Pak. J. Bot., 49(3): 913-919, 2017.

BIOCHEMICAL EVALUATION FOR WEAK-LIGHT TOLERANCE OF VARIOUS TOMATO (*SOLANUM LYCOPERSICUM* L.) CULTIVARS IN CHINA

XINCHENG XU[1*], WEIYI SONG[1], DING JINPING[1], ZULFIQAR ALI[3], RABIA FARIDI[3] AND HONGBO SHAO[2*]

[1]School of Life Sciences, Shangqiu Normal College, Shangqiu 476000, China
[2]Salt-soil Agricultural Center, Institute of Agricultural Resources and Environment, Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China
[3]Department of Plant Breeding and Genetics, University of Agriculture, Faisalabad-38040, Pakistan
[*]Corresponding author's email: xxcsq@126.com; shaohongbchu@126.com

Abstract

Enhancement in vegetable cultivation technologies remarkably popularized the construction and use of energy-saving sunlight greenhouses. Ten tomato cultivars in Central Plain of China were used as experimental materials. The effects of weak light stress (50% of normal light density) on the activities of SOD, POD and CAT were determined. Its effect on chlorophyll contents, soluble sugar, soluble protein, proline, and MDA were detected. Dry matter accumulation, fruit setting rate, average fruit weight/fruit and average yield per plant were also measured to observe their changes due to weak light stress. Correlation analysis and main factor analysis were conducted on the coefficients for weak light tolerance of all individual indices using DPS software. The D value of weak light tolerance of cultivar "Xinfen No. 8" (cultivar 5) was maximum, and that of "Jinguan No. 5" (cultivar 7) was minimum. Tomato cultivar "Xinfen No. 8" exhibited the strongest weak-light tolerance, whereas cultivar "Jinguan No. 5" (cultivar 7) showed the weakest weak-light tolerance. This research provides necessary reference for tomato breeding under weak light conditions.

Key words: Tomato cultivars; Biochemical indices; Soil management; Main factor analysis; Subordinate function analysis.

Introduction

As an agriculturally economic area, Central Plain of China bears a long history of crop cultivation. With the rapid worldwide technological development and enhancement in technologies for vegetable cultivation, the construction and use of energy-saving sunlight greenhouses has been remarkably popularized especially in Central Plain of China. Sunlight greenhouses can be used in cold seasons for vegetable cultivation. In recent years, technologies for the establishment of such greenhouses have been increasingly upgraded and perfected in Central Plain of China, generating huge amounts of economic and social benefits (Cockshull, 1992; Afshari *et al.*, 2011).

Tomato (*Solanum Lycopersicum* L.), one of the most widely used edible vegetables and useful for stomach invigoration, blood pressure reduction, diuresis, anti-inflammation and detoxification, is abundant in vitamin A & C, carotene and lycopene, which are beneficial for the prevention of vascular aging. In addition, tomato is also rich in anti-oxidants, which are beneficial for facial beautification (Garcia *et al.*, 2004; Estan *et al.*, 2005). Recently, it has been widely cultivated and generated huge economic benefits. As a common food rich in nutrition, tomato generates huge economic potentials in vegetable markets of Central Plain of China and represents one of the main vegetables for cultivation in greenhouses (Flores *et al.*, 2010).

Tomato, a light-requiring crop originating from tropical and sub-tropical areas, needs relatively high amount of illumination (Lazar *et al.*, 2006; Huang *et al.*, 2009). Whereas mulching materials and dusts cause light shortage and shading, which adversely affect planting and growing conditions of tomato in Central Plain of China, weak light stress also limits enhancement in crops' yields and their commodity qualities (Kim *et al.*, 2004; Li *et al.*, 2013). Therefore, researches concerning tomato's weak-light and low-temperature tolerances are of great importance and a variety of indices for the identification of weak-light tolerance have been proposed in recent years (Kim *et al.*, 2001; Shao *et al.*, 2005). However, no individual reliable trait of crop has been utilized for the identification of weak-light tolerance. Therefore, this paper aims to: 1) determine changes in physiological and biochemical indices, and weak light characteristics under weak light stress in 10 recent tomato cultivars grown in Central Plain of China, 2) sort quantitative indices for the identification of weak-light tolerance of these cultivars , and 3) explore rapid and effective approaches for the identification of their weak-light tolerances. These will provide theoretical basis for tomato breeding under weak light conditions.

Materials and Methods

Plant material and experimental treatments: Ten commonly-used tomato cultivars in Central Plain of China were applied as experimental plant materials, which included "Baiguo Qiangfeng" (cultivar 1), "Fendu No.79" (cultivar 2), "Jin Nabao" (cultivar 3), "Fendu No.80" (cultivar 4), "Xinfen No.8" (cultivar 5), "Fendu Liren No.2" (cultivar 6), "Jinguan No.5" (cultivar 7), "Fendu Queen" (cultivar 8), "Zhongza Fenguo 106" (cultivar 9), and "Asian Fen King" (cultivar 10).

Seeds of 10 tomato cultivars were sterilized, soaked and sown in trays for further breeding. During seedling growth period, seedlings with 8 true leaves were ridge-cultivated in the fields with a row distance of 55 cm and a plant distance of 35 cm (55 cm ×35 cm), and 24ºC in the day time was set. During the experimental period, illumination and temperature were measured at 10-11 o'clock every morning on clear days. Average illumination

intensity ranged 950-1120 µmol/ (m^2.s), and average day temperature was 24ºC and that of night 15ºC. The control plants (CK) were under 100 % natural light. Weak light stress (50 % natural light) was applied under average illumination intensities of 465.5-621 µmol/ (m^2.s) through utilizing black sun shading nets with a sun-shading rate of 50%. Agronomic, temperature, moisture/ water and manure/nutrition managements were kept uniform for both treatments. For each cultivar, data measurement was conducted in 6 randomly-selected plants.

On the 10th day of weak-light stress, healthy leaves of the third leaf position were sampled separately from randomly selected CK and treated seedlings. For each cultivar, some parts of leaf samples were randomly chosen for the measurement of dry matter and chlorophyll contents and others were stored at -80ºC for further use to determine relevant physiological and biochemical indices after major-vein elimination and liquid nitrogen fixation.

Measurement of anti-oxidative enzymatic activities: Activities of such anti-oxidative enzymes as superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT) were measured according to the following procedures.

SOD, POD and CAT activities were measured following nitrotetrazolium blue chloride (NBT) photochemical reduction method described by Shao *et al.* (2005) with a little modification.

For SOD activity measurement, seedling leaf samples of different tomato cultivars were taken 0.1 g for each measurement. Phosphate buffer saline (PBS) reactive solution (pH = 7, containing 13 mM methionine, 75 mM NBT and 0.1 mM Na_2EDTA) was added with 50 µL enzymatic solution. The measurement reaction was initiated through addition of 2 µM riboflavin. The mixed solution was illuminated at 25ºC for 5 min with an intensity of 4000 lx and the absorbance values at wavelength of 560 nm were measured using ultraviolet-visible spectrophotometer (manufactured by Shanghai Yuanxi Instrument Corporation, Shanghai, P. R. C). The un-illuminated solution was used as blank. The unit of SOD activity was represented by 50% a unit of enzymatic activity for inhibiting NBT photochemical reduction and was calculated according to the methods described Song *et al*. (a and b) and Zhu *et al*. (2005).

For POD activity measurement, 5 µL enzymatic solution was added with 3 mL of 50 mM PBS reactive solution (pH = 7, containing 20 mM guaigcol). The reaction measurement was initiated with the addition of 6 µM H_2O_2. Absorbance was measured at every 20 s interval for 2 min at wavelength of 470 nm. POD activity was represented by change in absorbance of every minute, namely ΔA_{470}/ [min． g (fresh weight)]. POD activity was calculated according to the methods described by Song *et al*. (2012) and Zhu *et al*. (2005).

For CAT activity measurement, 100 µL enzymatic solution was added with 3 mL of 50 mM PBS solution (pH = 7). The mixed solution was incubated at 25ºC for 5 min. The reaction measurement was initiated with the addition of 6 µM H_2O_2. Absorbance was measured at every 20 s interval for 2 min at wavelength of 240 nm. A unit of CAT activity was represented by enzymatic amount when A_{240} reduced by 0.1 within 1 min and calculated according to the methods described by Song *et al*. (2012).

Measurement of chlorophyll content: Chlorophyll content was measured according to spectrophotometry method (Madrid *et al.*, 2009). Three samples of tomato leaves, each sample of 0.3 g weight were cut and placed into test tubes. Then, 10 mL leaching liquor (a mixture of acetone: ethanol: water in a proportion of 4.5:4.5:1, respectively) was added in the test tubes and incubated in the dark at room temperature for more than 24 hours before extraction., The test tubes were shaken several times to make the leaves completely leached and obtain chlorophyll extract. The samples of extracted chlorophyll were used to determine optical density (OD) at 663 nm and 645 nm wave lengths in a spectrophotometer. Chlorophyll a & b contents were calculated according to the methods described by Song *et al*. (2012).

The measurement was repeated six times and averaged for each sample.

Measurement of other physiological indices: Soluble protein, MDA, soluble sugar and proline contents were measured according to the methods described by Shao *et al.* (2005) with slight modifications.

For measurement of soluble protein, method of coomassie blue staining was applied and the standard curve was constructed, and soluble protein was calculated methods described by Song *et al.* (a and b) and Zhu *et al.* (2005).

For measurement of MDA, the fresh leaves of tomato seedlings weighing 0.1 g for each sample were ground in 5 mL of 0.25% thiobarbituric acid. Ground leaves were incubated in the test tubes placed in a water bath at 98ºC for 30 min. After the cooling of test tubes, the materials were centrifuged at 10000 rpm for 10 min. The supernatant was used to measure absorbance values at wavelengths of 450 nm, 532 nm, and 600 nm. MDA content was calculated according to methods described by Song *et al*. (2012) and Zhu *et al*. (2005).

For measurement of soluble sugar content, 0.1 g fresh leaves of tomato seedlings of different genotypes were ground in 4 mL 80% ethanol. The ground samples were incubated in water bath set at 75ºC for 10 min. After incubation, samples were centrifuged at 5000 rpm for 10 min. The extracted, for each measurement 4 µL supernatant was taken, and100 µL 80% phenol and 4 mL concentrated sulfuric acid (H_2SO_4) were added into the supernatant. Absorbance values were recorded at 490 nm of wavelength. The standard curve was constructed, and the unit of soluble sugar content was presented as mg. mL^{-1} and calculated according to methods described Song *et al*. (2012) and Zhu *et al*. (2005).

For measurement of proline content, 0.1g fresh leaves of tomato seedlings were ground in 2 mL 3% sulfosalicylic acid. The ground samples were incubated into a boiling water bath for 10 min. After incubation, the samples were centrifuged at 15000 rpm for 15 min, and 0.25 mL of supernatant was taken for each measurement. After adding 0.75 mL of 3% sulfosalicylic acid, 1 mL of glacial acetic acid and 2 mL of 2.5% ninhydrin, the supernatant was incubated into a water bath at 95ºC for 60 min. The incubated supernatant was extracted utilizing 4 mL toluene. Absorbance values of toluene-extracted solutions were measured through applying visible spectrophotometer with a wavelength range of 320-1020nm. The standard curve was constructed and proline content was calculated according to methods described by Song *et al*. (a and b) and Zhu *et al*. (2005).

Observing flowering rate, fruit setting rate, weight per fruit and yield per plant: For each treatment, 15 plants were randomly chosen for observing flowering rate, fruit setting rate, weight per fruit and yield per plant were recorded. Average fruit yield per plant of the first three fruits was also recorded for further analysis.

Main factor analysis and membership function calculation: The originally-acquired data were statistically analyzed based on relative indices following Cockshull's method (Cockshull, 1992). Weak-light tolerance coefficients (α) of all physiological and biochemical indices were calculated using following function.

$$\alpha = (\text{determined value of treated group}/\text{determined value of CK}) \times 100 \quad (1)$$

Experimental data were analyzed using DPS 6.55 software, and the correlation coefficients were obtained for correlation and main factor analyses (Mukherjee *et al.,* 2010). Comprehensive analysis of weak-light tolerance was conducted on 10 tomato cultivars through the adoption of fuzzy mathematic method for acquiring the values of membership function (Mukherjee *et al.,* 2010). Membership function values (U(x) values) were calculated according to calculation method of membership function (Nobuoka *et al.,* 2005; Raines, 2011). The value of comprehensive evaluation for weak-light tolerance was marked as D value. D values of all cultivars were obtained according to Cockshull's method (Mukherjee *et al.,* 2010). Relevant values can be obtained according to methods described by Shao *et al*.

Results

All individual indices (α values) of weak-light tolerance are listed in Table 1. Different tomato cultivars exhibited different changing trends for different indices of weak-light tolerances. SOD activity, MDA, proline and chlorophyll contents increased significantly compared to those of CK (α>100). However, CAT and POD activities, soluble protein, soluble sugar and dry matter contents, and fruit setting rate, average per fruit weight and average per plant yield decreased considerably compared with those of CK (α<100).

Multivariate correlation coefficients for all determined indices are presented in Table 2. Various physiological and biochemical indices exhibited different degrees of correlations among themselves. Indices of SOD, SPC, MC and FSR showed significant correlation coefficients with indices of both APFW and APPY, among them only MC was negatively correlated. POD, PC and DC indices showed significant positive association with indices of APFW only while index of APFW was significantly correlated with index of APPY.

Table 1 The α values of various indices for weak light tolerance of tomato cultivars.

Cultivars	SOD	POD	CAT	SPC	SSC	PC	MC	CC	DC	FSR	APFW	APPY
Cultivar 1	189.91	82.48	47.37	99.82	60.96	96.24	155.82	106.44	39.64	74.11	73.91	73.65
Cultivar 2	537.70	123.56	103.98	119.83	77.68	131.15	114.62	163.90	89.61	99.45	93.49	91.28
Cultivar 3	353.47	77.15	99.57	70.70	26.73	99.34	205.47	81.73	84.46	74.21	82.49	51.22
Cultivar 4	252.26	74.16	75.25	86.70	45.89	93.88	154.80	100.50	58.73	70.46	68.92	74.15
Cultivar 5	440.65	86.59	122.30	75.48	60.25	116.20	263.40	104.12	88.14	83.79	78.44	53.79
Cultivar 6	263.33	72.42	51.41	97.08	30.43	96.71	220.88	133.09	86.83	73.37	78.01	79.65
Cultivar 7	398.12	79.50	80.34	81.20	74.83	107.15	186.95	123.34	78.61	74.54	64.50	79.41
Cultivar 8	510.35	120.99	124.17	126.59	74.97	152.44	133.45	136.49	93.42	98.97	91.19	87.16
Cultivar 9	44.13	39.15	96.45	69.81	43.85	93.44	297.86	118.40	53.45	44.08	40.36	38.30
Cultivar 10	73.91	99.70	93.52	73.85	40.30	89.64	240.20	130.88	52.08	5.95	54.65	34.87

Note: superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT), soluble protein content (SPC), soluble sugar content (SSC), proline content (PC), MDA content (MC), chlorophyll content (CC), dry matter content (DC), fruit setting rate (FSR), average per fruit weight (APFW) and average per plant yield (APPY)

Table 2 Correlation matrix of indices of various traits.

	SOD	POD	CAT	SPC	SSC	PC	MC	CC	DC	FSR	APFW	APPY
SOD	1.00											
POD	0.67*	1.00										
CAT	0.47	0.40	1.00									
SPC	0.59	0.72*	0.06	1.00								
SSC	0.61*	0.58	0.32	0.61*	1.00							
PC	0.83**	0.74**	0.63*	0.76**	0.72*	1.00						
MC	-0.59	-0.69*	0.09	-0.80**	-0.54	-0.53	1.00					
CC	0.28	0.56	0.12	0.65*	0.52	0.49	-0.33	1.00				
DC	0.84**	0.45	0.52	0.37	0.23	0.68*	-0.21	0.28	1.00			
FSR	0.86**	0.38	0.18	0.65*	0.53	0.70*	-0.61*	0.13	0.65*	1.00		
APFW	0.86**	0.73*	0.21	0.71*	0.35	0.69*	-0.71*	0.21	0.69*	0.81**	1.00	
APPY	0.69*	0.51	-0.18	0.83**	0.59	0.59	-0.83**	0.45	0.45	0.80**	0.71*	1.00

* $p<0.05$ ** $p<0.01$

Note: superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT), soluble protein content (SPC), soluble sugar content (SSC), proline content (PC), MDA content (MC), chlorophyll content (CC), dry matter content (DC), fruit setting rate (FSR), average per fruit weight (APFW) and average per plant yield (APPY). "* $p<0.05$" and "** $p<0.01$" represent significant correlation and extremely significant correlation, respectively

Table 3. Coefficients and contribution (*p*) of comprehensive indices [*Z*(*x*)].

Main factor	SOD	POD	CAT	SPC	SSC	PC	MC	CC	DC	FSR	APFW	APPY	ACR
1	0.912	0.808	0.346	0.864	0.714	0.903	-0.774	0.525	0.686	0.826	0.866	0.833	0.5955
2	0.275	0.025	0.855	-0.354	-0.069	0.291	0.487	-0.190	0.517	0.008	0.023	-0.455	0.743
3	-0.228	0.319	0.281	0.167	0.386	0.178	0.072	0.673	-0.261	-0.456	-0.359	-0.192	0.8547
4	-0.062	0.272	-0.100	0.096	-0.545	-0.104	0.005	0.258	0.261	-0.242	0.249	-0.067	0.9101

Note: superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT), soluble protein content (SPC), soluble sugar content (SSC), proline content (PC), MDA content (MC), chlorophyll content (CC), dry matter content (DC), fruit setting rate (FSR), average per fruit weight (APFW), average per plant yield (APPY) and accumulative contributive rate (ACR)

Table 4.Component score, index weights, subordinate and comprehensive evaluation of D values of various tomato cultivars.

Cultivars	C(1)	C(2)	C(3)	C(4)	U(1)	U(2)	U(3)	U(4)	D value
Cultivar 1	6.0326	-7.6132	2.6804	-3.9773	0.673	0.268	0.581	0.084	0.560
Cultivar 2	-0.1835	2.2751	-11.4623	2.6474	0.374	0.486	0.000	0.600	0.360
Cultivar 3	-4.1625	-19.7973	0.1647	-0.8593	0.183	0.000	0.478	0.327	0.198
Cultivar 4	0.3998	25.6294	-9.5160	7.7911	0.402	1.000	0.080	1.000	0.496
Cultivar 5	12.8532	23.3528	-3.5451	0.4561	1.000	0.950	0.325	0.429	0.875
Cultivar 6	3.0497	4.0281	3.8256	0.3999	0.529	0.524	0.628	0.425	0.534
Cultivar 7	-7.9815	-14.0369	7.4394	-3.6484	0.000	0.127	0.776	0.110	0.123
Cultivar 8	0.2107	-6.0316	12.8848	-5.0569	0.393	0.303	1.000	0.000	0.429
Cultivar 9	-5.4120	-6.6763	-4.4860	0.4133	0.123	0.289	0.287	0.426	0.188
Cultivar 10	-4.8064	-1.1301	2.0144	1.8340	0.152	0.411	0.554	0.536	0.267
Contributive rate	0.596	0.148	0.112	0.055					
Index weight					0.654	0.163	0.123	0.060	

Note: C(1), C(2), C(3) and C(4) represent comprehensive indices; U(1), U(2), U(3) and U(4) refer to member functions; D values represent values of comprehensive evaluation

Main factor analysis

Main factor analyses of different tomato cultivars were conducted on α value of 12 physiological and biochemical indices, and transformed into 4 new inter-independent comprehensive indices using DPS software (Table 3) with contributive rates of 0.595, 0.148, 0.112 and 0.055, respectively, and an accumulative contributive rate of 0.9101.

In the first main factor, nine indices characteristic vectors with relatively high absolute values included SOD, POD, soluble protein content, soluble sugar content, proline content, MDA content, fruit setting rate, average per fruit weight and average per plant yield. In the second main factor, CAT activity and dry matter content showed relatively high absolute values. In the third and fourth main factors, chlorophyll content and soluble sugar content showed relatively high absolute values respectively. Altogether, these 4 comprehensive factors accounted for 91.01% variation contained by the original 12 individual indices. Therefore, weak-light tolerance of tomato cultivars can be basically comprehensively evaluated using these four factors, and degrees of weak-light tolerances of different tomato cultivars can be reliably identified.

Comprehensive evaluation: According to all the individual indices of weak-light tolerance coefficients (listed in Table 1) and all comprehensive indices listed in Table 3 and Table 4, 4 values of comprehensive indices (C(x) values) of tested tomato cultivars were obtained. , Of the, Weights (significance of given factors) of 4 comprehensive indices were determined as 0.654, 0.163, 0.123 and 0.060, respectively according to their contributive rates. D values are listed in Table 4, which indicate weak-light tolerance capacities of different tested cultivars. Higher D values suggested stronger weak-tolerance capacities. D values representing weak-light tolerance capacities of different cultivars can be arranged in an order of: cultivar 5> cultivar 1> cultivar 6>cultivar 4> cultivar 8> cultivar 2> cultivar 10> cultivar 3> cultivar 9> cultivar 7. Among these 10 tomato cultivars, cultivar 5 exhibited the maximum D value (0.875) indicating the maximum capacity for weak-light tolerance followed by D value of cultivar 1 (0.560), whereas cultivar 7 showed the minimum D value (0.123) indicating the minimum capacity for weak-light tolerance.

Discussion

The effects of such adverse environmental factors as weak light and low temperature on plant cells can lead to a series of unfavorable physiological reactions during the process of metabolism. Although under slight weak light stress, plant metabolism and growth may be reversibly inhibited, irreversible damages can be brought about by severe weak light stress, which is usually an important cause of the death of individual plants. As a response to weak light stress, plants generally produce a large amount of reactive oxygen species, which often cause direct damages to their cells. Under weak light stress, individual plants routinely witness unbalanced generation and elimination of active oxygen species by their cells, and the cellular over-accumulation of reactive oxygen species (ROS) can result in the peroxidation of membrane lipids and the loss of membrane permeability, thus resulting in a variety of physiological and biochemical changes in plant cells and disorders in their metabolism, which can bring

about immediate damages to individual plants (Song *et al*., 2012, 2014). It is an indisputable fact that oxidation stresses are among the secondary stresses generated by multiple environmental stresses and that under adverse stresses, the chloroplasts generate reactive oxygen species. An effective elimination system of these species constitutes an indispensable part in plants' resistances or tolerances to adverse stresses, including weak light. Therefore, it is necessary to improve plants' resistances or tolerances to adverse stresses by enhancing their resistances or tolerances to oxidation under weak light stresses (Bote & Struik, 2011; Brestic *et al.,* 2014; Gratani, 2014; Zhu *et al*., 2005).

Plants' tolerances to adverse environmental stresses are generally controlled and regulated by multi-genes. As a result, plants exhibit diverse adaptations to these adverse environmental stresses including weak light stress. Weak-light tolerance of tomato cultivars received great importance since 1960s and became a critical domain in tomato cultivation and breeding (Malash *et al.,* 2008; Simion *et al.,* 2008). The botanical and physiological differences among different genotypes under weak light conditions were also extensively studied in tomato and other crops (Souza *et al.,* 2004; Rahmatian *et al.,* 2014). Majority of these reports focused on physiological indices of seedlings due to easy operations (Shao *et al.,* 2005) and fewer reports focused on physiological indices of adult tomato plants (Malash *et al.,* 2008; Madrid *et al.,* 2009). A considerable differences existed between the identification indices of seedlings' and adult plants' weak-light tolerances (Yu & Ong, 2003; Rahmatian *et al.,* 2014). In order find the accuracy of weak-light tolerances of tested materials, investigation on the identification of weak-light tolerance indexes should be more highly representative and provide higher referential and practical values for the selection and cultivation of weak-light tolerant tomato cultivars.

Anti-oxidative enzymes can eliminate reactive oxygen species (ROS) generated in plant cells under adverse stresses, such as weak-light stresses, thus improving plants tolerances or resistances to these stresses, or relieving plants of both biotic and abiotic stresses. Under weak-light stresses or sun-shade effects, when the concentrations of cellular reactive oxygen species reached or exceeded the "critical value", cellular membrane system was the first to be attacked by the generation of lipid free radicals, which on one hand combined to trigger a cascade of reactions in the peroxidation of membrane lipids under weak light stress or sun-shade effects, and on the other hand caused the formation of protein free radicals, thus producing more polymers of protein free radicals through additive reactions. Meanwhile, the creation of malondialdehyde (MDA) through peroxide splitting caused more MDA molecules to form intracellular or intercellular proteins' cross links, which disrupted the structures and functions of cellular membranes (Song *et al*., 2012). Under weak light stresses, such anti-oxidative enzymes as superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT) were favorable for the formation of a balanced metabolism process of cellular reactive oxygen species, and for the protection of the structures of cellular membrane structures, thereby enable individual plants to tolerate, relieve from or resist weak light stresses or sun-shade effects (Kalaji *et al.,* 2016; Liu *et al.,* 2011; Repková *et al.,* 2009; Zivcak *et al.,* 2014(a); Zhu *et al*., 2005).

Tomato, a kind of warmth-liking and light-liking vegetable, needs plentiful of illumination during its plant growth and fruit formation. However, during the process of tomato's protected cultivation, due to the adverse effects of such aspects as the ill-functions of old mulching materials, shading of Greenhouse skeleton structures and seasonally unfavorable climatic factors, in the greenhouses, adverse niches of weak light stresses often result from insufficient illumination, which exerts more severe disrupting effects especially during the most important growth periods. Activities of SOD, POD and CAT can serve as important gauges for the measurements of the effects exerted by weak light on individual tomato plants. (Cockshull, 1992; Zhu *et al*., 2005). Therefore, through the measurements of SOD, POD and CAT activities, the growth conditions of individual tomato plants can be directly analyzed, which will be favorable for the adjustment of surrounding environment for better tomato growth. The selection of low-temperature tolerant tomato cultivars can provide important referential values for the large-scale production of tomato by applying greenhouse technologies (Bote & Struik 2011; Kalaji *et al.,* 2016; Liu *et al.,* 2011; Repková *et al.,* 2009; Zivcak *et al.,* 2014 (a and b).

Superoxide Dismutase (SOD), peroxidase (POD) and catalase (CAT) are important anti-oxidative enzymes which specialize in eliminating super-oxygen ions and balancing reactive oxygen species in plant cells, thus playing paramount roles in protecting these cells from being disrupted by such adverse environmental factors as weak light, toxic chemicals, radiations and ultraviolet. These anti-oxidative enzymes have been paid more attentions and widely investigated, because they are involved in a cascade of physiological reactions in plant cells. The results of this research showed that superoxide dismutase, one of the important protective enzymes, can directly eliminate reactive oxygen species in plant cells and play an important part in preventing the peroxidation of membrane lipids under weak light stress; and SOD, POD and CAT activities of some cultivars decreased to some extent, which was consistent with the results of the experimental researches conducted by Song *et al.,* 2012. The results also showed that changes in activities were indirectly controlled by gene expression and interaction as an immediate response to weak-light stress. However, relative molecular mechanisms concerning the elaborate processes of this regard need to be further investigated and clarified.

Selection and cultivation of weak-light tolerant tomato cultivars and other plants is required to obtain high yield in protective areas. Yield changes under weak-light or sun-shade conditions reflect weak-light tolerance of a cultivar, and represents a crucial index for identification of that cultivar's weak-light tolerance or tolerance or resistance to sun-shade effects (Bote & Struik 2011; Brestic *et al.,* 2014; Gratani 2014; Hartz & Bottoms 2009; Kalaji *et al.,* 2016; Liu *et al.,* 2011; Repková *et al.,* 2009; Zivcak *et al.,* 2014 (a and b)). Yield represents a comprehensive trait, which can be readily affected by many factors (Simonne *et al.,* 2007; Patane *et al.,* 2011).

The effects of weak-light tolerance selection can be enhanced only through indirectly selecting relevant traits closely related to yield. Fruit setting rate can be used as an extremely important and credible index for the identification of tomato's weak-light tolerance (Harmanto *et al.,* 2005; Hanson and May, 2006), and considerably enhanced efficiency of tomato breeding. Results of some relevant researches indicated that different physiological and biochemical indexes play different roles in weak-light tolerance. Therefore, merely based on a few indexes, evaluation of weak-light tolerances of different tomato cultivars can not have easy access to objective and effective experimental results, and comprehensive analyses are needed for accurate identification of weak-light tolerances of tomato cultivars.

Weak-light tolerance or resistance of tomato is also controlled and regulated by complex quantitative traits. Under weak-light stress, the response of a certain index can be different in different cultivars or at different physiological periods in the same cultivar (Keiko *et al*., 2007; Huang *et al.,* 2009). Therefore, despite of relatively numerous previous physiological and biochemical studies conducted on weak-light tolerance of tomato, any individual physiological and biochemical index can not comprehensively reflect the degrees of tomato cultivars' weak light tolerance. In recent years, many scholars used comprehensive analysis for the evaluation of stress tolerance of plants, and revealed better relationships between relevant traits and plants' stress tolerance (Moon *et al.,* 2006; Madrid *et al.,* 2009). Few reports are focused on the identification of tomato's weak-light tolerance. In this research, 10 commonly used tomato cultivars in Central Plain of China were chosen. Our experimental results showed that cultivar 5 possessed certain tolerance to weak-light stress indicating that this cultivar is adaptive to plantation under weak-light environment in greenhouses in winter and early spring. Cultivar 7 exhibited the minimum capacity for weak-light tolerance showing that this cultivar needed adequate illumination during greenhouse cultivation under weak-light environment. Comprehensive evaluation of weak-light tolerance of tomato cultivars can be systematically acquired through measuring different physiological and biochemical indices of tomato cultivars and transforming quantitative indices of their weak-light tolerance into comprehensive evaluative indices. It is favorable for the rapid and effective exploration of identification technologies for weak-light tolerance of tomato cultivars, and beneficial for providing scientific basis for the regional selection and cultivation of these cultivars. However, the detail physiological, biochemical and molecular mechanisms for the cultivation of weak-light tolerant tomato cultivars still need to be further explored and clarified through successive studies in future.

Acknowledgements

This research was jointly supported by Henan Province Science and Technology Development Project (Grant No. 082102140018; 102300410034), National Natural Foundation of China (Grant No. 31000744).

References

Afshari, R.T., R. Fngoshtari and S. Kalantari. 2011. Effect of light and different plant growth regulators on induction of callus growth in rapeseed (*Brassica napus* L.) genotypes. *Plant Omics J*., 4: 60-67.

Benard, C., H. Gautier, F. Bourgaud, D. Grasselly, B. Navez, C.C. Veyrat, M. Weiss and M. Genard. 2009. Effects of low nitrogen supply on tomato (*Solanum lycopersicum*) fruit yield and quality with special emphasis on sugars, acids, ascorbate, carotenoids, and phenolic compounds. *J. Agri. Food Chem*., 57: 4112-4123.

Bote, A.D. and P.C. Struik. 2011. Effects of shade on growth, production and quality of coffee (*Coffea arabica*) in Ethiopia. *J. Horti. & Forest*., 3(11): 336-341

Brestic, M., M. Zivcak, K. Olsovska, H.B. Shao, H.M. Kalaji and S. Allakhverdiev. 2014. Reduced glutamine synthetase activity plays a role in control of photosynthetic responses to high light in barley leaves. *Plant Physiol. & Biochem*., 81: 74-83.

Cockshull, K. 1992. Shading on yield of glasshouse tomatoes. *J. Horti. Sci*., 67: 11-24.

Ertek, A., I. Erdal, H.I. Yilmaz and U. Senyigit. 2012. Water and nitrogen application levels for the optimum tomato yield and water use efficiency. *J. Agri. Sci. Technol*., 14: 889-902.

Estan, M.T., M.M.M. Rodrigues, F.P. Alfoce, T.J. Flowers and M.C. Bolarin. 2005. Grafting raises the salt tolerance of tomato through limiting the transport of sodium and chloride to the shoot. *J. Exp. Bot*., 56: 703-712.

Flores, F., B.P.S. Bell, M.T. Estan, M.M.M. Rodriguez, E. Moyano, B. Morales, J.F. Campos, J.O.G. Abellán, M.I. Egea, N.F. Garcia, F. Romojaro and M.C. Bolarín. 2010. The effectiveness of grafting to improve tomato fruit quality. *Horti. Sci*., 125: 211-217.

Garcia, N.F., V. Martinez, A. Cerda and M. Carvajal. 2004. Fruit quality of grafted tomato plants grown under saline conditions. *J. Horti. Sci. Biotechnol*., 79: 995-100.

Gratani, L. 2014. Plant Phenotypic Plasticity in Response to Environmental Factors. *Adv. Bot*., 4: 1-17. http://dx.doi.org/10.1155/2014/208747

Hanson, B.R. and D.M. May. 2006. Crop evapotranspiration of processing tomato in the San Joaquin Valley of California, USA. *Irrigation Sci*., 24: 211-221.

Harmanto, V., M. Salokhe, M.S. Babel and H.J. Tantau. 2005. Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment. *Agri. Water Manag*., 71: 225-242.

Hartz, T.K. and T.G. Bottoms. 2009. Nitrogen requirements of drip irrigated processing tomatoes. *Horti. Sci*., 44: 1988-1993.

Huang, L.H., Y.H. Hong, X.Z. Dai and X.W. Zhang. 2009. Effect of light quality on calluses induction and differentiation of *Capsicum annuum*. *J. Hunan Agri. Uni*., 35: 615-617.

Jang, Y.A., E. Goto, Y. Ishigami, B. Mun and C.H. Chun. 2011. Effect of light intensity and relative humidity on photosynthesis, growth and graft-take of grafted cucumber seedlings during healing and acclimatization. *Hort. Environ. Biotechnol*., 52: 331-338.

Kalaji, H.M., A. Jajoo, A. Oukarroum, M. Brestic, M. Zivcak, I.A. Samborska, M.D. Cetner, I. Łukasik, V. Goltsev and R.J. Ladle. 2016. Chlorophyll a fluorescence as a tool to monitor physiological status of plants under abiotic stress conditions. *Acta Physiologia Plantarum*., 38(4): 1-11.DOI 10.1007/s11738-016-2113-y

Keik, O.K., T. Masahide, K. Noya, F. Kazuhiro and K. Kenji. 2007. Effect of light quality on growth and vegetable quality in leaf lettuce, spinach, and komatsuna. *Environ. Control Biol*., 45: 189-198.

Kim, H.H., G.D. Goins and R.M. Wheeler. 2004. Stomatal conductance of lettuce grown under or exposed to different light qualities. *Ann. Bot*., 94: 691-697.

Kim, Y.H., C.S. Kim, J.W. Lee and S.G. Lee. 2001. Effect of vapor pressure deficit on the evapotranspiration rate and graft-taking of grafted seedlings population under artificial lighting. *J. Bio-Energy Control*, 10: 232-236.

Kuscu, H., A. Turhan, N. Ozmen, P. Aydinol and A.O. Demir. 2014. Optimizing levels of water and nitrogen applied through drip irrigation for yield, quality, and water productivity of processing tomato (*Lycopersicon esculentum* Mill.). *Horti. Environ. Biotechnol*., 55(2): 103-114.

Kuşçu, H., B. Çetin and A. Turhan. 2009. Yield and economic return of drip-irrigated vegetable production in Turkey. *New Zealand J. Crop Horti. Sci*., 37: 51-59.

Lambelet, P., M. Richelle, K. Bortlik, F. Franceschi and M. Giori. 2009. Improving the stability of lycopene Z-isomers in isomerised tomato extracts. *Food Chem*., 112: 156-161.

Lazar, D., P. Susila and J. Nauš. 2006. Early detection of plant stress from changes in distributions of chlorophyll a fluorescence parameters measured with fluorescence imaging. *J. Fluorescence*, 16: 173-176.

Li, H., Z. Xu and C. Tang. 2010. Effect of light-emitting diodes on growth and morphogenesis of upland cotton (*Gossypium hirsutum* L.) plantlets *In vitro*. *Plant Cell Tissue and Organ Culture*, 103: 155-163.

Li, X., S.D. Zhu and Y.X. Liu. 2013. Multivariate statistical analysis of low-light tolerance in tomato (*Solanum lycopersicum* Mill.) cultivars and their ultrastructural observations. *J. Plant Growth Regul*., 32(3): 646-653.

Liu, K., T.Q. Zhang, C.S. Tan and T. Astatkie. 2011. Responses of fruit yield and quality of processing tomato to drip-irrigation and fertilizers phosphorus and potassium. *J. Agron*., 103: 1339-1345.

Lyautey, E., S. Hallin and S.Teissier. 2013. Abundance, activity and structure of denitrifier communities in phototrophic river biofilms (River Garonne, France). *Hydrobiologia*, 716(1): 1-11.

Madrid, R., E.M. Barba, A. Sanchez and A.L. García. 2009. Effects of organic fertilisers and irrigation level on physical and chemical quality of industrial tomato fruit (cv. Nautilus). *J. Sci. Food Agri*., 89: 2608-2615.

Malash, N.M., T.J. Flowers and R. Ragab. 2008. Effect of irrigation methods, management and salinity of irrigation water on tomato yield, soil moisture and salinity distribution. *Irrigation Sci*., 26: 313-323.

Markovic, K., M. Hruškar and N. Vahčić. 2006. Lycopene content of tomato products and their contribution to the lycopene intake of Croatians. *Nutrition Res*., 26: 556-560.

Moon, H.K., S.K. Park, Y.W. Kim and C.S. Kim. 2006. Growth of Tsuru-rindo (*Tripterospermum japonicum*) cultured *In vitro* under various sources of light-emitting diode (LED) irradiation. *J. Plant Biol*., 49: 174-179.

Mukherjee, A., M. Kundu and S. Sarkar. 2010. Role of irrigation and mulch on yield, evapotranspiration rate and water use pattern of tomato (*Lycopersicon esculentum* L.). *Agri. Water Management*, 98: 182-189.

Nobuoka, T., T. Nishimoto and K. Toi. 2005. Wind and light promote graft-take and growth of grafted tomato seedlings. *J. Japanese Soc. Horti. Sci*., 74: 170-175.

Oda, M., M. Maruyama and G. Mori. 2005. Water transfer at graft union of tomato plants grafted onto Solanum rootstocks. *J. Japanese Soc. Horti. Sci*., 74: 458-463.

Patanè, C., S. Tringali and O. Sortino. 2011. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. *HortScience*, 129: 590-596.

Rahmatian, A., M. Delshad and R. Salehi. 2014. Effect of grafting on growth, yield and fruit quality of single and double stemmed tomato plants grown hydroponically. *Hort. Environ. Biotechnol*., 55(2): 115-119.

Raines, C.A. 2011. Increasing photosynthetic carbon assimilation in C_3 plants to improve crop yield: current and future strategies. *Plant Physiol*., 155: 36-42.

Repková, J., M. Brestič and K. Olšovská. 2009. Leaf growth under temperature and light control. *Plant, Soil & Environ*., 55(12): 551-557.

Shao, H.B., Z.S. Liang and M.A. Shao. 2005. Changes of anti-oxidative enzymes and MDA content under soil water deficits among 10 wheat (*Triticum aestivum* L.) genotypes at maturation stage. Colloids and Surfaces B: *Biointerfaces*, 45: 7-13.

Simion, V., G.H. Cămpeanu, G. Vasile, M. Artimon, L. Catană and M. Negoiţă. 2008. Nitrate and nitrite accumulation in tomatoes and derived products. *Roman Biotechnol. Letters*, 13: 3785-3790.

Simonne, A.H., J.M. Fuzeré, E. Simonne, R.C. Hochmuth and M.R. Marshall. 2007. Effects of nitrogen rates on chemical composition of yellow grape tomato grown in a subtropical climate. *J. Plant Nutrition*, 30: 927-935.

Song, W.Y., A.Z. Zheng, H.B. Shao, L.Y. Chu, M. Brestic and Z.B. Zhang. 2012. The alleviative effect of salicylic acid on the physiological indices of the seedling leaves in six different wheat genotypes under lead stress. *Plant Omics Journal*, 5(5): 486-493.

Song, W.Y., H.C. Yang, H.B. Shao and A.Z. Zheng. 2014a. The alleviative effects of salicylic acid on the activities of catalase and superoxide dismutase in malting barley (*Hordeum uhulgare* L.) seedling leaves stressed by heavy metals. *Clean – Soil, Air, Water*, 42(1): 88-97

Song, W.Y., S.P. Peng, C.Y. Shao, H.B. Shao and H.C. Yang. 2014b. Ethylene glycol tetra-acetic acid and salicylic acid improve anti-oxidative ability of maize seedling leaves under heavy-metal and polyethylene glycol 6000-simulated drought stress. *Plant Biosys*., 18(1): 96-108.

Souza, R.P., E.C. Machado and J.A.B. Silva. 2004. Photosynthetic gas exchange, chlorophyll fluorescence and some associated metabolic changes in cowpea (*Vigna unguiculata*) during water stress and in field-grown, grafted tomatoes. *Hort. Sci*., 48: 485-492.

Wang, M., W.J. Jiang and H.J. Yu. 2010. Effects of exogenous epibrassinolide on photosynthetic characteristics in tomato (*Lycopersicon esculentum* Mill) seedlings under weak light Stress. *J. Agri. & Food Chem*., 58(6): 3642-3645.

Yu, H. and B.L. Ong. 2003. Effect of radiation quality on growth and photosynthesis of *Acacia mangium* seedlings. *Photosynthetica*, 41: 349-355.

Zhu, Y.S., H. Feng and S.S. Gao. 2005. Effects of low light density stress on yield and physiological characteristics of different growth stages of tomato. *J. Jilin Agri. Uni*., 27(6): 634-638 (In Chinese with an English Abstract).

Zivcak, M., K. Olšovská, P. Slamka, J. Galambošová, V. Rataj, H.B. Shao, H.M. Kalaji and M. Brestič. 2014b. Measurements of chlorophyll fluorescence in different leaf positions may detect nitrogen deficiency in wheat. *Zemdirbyste Agri*., 101(4): 437-444.

Zivcak, M., M. Brestic and H.M. Kalaji. 2014a. Govindjee, Photosynthetic responses of sun and shade grown barley leaves to high light: Is the lower PSII connectivity in shade leaves associated with protection against excess of light? *Photosynthesis Res*., 119(3): 339-354.

(Received for publication 22 March 2016)