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Application of chlorophyll fluorescence to screen eggplant (*Solanum melongena* L.) cultivars for salt tolerance

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Abstract

The objective of this study was to investigate the relative salt tolerance of four eggplant cultivars (*Solanum melongena* L.) by studying chlorophyll (Chl) fluorescence parameters during the vegetative growth stage under increasing salinity levels. The plants were grown in pots filled with peat under controlled conditions and were subjected to the salt stress ranging from 0 (control), 20, 40, 80, and 160 mM NaCl for 25 days. The results showed that the increasing NaCl concentration affected hardly the maximum quantum yield of photosystem (PS) II. The quantum yield of PSII (Φ_{PSII}) decreased significantly in 'Adriatica' and 'Black Beauty' under the salt stress. The photochemical quenching decreased in 'Black Beauty' and nonphotochemical quenching increased in 'Adriatica' under the salt stress. The Chl fluorescence parameters did not change significantly under the salt stress in 'Bonica' and 'Galine', revealing their tolerance to salinity. After 25 days of the salt stress, the plant growth was reduced in all cultivars, however, this decline was more pronounced in 'Adriatica' and 'Black Beauty'. Additionally, a significant correlation between the biomass and Φ_{PSII} was observed in 'Adriatica' and 'Black Beauty'. Our results suggest that Φ_{PSII} can be used as a diagnostic tool to identify salt-tolerant egg-plant cultivars.

Additional key words: salt stress; biomass; photosystem II.

Introduction

The introduction of irrigated agriculture in arid and semiarid regions resulted in the development of soil salinization. It is reported that 15 million ha are already salinized in the Middle East and North Africa (Le Houérou *et al*. 1986). High salt concentrations in the soil decrease the yields of a wide variety of crops all over the world (Sekmen *et al*. 2007). Indeed, salinity is regarded as one of the most important environmental constraints that affect adversely plant growth and metabolism, particularly in the arid and semiarid regions (Munns and Tester 2008).

Plants respond to salt stress through a set of changes in basic biological functions including photosynthesis and photorespiration, synthesis of life-saving molecules, fine tuning in translation and transcription, and reactive molecule scavenging (Mittler 2002, de Azevedo Neto *et al*. 2006, Wei *et al*. 2009, Türkan and Demiral 2009). The lower photosynthetic rate under stressful environments was generally ascribed to stomata closure and to the decreased mesophyll conductance under the severe stress (Flexas *et al*. 2004, Sarker *et al*. 2005, Zribi *et al*. 2009). High salt concentrations contribute to leaf chlorosis, malfunction of the chloroplasts, and photoinhibition or photooxidation, which significantly affect the assimilation rate (Moradi and Ismail 2007). Maxwell and Johnson (2000) showed that Chl *a* fluorescence can constitute an important selection criterion to verify plant sensitivity or tolerance to environmental stresses and to determine the damage of the photosynthetic apparatus caused by these stresses. Zribi *et al*. (2009) reported a significant increase in the nonphotochemical quenching (NPQ) in salt-stressed tomato plants, without significant changes in the maximum quantum yield of PSII photochemistry (F_v/F_m). Chl fluorescence measurements also revealed that NPQ increased whereas the electron transport rate decreased in rice plants under salt stress (Moradi and Ismail 2007). In wheat, salt stress decreased F_v/F_m, Φ_{PSII}, and the photochemical quenching (q_P) while

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Abbreviations: Chl – chlorophyll; DSS – days of salt stress; ETR – electron transport rate; F_v/F_m – maximum quantum yield of PSII photochemistry; NPQ – nonphotochemical quenching; PCA – principal component analysis; PSII – photosystem II; q_P – photochemical quenching coefficient; S0, S40, S80, and S160 – salinity treatments with 0, 40, 80, and 160 mM NaCl, respectively; Φ_{PSII} – effective quantum yield of PSII photochemistry.

increasing NPQ (Zheng *et al.* 2009). Chl fluorescence could be used as a nondestructive and noninvasive tool to determine effects of salt stress on the photosynthetic machinery.

Eggplant (*Solanum melongena* L.) is the important vegetable crop in the Mediterranean area; Egypt, Iran, and Turkey belong to the top eggplant producing countries (Faostat 2010). Although salinization affects the irrigation dependent agriculture in these regions, only limited research has been carried out to evaluate the physiological and biochemical responses of eggplant to salt stress. Crop yield and growth parameters have been used to screen plants for salinity tolerance at the seedling stage (Akinci *et al.* 2004). Based on the growth and production parameters, eggplant is considered moderately sensitive to salinity (Savvas and Lenz 2000) with the significant genotype variation regarding to salt tolerance (Akinci *et al.* 2004). The physiological traits in a combination with growth performance should be also used in a screening for salt tolerance. The exposure of eggplant to sublethal salt concentrations causes stomata closure (osmotic stress) and reduces photosynthetic rates, which might lead to the inhibition of the electron transport through PSII. The objective of the present work was to investigate the relative salt tolerance of four eggplant cultivars by studying the selected Chl fluorescence parameters during the vegetative growth stage under increasing salinity levels.

Materials and methods

Plants: Four commercial eggplant (*S. melongena* L.) cultivars, *i.e.* two open-pollinated cultivars (‘Adriatica’ and ‘Black Beauty’) and two F_1 hybrids (‘Bonica’ and ‘Galine’) were used as the plant material. Seeds were sown into 80-mL plug trays containing a peat-based medium. They were placed in a growth chamber at a constant temperature of 25°C, relative humidity (RH) of 70%, photon flux density of 150 µmol m^{-2} s^{-1}, and the photoperiod of 16 h. After 25 d, the eggplant seedlings were selected according to their uniformity and transplanted into 2-L plastic pots at the stage of the 2nd true leaf. The plants were transferred to a heated glasshouse (located at 51°02’N, 03°42’E) and fertigated with 250 mL of the full-strength Hoagland’s solution, twice a week. The temperature in the glasshouse ranged between 22 and 27°C, while the daily maximum photon flux density averaged 340 µmol m^{-2} s^{-1}. Shading screens were used to prevent direct sunlight.

Salinity treatments: Five salinity treatments were applied starting 36 d after the transfer to the glasshouse. NaCl was added to the full-strength Hoagland’s solutions with the following electrical conductivities:

Treatment	NaCl [mM]	Electrical conductivity [dS m^{-1}]
S0	0	1.18
S20	20	1.42
S40	40	2.75
S80	80	3.05
S160	160	5.21

All solutions were prepared with distilled water. Plants were irrigated with 250 mL per pot, which was applied twice a week during 25 d.

Chl *a* fluorescence was measured in the dark- and light-adapted leaves with a portable fluorometer (*PAM-2500*, *Walz*, Effeltrich, Germany). After 30 min of dark-adaptation, F_v/F_m was calculated as $(F_m - F_0)/F_m$, where F_m [induced by a short pulse (0.6 s) of saturating light (3,450 µmol m^{-2} s^{-1})] and F_0 were the maximal and minimal fluorescence, respectively (Genty *et al.* 1989). After 4 min of illumination with continuous red, nonsaturating actinic light (447 µmol m^{-2} s^{-1}) and saturating pulses every 25 s, the maximum (F_m') and the steady state (F_s) fluorescence signals were measured in the light adapted leaves. Then, the actinic light was turned off and the far-red pulse was applied to obtain the minimal fluorescence after the PSI excitation (F_0'). Φ_{PSII} was calculated as $(F_m' - F_s)/F_m'$ and q_p was calculated as $(F_m' - F_s)/(F_m' - F_0')$ (van Kooten and Snel 1990). NPQ, which is proportional to the rate constant of the thermal energy dissipation, was estimated as $(F_m - F_m')/F_m'$ (Bilger and Björkman 1990). The electron transport rate (ETR) was calculated as $\Phi_{PSII} \times PAR \times 0.84 \times 0.5$, where the absorbed photon energy (PAR) is assumed to be equally distributed between PSI and PSII and 0.84 is the assumed light absorptance of the leaf.

The youngest, fully developed leaf was selected for measurements after 5, 10, 15, 20, and 25 d of the salt stress (DSS) in four replicates.

Determination of biomass production: The plant development was assessed by determination of the fresh mass in the plant aboveground parts (shoots and leaves) after 25 DSS. Two plants per block (eight plants in total) were randomly measured for each cultivar and treatment.

Statistical analysis: Each treatment was applied to 20 plants per cultivar. The experiment was designed as the randomized complete block design, with 4 blocks. Each experimental unit contained 5 plants. Data were subjected to one-way analysis of variance (*ANOVA*) followed by *Tukey*’s HSD test (*P*=0.05) to distinguish differences among the treatments. The principal component analysis (PCA) was carried out with the Chl fluorescence parameters. Only PCA with eigenvalues > 1, explaining more than a single parameter alone, were extracted. For these principal components, the varimax rotation was applied on the obtained factor. This rotation results in the factors, relating parameters mainly to one principal component axis (Manly 1994). All statistical analyses were carried out using *SPSS 19* (*IBM SPSS Statistics*, USA).

Results

NaCl-induced changes in Chl fluorescence parameters: Until 10 DSS, no significant effects on F_v/F_m, q_p, and NPQ were found (data not shown). The decline of F_v/F_m was noticed in 'Bonica' (P=0.046) after 15 DSS, although no significant negative effect was present after 25 DSS (Fig. 1*A*). The significant decrease of F_v/F_m was found in 'Black Beauty' after 25 DSS of S160 (Fig. 1*A*). F_v/F_m of 'Adriatica' and 'Galine' were not affected significantly by the salt concentrations during the whole experimental period.

The significant differences in Φ_{PSII} were observed in 'Adriatica' and 'Black Beauty' (Fig. 1*B*). Φ_{PSII} decreased progressively and significantly in 'Adriatica' after 10 DSS (P=0.010) and in 'Black Beauty' after 5 DSS (P<0.001). In 'Adriatica', Φ_{PSII} was reduced by 41% by S160 compared with the respective controls after 15 and 25 DSS. Similarly, S160 caused the decline of Φ_{PSII} in 'Black Beauty', by 39.7% and by 43.9% after 15 and 25 DSS, respectively, when compared with their respective controls. In contrast, in 'Bonica' and 'Galine', Φ_{PSII} was not affected significantly by the salt treatment (Fig. 1*B*).

The decrease in q_p was found only in 'Black Beauty' after 25 DSS (Fig. 1*C*). The similar, but opposite trend was observed in NPQ. After 15 DSS, the significant increase of NPQ was found at S40 (P=0.005) and S80 (P=0.023) in 'Adriatica' and 'Bonica', respectively. At the highest salt concentration (S160), NPQ increased by 26.7% and 25.0% in 'Adriatica' and 'Bonica', respectively. However, the only significant effect was observed in 'Adriatica' after 25 DSS, when NPQ increased from 0.97 in S0 to 1.58 in S160, *i.e.* by 63% (Fig. 1*D*). After 25 DSS, ETR decreased from 23.5 for S0 to 12.5 for S160 in 'Black Beauty' (P=0.008) and from 17.7 for S0 to 8.7 for S160 in 'Adriatica' (P=0.024). ETR was not influenced by the salt stress in 'Bonica' and 'Galine'.

The score scatter plot of the first two PCA (explaining 80.1% of the variation) showed the good separation of 'Bonica' from the other three cultivars after 25 DSS (Fig. 2). NPQ correlated positively with PCA1 (44.2%), Φ_{PSII} and q_P correlated positively with PCA2 (35.8%). F_v/F_m correlated negatively with PCA1. In all cultivars, the scores of the PCA moved to higher NPQ values and

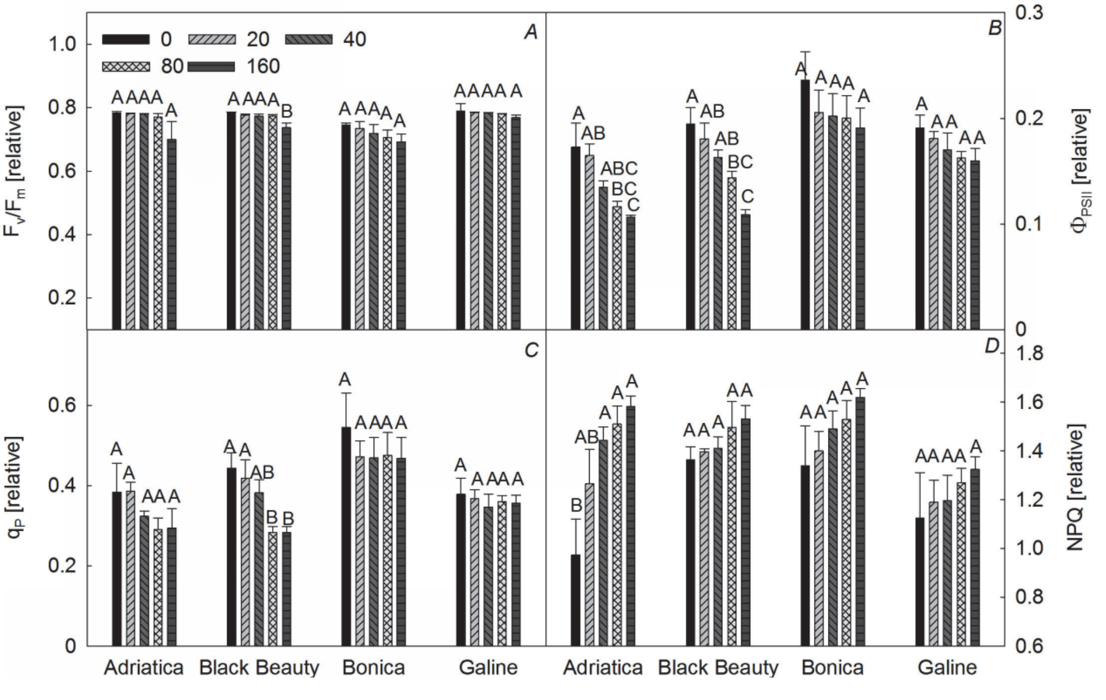

Fig. 1. Effects of different salt treatments (0, 20, 40, 80, and 160 mM) after 25 days under NaCl stress on chlorophyll fluorescence parameters: the maximum quantum yield of PSII (F_v/F_m) (*A*), the effective quantum yield of PSII (Φ_{PSII}) (*B*), the photochemical quenching (q_P) (*C*), and the nonphotochemical quenching (NPQ) (*D*). Different *uppercase letters* indicate significant differences using *Tukey*'s test (P=0.05). Data are means of four replicates ± SE.

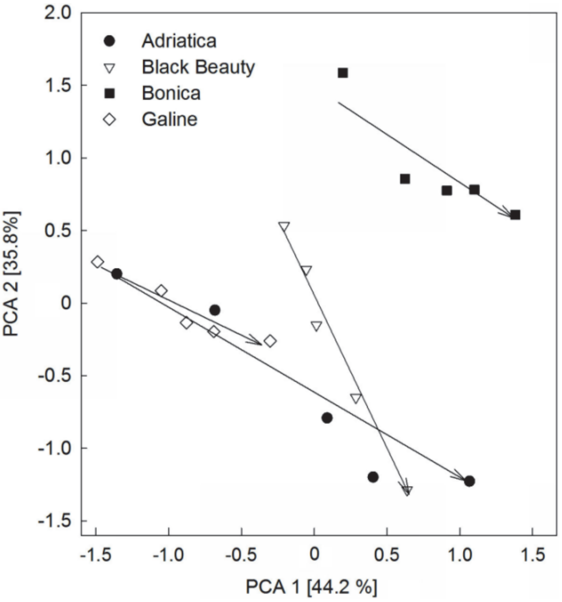

Fig. 2. Principal component analysis (PCA) of chlorophyll fluorescence parameters of the eggplant cultivars grown for 25 days under salt stress. PCA1 is positively correlated with the nonphotochemical quenching (NPQ) and negatively with the maximum quantum yield of PSII (F_v/F_m); PCA2 is positively correlated with the effective quantum yield of PSII (Φ_{PSII}) and the photochemical quenching (q_P). Each data point represents the mean of four replicates. *Arrows* indicate the increasing salt-stress level.

to lower F_v/F_m, Φ_{PSII}, and q_P under increasing salt stress. The separation of the control and the salt-stressed plants of 'Adriatica' according to PCA1 was higher compared with other cultivars (*see* arrows in Fig. 2). In 'Black Beauty', the control and salt-stressed plants were well separated along PCA2.

NaCl-induced changes in biomass production: The fresh aerial biomass of all cultivars decreased as the salinity increased (Fig. 3). The significant growth reduction was already present at the lowest salt concentration (S20). Although plant vigour differed among the cultivars as indicated by their biomass at 25 DSS without salt stress (S0), the salt-induced declines in fresh biomass showed an overall similar trend. The maximum decrease in the fresh biomass was observed in 'Adriatica' and 'Black Beauty'. As compared with the control conditions, the fresh biomass decreased by 86.6% in 'Adriatica' and by 87.8% in 'Black Beauty' at S160 (Fig. 3). In contrast, the decline of the fresh biomass under S160 was 36.9% and 35.9% in 'Bonica' and 'Galine', respectively (Fig. 3). There was the significant correlation between the fresh biomass and Φ_{PSII} in 'Adriatica' (R=0.760, P<0.001) and in 'Black Beauty' (R=0.762, P<0.001).

Discussion

In saline soils, plants experience first the osmotic stress as a consequence of the reduced osmotic potential of the soil solution. The accumulation of salts occurs in the plant tissues during the next stage of the exposure to salinity. The salt content can rise eventually up to the toxic concentrations and it may cause Na^+ toxicity (*i.e.* ionic stress), thereby reducing nutrient acquisition or causing the nutritional imbalance (Munns and Termat 1986). The osmotic and ionic damages are interrelated and coexist under the saline conditions (Castillo *et al.* 2007). Dry biomass is considered as an appropriate parameter for evaluating stress tolerance in crops (Munns *et al.* 2000) although fresh mass is often used in horticultural crops to describe plant biomass (Marcelis *et al.* 1998). In our experiment, salinity had the significant impact on the eggplant biomass. When the plants were expposed to S160 for 25 d, the decrease was found in the fresh biomass by more than 80% in 'Adriatica' and 'Black Beauty', and by more than 30% in 'Bonica' and 'Galine'. The significant decline of the plant biomass has been reported in green beans at 100 mM NaCl (Yasar 2007) and in rice at 120 mM NaCl (Demiral and Turkan 2005), while the decrease at 250 mM NaCl was found in more-salt-tolerant mangrove (Ru *et al.* 2009). Asch *et al.* (2000) reported that the salt-tolerant genotype of rice had the smallest reduction and the susceptible genotype had the greatest reduction of the biomass production.

Salt stress restricts CO_2 availability due to the stomata closure. It may lead to the reduced photosynthesis (Munns and Tester 2008) and hence to the reduced growth. In addition, nonstomatal factors also affect photosynthesis under higher salt concentrations (Stępień and Kłobus 2006); the accumulation of NaCl in chloroplasts of higher plants leads to the inhibition of PSII and to the increased susceptibility to photodamage (Sudhir and Murthy 2004). To evaluate the direct effect of the salt stress on PSII photochemistry, Chl *a* fluorescence was measured in four eggplant cultivars. In the present study, the results showed that F_v/F_m was generally unaffected after 25 DSS, with the exception of 'Black Beauty' at the highest NaCl concentration. Similar results have been reported for wheat (Gallé *et al.* 2002) and tomato (Zribi *et al.* 2009). The slight decrease of F_v/F_m is likely due to the reversible inactivation or downregulation of PSII rather than due to photodamage of PSII (Demmig-Adams and Adams 1996).

PSII activity and its regulation are characterized best by Φ_{PSII} (Genty *et al.* 1989). In two cultivars, the growth inhibition was correlated to the decline of Φ_{PSII}. The salt stress induced the significant and early reduction of Φ_{PSII} indicating the decrease in the electron transport through

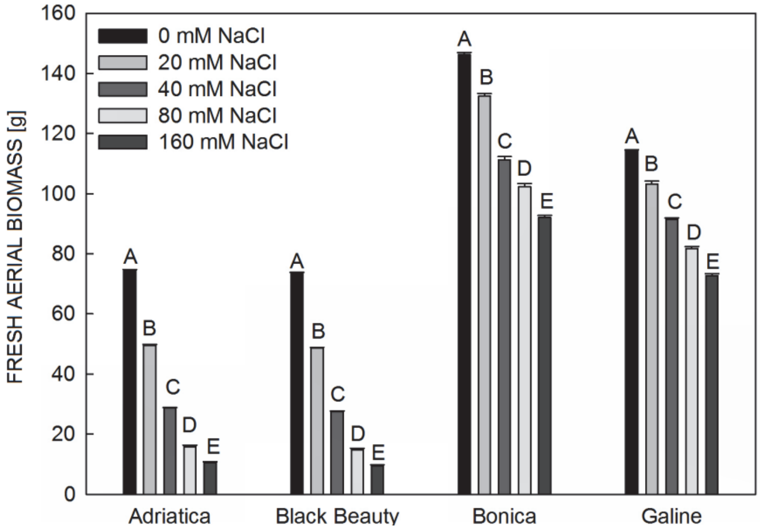

Fig. 3. Effect of increasing salt concentrations on the fresh aboveground biomass in four eggplant cultivars. Different *uppercase letters* indicate significant difference using *Tukey*'s test (P=0.05). Data are means of four replicates ± SE.

PSII in 'Adriatica' and 'Black Beauty' cultivars, which is in agreement with the findings of Zribi *et al*. (2009) in tomato and Lu *et al*. (2009) in soybean. This was also reflected in the decrease of q_P in 'Black Beauty' under increasing salinity. This parameter gives an indication of the PSII ability to reduce the primary electron acceptor Q_A under the applied salt stress as well as of the number of photons used by photochemical reactions per the number of absorbed photons (Govindjee *et al*. 1981). As Φ_{PSII} was affected after 5 and 10 DSS in 'Adriatica' and 'Black Beauty', respectively, this parameter has a potential to be the early and nodestructive tool to screen eggplant cultivars for salt tolerance. The same finding has been reported for soybean by Lu *et al.* (2009).

Φ_{PSII} was not affected in 'Bonica' and 'Galine' up to 25 DSS indicating better PSII functioning under the salt stress. Moreover, the whole chain electron flow continued at the effective rate in these cultivars. Indeed, q_P was hardly affected by increasing salt stress in these cultivars whereas q_P was reduced in 'Black Beauty'. The higher tolerance of PSII to salt stress in 'Bonica' and 'Galine' is also obvious from the limited variation along the PCA2 axis under increasing salt stress. The photochemical quenching can contribute to protect the photosynthetic apparatus by transferring electrons to O_2 under drought or salt stress (Ort and Baker 2002). Cornic and Fresneau (2002) showed that oxygenation of ribulose-1,5-bisphosphate in C_3 plants can efficiently replace the carboxylation when stomata close. We could assume the reduced CO_2 assimilation due to salt stress as the fresh biomass decreased in all cultivars. As Φ_{PSII} and ETR were not affected in 'Bonica' and 'Galine', we might argue that alternative electron sinks were more active in these cultivars. Besides photorespiration, photoreduction might also occur at the acceptor side of PSI in the Mehler reaction (Asada 2000) resulting in the pH gradient across the thylakoid membranes and enhancing the thermal dissipation of excess excitation energy (Johnson *et al*. 1994).

The increase in the nonphotochemical energy dissipation is probably the major process involved in a protection against the photodamage (Krause and Weiss 1991). This increase was more pronounced in 'Adriatica' at 25 DSS. The changes in PCA score by salt stress were also greater in 'Adriatica'. Apparently, the increase in NPQ of 'Adriatica' was effective in preventing the decline of F_v/F_m. The increased NPQ dissipates a part of the excitation energy at the expense of photochemical utilization (Osmond 1994, Zribi *et al*. 2009), thus contributing to a downregulation of PSII to avoid overreduction of the primary electron acceptor Q_A. This response reflects the protective or regulatory mechanism to avoid the photodamage of the photosynthetic apparatus (Demmig-Adams and Adams 1996).

In conclusion, 'Bonica' and 'Galine' tolerated better the applied salt stress as shown by the growth performance and the limited effect on primary photochemistry as compared with 'Adriatica' and 'Black Beauty'. Φ_{PSII} could be used to distinguish the different response to salt stress in the studied eggplant cultivars. Consequently, the light-adapted responses could be considered as the early indicator of salt-induced disturbances in eggplant.

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