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Light dependent arsenic uptake and growth in *Lactuca sativa* L.

Hyun-Gi Min, Eunjee Kim[1], Min-Suk Kim[2] and Jeong-Gyu Kim[1,*]

Ojeong Resilience Institute, Korea University, Seoul 02841, Republic of Korea
[1]Division of Environmental Science and Ecological Engineering, College of Life Science and Biotechnology, Korea University, Seoul 02841, Republic of Korea
[2]Waste Resources Management Division Resource Recirculation Bureau, Ministry of Environment, Sejong 30103, Republic of Korea

Contribution to Environmental Biology

- Arsenic is a common pollutant from mining activities that threatens nearby ecosystems and human health.
- This study analyzed the effects and interactions of light and arsenic toxicity on the growth of lettuce.
- These results could be used as a basis for future research on pollution and vegetation growth.

***Corresponding author**
Jeong-Gyu Kim
Tel. 02-3290-3024
E-mail. lemonkim@korea.ac.kr

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Abstract: Along with other heavy metals, arsenic (As) is one among the substances most harmful to living organisms including humans. Owing to its morphological similarity to phosphorus, the uptake of As is influenced by photosynthesis and the phosphorus uptake pathway. In this study, we varied arsenic exposure and light intensity during nutrient solution cultivation of lettuce (*Lactuca sativa* L.) to determine the effect of these two factors on arsenic uptake, lettuce growth, and electron transfer in photosystem II. In the treatment exposed to 30 μmol L^{-1} of arsenic, the shoot arsenic concentration increased from 4.73 mg kg^{-1} to 18.97 mg kg^{-1} as the light intensity increased from 22 to 122 μmol m^{-2} s^{-1}. The water content and ET2o/RC of the shoots were not affected by arsenic at low light intensity; however, at optimal light intensity, they decreased progressively with arsenic exposure. Increased light intensity stimulated the growth of plant roots and shoots; contrarily, the difference in growth decreased as the concentration of As exposure increased. The results of this study suggest that the effect of As on plant growth is dependent on light intensity; in particular, an increase in light intensity can increase the uptake of As, thereby affecting plant growth and As toxicity.

Keywords: arsenic, *Lactuca sativa* L., light intensity, chlorophyll a fluorescence

1. INTRODUCTION

Arsenic (As), a pervasive toxic metalloid, is present in both natural and anthropogenic environments (Carbonnell-Barrachina *et al.* 1999; Jedynak *et al.* 2010). Chronic arsenic exposure via contaminated food and water has been linked to cancer, dermatological conditions, and various non-carcinogenic ailments (Karagas *et al.* 1998; Smith *et al.* 2000).

Plants primarily absorb As from edaphic solutions in the form of arsenite and arsenate (Garg and Singla 2011). Plants promote various defense mechanisms within themselves to resist As, as it interferes with important plant functions, such as germination, growth, and photosynthesis (Ahsan *et al.* 2008). The harmful effects of arsenates and arsenites are largely caused by the generation of reactive oxygen species (ROS) such as superoxide - hydroxyl radicals and H_2O_2, leading to oxidative

stress, arsenate reduction to arsenite, and the production of enzymatic antioxidants. Moreover, the chemical resemblance of arsenate to inorganic phosphate results in competitive absorption through shared transport systems (Smith *et al.* 2010). Arsenate is efficiently transported across the plasmalemma by phosphate transporter (PHT) proteins (Wu *et al.* 2011). Phosphorus is an important nutrient for photosynthesis and its uptake is affected by photosynthesis (Zhou *et al.* 2019). Owing to its similarity to phosphorus, arsenic is affected by photosynthesis along with phosphorus (Yadav *et al.* 2014; Libatique *et al.* 2020). Following uptake, arsenate hinders oxidative phosphorylation by substituting phosphate in ATP generation, yielding unstable ADP-As and impeding various phosphorylation reactions, thus disrupting phosphate metabolism and promoting toxicity (Abedin *et al.* 2002).

Among numerous studies which have shown that photosynthesis, As uptake, and As toxicity are interrelated, a few studies have examined the changes in plant As uptake, growth, and photosynthesis in response to changes in light intensity and As exposure (Yadav *et al.* 2014). In the present study, lettuce, a representative species suitable for plant toxicity experiments (Hu *et al.* 2005), was grown in a nutrient solution. The objective of this study was to elucidate the effects of changes in light and As exposure on plant growth, As uptake, and electron transfer during different stages of photosynthesis. This study provides fundamental information for understanding As-induced growth inhibition and As uptake in plant growth environments.

2. MATERIALS AND METHODS

2.1. Plant material and treatment conditions

Lettuce seed was incubated on filter paper in deionized (DI) water for 7 d at 20 ± 2°C darkness. After germination, seedlings were cultivated with Clark's (1975) nutrient solution (pH 6.5) for three weeks in growth chamber with controlled light and temperature (21 ± 2°C, 122 μmol m^{-2} s^{-1}) and light conditions of 16 h of daylight and 8 h of darkness per day. The nutrient solution was changed every 7 d. After three weeks, plants were treated with As (Ⅴ) in the form of heptahydrated sodium arsenate ($Na_2HAsO_4 \cdot 7H_2O$) at concentrations of 0, 5, and 30 μmol L^{-1} As based on Clark's nutrient solution (pH 6.5), light intensity were 22 and 122 μmol m^{-2} s^{-1}. The plants were cultivated with different treatments for 7 d in a growth chamber under the same conditions as the initial growth temperature. After 7 d of treatment, the plants were harvested and analyzed. The experiments were performed in triplicate, and each time, the pots were randomly arranged during the growth period.

2.2. Measurement of fresh mass and root length

Seven days after the As treatment, the plants were harvested to determine their root growth using an image analysis program (WinRhizo 5.0a; Regent, Canada). After root length determination, the plants were separated into roots and shoots, and the fresh weights of the shoots were measured. Plants were rinsed with DI water and then the roots were immersed in 0.01 M $NH_4H_2PO_4$ for 1 min to remove arsenate adhering to the root surface. Separated samples were oven-dried for 3 d (60°C). Shoot water content was calculated as weight loss after drying.

2.3. Estimation of As content

Dried materials were pre-digested with 10 mL of HNO_3 overnight (16 h) at room temperature and the HNO_3 mixture was heated at 75°C for 10 min, followed by 109°C for 15 min. After cooling for 10 min, 1 mL of H_2O_2 was added to each vessel and the sample mixture was heated at 109°C for another 15 min (Wu *et al.* 2011). The samples were then filtered using filter paper (Whatman No. 45). The As concentrations in the samples were analyzed using inductively coupled plasma-optical emission spectrometer (ICP-OES) (730 series; Agilent, USA).

2.4. Estimation of photosynthetic activities

After 7 d of arsenate exposure, plants were analyzed for photosynthetic activity by measuring chlorophyll a fluorescence parameters using a chlorophyll fluorometer (FluorPen, OSI 30P; ADP, UK). Before the measurements, plants were dark-adapted for 30 min by fixing leaf clips in the middle part of a leaf, away from the main leaf vein, to ensure that all PSⅡ were in a dark-adapted state with open reaction centers (RCs). Chlorophyll a fluorescence transients were then recorded by illuminating the leaves with a beam of sat-

Table 1. Short description of chlorophyll fluorescence parameters used in the study (Stirbet 2011)

Abbreviation	Description
RC/Cs	Active reaction center per cross section
ETo/RC	Electron flux per active reaction center beyond Q_A^-
TRo/RC	Trapping of electrons per active reaction center

urating light (3,000 μmol m^{-2} s^{-1}) with a peak wavelength of 650 nm, obtained from three light-emitting diodes focused on the leaf surface through the clips on a 5-mm diameter circular spot. The fast fluorescence kinetics were recorded from 10 μs to 1 s and the fluorometer was set using the following program; the initial fluorescence (Fo) was set as O (50 μs), J and I are the intermediates of fluorescence value at 2 ms (Fj) and fluorescence value at 30 ms (Fi), respectively and P (500 ms) as the maximum fluorescence (Fm). The values analyzed based on the measurements are listed in Table 1.

2.5. Statistical analysis

All analyses were performed in triplicate. The relationships between As concentration, plant growth, and chlorophyll a fluorescence were analyzed using Pearson's correlation analysis. Significant differences were determined by Tukey's test and a mean $p < 0.05$ indicated statistical significance. All data were analyzed using statistical analysis software (SAS 9.4; SAS Institute Inc., Cary, NC, USA).

3. RESULTS AND DISCUSSION

3.1. Arsenic accumulation in lettuce shoots and roots

The As content and translocation in lettuce are shown in Fig. 1. Arsenic concentrations in plant roots increased with As exposure, regardless of light intensity. When the As exposure increased from 5 μmol L^{-1} to 30 μmol L^{-1} at low light, As content rose 2.5-fold; whereas, at optimal light intensity, a 2.8-fold increment was observed (Fig. 1a).

Arsenic concentration in shoot was highest at 30 μmol L^{-1} As exposure and optimal light intensity (Fig. 1b), which was 4-fold compared to 5 μmol L^{-1} As and optimal light intensity and 3.5-fold compared to 30 μmol L^{-1} As and low light intensity. The translocation factor showed a significant increase with increasing light at 30 μmol L^{-1} As (Fig. 1c).

These results suggest that As uptake by plants may be influenced by light intensity, which is consistent with the results of previous studies (Rofkar and Dwyer 2011; Yadav *et al.* 2014; Libatique *et al.* 2020). Increases in photosynthesis, ATP synthesis, transpiration, and nutrient uptake in response to moderate increases in light intensity increase the uptake of phosphorus (Saha *et al.* 1970), and the increased absorption of phosphorus affects As uptake (Yadav *et al.* 2014; Libatique *et al.* 2020).

3.2. Root and shoot growth

Root length and shoot fresh weight data are presented in Fig. 2. An increase in light intensity did not result in a significant change in root length among the treatments exposed to equivalent As concentrations (Fig. 2a). Under low light intensity, an increase in As concentration resulted in a reduction in root length. Conversely, under optimal light intensity, an increase in the As concentration resulted in a gradual decrease in the mean concentration, although this difference was not statistically significant.

The results under low light intensity aligned with the findings of Mascher *et al.* (2002), illustrating that As impedes root elongation by inhibiting photosynthesis and respiration, contributing to ROS toxicity. Conversely, under optimal light intensity, As exposure did not significantly affect root length, corroborating the findings of Jaipargas *et al.* (2016), which suggested that an increase in photosynthetic activity owing to higher light levels could mitigate the stress imposed by As toxicity.

A significant increase in the fresh weight of lettuce shoots was observed under enhanced light intensity in the absence of As exposure (Fig. 2b). In the unexposed treatment, the fresh weight of the shoots increased from 1,475.7 mg at low light intensity to 1,894.6 mg at optimal light intensity, representing an increase of 23%. Contrarily, in the As-exposed treatment, an average increase in light intensity was observed; however, this difference was not statistically significant. As the As exposure concentration increased from 0−30 μmol L^{-1}, a significant decrease in the fresh weight of the shoot part was observed at both low and optimal light intensities.

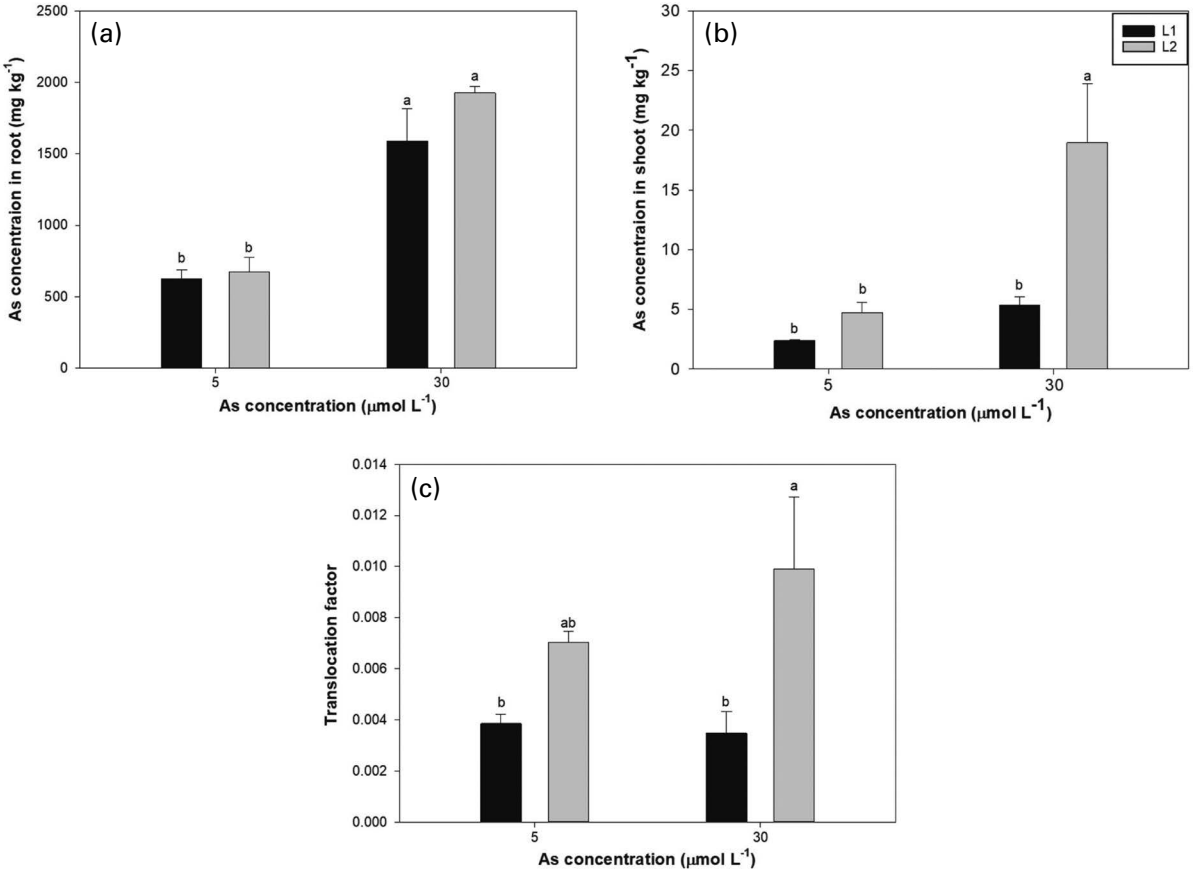

Fig. 1. Arsenic concentration in lettuce and translocation factor. (a) As concentration in root. (b) As concentration in shoot. (c) translocation factor from root to shoot. As concentration (μmol L^{-1}) is exposed As concentration in nutrient solution. L1 means 22 μmol m^{-2} s^{-1} light intensity and L2 means 122 μmol m^{-2} s^{-1} light intensity. Different letters indicate significant differences at the 5% level determined via Tukey's test.

Increased light intensity inherently amplify plant growth (Zhang *et al.* 2020), and mitigates As toxicity within the plant body (Jaipargas *et al.* 2016). Therefore, based on previous studies, increasing light intensity should enhance plant growth in both As-exposed and unexposed treatments. The root length and shoot weight increased with increasing light intensity; however, the differences were not statistically significant.

Shoot water content was significantly lower at the optimal light intensity than at low light intensity for all As concentrations (Fig. 2c). The range of water content at low light intensity was 94.22–95.79% and that at optimal light intensity was 88.15–92.39%. No significant difference was observed in water content between the As concentrations at low light intensity. However, at optimal light intensity, the water content progressively decreased with increasing As exposure. Elevated light intensity can reduce plant water content due to increased transpiration and high transpiration levels can affect plant water content (Livingston 1911; Pan and Guo 2016). The reduced water content of heavy metal-stressed plants and the toxic effects of As may be indirectly due to decreased water uptake (Mourato *et al.* 2015). High As levels disrupt plant - water relationships and contribute to the generation of ROS, leading to oxidative stress within plants (Bali and Sidhu 2021). This suggests that As exposure can disturb the normal water balance in plants, potentially diminishing their water content.

3.3. Impact of arsenic exposure on photosynthesis: Fluorescence of chlorophyll a

The fluorescence of chlorophyll a is shown in Fig. 3.

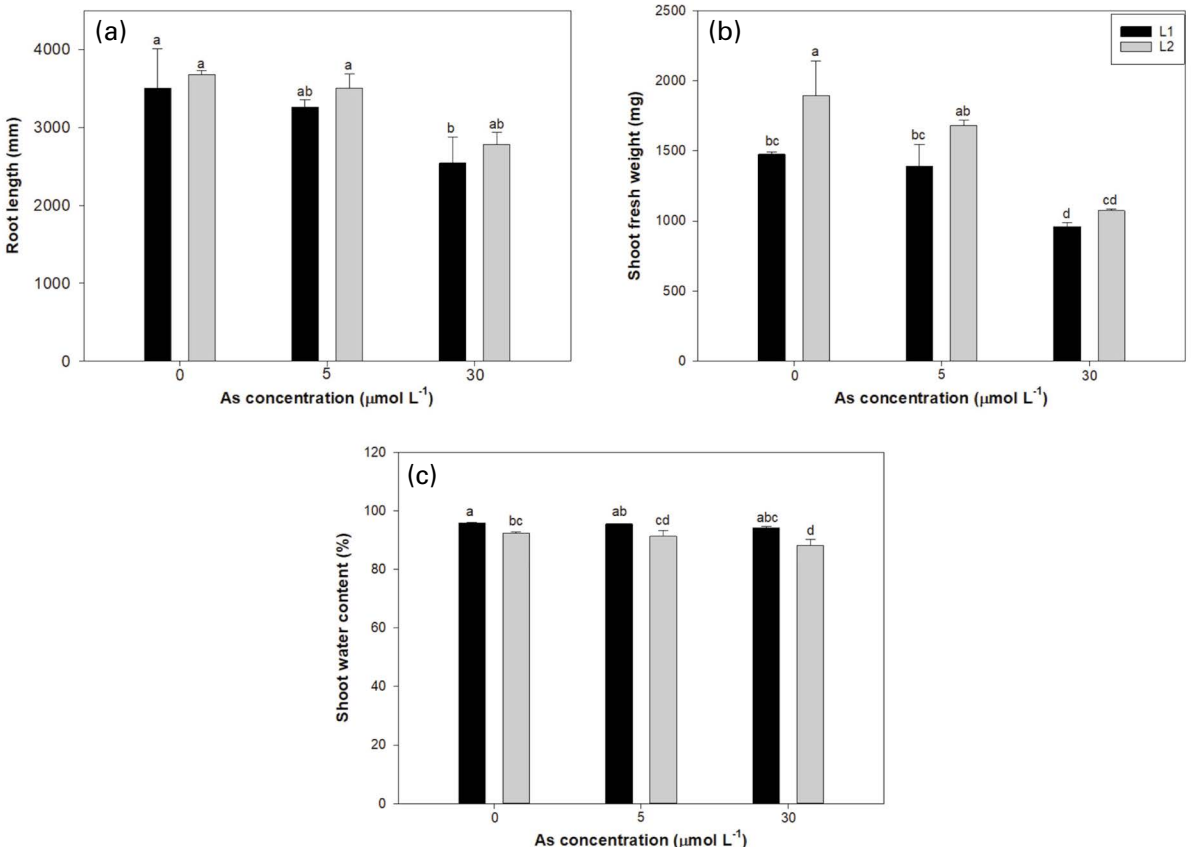

Fig. 2. Root length and shoot fresh weight depend on light intensity and As exposure of lettuce. (a) Root length of lettuce, (b) shoot fresh weight of lettuce, and (c) water content of shoot part. As concentration (μmol L^{-1}) is exposed As concentration in nutrient solution. L1 means 22 μmol m^{-2} s^{-1} light intensity and L2 means 122 μmol m^{-2} s^{-1} light intensity. Different letters indicate significant differences at the 5% level determined via Tukey's test.

At low light intensity, RC/Cs did not show a significant difference by the As exposure and the range of RC/Cs was from 21,781.6−23,053.2 (Fig. 3a). At optimal light intensity, RC/Cs showed highest value at the treatment exposed to 5 μmol L^{-1} of As (Fig. 3a). However, the difference in RC/Cs was not a gradual change with concentration, and assuming the effect of increasing As concentrations is difficult. The change in RC/Cs related to light intensity was a 15% increase at optimum light compared to low light in the As unexposed treatments and a 17% increase in the treatments exposed to 5 μmol L^{-1} of As. Conversely, the treatment exposed to 30 μmol L^{-1} of As showed no significant change with increasing light intensity.

Reaction center activity, which is closely related to chlorophyll content, tends to increase with optimal light intensity, thereby increasing photosynthesis (Fu *et al.* 2012). This is substantiated by the elevation of RC/Cs values with augmented light in the treatments that were subjected to 0 and 5 μmol L^{-1} of As in our study. At low light intensities, ET2o/RC did not show a significant difference from As exposure, and the ET2o/RC ranged 1.22−1.27 (Fig. 3b). At optimal light intensity, ET2o/RC showed a gradual decrease with the As concentration exposed and the values were 1.21, 1.08, and 1.06 for As exposures of 0, 5, and 30 μmol L^{-1}, respectively (Fig. 3b). TRo/RC did not show significant differences depending on the concentration of As exposed (Fig. 3c). No differences were observed in light intensity in the As unexposed treatment, however, TRo/RC decreased significantly with increasing light intensity in both As-exposed treatments.

For the metrics associated with chlorophyll a, although RC/Cs generally increased with light intensity, they did not differ at the highest As exposure. ET2o/RC, which showed no significant light-based

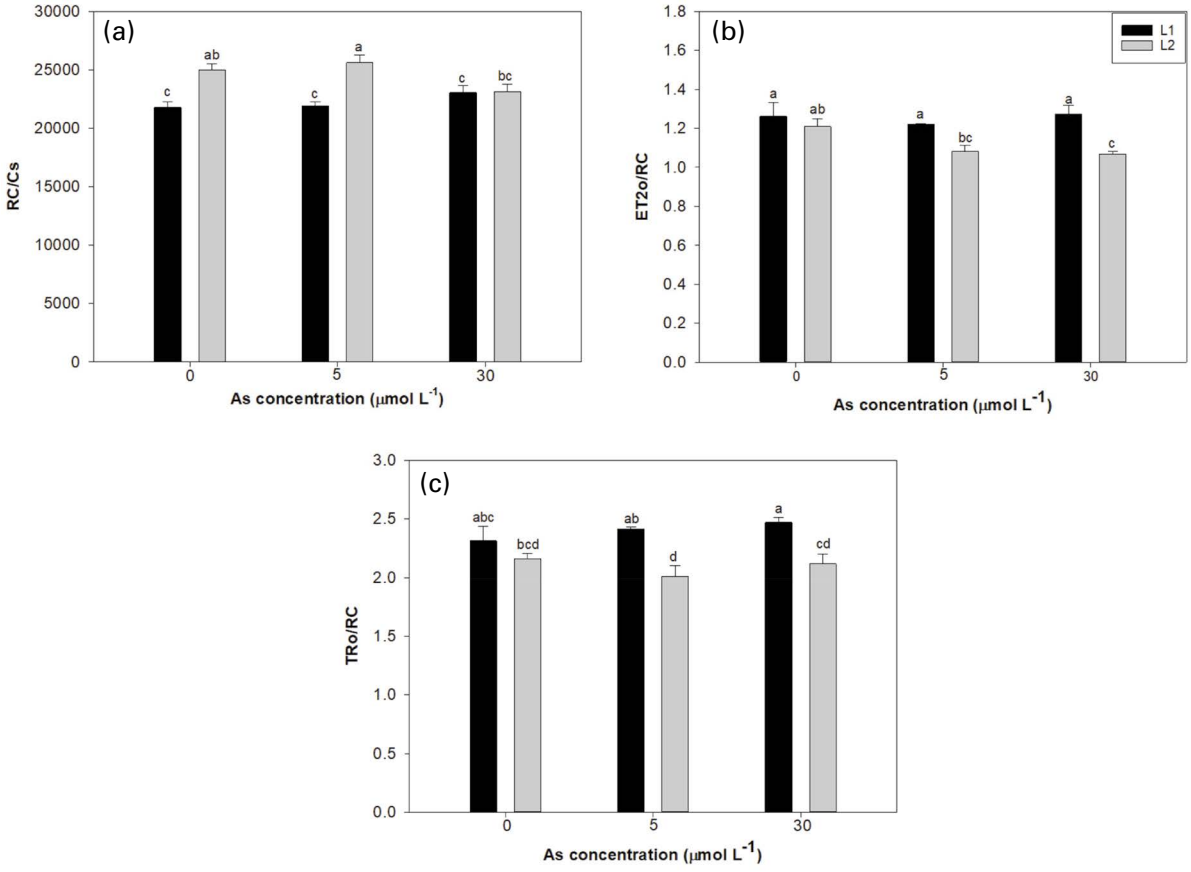

Fig. 3. Fluorescence of chlorophyll a depend on light intensity and As exposure of lettuce. (a) RC/Cs, Active reaction center per cross section. (b) ET2o/ RC, Electron flux per reaction center. (c) TRo/RC, Trapping of electrons per excited reaction center. L1 means 22 μmol m^{-2} s^{-1} light intensity and L2 means 122 μmol m^{-2} s^{-1} light intensity. Different letters indicate significant differences at the 5% level determined via Tukey's test.

differences under As-free conditions, decreased with heightened light at increased As concentrations. These observations suggest that As exposure may affect chlorophyll a fluorescence relative to the light intensity. Owing to its chemical analog nature, As interferes with various phosphorus-related mechanisms (Patel *et al.* 2018). In particular, it affects ATP synthesis and transport, which are highly correlated with photosynthesis (Patel *et al.* 2018). The assimilation of phosphorus profoundly influences reaction center formation and activity and As toxicity is known to reduce RC/Cs (Wang *et al.* 2012; Vezza *et al.* 2021). Moreover, the interference of As with electron transfer in photosynthesis is likely mediated by As-induced ROS rather than by direct interactions (Zhang *et al.* 2020). Arsenic toxicity can also indirectly affect plant photosynthesis, as it can interfere with various metabolisms in the plant body, including glutathione, carbohydrates, lipids, and proteins (Zhang *et al.* 2020). Arsenic toxicity reduces water and nutrient uptake, which indirectly inhibits photosynthesis (Yadav *et al.* 2014; Kang *et al.* 2023).

3.4. Correlation coefficient with As concentration in plant

This study aimed to analyze the effect of As toxicity on plant growth with changes in light intensity and the analysis results of As concentration varied depending on light intensity. However, since the toxicity of As inside the plant body can be affected by the concentration of externally applied As and by the concentration of internally absorbed As, we analyzed how the concentration of As in the nutrient solution, roots, and shoots correlated with plant growth and photosynthesis using Pearson's correlation coefficient (Table 2). Root weight and shoot length showed a significant negative

Table 2. Pearson's correlation coefficient (*r*) with As concentration in plant

	Plant growth			Chlorophyll a fluorescence		
	Root length (mm)	Shoot fresh weight (mg)	Shoot water content (%)	RC/Cs[a]	ET2o/RC[b]	TRo/RC[c]
As concentration in nutrient solution (μmol L^{-1})	−0.805***	−0.828***	−0.439	−0.124	−0.175	−0.172
As concentration in root (mg kg^{-1})	−0.774**	−0.794***	−0.499*	−0.108	−0.303	0.053
As concentration in shoot (mg kg^{-1})	−0.523*	−0.549*	−0.773**	0.012	−0.595*	−0.260

*,**,*** represent significant at $p<0.05$, $p<0.001$, and $p<0.0001$, respectively.
[a]Active reaction center per cross section.
[b]Electron flux per reaction center.
[c]Trapping of electrons per excited reaction center.

correlation with the As concentration, most strongly in the nutrient solution. Conversely, shoot water content did not correlate significantly with nutrient solution As levels; however, showed a strong negative correlation with shoot As levels. Photosynthetic indicators, such as RC/Cs and TRo/RS displayed no significant correlation with As concentrations, whereas ET2o/RS was significantly negatively correlated with shoot As levels. Shoot water content and ET2o/RS exhibited no significant correlation with the As concentrations to which they were exposed. However, they displayed a significant negative correlation with As accumulation in the shoots, implying that As toxicity impedes plant growth and photosynthetic processes. The high translocation of As can increase its toxicity of As (Verma *et al.* 2020). In the present study, increased light intensity was a factor that increased As concentration and translocation in shoots when exposed to As at the same concentration (Fig. 1). In theory, optimal light intensity should promote plant growth more than lower light levels (Jaipargas *et al.* 2016; Zhang *et al.* 2020), however, the increased shoot uptake of As with increasing light intensity had the opposite effect (Fig. 1). Therefore, careful modulation of light conditions is imperative for optimizing plant development in As-exposed environments.

4. CONCLUSION

This study aimed to elucidate the effects of light intensity and As toxicity on plant growth and photosynthesis. Both variables were measured in the lettuce nutrient solutions. Increased light intensity generally supported plant growth; however, concurrently elevated As uptake in the shoots, impaired water uptake and disrupted photosynthetic electron transport. Consequently, this study suggests that an intricate balance is required for plant development in As-polluted environment. Adequate lighting is essential for growth, however, may exacerbate As uptake and toxicity. Hence, comprehensive strategies that minimize contaminant absorption while optimizing growth are necessary, particularly for crop vegetation such as lettuce, necessitating a refined approach for cultivation in toxic element-laden environments.

CRediT authorship contribution statement

HG Min: Investigation, Writing - Original draft, Visualization. **E Kim:** Methodology, Investigation. **MS Kim:** Conceptualization, Methodology. **JG Kim:** Resources, Writing - Review & editing Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare no conflicts of interest.

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