THE EFFECTS OF CD^{2+} STRESS ON PHOTOSYSTEM Ⅱ FUNCTIONING OF RICE (*ORYZA SATIVA* L.) LEAVES UNDER ELEVATED CO_2 LEVEL

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(Received 18th Oct 2020; accepted 21st Dec 2020)

Abstract. The effects of elevated levels of CO_2 (EC) and cadmium (Cd^{2+}) on the photosystem II of rice leaves were studied using fast chlorophyll fluorescence technique. Rice seedlings (two-leaves-stage) were treated under atmospheric CO_2 (AC, 400 μmol/mol) and elevated CO_2 (EC, 800 μmol/mol), while applied 0, 50, 150, 250 and 500 μmol/L Cd^{2+} concentrations respectively. Chlorophyll fluorescence parameters were measured after six days treatments. The results showed that: (1) Under Cd^{2+}, F_V/F_0, φPo, Ψo, φEo and PI_{ABS} decreased significantly, while V_K, V_J, W_K, M_0, φDo, ABS/RC, TR_0/RC, DI_0/RC increased significantly compared to AC. Additional effects were found on the donor side, reaction centers and acceptor side under Cd^{2+}, which caused a lower energy connectivity, reduction of PSⅡ activity and electron transfer efficiency as well as an increase of heat dissipation. (2) EC significantly increased F_V/F_0, φPo, Ψo, φEo and PI_{ABS}, while significantly decreased V_J and φDo compared to AC. EC increased the photo-energy conversion efficiency of PSⅡ. (3) Under EC and Cd^{2+} treatments, the adverse effects of Cd^{2+} were slightly alleviated by EC in EC 50 (EC + 50 μmol/L Cd^{2+}, the following abbreviations are consistent with this), but the negative influence on photosystem Ⅱ was still the most significant.
Keywords: *JIP-Test, OJIP curve, quantum efficiency, specific energy fluxes, performance index*

Introduction

Most of the heavy metal pollutions in soil are from the industrial wastewater discharge, agricultural phosphate fertilizer and sewage sludge, and have seriously affected much farmland and crops (Zou et al., 2020). Cadmium and mercury pollutions are especially severer than other elements (Xiao et al., 2019; Hang et al., 2009). The plants under Cd^{2+} stress will affect in cell damages, production of toxic metabolites, inhibition of photosynthesis and respiration (Hassan et al., 2014; Meng et al., 2009; Liu et al., 2012; Singh et al., 2016). Recently, the NOAA (national oceanic and atmospheric administration, USA) detected CO_2 concentrations in the atmosphere as high as 414.7 μmol/mol peak, and it will continue to grow in the coming years (Kalva et al., 2014; Killi et al., 2018; Frew and Prince, 2019). Photosynthesis, as a very important metabolic reaction in green plants, responds to heavy metal stresses very quickly (Belatik et al., 2013). Fast chlorophyll fluorescence can reflect the state of photosystem II (PSII), the main part of light reaction in photosynthesis, and it has been widely used because of its convenience and non-destructiveness (Strasser et al., 2004; Chen et al., 2016). In this study, the rapid chlorophyll fluorescence induction curves and parameters of rice (*Oryza sativa* L.) seedling leaves under Cd^{2+} and/or EC treatments were tested, so as to explore the photosynthetic effects of plants under the environmental changes.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1901_739750

Materials and methods

Rice seedlings (Beijing 2, which has been widely planted in Liaoning province, China) were cultured under Hoagland nutrient solution with the control of 26 °C/22 °C day/night, 16 h/8 h light/dark period, 3000 lux illumination intensities using carbon dioxide artificial climate box. When the seedlings grew to the two-leaves-stage, applied ten treatments, each treatment had 6 pots (*Table 1*).

Table 1. *Name of treatments*

Cd^{2+}(μmol/L)	0	50	150	250	500
AC (400 μmol/mol CO_2)	AC	AC 50	AC 150	AC 250	AC 500
EC (800 μmol/mol CO_2)	EC	EC 50	EC 150	EC 250	EC 500

After 6 days treatments, leaves of rice seedlings were measured by Pocket PEA (Hanshatech, UK) during 11:00-12:00 which had 20 min dark adaption before measurements. The positions of measurements were located in the middle and front of the second complete leaves. Three repeats were selected randomly in each pot (6 pots/treatment, a total of 18 repeats/treatment).

According to the Kautsky effect, the fluorescence change process from O step to P step is the fast chlorophyll fluorescence induction kinetic curve, and the data analysis and processing for this curve is summarized as JIP-test (Strasser et al., 2004; Guisse et al., 1995). The parameters of JIP-test are presented in *Table 2*. According to the JIP-test, the fluorescence OJIP transients were analyzed. Variable fluorescence $V_{OP} = (F_t\text{-}F_0)/(F_P\text{-}F_0)$ (Eq. 1) were normalized on a logarithmic time scale while $V_{OK} = (F_t\text{-}F_0)/(F_K\text{-}F_0)$ (Eq. 2) and $V_{OJ} = (F_t\text{-}F_0)/(F_J\text{-}F_0)$ (Eq. 3) were normalized on a linear time scale. And the different kinetics, ΔV_{OK} and ΔV_{OJ} of treatments versus AC, can show normalized transients between the O, J, I, P steps (Li et al., 2014), which were called L-band and K-band respectively.

The significant differences of parameters were using the method of two-way ANOVA followed by LSD’s multiple-range test for multiple comparisons. The data analysis was done with the SPSS statistical software (*v*20.0, SPSS, USA) and the figures were drawn by Origin (*v*9.0, Origin, USA) software.

Results

OJIP curve

The typical OJIP curve suggested that all leaves were photosynthetically active, but all curves showed inhibition tendency except under EC compared with AC. Fluorescence intensity under EC were the highest at phases I and P steps, and fluorescence intensity under AC 500 was the lowest at J, I and P steps. Fluorescence intensity of Cd^{2+} treatments was lower than AC at I and P steps (*Fig. 1*).

Fluorescence data between O step and P step (V_{OP}) were deviation normalized under different treatments. V_{OP} under Cd^{2+} treatments were higher than AC. However, there was no significant difference between different Cd^{2+} treatments. V_{OP} under EC was lower than AC (*Fig. 2*).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Table 2. *Summary of parameters, formulae and their description using JIP-test for the analysis of the fluorescence transient O-J-I-P*

Fluorescence parameters	Description
Fluorescence parameters derived from the extracted data	
F_t	Fluorescence intensity at time t after onset of actinic illumination
F_0	Minimal reliable recorded fluorescence, at 50 μs
F_P	Maximum fluorescence, when all PSⅡ RCs are closed
F_K	Fluorescence intensity at 300 μs
F_V/F_0	Potential photochemical efficiency
$V_K = (F_K-F_0)/(F_M-F_0)$	Relative variable fluorescence intensity at the K-step
$V_J = (F_J-F_0)/(F_M-F_0)$	Relative variable fluorescence intensity at the J-step
$W_K = (F_K-F_0)/(F_J-F_0)$	The ratio of K step relative variable fluorescence to J step
$M_0 = 4(F_K-F_0)/(F_M-F_0)$	Approximated initial slope of the fluorescence transient
$Sm = (Area)/(F_M-F_0)$	Normalized total complementary area above the O-J-I-P transient
Yields or flux ratios	
$\varphi Po = TR_0/ABS = [1-(F_0/F_M)]$	Maximum quantum yield of primary photochemistry (at t = 0)
$\Psi o = ET_0/TR_0 = (1-V_J)$	Probability (at t = 0) that a trapped exciton moves an Electron into the electron transport chain beyond Q_A^-
$\varphi Eo = ET_0/ABS = [1-(F_0/F_M)]\ \Psi o$	Quantum yield of electron transport (at t = 0)
$\varphi Do = 1-\varphi Po$	Quantum yield (at t = 0) of energy dissipation
Specific energy fluxes (per Q_A^- reducing PS Ⅱ reaction center)	
$ABS/RC = M_0(1/V_J)(1/\varphi Po)$	Absorption flux per RC
$TR_0/RC = M_0(1/V_J)$	Trapped energy flux per RC (at t = 0)
$ET_0/RC = M_0(1/V_J)\ \Psi o$	Electron transport flux per RC (at t = 0)
$DI_0/RC = (ABS/RC)-(TR_0/RC)$	Dissipated energy flux per RC (at t = 0)
Performance index	
$PI_{ABS} = (RC/ABS)[\varphi Po/(1-\varphi Po)][\Psi o/(1-\Psi o)]$	Performance index on absorption basis

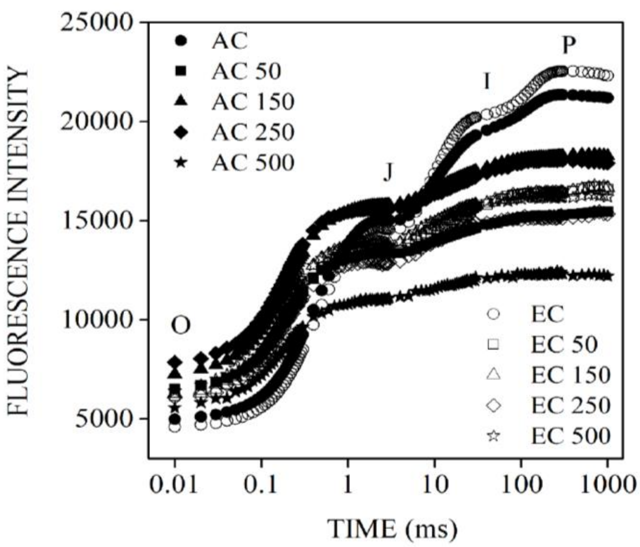

Figure 1. *Chl a fluorescence intensity of different treatments (n = 18)*

L-band and K-band

The L-band reflects the energy connection of PSⅡ units, and the negative L-band indicates a high system connection degree or high excitation energy utilization rate. In

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our study, V_{OK} and ΔV_{OK} showed the energy connection of PSⅡ was higher under EC. Cd^{2+} treatments result in a destruction of PSⅡ energy connectivity, and the destruction became severer with the increases of Cd^{2+} concentration (*Fig. 3A*).

The K-band reflects the activity of the oxygen evolving complex (OEC). A negative K-band indicates the intactness of the functional antenna. Similar to the L-band, only EC presented a negative band, while seedlings under Cd^{2+} stress all showed OEC damage in different degrees (*Fig. 3B*).

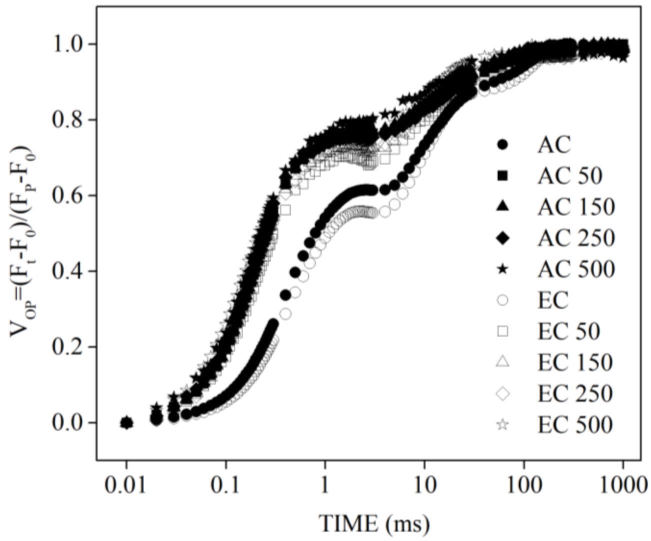

Figure 2. *V_{OP} on the logarithmic scale (n = 18)*

Kinetic parameters changes of rapid chlorophyll fluorescence induction

Under Cd^{2+} treatments, F_V/F_0 were significantly lower, while V_K, V_J, W_K, M_0 were significantly higher compared with AC ($P < 0.01$). Under EC, F_V/F_0 was significantly higher, while V_J was significantly lower than AC ($p < 0.05$). Under combined treatments, V_K, V_J and M_0 under EC 50 treatment were significantly lower than AC 50 ($p < 0.05$). Sm was significantly higher under EC 150 and EC 250 compared with the same concentrations under AC ($p < 0.05$). Under EC 500, F_V/F_0 and Sm were significantly higher than AC 500 ($p < 0.05$) (*Fig. 4*).

φPo, Ψo and φEo were significantly lower, but φDo was significantly higher under Cd^{2+} treatments compared with AC ($p < 0.01$). Under EC, φPo, Ψo, and φEo were significantly higher, but φDo were significantly lower compared with AC ($p < 0.05$). Under EC 50, φEo and Ψo were significantly higher than AC 50 ($p < 0.01$). Under EC 500, φPo and φEo were significantly higher but φDo was significantly lower compared with AC 500 ($p < 0.05$) (*Fig. 5*).

Under Cd^{2+} treatments, ABS/RC, TR_0/RC and DI_0/RC were all significantly higher compared with AC ($P < 0.01$). Under combined treatments, ET_0/RC was significantly higher in EC 50 compared with AC 50 ($p < 0.05$). Under EC 500, ET_0/RC was significantly higher, but DI_0/RC was significantly lower than AC 500 ($p < 0.05$) (*Fig. 6*).

PI_{ABS} was significantly decreased compared with AC ($p < 0.05$). Under EC, PI_{ABS} was significantly higher than AC ($p < 0.05$). Under the combined treatments, PI_{ABS} of EC 50 was significantly higher than AC 50 ($p < 0.05$) (*Fig. 7*).

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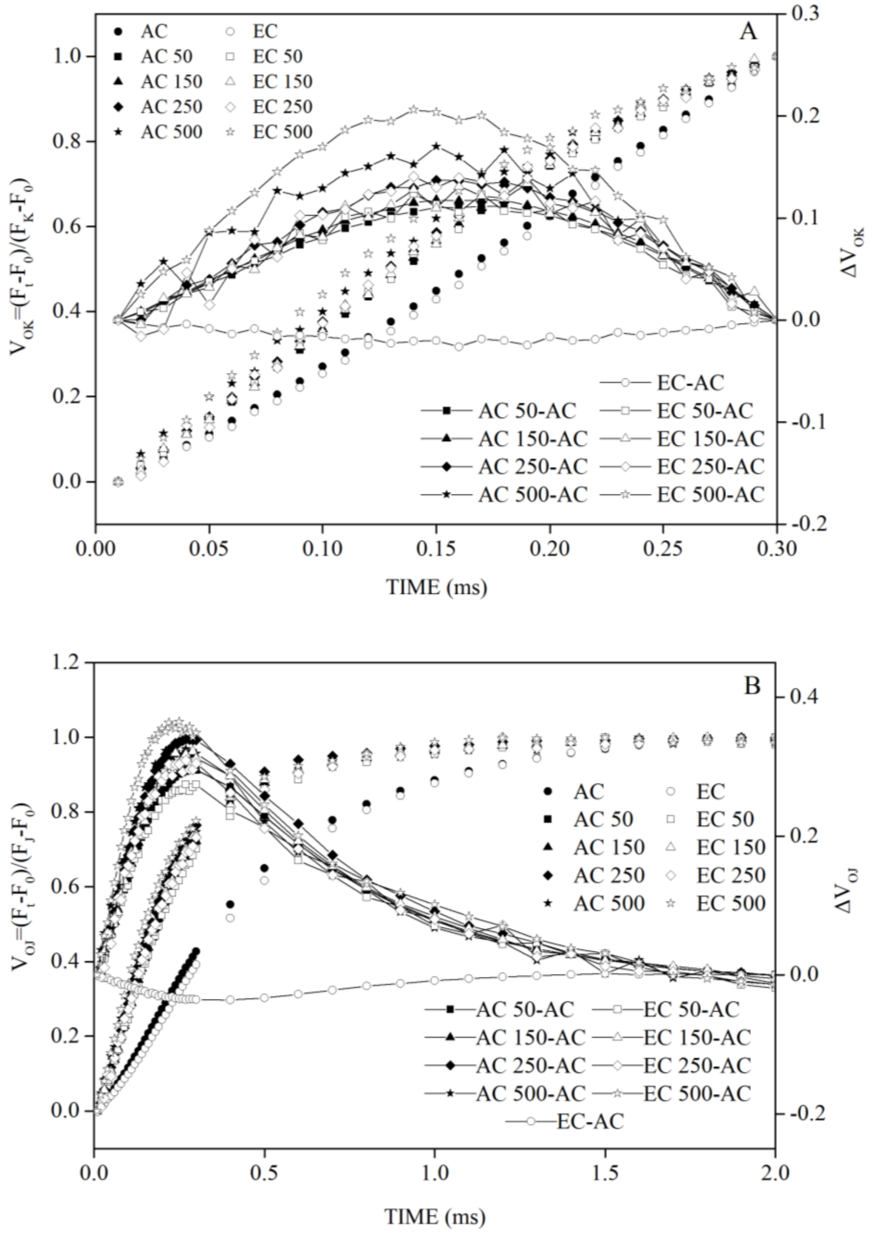

Figure 3. *(A) V_{OK} and ΔV_{OK}; (B) V_{OJ} and ΔV_{OJ}. In (A) and (B), open symbol curves represent left y-axis and closed symbol curves represent right y-axis. Left axis shows the V_{OK} and V_{OJ}. Right axis shows the ΔV_{OK} and ΔV_{OJ} stand for stress treatments versus control (AC). ΔV_{OK} and ΔV_{OJ} revealing the L-band and K-band respectively (n = 18)*

Discussion

The effects of Cd^{2+} stress

Our study showed that Cd^{2+} stress improved the K step of the OJIP curve, and also caused positive K-band and L-band. W_K is the ratio of variable fluorescence F_K to the amplitude F_J-F_0, and V_K is the relative variable fluorescence intensity at the K step. Both these two parameters reflect the damage of OEC. In our results, Cd^{2+} treatment caused lower energy connectivity and destruction of OEC intactness. The electron transfer on the PSⅡ donor side was also affected.

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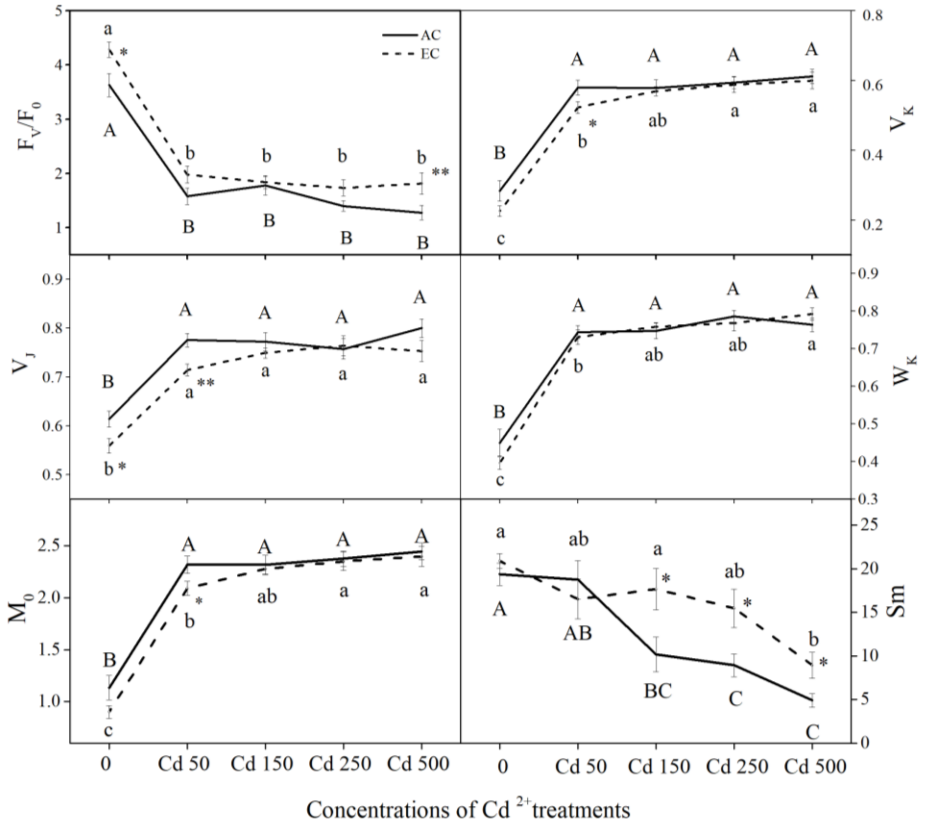

Figure 4. *The variation trend and significant difference of fluorescence parameters under different treatments. The bars indicated standard error. For the same CO_2 treatments, significance differences were marked as ABC (for AC) and abc (for EC) at P < 0.05 (LSD test). For the same Cd^{2+} concentration, an asterisk was marked to indicates significant difference in comparison with AC (*P < 0.05; **P < 0.01). The following figures are consistent with this figure (n = 18)*

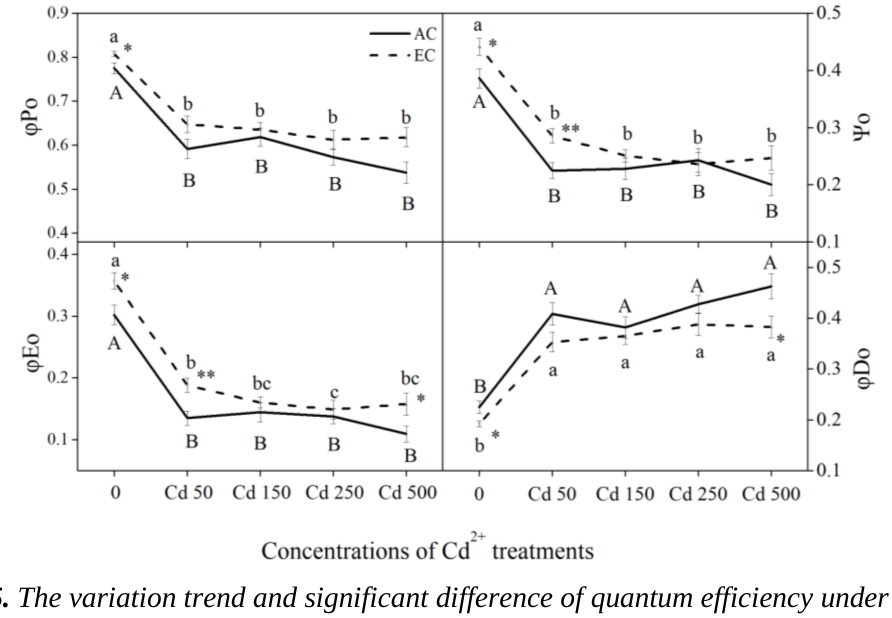

Figure 5. *The variation trend and significant difference of quantum efficiency under different treatments (n = 18)*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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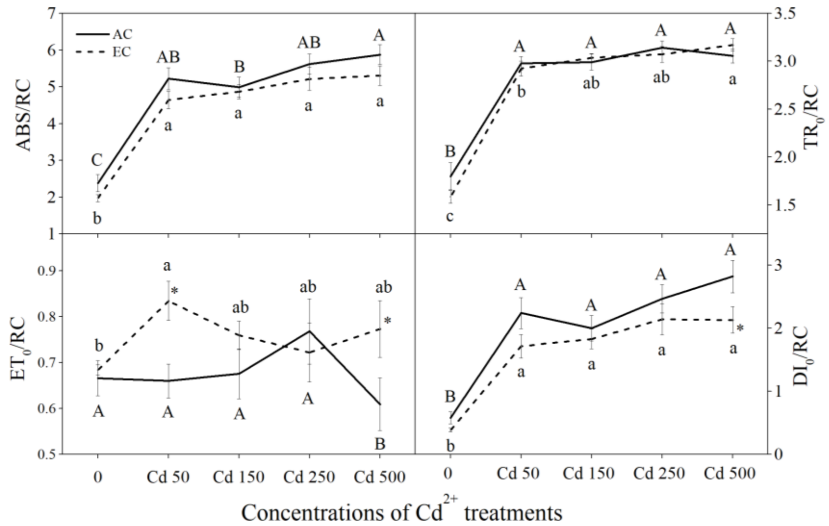

Figure 6. *The variation trend and significant difference of specific energy fluxes under different treatments (n = 18)*

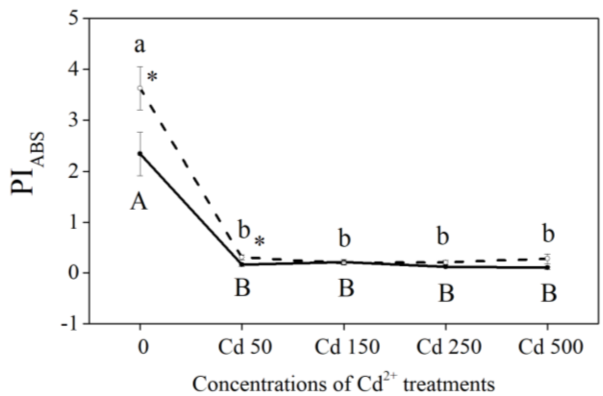

Figure 7. *The variation trend and significant difference of comprehensive performance index under different treatments (n = 18)*

M_0 is the initial slope of the OJIP curve, reflecting the rate at which Q_A's reduction during O-J. Sm is the integral area of normalized OJIP curve, reflecting the energy required when Q_A is completely reduced, that is, reflecting the capacity of plastoquinone (PQ) (Strasser et al., 1995) on the acceptor side of PSⅡ reaction center. Ψo reflects the ability of PSⅡ to transfer electrons to the downstream electron transport chain. Our study showed that in PSⅡ acceptor side, decreases in Sm and Ψo and the increase in M_0 compared with AC showed that the activity of the electron transport beyond Q_A was inhibited under Cd^{2+} stress. This is the same as Chu's results (Chu et al., 2018). φEo reflects the quantum yield for electron transport in the reaction center. φDo represents the maximum quantum yield of non-photochemical de-excitation (Li and Zhang, 2015). In this study, the capacity of PQ pool on the acceptor side decreased with the increase of Cd^{2+} concentrations, which led to the increase of φEo and φDo, that is, the quantum ratio of PSⅡ reaction center for heat dissipation increased under Cd^{2+}stress, and the quantum ratio for electron transfer decreased. The Q_A reduction

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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accumulates, and more surplus energy was used to reduce Q_A, which hinders the electron transfer. The ability of PSⅡ to transfer electrons to the downstream electron transport chain was destroyed by Cd^{2+}. The electron transfer on the acceptor side was inhibited.

F_v/F_0 reflects the potential activity of PSⅡ, which is proportional to the amount of PSⅡ RCs (Luo et al., 2016) and is often used to judge whether the leaves of plants are photo-inhibition. In our study, Cd^{2+} treatment significantly reduced F_v/F_0 compared with AC. This is similar to the result of Essemine et al. (2020). φPo reflects the maximum photochemical quantum efficiency of the PSⅡ reaction center which is generally stable and rarely affected by growth conditions (Kramer et al., 2004), but decreases under the stress condition (Baker, 2008). It can be seen from our results that F_v/F_0 and φPo had the same downward trends under Cd^{2+} stress, which might be the PSⅡ reaction center had photo-inhibition and PSⅡ electron transfer was blocked. V_J represents the degree of closure of the reactive center of PSⅡ. Under the treatments of Cd^{2+}, the number of RCs decreased, and a large number of RCs closed.

Specific energy flux includes ABS/RC, TR_0/RC, ET_0/RC, DI_0/RC etc. (Strasser et al., 2004), which reflecting the activity of PSⅡ reaction center when Q_A is in reducible state. Our results showed that under Cd^{2+} treatments, the absorption flux per RC (ABS/RC), the energy flux trapped per RC (TR_0/RC) and the dissipated energy fluxes per RC (DI_0/RC) all significantly higher than AC, while the electron transport flux per RC (ET_0/RC) was significantly lower under AC 500. Increase in trapping per RC (TR_0/RC) can indicate impairment of the oxygen evolving complex (Kalaji et al., 2014; Franić et al., 2018). After absorbed by PSⅡ reaction center, the light was trapped by reaction center (TR_0/RC), the ABS/RC was mainly used for electron transport flux ET_0/RC and dissipated flux DI_0/RC (Strasser et al., 2010; Tsimilli-Michael and Strasser, 2008). It can be found from our results that, although the light energy absorbed and trapped by unit RC increased under the stress of Cd^{2+}, the light energy used for electron transfer increased limited, so more light energy consumption occurred in dissipation flux, while photosynthesis did not increase much. This is the same as Xue's results (Xue et al., 2018). A study suggested that plants dissipate excess light energy which was not available for photosynthesis in order to reduce damage to PSⅡ reactive centers (Appenroth et al., 2001). In our study, rice leaves may also had such a protective mechanism.

PI_{ABS}, a comprehensive performance index based on light absorption (Brestic et al., 2012; Heerden et al., 2004) which reflects the overall function of PSⅡ system, is the most sensitive parameter to the stressed environment. It was significantly reduced by Cd^{2+} and inversely proportional to Cd^{2+} concentration in our study. The result showed that Cd^{2+} had obvious damage to photosynthetic performance of rice seedlings.

The effects of EC

Elevated CO_2 has been proved to be able to enhanced photosynthesis of C_3 plants (Lahijani et al., 2018). The OJIP curve under EC was higher at I and P steps than AC, which means the promotion of electron transport at the donor side of PSⅡ. The change in fluorescence is the result of variation in the redox state of the PSⅡ RCs complex (Haldimann and Strasser, 1999). Strasser et al. (1995) reported that the decrease of electron transport beyond Q_A^- results the high fluorescence. In our study, the difference

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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kinetics ΔV_{OP} revealed that seedlings under EC produced lower fluorescence, which showed less biochemical inhibition. EC produced a negative K-band and L-band, suggesting better energetic connectivity of PSⅡ and photosynthetic performance compared with AC.

Under EC, M_0 and Sm significantly decreased compared with AC, that is, the degree of openness of the RCs increased and the proportion of the inactivated RCs decreased, which was conducive to the electron transfer down from Q_A^-. The increases in Ψo and φEo under EC indicated that EC promoted the primary light reaction and the redox reactions after Q_A.

Both Fv/F_0 and φPo under EC showed an increasing trend in different degrees, indicating that the increase of CO_2 concentration enhanced the electron transfer efficiency and the PSⅡ light energy conversion. Compared with AC, φDo and V_J were significantly reduced by EC, indicating that EC reduced the heat dissipation and increases the opening degree of RCs. In conclusion, photo-energy conversion efficiency of PSⅡ active center can be alleviated under elevated CO_2.

In the composite index of PI_{ABS}, EC significantly improved it compared with AC. The result showed that EC could improve the photosynthetic performance of rice seedlings.

The effects of Cd^{2+} stress and EC

In our study, the K-band and L-band showed that the alleviated effect of EC on PSⅡ donor side was not obvious under Cd^{2+} stress. Under EC 50, the significant decrease of V_K compared with AC 50 indicated that EC could alleviate the damage of OEC caused by lower Cd^{2+} stress.

Compared with AC 50, EC 50 had a significant decrease in M_0 and a significant increase in Ψo and φEo. These suggested that reduction of Q_A to Q_A^- was higher in EC 50 than AC 50. There were no significant differences in Ψo and φEo under EC 150, EC 250 and EC 500 compared with the same Cd^{2+} concentrations under AC. To sum up, elevated CO_2 alleviates lower concentration Cd^{2+} stress to a certain extent in terms of PSⅡ energy distribution.

In the specific fluxes, ET_0/RC was significantly higher under EC 50 compared with AC 50. There were no significant differences in ABS/RC and TR_0/RC under EC 50, EC 150, EC 250 and EC 500 compared with the same Cd^{2+} concentrations under AC. V_J was significantly decreased under EC 50 compared with AC 50. It can be seen that the degree of closure of PSⅡ active RCs was alleviated, and the electron transport was significantly increased in lower Cd^{2+} treatment under EC. Under some stresses, PSⅡ RCs were reversibly inactivated and became an energy trap, which could absorb light energy but could not promote electron transfer (Lee et al., 2001). In our study, EC can alleviate the energy trap, but the effect of cadmium stress cannot be completely eliminated.

PI_{ABS} of EC 50 was significantly higher than AC 50. In terms of the comprehensive performance index, the effect of EC had some mitigation on 50 μmol/L Cd^{2+}, but was not particularly obvious in other concentrations.

Compared with the same Cd^{2+} concentrations under AC treatments, EC 150, EC 250 and EC 500 showed little alleviated effects on specific energy flux, quantum efficiency and comprehensive performance index.

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Conclusions

In this study, the effects of elevated CO_2 and/or Cd^{2+} stress in leaves of rice were studied using the rapid chlorophyll fluorescence technique. The main results were as follows: (1) Cd^{2+} stress damaged the integrity of OEC in rice seedling leaves, which result in lower energy connectivity at the PSⅡ donor side. Also, the effects on receptor side and the reaction centers were the decrease of RCs' number and the inhibition of the electron transfer. RCs absorbed more energy but most of the energy was used for heat dissipation; (2) Short-term elevated CO_2 can promote electron transfer in PSⅡ donor side of rice seedling leaves. The photo-energy conversion efficiency of PSⅡ increased with the increase of the openness of the RC; (3) Short-term elevated CO_2 can relieve the adverse effects of lower concentration Cd^{2+} treatment, but it cannot significantly eliminate the damage of higher Cd^{2+} stress. (4) In the future study, the intrinsic molecular mechanism changes of chlorophyll fluorescence should be concerned.

Acknowledgements. This work was founded by the National Natural Science Foundation of China (31600314), the Department of Education of Liaoning province Foundation (LZD201901, LZD202004).

REFERENCES

[1] Appenroth, K. J., Stöckel, J., Srivastava, A., Strasser, R. J. (2001): Multiple effects of chromate on the photosynthetic apparatus of Spirodela polyrhiza as probed by OJIP chlorophyll a fluorescence measurements. – Environmental Pollution 115: 49-64.

[2] Baker, N. R. (2008): Chlorophyll fluorescence: a probe of photosynthesis in vivo. – Annual Review of Plant Biology 59: 89-113.

[3] Belatik, A., Hotchandani, S., Tajmir-Riahi, H. A., Carpentier, R. (2013): Alteration of the structure and function of photosystem I by Pb2+. – Journal of Photochemistry and Photobiology B Biology 123: 41-47.

[4] Brestic, M., Zivcak, M., Kalaji, H. M., Carpentier, R., Allakhverdiev, S. I. (2012): Photosystem II thermostability in situ: environmentally induced acclimation and genotype-specific reactions in Triticum aestivum L. – Plant Physiology and Biochemistry 57: 93-105.

[5] Chen, S. G., Yang, J., Zhang, M. S., Strasser, R. J., Qiang, S. (2016): Classification and characteristics of heat tolerance in Ageratina adenophora populations using fast chlorophyll a fluorescence rise O-J-I-P. – Environmental and Experimental Botany 122: 126-140.

[6] Chu, J. J., Zhu, F., Chen, X. Y., Liang, H. Z., Wang, R. J. (2018): Effects of cadmium on photosynthesis of Schima superba young plant detected by chlorophyll fluorescence. – Environmental Science and Pollution Research 25: 10679-10687.

[7] Essemine, J., Qu, M. N., Lyu, M. J. A., Song, Q. F., Khan, N., Chen, G. Y., Wang, P., Zhu, X. G. (2020): Photosynthetic and transcriptomic responses of two C4 grass species with different NaCl tolerance. – Journal of Plant Physiology 253: 153244.

[8] Franić, M., Galić, V., Mazur, M., Šimić, D. (2018): Effects of excess cadmium in soil on JIP-test parameters, hydrogen peroxide content and antioxidant activity in two maize inbreds and their hybrid. – Photosynthetica 55: 660-669.

[9] Frew, A., Price, J. N. (2019): Mycorrhizal-mediated plant-herbivore interactions in a high CO2 world. – Functional Ecology 33: 1376-1385.

[10] Guisse, B., Srivastava, A., Strasser, R. J. (1995): The polyphasic rise of the chlorophyll a fluorescence (O-K-J-I-P) in heat stressed leaves. – Archives Des Sciences 48: 147-160.

[11] Haldimann, P., Strasser, R. J. (1999): Effects of anaerobiosis as probed by the polyphasic chlorophyll a fluorescence rise kinetic in pea (Pisum sativum L.) – Photosynthesis Research 62: 67-83.
[12] Hang, X. S., Wang, H. Y., Zhou, J. M., Ma, C. L., Du, C. W., Chen, X. Q. (2009): Risk assessment of potentially toxic element pollution in soils and rice (Oryza sativa) in a typical area of the Yangtze River Delta. – Environmental Pollution 157: 2542-2549.
[13] Hassan, M. J., Shao, G. S., Zhang, G. P. (2014): Influence of cadmium toxicity on growth and antioxidant enzyme activity in rice cultivars with different grain cadmium accumulation. – Journal of Plant Nutrition 28: 1259-1270.
[14] Heerden, P. D. R., Strasser, R. J., Krüger, G. H. J. (2004): Reduction of dark chilling stress in N2-fixing soybean by nitrate as indicated by chlorophyll a fluorescence kinetics. – Physiologia Plantarum 121: 239-249.
[15] Kalaji, H., Oukarroum, A., Alexandrov, V., Kouzmanova, M., Brestic, M., Zivcak, M., Samborska, I. A., Cetner, M. D., Allakhverdiev, S. I., Goltsev, V. (2014): Identification of nutrient deficiency in maize and tomato plants by in vivo chlorophyll a fluorescence measurements. – Plant Physiology Biochemistry 81: 16-25.
[16] Kalva, M. S., Sreeharsha, R. V., Shalini, Mudalkar, S., Reddy, A. R. (2014): Persistent stimulation of photosynthesis in short rotation coppice mulberry under elevated CO2 atmosphere. – Journal of Photochemistry and Photobiology B: Biology 137: 21-30.
[17] Killi, D., Bussotti, F., Gottardini, E., Pollastrini, M., Mori, J., Tani, C., Papini, A., Ferrini, F., Fini, A. (2018): Photosynthetic and morphological responses of oak species to temperature and [CO2] increased to levels predicted for 2050. – Urban Forestry and Urban Greening 31: 26-37.
[18] Kramer, D. M., Johnson, G., Kiirats, O., Edwards, G. E. (2004): New fluorescence parameters for the determination of QA redox state and excitation energy fluxes. – Photosynthesis Research 79: 209-218.
[19] Lahijani, M. J. A., Kafi, M., Nezami, A., Nabati, J., Mehrjerdi, M. Z., Shahkoomahally, S., Erwin, J. (2018): Variations in assimilation rate, photoassimilate translocation, and cellular fine structure of potato cultivars (Solanum tuberosum L.) exposed to elevated CO2. – Plant Physiology and Biochemistry 130: 303-313.
[20] Lee, H. Y., Hong, Y. N., Chow, W. S. (2001): Photoinactivation of photosystem II complexes and photoprotection by non-functional neighbours in Capsicum annuum L. leaves. – Planta 212: 332-342.
[21] Li, X. M., Zhang, L. H. (2015): Endophytic infection alleviates Pb2+ stress effects on photosystem II functioning of Oryza sativa leaves. – Journal of Hazardous Materials 295: 79-85.
[22] Li, X. M., Chen, M. J., Li, J., Ma, L. J., Bu, N., Li, Y. Y., Zhang, L. H. (2014): Effect of endophyte infection on chlorophyll a fluorescence in salinity stressed rice. – Biologia Plantarum 58: 589-594.
[23] Liu, C. H., Huang, W. D., Kao, C. H. (2012): The decline in potassium concentration is associated with cadmium toxicity of rice seedlings. – Acta Physiologiae Plantarum 34: 495-502.
[24] Luo, H. H., Tsimilli-Michael, M., Zhang, Y. L., Zhang, W. F. (2016): Combining gas exchange and chlorophyll a fluorescence measurements to analyze the photosynthetic activity of drip-irrigated cotton under different soil water deficits – Journal of Integrative Agriculture 15(6): 1256-1266.
[25] Meng, H. B., Hua, S. J., Shamsi, I. H., Jilani, G., Li, Y. L., Jiang, L. X. (2009): Cadmium-induced stress on the seed germination and seedling growth of Brassica napus L., and its alleviation through exogenous plant growth regulators. – Plant Growth Regulation 58: 47-59.
[26] National Oceanic and Atmospheric Administration (NOAA) (2019): Carbon Dioxide Levels in Atmosphere Hit Record High in May. Calfornia. – https://www.noaa.gov/news/carbon-dioxide-levels-in-atmosphere-hit-record-high-in-may.

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DOI: http://dx.doi.org/10.15666/aeer/1901_739750

[27] Singh, S., Singh, A., Bashri, G., Prasad, S. M. (2016): Impact of Cd stress on cellular functioning and its amelioration by phytohormones: an overview on regulatory network. – Plant Growth Regulation 80: 253-263.

[28] Strasser, R. J., Srivastava, A., Govindjee (1995): Polyphasic chlorophyll a fluorescence transient in plants and cyanobacteria. – Photochemistry and Photobiology 61: 32-42.

[29] Strasser, R. J., Tsimilli-Michael, M., Srivastava, A. (2004): Analysis of the Chlorophyll A Fluorescence Transient. – In: Papageorgiou, G. C., Govindjee (eds.) Chlorophyll A Fluorescence. Advances in Photosynthesis and Respiration. Springer, Dordrecht.

[30] Strasser, R. J., Tsimilli-Michael, M., Qiang, S., Goltsev, V. (2010): Simultaneous in vivo recording of prompt and delayed fluorescence and 820-nm reflection changes during drying and after rehydration of the resurrection plant Haberlea rhodopensis. – Biochimca et Biophysica Acta 1797: 1313-1326.

[31] Tsimilli-Michael, M., Strasser, R. J. (2008): In Vivo Assessment of Stress Impact on Plant's Vitality: Applications in Detecting and Evaluating the Beneficial Role of Mycorrhization on Host Plants. – In: Varma, A. (ed.) Mycorrhiza. Springer, Berlin.

[32] Xiao, X., Zhang, J. X., Wang, H., Han, X. X., Ma, J., Ma, Y., Luan, H. J. (2019): Distribution and health risk assessment of potentially toxic elements in soils around coal industrial areas: a global meta-analysis. – Science of The Total Environment 713: 135292.

[33] Xue, Z. C., Li, J. H., Li, D. S., Li, S. Z., Jiang, C. D., Liu, L. A., Wang, S. Y., Kang, W. J. (2018): Bioaccumulation and photosynthetic activity response of sweet sorghum seedling (Sorghum bicolor L. Moench) to cadmium stress. – Photosynthetica 56(4): 1422-1428.

[34] Zou, Z. K., Wang, Y. Q., Huang, J. L., Lei, Z., Wan, F. T., Dai, Z. Y., Yi, L. C., Li, J. L. (2020): A study on the mixture repairing effect of biochar and nano iron oxide on toxicity of Cd toward muskmelon. – Environmental Pollution 266: 115371.

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DOI: http://dx.doi.org/10.15666/aeer/1901_739750