – 0, 10, 20, 30, 40, and 50 μmol L^{-1} sodium selenate, respectively.

Cultivar	Treatment	Brown rice rate [%]	Milled rice rate [%]	Head rice rate [%]	Crude protein content [%]	Amylose content [%]	Akali	Chalky rice rate [%]	Chalkiness [%]
Meixiangzhan-2	CK	69.52^{b}	66.16^{b}	48.76^{c}	8.33^{d}	17.27^{a}	6.33^{a}	9.69^{a}	2.73^{a}
	Se1	78.18^{ab}	68.72^{ab}	55.99^{b}	8.42^{c}	17.91^{a}	6.41^{a}	6.07^{bc}	2.14^{a}
	Se2	77.30^{ab}	70.46^{a}	53.39^{b}	8.45^{b}	17.41^{a}	6.07^{a}	5.93^{bc}	2.01^{ab}
	Se3	83.09^{a}	69.54^{a}	62.62^{a}	8.51^{a}	17.38^{a}	6.15^{a}	4.10^{c}	1.03^{b}
	Se4	81.48^{a}	71.73^{a}	61.06^{a}	8.52^{a}	17.94^{a}	6.37^{a}	7.27^{abc}	2.15^{a}
	Se5	76.25^{ab}	70.02^{ab}	50.32^{cb}	8.50^{a}	17.26^{a}	6.43^{a}	8.06^{ab}	2.18^{a}
Xiangyaxiangzhan	CK	80.06^{b}	59.90^{b}	57.64^{b}	7.84^{d}	18.74^{a}	6.77^{a}	2.24^{ab}	2.47^{abc}
	Se1	81.27^{b}	60.93^{b}	56.09^{b}	7.90^{c}	18.31^{a}	6.77^{a}	2.14^{b}	2.15^{bc}
	Se2	83.53^{b}	62.21^{b}	58.40^{b}	7.97^{b}	18.92^{a}	6.71^{a}	2.25^{ab}	1.91^{c}
	Se3	87.83a	63.63^{ab}	57.88^{b}	8.00^{ab}	18.73^{a}	6.76^{a}	2.73^{ab}	2.51^{ab}
	Se4	89.20^{a}	66.51^{a}	61.38^{a}	8.03^{a}	18.22^{a}	6.63^{a}	2.54^{ab}	2.59^{ab}
	Se5	87.49^{a}	66.18^{a}	61.32^{a}	7.99^{ab}	18.02^{a}	6.78^{a}	3.08^{a}	2.82^{a}
Analysis of variance									
Cultivar (C)		*	*	ns	**	*	*	**	ns
Selenium (Se)		*	ns	ns	**	ns	ns	*	ns
Se × C		ns	ns	ns	ns	ns	ns	*	**

who demonstrated that spraying appropriate concentration of sodium selenate solution at rupturing stage can increase Chl content of rice leaves. Chl is the pigment for plant photosynthesis and the detergent-soluble protein forms of stored N might be the main nitrogen sources for maintaining photosynthesis (Liu *et al.* 2018). The biosynthesis of Chl is a complicated phenomenon which involves many elements such as Fe, Mn, Cu, and Zn (Wang and Grimm 2015). Therefore, the increment in Chl content is probably because the Se application promoted the absorption of mineral elements related to Chl biosynthesis (Põldma *et al.* 2011, Dong *et al.* 2013). On the other hand, previous studies also showed that appropriate selenium application could promote net photosynthetic rate of plants by reducing stomatal resistance, increasing stomatal conductance, and stomatal CO_2 flux (Feng *et al.* 2015, Haghighi *et al.* 2016).

As far as fragrant rice yield was concerned, the response of 'Meixiangzhan-2' and 'Xiangyaxiangzhan' to sodium selenate application was different. For 'Meixiangzhan-2', only the Se4 treatment significantly increased the grain yield, whilst for 'Xiangyaxiangzhan', all Se treatments except Se1 remarkably increased the grain yield. The difference might be due to the different sensitivity of two fragrant rice varieties to selenium. The results are in agreement with the study of Terry *et al.* (2000) who demonstrated that the physiological response to Se varies considerably among plants because some plant species growing on splendiferous soils are tolerant and could accumulate abundant Se, but most plants are Se non-accumulators and Se-sensitive. The increment in fragrant rice yield due to sodium selenate application could be explained by the improvement in seed-setting rate and 1,000-grain mass. Compared with CK, foliar application of sodium selenate increased the seed-setting rate and grain mass for both fragrant rice cultivars and it might occur because the Se treatment enhanced the photosynthesis during the grain-filling stage. The study of Huang *et al.* (2015) also revealed that at least 90% organic matter of rice plant was translated and accumulated by CO_2 assimilation. Current study agreed with the study of Kong *et al.* (2017) which indicated that the photosynthetic rate at grain-filling stage is one of the important factors affecting the yield of aromatic rice. Our result was also consistent with the study of Lai *et al.* (2019) who indicated that exogenous Se applications could increase the rice yield by regulating the photosynthesis.

Rice quality is accessed by a few characteristics, such as milling, appearance, cooking, eating, and nutrient qualities (Luo *et al.* 2018). Present study manifested some attributes of grain quality including milling, appearance, and nutrient quality were significantly influenced by Se applications. The results depicted that foliar application of sodium selenate not only increased the head rice rate and crude protein content in fragrant rice grain, but also decreased chalk rice rate. The improvements in fragrant rice quality could be explained by the enhanced net photosynthetic rate during the grain-filling stage. Previous study revealed that there was a strong correlation between photosynthesis during grain-filling stage and grain quality, and early study also evidenced that photosynthesis was a determining factor to grain quality of rice (Chaturvedi *et al.* 2017). Furthermore, present study showed that Se applications could significantly increase the Se content in fragrant rice grain. As an essential element to humans, Se sufficiency or supplementation has antiviral effects and reduces the risk of autoimmune thyroid disease. Hence, foliar application of sodium selenate at heading stage was beneficial to the cultivation of selenium-rich rice in fragrant rice production.

Conclusion: Foliar application of sodium selenate at the heading stage affected the grain yield and some quality characteristics of fragrant rice, while the best effects were recorded in Se4 treatment for both cultivars. Significant increases were observed in chlorophyll content, net photosynthetic rate, and stomatal conductance at the grain-filling stage. Furthermore, foliar application of sodium selenate could increase seed-setting rate and grain mass. In order to reveal the mechanism of selenium effect on the fragrant rice photosynthesis, much work should be done at molecular level.

References

Chaturvedi A.K., Bahuguna R.N., Pal M. *et al.*: Elevated CO_2 and heat stress interactions affect grain yield, quality and mineral nutrient composition in rice under field conditions. – Field Crop. Res. **206**: 149-157, 2017.

Dong J.Z., Wang Y., Wang S.H. *et al.*: Selenium increases chlorogenic acid, chlorophyll and carotenoids of *Lycium chinense* leaves. – J. Sci. Food Agr. **93**: 310-315, 2013.

Feng T., Chen S.S., Gao D.Q. *et al.*: Selenium improves photosynthesis and protects photosystem II in pear (*Pyrus bretschneideri*), grape (*Vitis vinifera*), and peach (*Prunus persica*). – Photosynthetica **53**: 609-612, 2015.

Gotsis O.: Combined effects of selenium/mercury and selenium/copper on the cell population of the alga *Dunaliella minuta*. – Mar. Biol. **71**: 217-222, 1982.

Haghighi M., Sheibanirad A., Pessarakli M.: Effects of selenium as a beneficial element on growth and photosynthetic attributes of greenhouse cucumber. – J. Plant Nutr. **39**: 1493-1498, 2016.

He L.X., Zheng A.X., Du B. *et al.*: Low-concentration sodium selenate applications improve oxidation resistance of filling-stage rice. – Appl. Ecol. Env. Res. **17**: 989-998, 2019.

Hu Y., Norton G.J., Duan G. *et al.*: Effect of selenium fertilization on the accumulation of cadmium and lead in rice plants. – Plant Soil **384**: 131-140, 2014.

Huang L., Dai L., Wang L. *et al.*: Genetic dissection for chlorophyll content of the top three leaves during grain filling in rice (*Oryza sativa* L.). – J. Plant Growth Regul. **34**: 381-391, 2015.

Kong L., Ashraf U., Cheng S. *et al.*: Short-term water management at early filling stage improves early-season rice performance under high temperature stress in South China. – Eur. J. Agron. **90**: 117-126, 2017.

Lai R.F., Zhang T.T., Gao Y.H. *et al.*: The effect of EDTA-Se with different concentrations on photosynthesis of fragrant rice (*Oryza sativa* L.). – Appl. Ecol. Env. Res. **17**: 3293-3303, 2019.

Liu T., Ren T., White P.J. *et al.*: Storage nitrogen co-ordinates leaf expansion and photosynthetic capacity in winter oilseed rape. – J. Exp. Bot. **69**: 2995-3007, 2018.

Luo H.W., Wang Z.M., Chen Y.Y. *et al.*: The effects of different temperatures on the biosynthesis of grain protein in rice at filling stage. – Appl. Ecol. Env. Res. **16**: 8017-8027, 2018.

Mo Z., Huang J., Xiao D. *et al.*: Supplementation of 2-AP, Zn and La improves 2-acetyl-1-pyrroline concentrations in detached aromatic rice panicles *in vitro*. – PLoS ONE **11**: e149523, 2016.

Petridis A., van der Kaay J., Chrysanthou E. *et al.*: Photosynthetic limitation as a factor influencing yield in highbush blueberries (*Vaccinium corymbosum*) grown in a northern European environment. – J. Exp. Bot. **69**: 3069-3080, 2018.

Põldma P., Tõnutare T., Viitak A. *et al.*: Effect of selenium treatment on mineral nutrition, bulb size, and antioxidant properties of garlic (*Allium sativum* L.). – J. Agr. Food Chem. **59**: 5498-5503, 2011.
Ren Y., Ashraf U., He L.X. *et al.*: Irrigation and nitrogen management practices affect grain yield and 2-acetyl-1-pyrroline content in aromatic rice. – Appl. Ecol. Env. Res. **15**: 1447-1460, 2017.
Terry N., Zayed A.M., de Souza M.P., Tarun A.S.: Selenium in higher plants. – Annu. Rev. Plant Phys. **51**: 401-432, 2000.
Thussagunpanit J., Jutamanee K., Kaveeta L. *et al.*: Comparative effects of brassinosteroid and brassinosteroid mimic on improving photosynthesis, lipid peroxidation, and rice seed set under heat stress. – J. Plant Growth Regul. **34**: 320-331, 2015.
Wang P., Grimm B.: Organization of chlorophyll biosynthesis and insertion of chlorophyll into the chlorophyll-binding proteins in chloroplasts. – Photosynth. Res. **126**: 189-202, 2015.
Wang Y.D., Wang X., Wong Y.S.: Proteomics analysis reveals multiple regulatory mechanisms in response to selenium in rice. – J. Proteomics **75**: 1849-1866, 2012.
Wang Y.D., Wang X., Wong Y.S.: Generation of selenium-enriched rice with enhanced grain yield, selenium content and bioavailability through fertilisation with selenate. – Food Chem. **141**: 2385-2393, 2013.
Wu W.G., Zhang H.C., Qian Y.F. *et al.*: Analysis on dry matter production characteristics of super hybrid rice. – Rice Sci. **15**: 110-118, 2008.