THE EFFECTS OF Cd²⁺ STRESS ON PHOTOSYSTEM II FUNCTIONING OF RICE (ORYZA SATIVA L.) LEAVES UNDER ELEVATED CO₂ LEVEL

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Abstract. The effects of elevated levels of CO₂ (EC) and cadmium (Cd²⁺) on the photosystem II of rice leaves were studied using fast chlorophyll fluorescence technique. Rice seedlings (two-leaves-stage) were treated under atmospheric CO₂ (AC, 400 μmol/mol) and elevated CO₂ (EC, 800 μmol/mol), while applied 0, 50, 150, 250 and 500 μmol/L Cd²⁺ concentrations respectively. Chlorophyll fluorescence parameters were measured after six days treatments. The results showed that: (1) Under Cd²⁺, Fv/Fo, φPo, Ψo, φEo and PIABS decreased significantly, while V½, V½, W½, M½, φDo, ABS/RC, TR/F0, RC/RC increased significantly compared to AC. Additional effects were found on the donor side, reaction centers and acceptor side under Cd²⁺, which caused a lower energy connectivity, reduction of PS II activity and electron transfer efficiency as well as an increase of heat dissipation. (2) EC significantly increased Fv/Fo, φPo, Ψo, φEo and PIABS, while significantly decreased V½ and φDo compared to AC. EC increased the photo-energy conversion efficiency of PS II. (3) Under EC and Cd²⁺ treatments, the adverse effects of Cd²⁺ were slightly alleviated by EC in EC 50 (EC + 50 μmol/L Cd²⁺), 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 Cd²⁺ 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 CO₂ 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 Cd²⁺ and/or EC treatments were tested, so as to explore the photosynthetic effects of plants under the environmental changes.
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

| Cd²⁺(μmol/L) | 0   | 50  | 150 | 250 | 500 |
|--------------|-----|-----|-----|-----|-----|
| AC (400 μmol/mol CO₂) | AC  | AC 50 | AC 150 | AC 250 | AC 500 |
| EC (800 μmol/mol CO₂) | 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; Guissé 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 $V_{OP} = (F_F - F_0)/(F_F - F_0)$ (Eq. 1) were normalized on a logarithmic time scale while $V_{OK} = (F_F - F_0)/(F_F - F_0)$ (Eq. 2) and $V_{OJ} = (F_F - F_0)/(F_F - F_0)$ (Eq. 3) were normalized on a linear time scale. And the different kinetics, $\Delta V_{OK}$ and $\Delta V_{OJ}$ 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 (v20.0, SPSS, USA) and the figures were drawn by Origin (v9.0, 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 Cd²⁺ 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 Cd²⁺ treatments were higher than AC. However, there was no significant difference between different Cd²⁺ treatments. $V_{OP}$ under EC was lower than AC (Fig. 2).
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 |
|-------------------------|-------------|
| \( F_I \)               | Fluorescence intensity at time t after onset of actinic illumination |
| \( F_0 \)               | Minimal reliable recorded fluorescence, at 50 \( \mu \)s |
| \( F_F \)               | Maximum fluorescence, when all PS II RCs are closed |
| \( F_R \)               | Fluorescence intensity at 300 \( \mu \)s |
| \( V_k \)               | Potential photochemical efficiency |
| \( V_I \)               | Relative variable fluorescence intensity at the K-step |
| \( V_P \)               | Relative variable fluorescence intensity at the J-step |
| \( W_K \)               | The ratio of K step relative variable fluorescence to J step |
| \( W_F \)               | Approximated initial slope of the fluorescence transient |
| \( S_m = (Area)/(F_{300}-F_0) \) | Normalized total complementary area above the O-J-I-P transient |

Yields or flux ratios

\( \phi_{Po} = TR_o/ABS = [1-(F_F/F_0)] \) Maximum quantum yield of primary photochemistry (at t = 0)

\( \Psi_0 = ET_o/TR_0 = (1-V_I) \) Probability (at t = 0) that a trapped exciton moves an Electron into the electron transport chain beyond \( \Phi_{A} \)

\( \phi_{Eo} = ET_o/ABS = [1-(F_F/F_0)] \Psi_0 \) Quantum yield of electron transport (at t = 0)

\( \phi_{Do} = 1-\phi_{Po} \) Quantum yield (at t = 0) of energy dissipation

Specific energy fluxes (per \( \Phi_{C} \) reducing PS II reaction center)

\( ABS/RC = M_d(1/V_I)/(\phi_{Po}) \) Absorption flux per RC

\( TR_o/RC = M_d(1/V_I) \) Trapped energy flux per RC (at t = 0)

\( ET_o/RC = M_d(1/V_I) \Psi_0 \) Electron transport flux per RC (at t = 0)

\( DL_o/RC = (ABS/RC)-(TR_o/RC) \) Dissipated energy flux per RC (at t = 0)

Performance index

\( PI_{ABS} = (RC/ABS)[\phi_{Po}(1-\phi_{Po})]/[\Psi_0(1-\Psi_0)] \) 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 PS II units, and the negative L-band indicates a high system connection degree or high excitation energy utilization rate. In
our study, \( V_{\text{OK}} \) and \( \Delta V_{\text{OK}} \) showed the energy connection of PS II was higher under EC. Cd\(^{2+}\) treatments result in a destruction of PS II 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.** \( V_{\text{OPT}} \) on the logarithmic scale (\( n = 18 \))

**Kinetic parameters changes of rapid chlorophyll fluorescence induction**

Under Cd\(^{2+}\) treatments, \( F_{\text{v}}/F_{\text{0}} \) were significantly lower, while \( V_{\text{K}}, V_{\text{I}}, W_{\text{K}}, M_{\text{O}} \) were significantly higher compared with AC (\( P < 0.01 \)). Under EC, \( F_{\text{v}}/F_{\text{0}} \) was significantly higher, while \( V_{\text{I}} \) was significantly compared lower than AC (\( p < 0.05 \)). Under combined treatments, \( V_{\text{K}}, V_{\text{I}} \) and \( M_{\text{O}} \) under EC 50 treatment were significantly lower than AC 50 (\( p < 0.05 \)). \( S_{\text{m}} \) was significantly higher under EC 150 and EC 250 compared with the same concentrations under AC (\( p < 0.05 \)). Under EC 500, \( F_{\text{v}}/F_{\text{0}} \) and \( S_{\text{m}} \) were significantly higher than AC 500 (\( p < 0.05 \)) (Fig. 4).

\( \phi_{\text{Po}}, \Psi_{\text{o}} \) and \( \phi_{\text{Eo}} \) were significantly lower, but \( \phi_{\text{Do}} \) was significantly higher under Cd\(^{2+}\) treatments compared with AC (\( p < 0.01 \)). Under EC, \( \phi_{\text{Po}}, \Psi_{\text{o}}, \) and \( \phi_{\text{Eo}} \) were significantly higher, but \( \phi_{\text{Do}} \) were significantly lower compared with AC (\( p < 0.05 \)). Under EC 50, \( \phi_{\text{Eo}} \) and \( \Psi_{\text{o}} \) were significantly higher than AC 50 (\( p < 0.01 \)). Under EC 500, \( \phi_{\text{Po}} \) and \( \phi_{\text{Eo}} \) were significantly higher but \( \phi_{\text{Do}} \) was significantly lower compared with AC 500 (\( p < 0.05 \)) (Fig. 5).

Under Cd\(^{2+}\) treatments, \( \text{ABS}/\text{RC}, \text{TR}_{\text{0}}/\text{RC} \) and \( \text{DI}_{\text{0}}/\text{RC} \) were all significantly higher compared with AC (\( P < 0.01 \)). Under combined treatments, \( \text{ET}_{\text{0}}/\text{RC} \) was significantly higher in EC 50 compared with AC 50 (\( p < 0.05 \)). Under EC 500, \( \text{ET}_{\text{0}}/\text{RC} \) was significantly higher, but \( \text{DI}_{\text{0}}/\text{RC} \) was significantly lower than AC 500 (\( p < 0.05 \)) (Fig. 6).

\( \text{PI}_{\text{ABS}} \) was significantly decreased compared with AC (\( P < 0.05 \)). Under EC, \( \text{PI}_{\text{ABS}} \) was significantly higher than AC (\( p < 0.05 \)). Under the combined treatments, \( \text{PI}_{\text{ABS}} \) of EC 50 was significantly higher than AC 50 (\( p < 0.05 \)) (Fig. 7).
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Figure 3. (A) $V_{OK}$ and $\Delta V_{OK}$; (B) $V_{OJ}$ and $\Delta V_{OJ}$. 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 $\Delta V_{OK}$ and $\Delta V_{OJ}$ stand for stress treatments versus control (AC). $\Delta V_{OK}$ and $\Delta V_{OJ}$ revealing the L-band and K-band respectively ($n = 18$)

Discussion

**The effects of Cd\textsuperscript{2+} stress**

Our study showed that Cd\textsuperscript{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 $F_F-F_0$, 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\textsuperscript{2+} treatment caused lower energy connectivity and destruction of OEC intactness. The electron transfer on the PS II donor side was also affected.
Figure 4. The variation trend of fluorescence parameters under different treatments. The bars indicated standard error. For the same CO₂ treatments, significance differences were marked as ABC (for AC) and abc (for EC) at P < 0.05 (LSD test). For the same Cd²⁺ 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 of quantum efficiency under different treatments (n = 18)
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)

M₀ is the initial slope of the OJIP curve, reflecting the rate at which Qₓ’s reduction during O-J. Sm is the integral area of normalized OJIP curve, reflecting the energy required when Qₓ is completely reduced, that is, reflecting the capacity of plastoquinone (PQ) (Strasser et al., 1995) on the acceptor side of PS II reaction center. Ψ₀ reflects the ability of PS II to transfer electrons to the downstream electron transport chain. Our study showed that in PS II acceptor side, decreases in Sm and Ψ₀ and the increase in M₀ compared with AC showed that the activity of the electron transport beyond Qₓ was inhibited under Cd²⁺ stress. This is the same as Chu’s results (Chu et al., 2018). φE₀ reflects the quantum yield for electron transport in the reaction center. φD₀ 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 Cd²⁺ concentrations, which led to the increase of φE₀ and φD₀, that is, the quantum ratio of PS II reaction center for heat dissipation increased under Cd²⁺ stress, and the quantum ratio for electron transfer decreased. The Qₓ reduction
accumulates, and more surplus energy was used to reduce Q_A, which hinders the electron transfer. The ability of PS II 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 PS II, which is proportional to the amount of PS II 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 Essemé et al. (2020). φPo reflects the maximum photochemical quantum efficiency of the PS II 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 PS II reaction center had photo-inhibition and PS II electron transfer was blocked. V_i represents the degree of closure of the reactive center of PS II. Under the treatments of Cd^{2+}, the number of RCs decreased, and a large number of RCs closed.

Specific energy flux includes ABS/RC, TRo/RC, ETo/RC, DIo/RC etc. (Strasser et al., 2004), which reflecting the activity of PS II 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 (TRo/RC) and the dissipated energy fluxes per RC (DIo/RC) all significantly higher than AC, while the electron transport flux per RC (ETo/RC) was significantly lower under AC 500. Increase in trapping per RC (TRo/RC) can indicate impairment of the oxygen evolving complex (Kalaji et al., 2014; Franić et al., 2018). After absorbed by PS II reaction center, the light was trapped by reaction center (TRo/RC), the ABS/RC was mainly used for electron transport flux ETo/RC and dissipated flux DIo/RC (Strasser et al., 2010; Tsimili-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 PS II reactive centers (Appenroth et al., 2001). In our study, rice leaves may also had such a protective mechanism.

P_lABS, a comprehensive performance index based on light absorption (Brestic et al., 2012; Heerden et al., 2004) which reflects the overall function of PS II 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 PS II. The change in fluorescence is the result of variation in the redox state of the PS II 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
kinetics $\Delta V_{OP}$ 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 PS II and photosynthetic performance compared with AC.

Under EC, M₀ 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 $\Psi_0$ and $\phi E_o$ under EC indicated that EC promoted the primary light reaction and the redox reactions after $Q_A$.

Both Fv/F₀ and $\phi P_o$ under EC showed an increasing trend in different degrees, indicating that the increase of CO₂ concentration enhanced the electron transfer efficiency and the PS II light energy conversion. Compared with AC, $\phi D_o$ and $V_1$ 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 PS II active center can be alleviated under elevated CO₂.

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

**The effects of Cd²⁺ stress and EC**

In our study, the K-band and L-band showed that the alleviated effect of EC on PS II donor side was not obvious under Cd²⁺ 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 Cd²⁺ stress.

Compared with AC 50, EC 50 had a significant decrease in M₀ and a significant increase in $\Psi_0$ and $\phi E_o$. These suggested that reduction of $Q_A$ to $Q_A^-$ was higher in EC 50 than AC 50. There were no significant differences in $\Psi_0$ and $\phi E_o$ under EC 150, EC 250 and EC 500 compared with the same Cd²⁺ concentrations under AC. To sum up, elevated CO₂ alleviates lower concentration Cd²⁺ stress to a certain extent in terms of PS II energy distribution.

In the specific fluxes, ET₀/RC was significantly higher under EC 50 compared with AC 50. There were no significant differences in ABS/RC and TR₀/RC under EC 50, EC 150, EC 250 and EC 500 compared with the same Cd²⁺ concentrations under AC. $V_1$ was significantly decreased under EC 50 compared with AC 50. It can be seen that the degree of closure of PS II active RCs was alleviated, and the electron transport was significantly increased in lower Cd²⁺ treatment under EC. Under some stresses, PS II 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.

PIÅB 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 Cd²⁺, but was not particularly obvious in other concentrations.

Compared with the same Cd²⁺ 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.
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 PS II 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 PS II donor side of rice seedling leaves. The photo-energy conversion efficiency of PS II 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.

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