

Response of photosynthesis and chlorophyll fluorescence to acute ozone stress in tomato (*Solanum lycopersicum* Mill.)

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Abstract

The crop sensitivity to ozone (O₃) is affected by the timing of the O₃ exposure, by the O₃ concentration, and by the crop age. To determine the physiological response to the acute ozone stress, tomato plants were exposed to O₃ at two growth stages. In Experiment I (Exp. I), O₃ (500 µg m⁻³) was applied to 30-d-old plants (PL30). In Experiment II (Exp. II), three O₃ concentrations (200, 350, and 500 µg m⁻³) were applied to 51-d-old plants (PL51). The time of the treatment was 4 h (7:30 – 11:30 h). Photosynthesis and chlorophyll fluorescence measurements were done 4 times (before the exposure; 20 min, 20 h, and 2–3 weeks after the end of the treatment) using a LI-COR 6400 photosynthesis meter. The stomatal pore area and stomatal conductance were reduced as the O₃ concentration increased. Ozone induced the decrease in the photosynthetic parameters of tomato regardless of the plant age. Both the photosystem (PS) II operating efficiency and the maximum quantum efficiency of PSII photochemistry declined under the ozone stress suggesting that the PSII activity was inhibited by O₃. The impaired PSII contributed to the reduced photosynthetic rate. The greater decline of photosynthetic parameters was found in the PL30 compared with the PL51. It proved the age-dependent ozone sensitivity of tomato, where the younger plants were more vulnerable. Ozone caused the degradation of photosynthetic apparatus, which affected the photosynthesis of tomato plants depending on the growth stage and the O₃ concentration.

Introduction

Ozone is regarded as one of the most widespread air pollutants around the world and now it is recognized as a global problem (UNECE 2010). Ground-level O₃ is formed from the pollutants emitted from vehicle exhausts, industrial production, and photochemical reactions with

the O₃ precursors. The elevated O₃ concentration is also a growing concern for rapidly developing nations with rising emissions of the O₃ precursors from expanding transportation networks (Bell *et al.* 2006).

Ozone modifies different physiological processes in

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Abbreviations: ATP – adenosine triphosphate; ETR – electron transport rate; F₀ – minimal fluorescence of the dark-adapted leaf; F₀' – minimal fluorescence of the light-adapted leaf; F_m – maximal fluorescence of the dark-adapted leaf; F_m' – maximal fluorescence of the light-adapted leaf; F_s – steady-state fluorescence; g_s – stomatal conductance; J_{max} – the maximum rate of carboxylation limited by electron transport rate for RuBP generation; NADPH – nicotinamide adenine dinucleotide phosphate; O₂₀₀ – ozone treatment of 200 µg m⁻³; O₃₅₀ – ozone treatment of 350 µg m⁻³; O₅₀₀ – ozone treatment of 500 µg m⁻³; P_{max} – light-saturated photosynthetic rate; P_N – net photosynthetic rate; PL30 – 30-d-old plants; PL51 – 51-d-old plants; PPFD – photosynthetic photon flux density; PS – photosystem; q_p – photochemical quenching coefficient; R_D – dark-respiration rate; Rubisco – ribulose-1,5-bisphosphate carboxylase/oxygenase; t_b – before O₃ treatment; t_{20m} – 20 min after O₃ treatment; t_{20h} – 20 h after O₃ treatment; t_{3w} – 2–3 weeks after O₃ treatment; TPU – triose phosphate use; V_{cmax} – maximum carboxylation velocity of Rubisco; α – initial slope of the light curve at low PPFD; Θ – curve convexity; Φ_{CO2} – quantum yield of carboxylation rate; Φ_{PSII} – effective quantum yield of photosystem II photochemistry.

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plants: photosynthesis (Nighat *et al.* 2000, Calatayud *et al.* 2011), stomata function (Robinson *et al.* 1998, Singh *et al.* 2009), plant growth and development (Saitanis and Karandinos 2002, Kharel and Amgain 2010, Mina *et al.* 2010), and crop productivity (Chen *et al.* 2008). Ozone enters a leaf through the stomata by a diffusion process and it is quickly destroyed in the cellular wall and plasmalemma (Laisk *et al.* 1989). Contran and Paoletti (2007) reported that stomata played the main role in O₃ uptake as a higher stomatal conductance was related to a larger potential of O₃ uptake (Nighat *et al.* 2000, Paoletti and Grulke, 2010, Yan *et al.* 2010). Some authors (Reinert and Henderson 1980, Lyons and Barnes 1998) have suggested that the crop sensitivity to O₃ might be influenced by the timing of the O₃ exposure and a stage of the plant development. In *Plantago major* L., the increased resistance to O₃ was observed in relation to plant age, due to changes in the leaf tissue features (Lyons *et al.* 1999). The similar, tissue-age-dependent ozone sensitivity was observed in other crops. Young cereals and spinach were more susceptible to O₃ compared with mature ones and the sensitive cultivars of sweet corn were not injured since they reached a height of 45 cm (Hill *et al.* 1970). In legumes, the plants in the early growth stage were very vulnerable to O₃ (Kasana 1991).

Ozone induces a decline of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) activity and depresses the CO₂ fixation rate (Degl'Innocenti *et al.* 2002b,

Goumenaki *et al.* 2010). As Rubisco is the important enzyme of the Calvin cycle, the enzyme degradation due to O₃ is associated with the reduced potential to consume ribulose-1,5-bisphosphate (RuBP) at this stage of carbon fixation. Since PSI and PSII produce the power to generate ATP and NADPH, which are used in the Calvin cycle (Moore *et al.* 1995), any impairment of PS by O₃ (Carrasco-Rodriguez and del Valle-Tascon 2001) could cause dysfunction of the whole photosynthetic process. Any alteration of the photosynthetic efficiency by O₃ could impair the further plant growth and development. The chlorophyll (Chl) fluorescence measurement provides information on light reaction of photosynthesis. It serves as the noninvasive indicator of the photosynthetic apparatus and is therefore very useful for detection of environmental stresses (Guidi *et al.* 1997, Degl'Innocenti *et al.* 2002a, Baker and Rosenqvist 2004).

Among the horticultural crops, tomato is an ozone-sensitive crop (Iriti *et al.* 2006), the sensitivity of which can vary according to the plant age and stress conditions. To better understand crop sensitivity to O₃, it is important to know the crop response to stress intensity at the specific growth stages. Based on this information, experiments were carried out to determine the impacts of O₃ on photosynthesis and Chl fluorescence parameters in the vegetative and generative growth stages of tomato under three O₃ concentrations.

Materials and methods

Study site and crop management practices: Two experiments (Exp. I – August to September 2010; Exp. II – November 2010 to February 2011) were carried out at Kasetsart University, Thailand. The soil (30% sand, 22% silt, and 48% clay) was mixed well with decomposed cow dung and burned rice husk in a ratio of 2:1:1 (v/v/v) and the soil mixture was filled into 12.6 L glass pots. Tomato seeds (*Solanum lycopersicum* Mill.) var. 'Look Tor' (indeterminate type) were sown directly into the glass pots (3 seeds per pot). The glass pots were arranged in a randomized complete block design with five replications. The pots were spaced 60 cm within the row from center to center and 90 cm between the rows. When the seeds started to germinate, thinning was done leaving the strongest plant per pot. All plants were grown under the white net house throughout the experimental period. The glass pots were covered with black plastic sheets to protect the root zone from radiation. The white reflective plastic sheets were used over the black sheets to reduce light absorption and hence heating. The experimental setup, cultural practices, and all fertilizer applications used were the same procedures as reported by Thwe *et al.* (2013).

Ozone exposure: Two closed-top chambers (one for the O₃ exposure and one for the control) with dimensions of

120 cm × 120 cm × 200 cm were made from polyethylene clear plastic.

Ozone was supplied for 4 h (from 7:30 to 11:30 h) by the O₃ generator (*Model OZ 8010, Ozonic International Co. Ltd.*, Thailand) and the ambient air, which passed from the cooling pad, was mixed in the ozone chamber. The O₃ concentrations inside the chamber were measured by the computerized ozone analyzer (*Model 49i, Thermo Fisher Scientific Inc.*, USA) throughout the fumigation period. The ambient air passing the cooling pad was blown to the control chamber during the fumigation period. The temperature and relative humidity inside and outside the chamber were measured using the USB data logger (*OM-EL-USB-2, Omega Engineering, Inc.*, USA).

In Exp. I, fumigation by O₃ (500 µg m⁻³) was applied to PL30 (the vegetative stage). In Exp. II, three concentrations of O₃ (200, 350, and 500 µg m⁻³, *i.e.* O₂₀₀, O₃₅₀, and O₅₀₀, respectively) were given to PL51 (the generative stage bearing some trusses and fruits).

Leaf photosynthesis measurement: The leaf photosynthetic rate was measured four times: before the O₃ exposure (t_b), 20 min (t_{20m}), 20 h (t_{20h}), and 2–3 weeks (t_{3w}) after the O₃ fumigation. The photosynthesis meter (*LI-COR 6400, LI-COR Inc.*, Lincoln, NE, USA) was used

for Exp. I and the *LI-COR 6400* in addition with a fluorescence meter (*LI-COR 6400-40*, *LI-COR Inc.*, Lincoln, NE, USA) was used in Exp. II.

First measurements were done 2–3 d before the O_3 fumigation. The youngest, fully developed leaf of each plant was chosen for all photosynthetic measurements. CO_2 response curves (P_N-C_i) were calculated from the selected leaves using different CO_2 concentrations and the maximum light intensity ($1,400 \mu mol m^{-2} s^{-1}$). The sequence of CO_2 concentrations started from $400 \mu mol(CO_2) mol^{-1}$ and decreased gradually to $50 \mu mol mol^{-1}$. Then, the value increased again from $400 \mu mol mol^{-1}$ to the highest value of $1,200 \mu mol mol^{-1}$. The sequence for the light response curve started from $1,800 \mu mol(photon) m^{-2} s^{-1}$ and decreased gradually to zero, with a 15 step decrease, under the controlled CO_2 concentration ($400 \mu mol mol^{-1}$). P_N-C_i curves were measured at t_b , t_{20m} , and t_{3w} . Light-response curves were measured at t_b , t_{20h} , and t_{3w} in both experiments. In Exp. II, Chl fluorescence light curves and fluorescence CO_2 response curves were additionally measured on the light-adapted leaves, and Chl fluorescence parameters were calculated.

Stomata aperture measurement: To determine the response of stomata to O_3 , epidermis printings were taken using clear nail polish, clear tape and a glass slide within 20 min after ending the O_3 exposure. The clear nail polish was applied to the abaxial surface of the leaf and left for a few minutes to dry completely. Then, the clear tape was put on the surface of the stained area, pressed firmly and the tape was removed carefully. The epidermal prints were examined under the microscope and the images of stomata were recorded. The images were analyzed using the *J program* (National Institute of Health, Bethesda, MD, USA) to determine the length and width of the stomata aperture. The area of the stomata aperture was calculated assuming an elliptical-like shape as $[A = \pi \times L \times W/2]$, where W and L are the length and width of the stomata pore. The values of the stomata aperture were expressed in relation to the control.

P_N-C_i curves were fitted using an *A-C_i curve-fitting utility, version 1.1* (Sharkey *et al.* 2007). In this model, the maximum velocity of Rubisco for carboxylation (V_{cmax}) was estimated at low CO_2 concentrations (~ 200 ppm) and the maximum rate of carboxylation limited by the electron transport rate for RuBP generation (J_{max}) was estimated at the CO_2 concentration which was higher than 300 ppm. Between 200 and 300 ppm, there is a transition from one limitation to the other one and these points were normally excluded. The triose phosphate use (TPU) limitation was calculated when the photosynthesis became stable or declined with increasing CO_2 concentrations.

Light-response curve: The photosynthetic response of an individual leaf to the incident solar radiation can be described by the photosynthetic response-to-irradiance

curve (Thornley 1998). The net photosynthetic rate of a leaf (P_N) was described as:

$$P_N = \frac{\alpha PPFD + P_{max} - \sqrt{(\alpha PPFD + P_{max})^2 - 4\Theta \alpha PPFD P_{max}}}{2\Theta} - R_D \quad (1)$$

where the photosynthetic photon flux density (PPFD) is the PPFD absorbed by the leaf, α is the initial slope of the light curve at low PPFD, P_{max} is the light-saturated value for photosynthesis, Θ is the convexity of the light curve, and R_D is the dark respiration rate.

Chl fluorescence parameters: Chl fluorescence measurements were recorded from the fluorescence light curve and fluorescence CO_2 response curve of the light-adapted leaves. The values of minimal fluorescence (F_0) and maximal fluorescence (F_m) from the dark-adapted leaves were determined after 30 min dark period. Exposure of each dark-adapted leaf to the weak, modulated measuring beam [PPFD of *ca.* $0.1 \mu mol m^{-2} s^{-1}$] resulted in the minimal fluorescence (F_0). The short actinic pulse of high PPFD (less than 1 s at several thousands $\mu mol m^{-2} s^{-1}$) to the dark-adapted leaf gave the maximal fluorescence (F_m). Calculations for fluorescence parameters were based on the *LI-6400/LI-6400XT Version 6.1* software program (LI-6400/LI-6400XT 2008).

When the leaf was completely dark-adapted, the optimal quantum efficiency of PSII photochemistry (F_v/F_m) was calculated as:

$$p_{dark} = \frac{F_m - F_0}{F_m} = \frac{F_v}{F_m} \quad (2)$$

where F_0 is known as the minimal fluorescence, F_m is the maximal fluorescence, and p_{dark} is the fraction of absorbed photons that are used for photochemistry in the dark-adapted leaf.

If the leaf was completely adapted to light, the efficiency of PSII photochemistry was calculated as:

$$\Phi_{PSII} = \frac{(F_m' - F_s)}{F_m'} \quad (3)$$

where Φ_{PSII} is the effective quantum yield of PSII photochemistry, F_m' is the maximum Chl fluorescence yield under the light conditions and F_s is the steady state fluorescence prior to the flash.

The effective quantum yield of PSII photochemistry was also determined in terms of the efficiency of the energy harvesting by oxidized (open) PSII reaction centers in the light, also referred as the maximal quantum efficiency of PSII and it was calculated as:

$$\frac{F_v'}{F_m'} = \frac{F_m' - F_0'}{F_m'} \quad (4)$$

The electron transport rate (ETR) was determined as:

$$\text{ETR} = \Phi_{\text{PSII}} \times I \times 0.5 \times \alpha_{\text{leaf}} \quad (5)$$

where I is the incident photon flux density [$\mu\text{mol m}^{-2} \text{s}^{-1}$], 0.5 is the factor that accounts for the partitioning of energy between PSII and PSI, and α_{leaf} is the leaf absorbance. A value of 0.84 was used for α_{leaf} .

The quantum yield of the carboxylation rate (Φ_{CO_2}) was calculated as:

$$\Phi_{\text{CO}_2} = \frac{P_N - P_{\text{Ndark}}}{I \times \alpha_{\text{leaf}}} \quad (6)$$

where P_N is the assimilation rate and P_{Ndark} is the dark assimilation rate [$\mu\text{mol m}^{-2} \text{s}^{-1}$].

The photochemical quenching coefficient (q_P) was computed from:

$$q_P = \frac{F_m' - F_s}{F_m' - F_0'} \quad (7)$$

where F_s is the steady state fluorescence and F_0' is the

minimal fluorescence of the light-adapted leaf that was momentarily darkened. The minimal fluorescence (F_0') was determined using far-red light to excite PSI and to force electrons to drain from PSII. The *LI-COR 6400* – 40 provided a ‘dark pulse’ routine to determine F_0' .

Curve fitting: The exponential decay function with two parameters was utilized to fit the curve of the Φ_{PSII} (Ritchie 2008, Iacono and Sommer 2000), the Φ_{CO_2} , F_v/F_m' , and q_P with varying PPFD. To fit the growth curve for ETR vs. PPFD, the nonrectangular hyperbola was used (Thornley 1998, Iacono and Sommer 2000). The slope of the curve and the maximum value of each function were compared between the treatments and controls.

Statistical analysis: Data was analyzed using *SAS version 9.2* (SAS Institute Cary 2007). To determine mean values of two groups (before and after the O_3 exposure or exposed and nonexposed O_3), a *t*-test comparison was used. Differences in O_3 concentrations were assessed using one-way comparison by *ANOVA* followed by LSD test at the significant level of 5%.

Results

Impacts on stomatal conductance (g_s) and stomata aperture: Ozone reduced g_s regardless of the plant age. Before the O_3 exposure, the PL30 had higher g_s than the PL51. Twenty minutes after the end of the treatment, g_s was reduced by 85%, from 1.19 to 0.21 $\text{mol}(\text{H}_2\text{O}) \text{m}^{-2} \text{s}^{-1}$, in the PL30 and by 32%, from 0.46 to 0.28 $\text{mol}(\text{H}_2\text{O}) \text{m}^{-2} \text{s}^{-1}$, in the PL51 at O_{500} . The g_s reduction was higher as the O_3 concentrations increased (Fig. 1B). Stomata openness was also reduced by O_3 . The relative value of the stomata pore area (ozone-treated plants compared with the control) decreased from 99% to 71% as the O_3 concentration increased from O_{200} to O_{500} (Fig. 1A).

Response of photosynthesis: The negative response of photosynthesis to ozone stress was observed. Twenty minutes after the end of the O_3 exposure, V_{cmax} of the PL30 was reduced from 89 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (control) to 37 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (O_{500}); this represented the 58% reduction relative to the control (Fig. 2A). Similarly, J_{max} was depressed by 70% (Fig. 2B) and TPU by 68% relative to the control (Fig. 2C). In the PL51, the maximum decline was observed at O_{500} (reduction of 42% V_{cmax} , 33% J_{max} , and 35% TPU relative to the control), followed by O_{350} and O_{200} , respectively (Fig. 2D,E,F).

At t_{20h} , the similar and consistent reduction was observed in both experiments. For O_{500} , and in the PL30 (Exp. I), P_{max} was reduced by 78 %, Θ by 4 %, and α by 68 %. In the PL51 (Exp. II), P_{max} was depressed by 33%, Θ by 7%, and α by 15% (Table 1). The reduction intensified as the O_3 concentration rose during both measurements

(t_{20m} and t_{20h}) (Fig. 2, Table 1). Comparing both growth stages, the PL30 showed the higher reduction than that of the PL51 under the same concentration O_{500} (Fig. 2, Table 1).

After t_{3w} , no significant differences of the parameters (*i.e.* light- and CO_2 -response curves) could be observed between the ozone-exposed and the control plants in both growth stages (Fig. 2, Table 1). It suggested that leaf photosynthesis was not permanently affected in tomato by the acute ozone stress regardless of the growth stage.

Response of Chl fluorescence characteristics: The parameters of Chl fluorescence were measured only during Exp. II (PL51). The results indicated that O_3 reduced the value of the F_v/F_m ratio just after the O_3 treatment. Significant differences were observed at O_{500} (0.73) and O_{350} (0.77) in comparison with the control plants. The O_3 concentration O_{200} did not show any significant impact on F_v/F_m (Table 2). The changes of the Chl fluorescence parameters in response to the increasing light intensity are described in Fig. 3. The ETR gradually rose as the light intensity increased. Other parameters (Φ_{PSII} , Φ_{CO_2} , q_P , and F_v/F_m') showed the exponential decrease with the increasing light intensity. To compare the parameters of the curves among the treatments, the curves were fitted using different parameters. For all fitted curves, the initial slope as well as the maximum value of the curve from the ozone-treated plants was reduced under the ozone stress. The greatest rate of the decrease was observed for O_{500} , followed by O_{350} and O_{200} in all parameters measured

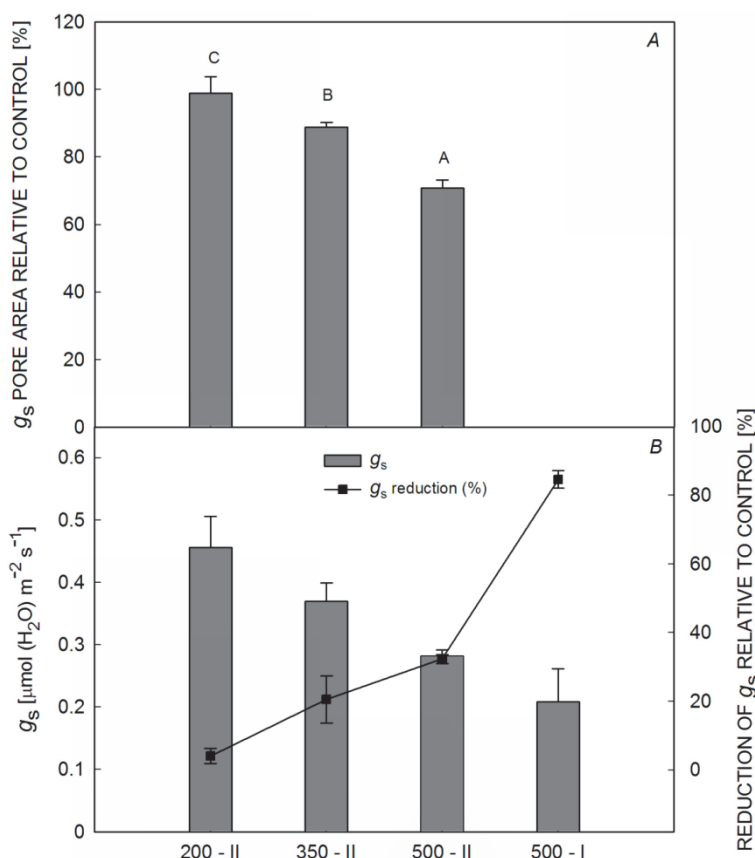


Fig. 1 A: Comparison of stomata pore area (stomatal openness) relative to control after ozone (O_3) treatment, B: Comparison of stomatal conductance (g_s) and reduction of g_s relative to control after O_3 exposure. Measurements for stomata pore area were taken within 20 min after the end of O_3 exposure. Mean \pm SE ($n = 70\sim 90$). I and II – ozone experiments I and II.

(Fig. 3, Table 3). Moreover, these parameters (slope and the maximum asymptote of the curve) were significantly different among the treatments.

To determine the characteristics of the fluorescence parameters among the different O_3 concentrations and their recovery potential, the parameters were measured 4 times in different evaluation periods. The significant differences

were observed just after the O_3 exposure (at t_{20m} and t_{20h}). No significant difference of reduction percentage was observed between t_{20m} and t_{20h} . Among the treatments, O_{350} and O_{500} showed significantly lower values (ETR , Φ_{PSII} , Φ_{CO_2} , and q_p) than the control. Measurements done 3 weeks later suggested a recovery process from O_3 injury in tomato (Fig. 4).

Discussion

The experiments were carried out to characterize the ozone impacts on photosynthesis and Chl fluorescence parameters at two growth stages of tomato. The results demonstrated that the photosynthetic apparatus of tomato was impaired by the O_3 exposure. The damage varied with regard to the O_3 concentrations and plant age. The higher impact was observed as the O_3 concentrations increased. Moreover, the younger plants suffered more than the older ones.

$P_N\text{-C}_i$ curve parameters measured at t_{20m} indicated that O_3 induced the inhibition of the biochemical kinetic variables (V_{cmax} , J_{max} , TPU) irrespective of the plant age. The significant decline was detected just after the O_{500} exposure and above (Fig. 2). The O_3 concentration O_{200} did not show any significant impact. Ozone promotes proteolysis, accelerates the reduction of Rubisco (Dann and Pell 1989) and induces the ethylene production that

reduces the Rubisco protein content (Glick *et al.* 1995). Since Rubisco is the crucial enzyme of the Calvin cycle, the enzyme degradation could lower the capacity of Rubisco to consume RuBP (Sage and Reid 1994). Based on the current results, V_{cmax} was reduced as the O_3 concentration rose (Fig. 2). In addition, the younger plants were more affected at the same O_3 concentration indicating that Rubisco degradation was higher under stress during the earlier stage of plant development.

The same trend was also observed in ETR for RuBP generation (J_{max}). The ETR reduction in dependence on the increasing O_3 concentration could be linked to α . Under ozone stress, the ability of the plants to produce oxygen decreased and it lowered the quantum yield. In both experiments, α was significantly reduced at O_{500} with the greater reduction in the younger plants (68%) than in the older ones (15%) (Table 1). The reduced α lowers

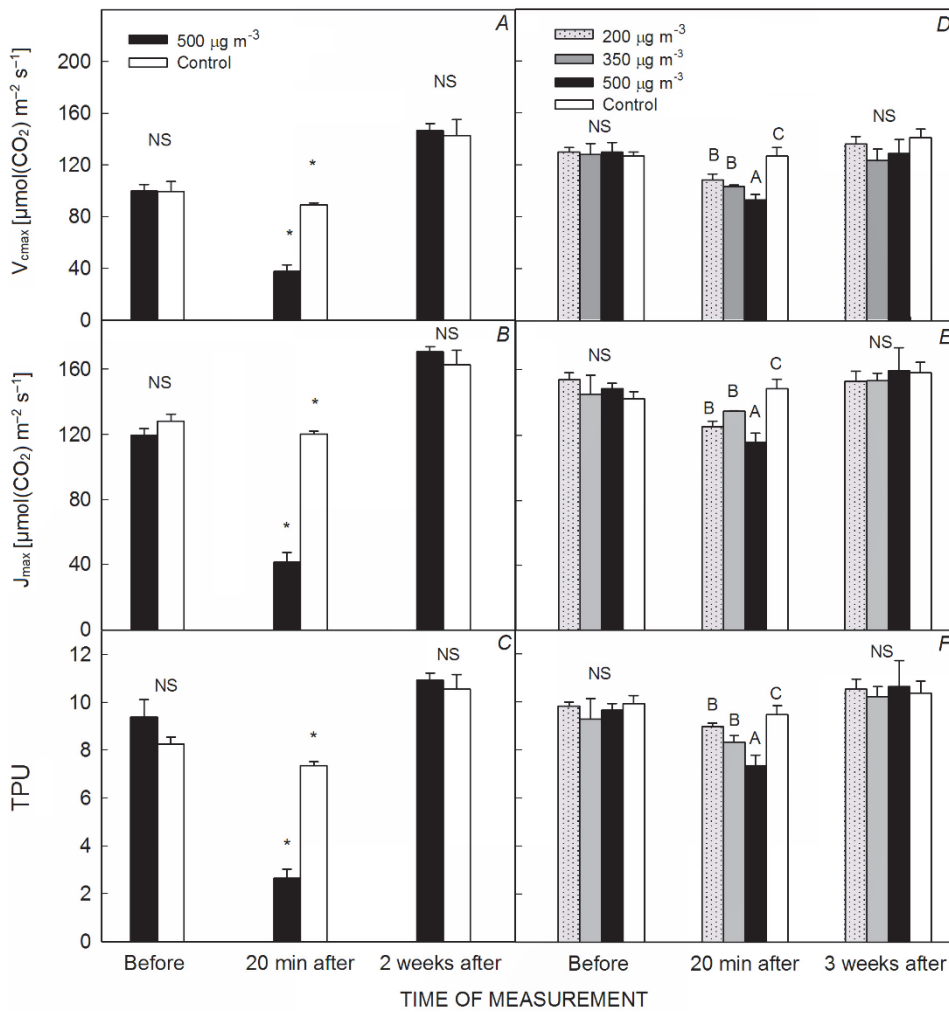


Fig. 2. Comparison of P_N-C_i curve parameters between two different growth stages. *A–C*: 30-day-old plants (PL30) and *D–F*: 51-day-old plants (PL51). *A,D*: V_{\max} – maximum apparent rate of Rubisco carboxylation, *B,E*: J_{\max} – maximum electron transport rate for RuBP regeneration, and *C,F*: TPU – triose phosphate use. Mean \pm SE ($n = 5$). Open symbols indicate control and closed symbols indicate O_3 -treated plants.

Table 1. Comparison of light-response curve parameters for 30- (PL30) and 51-d-old plants (PL51) at different ozone concentrations. P_{\max} – light-saturated photosynthetic rate, α – initial slope of the light curve at low PPFD, Θ – convexity of the light curve. Parameters were derived from light-response curves measured at 20 h (t_{20h}) and 2–3 weeks (t_{3w}) after the end of ozone exposure. Parameters were compared for each treatment and each control. Mean ($n = 5$). The value inside the parentheses is the reduction percentage of ozone-treated plants relative to control. * in the same column indicates the significant level between the treatment and control for each ozone concentration. * – significant at $p < 0.05$, ** – significant at $p < 0.01$.

Plant	Ozone [$\mu\text{g m}^{-3}$]	α t_{20h}	Θ	P_{\max} [$\mu\text{mol}(\text{CO}_2) \text{ m}^{-2} \text{ s}^{-1}$]	α t_{3w}	Θ	P_{\max} [$\mu\text{mol}(\text{CO}_2) \text{ m}^{-2} \text{ s}^{-1}$]
PL30	0	0.06**	0.73	32.10**	0.06	0.75	30.44
	500	0.02 (– 68%)**	0.70 (– 4%)	5.15 (– 78%)**	0.06	0.73	32.10
PL51	0	0.06	0.79	26.05	0.07	0.87	23.74
	200	0.06 (– 4%)	0.71 (– 5%)	23.30 (– 9%)	0.06	0.77	20.58
	0	0.06	0.81	27.80	0.06	0.79	22.60
	350	0.06 (– 5%)	0.77 (– 5%)	24.02 (– 10%)	0.06	0.74	19.10
	0	0.06*	0.86	19.87*	0.07	0.76	24.57
	500	0.05 (– 15%)*	0.83 (– 7%)	13.29 (– 33%)*	0.06	0.82	23.51

Table 2. Comparison of maximum quantum efficiency of PSII photochemistry (F_v/F_m) from the dark-adapted leaf between the treatments and controls. Mean \pm SE ($n = 5$). Comparisons were made for each ozone concentration between the treatment and control (the same row) and among different ozone concentrations (the same column). * in the same row indicates the significant level between the treatment and control and a capital letter in the same column indicates a comparison among the ozone concentrations. The same letters in the same column assign not significantly different values. ns – not significant, * – significant at $p < 0.05$, ** – significant at $p < 0.01$.

Ozone [$\mu\text{g m}^{-3}$]	Before treatment	Control	Just after treatment	Control	3 weeks after treatment	Control
200	$0.80 \pm 0.004^{\text{ns}}$	$0.79 \pm 0.013^{\text{ns}}$	$0.78 \pm 0.005^{\text{ns B}}$	$0.80 \pm 0.004^{\text{ns}}$	$0.79 \pm 0.004^{\text{ns}}$	$0.80 \pm 0.004^{\text{ns}}$
350	$0.81 \pm 0.006^{\text{ns}}$	$0.79 \pm 0.010^{\text{ns}}$	$0.77 \pm 0.008^* \text{ B}$	$0.79 \pm 0.007^*$	$0.81 \pm 0.006^{\text{ns}}$	$0.81 \pm 0.010^{\text{ns}}$
500	$0.79 \pm 0.004^{\text{ns}}$	$0.79 \pm 0.006^{\text{ns}}$	$0.73 \pm 0.002^{** \text{ A}}$	$0.80 \pm 0.002^{**}$	$0.81 \pm 0.008^{\text{ns}}$	$0.82 \pm 0.004^{\text{ns}}$

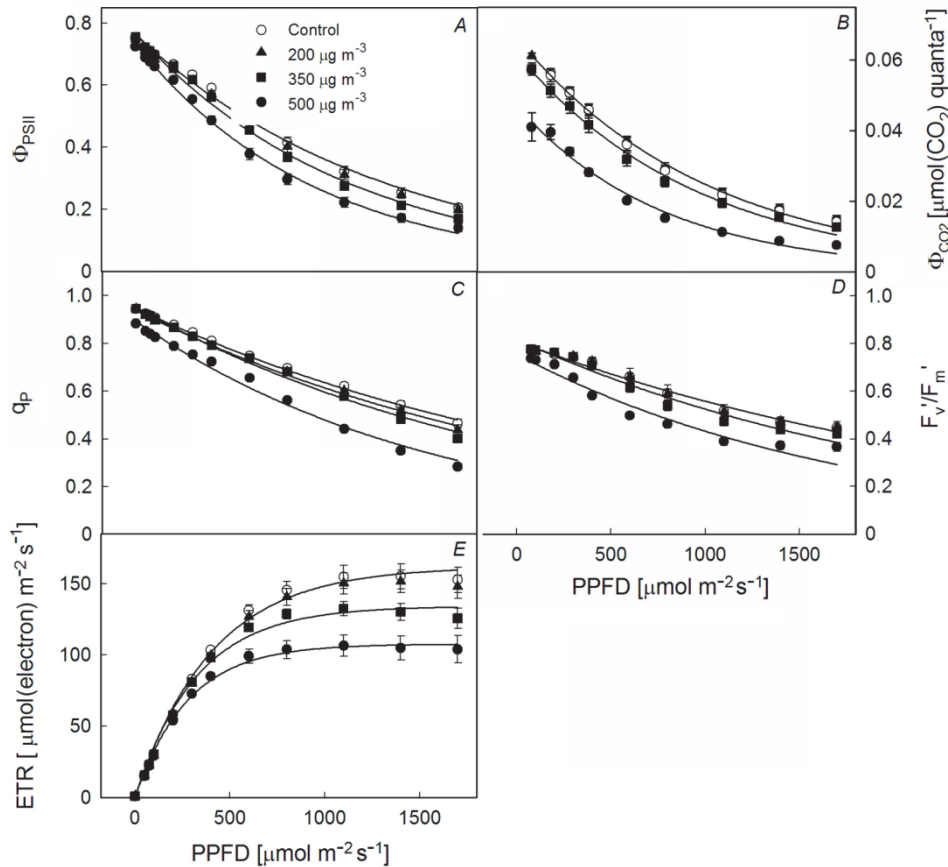


Fig. 3. Comparison of fluorescence parameters between the O_3 -treated plants and control to varying PPFD. A: Quantum yield of PSII (Φ_{PSII}), B: Quantum yield of CO_2 assimilation (Φ_{CO_2}), C: Photochemical quenching (q_p), D: Photosystem II maximum efficiency (F_v/F_m), and E: Electron transport rate (ETR). Measurements were taken 20 h after the end of fumigation. (○) Control, (▲) $200 \mu\text{g m}^{-3}$, (■) $350 \mu\text{g m}^{-3}$, (●) $500 \mu\text{g m}^{-3}$. Open symbols indicate control and closed symbols indicate O_3 -treated plants. Mean \pm SE ($n = 5$). Lines were fitted curve using estimated parameters.

ETR and reduces the strength of ATP production (Moore *et al.* 1995). Moreover in our experiments, the decline in TPU (Fig. 2C,F) revealed the lowered α and the reduced carboxylation efficiency under ozone stress. Thus, the capacity of starch and sucrose synthesis to regenerate inorganic phosphate (P_i) from triose phosphate was limited

under ozone stress. Sage and Reid (1994) reported that starch and sucrose synthesis can influence the rate of RuBP regeneration by failing to metabolize triose phosphates as fast as they are produced. As a result, the level of P_i becomes progressively lower under the high O_3 concentration.

Table 3. Chlorophyll fluorescence parameters between ozone-treated and nontreated plants to varying light intensity PPFD. ETR – electron transport rate, Φ_{PSII} – effective quantum yield of photosystem II photochemistry, Φ_{CO_2} – quantum yield of carboxylation rate, q_P – photochemical quenching coefficient, F_v'/F_m' – maximal quantum efficiency of PSII. Parameters were derived from nonlinear curve fitting. Equation parameter ‘a’ means maximum asymptote and ‘b’ means the slope of the fitted curve. Mean ($n = 5$). Measurements were taken 20 h after the end of ozone exposure.

Parameter	Equation	Ozone [$\mu\text{g m}^{-3}$]	Parameters from equation		r^2
			a	b	
ETR	Refer to Eq. 1	0	161.750 ^d	0.29 ^c	0.99
		200	152.974 ^c	0.28 ^b	0.99
		350	139.480 ^b	0.28 ^b	0.99
		500	106.600 ^a	0.26 ^a	0.99
Φ_{PSII}	$Y = a e^{-bx}$	0	0.760 ^{ab}	0.00070 ^a	0.99
		200	0.750 ^{ab}	0.00070 ^a	0.99
		350	0.770 ^b	0.00080 ^b	0.99
		500	0.730 ^a	0.00110 ^c	0.99
Φ_{CO_2}	$Y = a e^{-bx}$	0	0.066 ^b	0.00096 ^a	0.99
		200	0.064 ^b	0.00107 ^c	0.99
		350	0.069 ^b	0.00100 ^b	0.99
		500	0.053 ^a	0.00142 ^d	0.99
q_P	$Y = a e^{-bx}$	0	0.950 ^{ns}	0.00039 ^a	0.99
		200	0.950 ^{ns}	0.00045 ^a	0.99
		350	0.940 ^{ns}	0.00045 ^a	0.99
		500	0.850 ^{ns}	0.00077 ^b	0.99
F_v'/F_m'	$Y = a e^{-bx}$	0	0.807 ^b	0.00035 ^a	0.98
		200	0.804 ^b	0.00038 ^a	0.98
		350	0.811 ^b	0.00045 ^b	0.97
		500	0.763 ^a	0.00057 ^c	0.92

If P_i decline to the critical levels, photophosphorylation can be inhibited, reducing ATP synthesis and in turn RuBP regeneration. Consequently, photosynthesis declined due to the increasing O_3 concentration (Table 1).

The above results indicated that the responses to O_3 were stronger as the concentrations increased with a significant reduction at O_{350} (P_N - C_i curve parameters) and O_{500} (P_N - C_i and light curve parameters). In addition, there was a consistent reduction in the photosynthetic parameters of the younger plants compared with the older ones at O_{500} . It highlighted that younger plants were more susceptible. The variation in the foliar injury between both growth stages supported the above results. The higher foliar injury from O_3 have been already reported in PL30 compared with the PL51 (Thwe *et al.* 2013). This indicated the age-dependent O_3 sensitivity in tomato. Kolb *et al.* (1997) stated that O_3 sensitivity depends on the ontogenetic changes of g_s in accordance with the plant age. The O_3 uptake could be higher in the plants that have the higher g_s than in those having the lower g_s (Reich 1987, Fredericksen *et al.* 1996). Although there were large differences in the g_s between both growth stages in our experiments, they could be explained partially by the age-related differences in O_3 -susceptibility. The literature shows that O_3 -sensitivity is related to ontogenetic trends in leaf morphology (Ferdinand *et al.* 2000) and biochemistry

(Wellburn and Wellburn 1996, Burkey *et al.* 2000). Ozone sensitivity is associated with leaf characteristics related to the ability of O_3 to diffuse into the leaves (high stomata densities) and the ability of O_3 to diffuse among the target cells (high percentage of intercellular spaces among palisade parenchyma cells) (Evans *et al.* 1996, Wieser *et al.* 2002). In our experiments, the younger plants were at the vegetative stage while the older ones were at the generative stage bearing fruits at the time of the O_3 exposure. Pressman *et al.* (1997) indicated that concentrations of soluble sugars and starch in leaves were promoted with the increasing truss number in tomato, and these increased the sugar content of the leaves which could cause the closure of stomata leading to a reduction in leaf injury (Leipner *et al.* 2001). Thus, different contents of biochemical compounds and leaf morphological characteristics in accordance with the plant growth stage modify the entry of O_3 into the plant cells (Fredericksen *et al.* 1995). In addition, the strong reduction of g_s and the stomata pore area revealed the direct effect on the stomata, as the O_3 concentrations increased. Stomata closure in response to O_3 is regarded as a protective mechanism and has been documented by other authors (Hill and Littlefield 1969, Calatayud *et al.* 2002, 2004, McKee *et al.* 1995). Even if stomata closure was larger as the O_3 concentrations increased, it would not prevent the leaf injury.

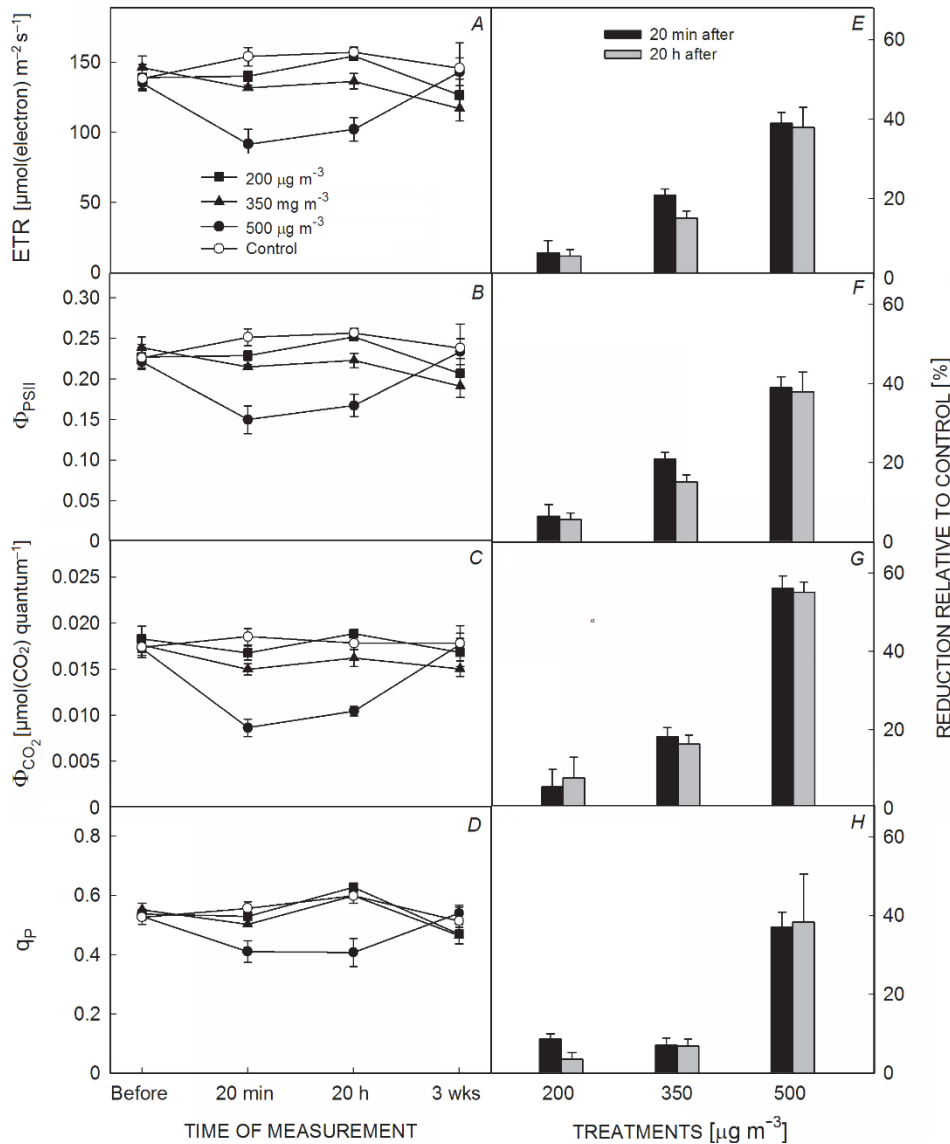


Fig. 4. Comparison of chlorophyll fluorescence parameters and the percentage of a reduction among different O_3 concentrations at different evaluation periods, and for $1,400 \mu\text{mol m}^{-2} \text{s}^{-1}$ PPFD and $400 \mu\text{mol mol}^{-1}(\text{CO}_2)$. *A,E*: Electron transport rate (ETR), *B,F*: Quantum yield of PSII (Φ_{PSII}), *C,G*: Quantum yield of CO_2 assimilation (Φ_{CO_2}), and *D,H*: Photochemical quenching efficiency (q_p). (○) control, (▲) $200 \mu\text{g m}^{-3}$, (■) $350 \mu\text{g m}^{-3}$, (●) $500 \mu\text{g m}^{-3}$. Open symbols indicate control and closed symbols indicate O_3 -treated plants. Mean \pm SE ($n = 5$). Measurements were started before O_3 exposure (Before), 20 min, 20 h, and 3 weeks after the end of O_3 exposure (20 min, 20 h, and 3 weeks).

It suggests that O_3 had already entered the plant cells before the measurements were recorded because stomata responses were measured 20 min after the end of the O_3 exposure. Stomata closure influences the CO_2 uptake; thus the reduction in the CO_2 uptake could be partially responsible for the decline of photosynthesis.

Since Chl fluorescence provides information about the light reaction of photosynthesis, it serves as a noninvasive indicator of the status of photosynthetic reaction centers (Calatayud *et al.* 2006). The results of our Exp. II showed that the ratio of F_v/F_m from the dark-adapted leaves decreased more apparently at the highest O_3 concentration

(O_{500}). It revealed that O_3 limits the capability of the plant to use photon energy and thus it alters photosynthetic processes (Calatayud *et al.* 2006). Our fluorescence parameters (ETR, Φ_{PSII} , Φ_{CO_2} , and q_p) supported these findings. Among the four evaluation periods (t_b , t_{20m} , t_{20h} , and t_{3w}), the ozone-treated plants showed consistently the significant and more obvious depression in both t_{20m} and t_{20h} at O_{500} . No significant difference between t_{20m} and t_{20h} implied that stress still proceeded until 20 h (Fig. 4). The curves (fluorescence parameters vs. PPFD) were fitted and the fitted parameters were evaluated to determine the stress intensity among the O_3 concentrations. The results

indicated that the initial slope as well as the maximum value (the maximum asymptote) of the fitted curves were significantly different among the treatments with the highest decline or the lowest rate of increase at O_{500} suggesting the dysfunction of photosystems under O_3 stress. Reduced Φ_{PSII} revealed that the ability of the leaf to remove electrons from the quinone acceptors of PSII was reduced. The decrease in the rate of NADPH and ATP consumption can result from the decrease in the carboxylation efficiency, in the rate of regeneration of RuBP, and in the supply of CO_2 via the stomata to the sites of carboxylation. Such restrictions on PSII electron transport reduce the rate of excitation of the PSII reaction centers and prevent the PSII quinone acceptors becoming highly reduced. With the increasing level of stress, the increase in nonphotochemical quenching can be insufficient to maintain the partial oxidization of the PSII electron acceptors and then photodamage to PSII occurs (Ort and Baker 2002). Calatayud *et al.* (2004) also stated that the limitation of photosynthesis is correlated with the reduction in the efficiency of energy conversion of PSII, decreasing the rate of noncyclic electron flow and the capacity to reduce the quinone pool. Thus, a decline in photosynthesis and other related parameters at increasing ozone concentrations reflects the occurrence of damaged photosystems.

With regard to the recovery process, photosynthetic depression was not the permanent process and tomato plants had the potential to regain photosynthetic activity after the acute O_3 exposure. Since photosynthetic measurements were made on the youngest, fully developed leaf, the interpretation of the photosynthetic recovery process did not represent the whole plant recovery function. The whole plant recovery process is different, it depends on the level of O_3 injury in accordance with the

plant age and the O_3 concentration at the time of stress as it has been described in the previous article (Thwe *et al.* 2013). Thus, the permanent decrease of photosynthesis linked to the irreversible leaf injury was associated with the temporary depression of photosynthesis linked to g_s and the photosynthetic system. Hence, acquisition of carbohydrates and their next translocation in accordance with the photosynthetic injury should be considered for further plant growth and development.

Conclusion: Tomato is the ozone-sensitive crop. The biochemical kinetic variables (V_{max} , J_{max} , TPU) and α were inhibited under ozone stress leading to reduced P_N irrespective of the plant age. The intensity of the O_3 injury was stronger as the concentrations increased with a significant difference at O_{350} (P_N-C_i curve parameters) and O_{500} (P_N-C_i and light curve parameters). At O_{500} , the injury was higher in the younger plants than in the older ones revealing that younger plants were more susceptible. The worse photosynthetic injuries of the younger plants (PL30) than in the older ones (PL51) indicated the age-dependent O_3 sensitivity. The strong reduction of g_s and the stomata pore area as the O_3 concentration highlighted the direct impact of O_3 on the stomata. The decline of F_v/F_m from the dark-adapted leaf indicated that O_3 caused the photo-inhibition of PSII activity. Thus, the decline of photosynthesis as the O_3 concentrations increased reflected the dysfunction of PS under ozone stress. This data confirmed that the O_3 impacts were different depending on the crop developmental stage and the O_3 concentration. With regard to the recovery process, the photosynthetic depression was not the permanent process under the acute O_3 exposure. Further research for the long-term O_3 exposure is necessary to determine the injury level and the recovery potential of tomato.

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