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Potassium-induced alleviation of salinity stress in *Brassica campestris* L.

Research Article

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Abstract: Salinity is an important abiotic factor that adversely affects major agricultural soils of the world and hence limits crop productivity. An optimum mineral-nutrient status of plants plays critical role in determining plant tolerance to various stresses. A pot experiment was conducted on mustard (*Brassica campestris* L.) to study the protective role of added potassium (K, 40 mg kg^{-1} soil) against salinity-stress (0, 40 and 80 mM NaCl)-induced changes in plant growth, photosynthetic traits, ion accumulation, oxidative stress, enzymatic antioxidants and non-enzymatic antioxidants at 30 days after sowing. Increasing NaCl levels decreased the growth, photosynthetic traits and the leaf ascorbate and glutathione content but increased the leaf ion accumulation and oxidative stress, and the activity of antioxidant enzymes. In contrast, K-nutrition improved plant growth, photosynthetic traits, activity of antioxidant enzymes and the ascorbate and glutathione content, and reduced ion accumulation and oxidative stress traits in the leaves, more appreciably at 40 mM than at 80 mM NaCl. The study illustrates the physiological and biochemical basis of K-nutrition-induced NaCl tolerance in mustard as a means to achieving increased crop productivity in a sustainable way.

Keywords: *Antioxidant defence system • Brassica campestris • Ion accumulation • Oxidative stress • Plant growth • Potassium nutrition • Soil-salinity*

Abbreviations

APX - ascorbate peroxidase;
AsA - ascorbate (reduced);
DAS - days after sowing;
DHA - dehydroascorbate;
DTNB - 5´,5´-dithio-bis-2-nitro-benzoic acid;
DTT - 1,4-dithiothreitol;
EDTA - ethylenediaminetetraacetic acid;
FW - fresh weight;
GR - glutathione reductase;
GSH - glutathione (reduced);
GSSG - glutathione (oxidized);
LA - leaf area;
MBTH - 3-methyl-2-benzothiazoline hydrazone;
NBT - nitroblue tetrazolium;
NEM - N'N-ethylemaleimide;
P_N - net photosynthetic rate;
ROS - reactive oxygen species;
SOD - superoxide dismutase;
TBARS - thiobarbituric acid reactive substances.

1. Introduction

Salt affected soils are an integral part of the landscape in arid and semiarid tropical and/or non-tropical regions. It is estimated that approximately 831 million hectare (mha) are affected world wide, which accounts for more than 6% of the world's land surface area [1]. Plants growing in salt affected soils are exposed to a number of unfavourable conditions which include low soil water potential, nutrient imbalance and excessive Na^+ and Cl^- accumulation and/or K^+ deficiency in cells [2-4]. The cumulative effects

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of all the above factors adversely affect physiological and biochemical processes of plants leading to poor growth and yield [5,6]. Oxidative damage at the cellular/organ level under adverse conditions including salt stress resulting from the imbalance between production of reactive oxygen species (ROS) and antioxidant defence is often studied to understand the mechanisms of injury [4,7]. ROS are highly reactive and cause damage to major cellular components [8]. Plant tolerance to salinity stress may be due to ion homeostasis, osmotic adjustment and efficient and synchronous action of various enzymatic and non-enzymatic components of the antioxidant defence system [6]. A level of nutrients considered being sufficient for plant growth under non-stress conditions may or may not be sufficient under salt stress. Where plant growth is also adversely affected because of higher nutrient requirement under salt stress, increased supply of nutrients is likely to benefit plants under stress [9,10]. Grattan and Grieve [11] have extensively reviewed the impact of increased nutrient supply on horticultural crops under salt stress.

The macronutrient potassium (K) plays an important role in stimulation of root growth, increasing leaf area, chlorophyll content, net assimilation rate, balancing membrane potential and turgor, activating enzymes, regulating osmotic pressure, stomatal movement and tropisms and reduction of the excess uptake and translocation of ions such as Na^+ and Cl^- [12,13]. The antagonistic effect of Na^+ (the predominant cation in salt affected soil) on uptake of K is well established. Externally supplied K may also increase endogenous K^+ content of seeds, required to tolerate salinity at germination [14], and ameliorate abiotic-stress effects [13]. However, there is limited understanding of the mechanisms associated with K alleviating the adverse effects of salt stress accrued oxidative stress in plants.

The present study is aimed at studying the effects of added K (through nutrient solution) on photosynthetic functions, reducing equivalents (AsA-GSH) and control of the coordination of enzymatic (SOD, APX, GR) and non-enzymatic (AsA, GSH) in pot culture raised-*Brassica campestris* plants exposed to varying salinity levels. The outcome of the study may be helpful in formulating a protocol for the application of a proper level of K to NaCl-affected soil which consequently may be helpful in achieving increased crop productivity in a sustainable way.

2. Experimental Procedures

2.1 Plant material and growth conditions

Seedlings of mustard (*Brassica campestris* L. cv. Pusa Gold) were raised from seeds in 40-cm-diameter plastic pots filled with 8 kg soil. The experimental soil had the following characteristics: texture - loamy sand (83.6% sand, 6.8% silt and 9.6% clay), pH - 7.1, E.C. - 0.23 dsm^{-1}, organic C - 0.28%, available P - 14 kg ha^{-1}, available K - 158 kg ha^{-1} [15]. The experiment was carried out during winter under natural day/night [photosynthetically active radiation (PAR) >900 µmol (photon) m^{-2} s^{-1}, temperature 22±3ºC; relative humidity (RH) 62–72% in the Department of Botany, Hamdard University, New Delhi, India (28.380´ N, 77.110´ E and 228 m altitude). Two plants per pot were grown with Hoagland's nutrient solution [16] and were fed with 250 ml of nutrient solution with 0 (control), 40, 80 mM NaCl solution (*i.e.* 0.001, 5.0, and 8.0 dS m^{-1}, respectively) every alternate day and 200 ml of deionized water daily. Extra K (KCl, Analytical grade) was applied at 40 mg kg^{-1} soil once at the start of the study. The pots were arranged in a randomized block design and replicated three times. All the measurements were performed at 30 d after sowing (DAS).

2.2 Measurements of growth and photosynthetic traits

Plant dry mass (PDM) was recorded after drying the plants for 48 h to a constant weight at 80°C. Leaf area (LA) was measured by a leaf area meter (Licor 300 model). Net photosynthetic rate (P_N), stomatal conductance (gs) and intercellular CO_2 concentration (Ci) were measured on a fully expanded third leaf from the top of the main shoot, using an infra red gas analyzer (Licor 6400 model) at 9:00-11:00 am at saturating light intensity.

2.3 Oxidative stress traits

2.3.1 Thiobarbituric acid reactive substances content

For measuring lipid peroxidation, the content of thiobarbituric acid reactive substances (TBARS) was measured by the method of Cakmak and Horst [17], recording the absorbance at 532 nm and correcting it for non-specific turbidity by subtracting the absorbance at 600 nm. The TBARS content was calculated using the extinction coefficient of 155 mM^{-1} cm^{-1}.

2.3.2 H_2O_2 content

H_2O_2 assay was done according to Okuda *et al*. [18]. Fresh leaf (0.5 g) was homogenized in 2.0 ml of pre-chilled $HClO_4$ (0.2 N), and the homogenate was centrifuged at 20,000×*g* for 5 min. To remove $HClO_4$, the supernatant was neutralized to pH 7.5 with KOH (4 N), followed by centrifugation at 1,000×*g* for 1 min. Ten units of catalase were added to an aliquot, and the mixture was incubated for 15 min at 25ºC. The reaction was stopped by boiling for 1 min. The reaction mixture (1.5 ml) contained 1.0 ml of aliquot, 400 µl of 3-(dimethylamino) benzoic acid (DMAB, 12.5 mM)

prepared in phosphate buffer (0.375 M, pH 6.5), 80 µl of 3-methyl-2-benzothiazoline hydrazone (MBTH) and 20 µl of peroxidase (0.25 unit). The reaction was started by the addition of peroxidase, and the increase in absorbance was recorded at 590 nm.

2.4 Components of the antioxidant defence system

2.4.1 Contents of non-enzymatic components - reduced ascorbate and glutathione

The content of reduced (GSH) glutathione was estimated following the method of Anderson [19]. Fresh leaf (0.5 g) was homogenized in 2.0 ml of 5% (w/v) sulphosalicylic acid at 4ºC. The homogenate was centrifuged at 10,000×*g* for 10 min. To 0.5 ml of supernatant, 0.6 ml of K-phosphate buffer (100 mM, pH 7.0) and 40 µl of 5´ 5´ dithiobis-2-nitrobenzoic acid (DTNB) were added and absorbance was recorded after 2 min at 412 nm on a UV-VIS spectrophotometer (Lambda Bio 20, Perkin Elmer, MA, USA).

The content of reduced (AsA) ascorbate was determined by the method of Law *et al.* [20]. Fresh leaf (0.5 g) was homogenized in 2.0 ml of K-phosphate buffer (100 mM, pH 7.0) containing 1 mM EDTA and centrifuged at 10,000×*g* for 10 min. To 1.0 ml of supernatant, 0.5 ml of 10% (w/v) trichloroactetic acid (TCA) was added, thoroughly mixed and incubated for 5 min at 4°C. To 1.5 ml of the above solution, 0.5 ml of NaOH (0.1 M) was mixed and centrifuged at 5,000×*g* for 10 min at 20°C. The aliquot thus obtained was equally distributed into two separate microfuge tubes (750 µl each). For estimation of AsA, 200 µl of K-phosphate buffer (150 mM, pH 7.4) was added to 750 µl of aliquot. For DHA estimation, 750 µl of aliquot was added to 100 µl of 1,4-dithiothreitol (DTT) followed by vortex-mixing, incubation for 15 min at 20°C and addition of 100 µl of 0.5% (w/v) NEM. Both the microfuge tubes were then incubated for 30 s at room temperature. To each sample tube, 400 µl of 10% (w/v) TCA, 400 µl of H_3PO_4, 400 µl of 4% (w/v) bipyridyl dye (N'N-dimethyl bipyridyl) and 200 µl of 3% (w/v) $FeCl_3$ were added and thoroughly mixed. Absorbance was recorded at 525 nm after incubation for 1 h at 37°C.

2.4.2 Assays of enzymatic components

Fresh leaf (0.5 g) was homogenized in K-phosphate buffer (100 mM, pH 7.0) containing 0.5% (v/v) Triton X-100 and 1% (w/v) polyvinylpyrrolidone (PVP) in a pre-chilled mortar and pestle. The homogenate was centrifuged at 15,000×*g* for 20 min at 4ºC. The supernatant was used for the enzyme assays. For APX, the homogenizing buffer was supplemented with 2 mM ascorbate.

Superoxide dismutase (SOD) activity was assayed by monitoring the inhibition of photochemical reduction of nitroblue tetrazolium (NBT), according to Dhindsa *et al*. [21]. One unit of SOD was defined as the amount of enzyme required to cause 50% inhibition of the NBT reaction.

Activity of ascorbate peroxidise (APX) was determined according to Nakano and Asada [22] and calculated by using extinction coefficient 2.8 $mM^{-1}cm^{-1}$. One unit of enzyme was the amount necessary to decompose 1.0 µmol of the substrate min^{-1} at 25ºC.

Glutathione reducatse (GR) activity was determined, following Foyer and Halliwell [23], by monitoring the GSH-dependent oxidation of NADPH. It was calculated by using the extinction coefficient 6.2 $mM^{-1}cm^{-1}$. One unit of enzyme was the amount necessary to decompose 1.0 µmol of NADPH min^{-1} at 25ºC.

2.5 Na^+, Cl^- and K^+ contents

Na^+ and Cl^- content was determined in digested plant samples as described by Khan *et al*. [6] using Tri acid mixture (TAM). TAM is a mixture of nitric acid, sulphuric acid and perchloric acid (10:5:4). Na^+ content in the digested samples of root and leaf was estimated using a flame photometer (2273, Khera, New Delhi, India) and values were compared with a standard curve prepared from NaCl. The content of Cl^- in digested root and leaf samples was estimated by titration against 0.02 N silver nitrate solution using 5% K_2CrO_4 as indicator.

K^+ was estimated by the method of Lindner [24]. Potassium (K) was analyzed in the digested sample using flame photometry. The instrument was adjusted to zero (0 ppm), 25, 50 and 100 ppm readings. The readings were recorded directly in ppm and converted to actual values of K in plant samples by multiplying by a dilution factor and expressed as %.

2.6 Statistical analysis

The data were analysed statistically and standard errors calculated. Analysis of variance (ANOVA) was performed using SPSS (10.0 Inc., USA). The presented mean values were separated using Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$.

3. Results

3.1 Growth and photosynthetic traits

Increasing salinity stress had an inhibitory effect on plant dry mass, leaf area, net photosynthesis, stomatal conductance and intercellular CO_2 concentration. These variables declined by 21.47%, 15.0%, 13.0%, 33.3% and 8.52%, at 40 mM NaCl and by 42.9%, 66.4%, 37.0%, 51.2% and 42.6%, at 80 mM NaCl in comparison with respective values in the control

(0 mM NaCl). Supply of K (40 mg kg^{-1} soil) maximally mitigated the 40 mM NaCl-caused decrease in plant dry mass, leaf area and photosynthetic traits. Compared with controls, only 5.0%, 6.6%, 1.3%, 7.6% and 2.8% increase was noticed in plant dry mass, leaf area, net photosynthesis, stomatal conductance and intercellular CO_2 concentration respectively (Figure 1).

3.2 Oxidative stress traits and Na^+, Cl^- and K^+

Figure 2 shows that the level of lipid peroxidation, in terms of TBARS content, increased with an increase in the degree of soil salinity. Soil NaCl (80 mM) caused a significantly high lipid peroxidation and H_2O_2 generation. The contents of TBARS, H_2O_2, Na^+ and Cl^- increased by 116.3%, 150.5%, 129.3% and 51.8% respectively, due to application of 40 mM NaCl, compared with the control. These variables increased by 365.2%, 531.3%, 219.0% and 98.4% respectively, at 80 mM NaCl salinity. However, addition of K (40 mg K kg^{-1} soil) completely alleviated the adverse effects of 40 mM NaCl salinity in terms of increased TBARS, H_2O_2, Na^+ and Cl^- contents. Even at 80 mM NaCl, K fertilisation significantly mitigated the adverse effects of salinity stress on these parameters. The K^+ content was decreased by 14.1% and 21.1% under the influence of 40 and 80 mM NaCl, respectively, compared with the control. Whereas, the addition of K improved K content at both levels of salinity.The maximum (3.8%) increase was observed when 40 mg K kg^{-1} soil was supplied (Figure 2).

3.3 Non-enzymatic and enzymatic components of the antioxidant defence system

AsA and GSH content decreased by 16.6% and 20.5% in plants exposed to 40 mM NaCl and by 30.1% and 67.9% at 80 mM NaCl. However, at 40 mM NaCl, added K helped to reverse this decrease and values reached parity with those in plants at 0 mM NaCl (Table 1). At 80 mM NaCl, K application was effective in reducing the adverse effects of salinity on AsA and GSH.

The activities of SOD, APX and GR enzymes were increased over the control in response to salt stress. These increases were 29.2, 62.6 and 16.6% respectively at 40 mM NaCl, and 45.1, 79.8 and 92.2% at 80 mM NaCl. The addition of K to plants grown at 40 mM NaCl showed a tendency to achieve the SOD level of unstressed plants (0 mM NaCl), with a 13.2% increase. This was also true with plants at 80 mM NaCl with added K. In contrast, there was a further increase in the activity of APX and GR in response to added K both at 40 mM and 80 mM NaCl. There was a 74.4% and 85.5% increase, respectively, in APS and GR activities at 40 mM NaCl compared with the control. When 80 mM NaCl treated plants were supplemented with the same K dose the same trend of increase in activity of these enzymes was observed over the control. The increase in APX and GR was 85.4% and 96.4% respectively (Table 2).

Treatments	AsA content (nmol g^{-1} FW)	GSH content (nmol g^{-1} FW)
Control	$186^{d} \pm 22.32$	$312^{a} \pm 37.44$
40 mM NaCl	$155^{f} \pm 18.60$ (-16.67)	$248^{b} \pm 29.76$ (-20.51)
40 mM NaCl + 40 mg K kg^{-1} soil	$191^{c} \pm 22.92$ (2.69)	$318^{a} \pm 38.16$ (1.92)
80 mM NaCl	$130^{g} \pm 15.60$ (-30.11)	$100^{h} \pm 12.00$ (-67.95)
80 mM NaCl + 40 mg K kg^{-1} soil	$162^{e} \pm 19.44$ (-12.90)	$129^{g} \pm 15.48$ (-58.65)

Table 1. Contents of ascorbate (AsA) and glutathione (GSH) in *Brassica campestris* L. leaves as influenced by NaCl stress and K nutrition at 30 d after sowing. Values [means ± SE (n=3)] in parenthesis show percent variation over the control and the values showing the same letter within the same column are not significantly different at $P \leq 0.05$, according to Duncan's Multiple Range Test. FW = Fresh weight.

Treatments	SOD activity (mg^{-1} protein m^{-1})	APX activity (mg^{-1} protein m^{-1})	GR activity (mg^{-1} protein m^{-1})
Control	$5.10^{d} \pm 0.40$	$0.541^{j} \pm 0.04$	$0.160^{k} \pm 0.011$
40 mM NaCl	$7.21^{c} \pm 0.57$ (29.26)	$1.45^{i} \pm 0.11$ (62.69)	$0.192^{k} \pm 0.013$ (16.67)
40 mM NaCl + 40 mg K kg^{-1} soil	$5.88^{d} \pm 0.47$ (13.27)	$2.12^{h} \pm 0.16$ (74.48)	$2.11^{h} \pm 0.14$ (85.59)
80 mM NaCl	$9.30^{a} \pm 0.83$ (45.16)	$2.69^{f} \pm 0.21$ (79.89)	$2.35^{g} \pm 0.16$ (92.20)
80 mM NaCl + 40 mg K kg^{-1} soil	$8.55^{b} \pm 0.68$ (40.35)	$3.71^{e} \pm 0.29$ (85.42)	$2.88^{f} \pm 0.20$ (96.53)

Table 2. Activity of superoxide dismutase (SOD), ascorbate peroxidise (APX) and glutathione reductase (GR) in *Brassica campestris* L. leaves as influenced by NaCl stress and K nutrition at 30 d after sowing. Values [means ± SE (n=3)] in parenthesis show percent variation over the control and the values showing the same letter within the same column are not significantly different at $P \leq 0.05$, according to Duncan's Multiple Range Test.

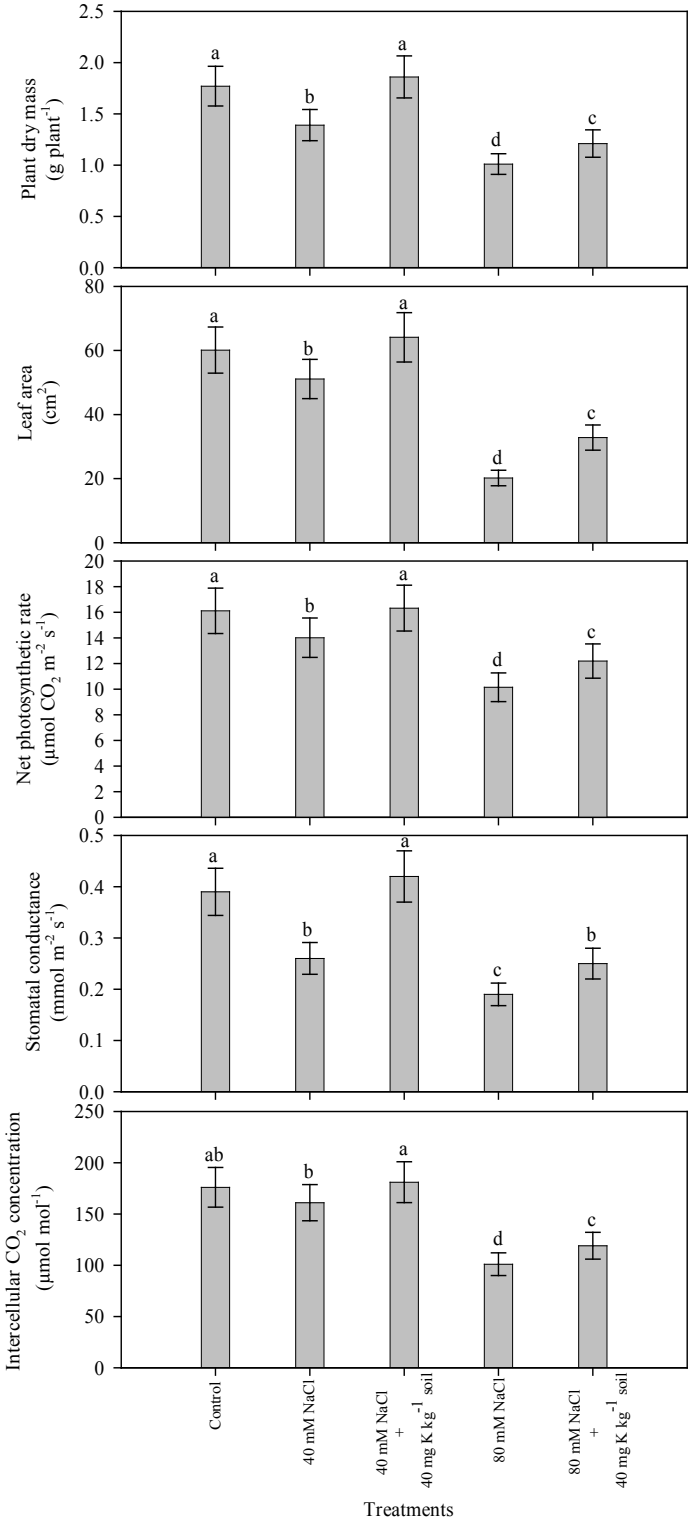

Figure 1. Plant dry mass, leaf area, net photosynthetic rate, stomatal conductance and intercellular CO_2 concentration in *Brassica campestris* L. as influenced by NaCl stress and K nutrition at 30 d after sowing. Values are means ± SE (n=3). Bars showing the same letter are not significantly different at P≤0.05, according to Duncan's Multiple Range Test.

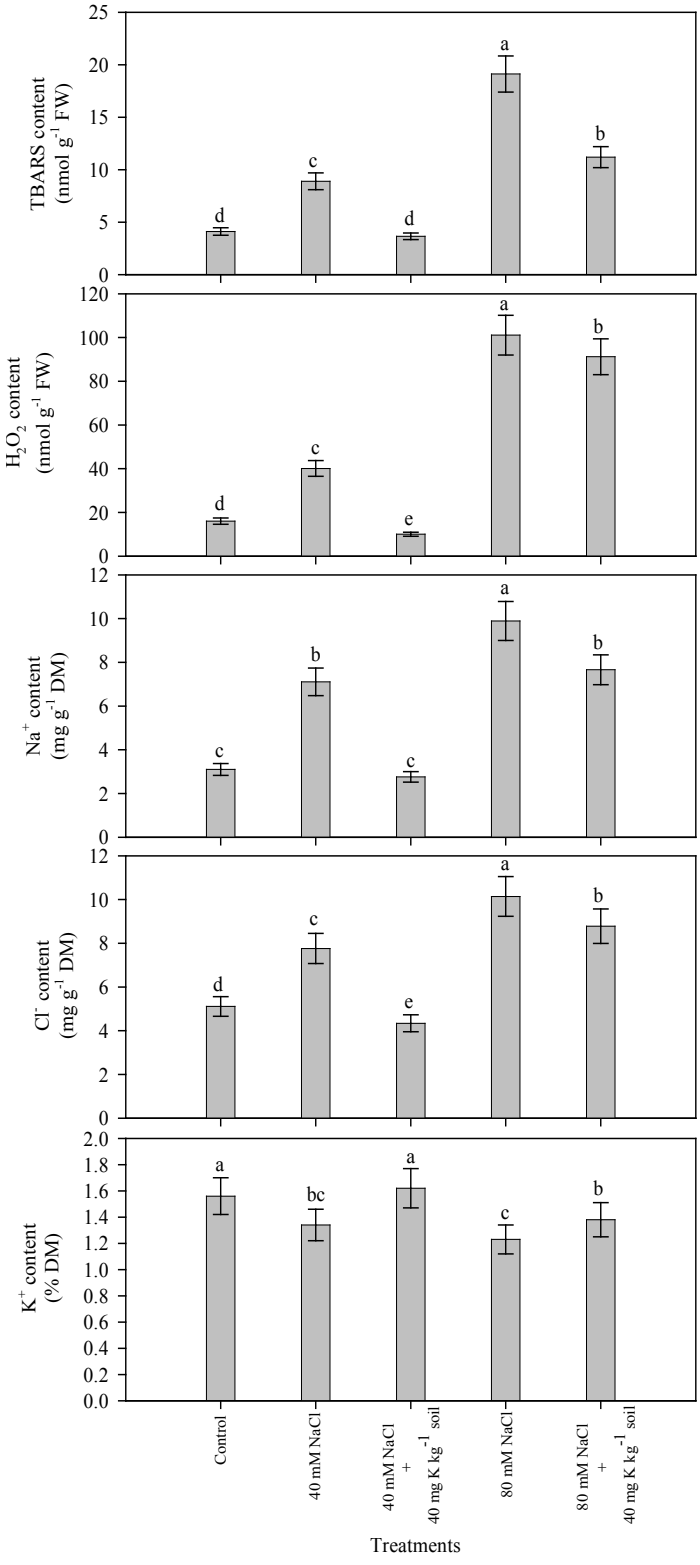

Figure 2. TBARS, H_2O_2, Na^+, Cl^- and K^+ contents in *Brassica campestris* L. leaves as influenced by NaCl stress and K nutrition at 30 d after sowing. Values are means ± SE (n=3). Bars showing the same letter are not significantly different at P≤0.05, according to Duncan's Multiple Range Test.

4. Discussion

The adverse effect of increased soil-salinity on plant growth and development has been widely documented [2,6,25]. Growth and development are an outcome of coordination of the main biological processes in plants [26]. Availability of nutrients and the presence of stressors influence overall growth performance. Nutrient availability can be positively correlated whereas stress conditions are often negatively correlated to growth phenomena [27].

In the present study, increase in soil salinity caused a significant decline in leaf area and plant dry mass. Leaf area is considered a sensitive measure if effect in various salt-stressed plants and is also regarded as a major factor responsible for decreased dry mass of the affected individuals [25,28]. Reduction in leaf area expansion due to salinity stress has been observed in pepper [29,30] and strawberry [31]. The decrease in leaf area is attributed to decreased leaf cellular expansion and/or to physiological disorders triggered by salt stress, accumulation of Na^+ and Cl^- in different plant tissues and by reduction of net photosynthesis rate and chlorophyll content in leaf tissue [27,28]. Reduction in leaf area means reduction in size of the solar panel to harvest solar energy [32] Even if the rate of photosynthesis remains unaffected under stress, decrease in leaf area itself is likely to have a negative impact on total dry matter production. Potassium application (40 mg K kg^{-1} soil) mitigated the adverse effects of salinity stress and improved the leaf area and plant dry mass significantly (Figure 1). K nutrition restored the NaCl-induced decline in the K^+ and Ca^{2+} content in plants and might help in improving the growth of stressed plants in terms of leaf area, leaf dry mass and plant dry mass. Our findings are in agreement with those of Arshi *et al*. [28] and Elkhatib *et al*. [33].

Salinity stress (40 and 80 mM NaCl) severely affected the photosynthetic traits such as net photosynthetic rate (P_N), stomatal conductance (gs) and intercellular CO_2 concentration (Ci). This agrees with the finding of others in various plant species [5,34]. Added K improved these traits considerably in the present study. High K concentrations in the stroma are reported to be necessary to maintain optimum photosynthetic capacity under stress conditions [35]. Added K at both the salinity levels (40 and 80 mM) significantly improved stomatal conductance, net photosynthesis, leaf area and plant dry weight. The values for these attributes in plants exposed to 40 mM NaCl were at par with those of unstressed plants (0 mM NaCl), as if the plants were not experiencing any stress. However, at 80 mM NaCl, K application did little to towards bringing parity with the control level (0 mM NaCl). Salt stress resulted in a decrease in intracellular CO_2 concentration particularly at 80 mM NaCl, and K fertilization did help to improve this. Like other attributes mentioned above, it was at parity with the control (0 mM NaCl) but not significantly different from the value at 40 mM NaCl. At 80 mM NaCl, intracellular CO_2 concentration decreased significantly over the control and K addition improved it significantly, but it did not attain the level observed in the control.

The photosynthetic process can be negatively affected by salinity due most importantly to (i) altered stomatal closure thus limiting CO_2 diffusion to the chloroplasts, (ii) modification in the structure and function of photosynthetic organelles (iii) alterations in light reactions (leading to increase in electron flux to O_2 resulting consequently in an accumulation of oxidative stressors, including TBARS, in the chloroplast), and/or (iv) reduced rate of transport of assimilates and intermediary compounds to the metabolic sinks, (v) efficiency of the root system in limiting the transport of ions to shoots [5,13,34,36,37].

The deleterious effects of salinity on plant growth and physiology are associated with a number of other important factors, including nutrient imbalance, the toxic effects of ions (mainly Na^+ and Cl^-) and/or the oxidative damage resulting from imbalance between production of reactive oxygen species (ROS) and the antioxidant defence [7].

Plant tolerance to salinity stress may be due to ion homeostasis, osmotic adjustment, and a synchronous action of different components of the antioxidant defence system [6,38]. In addition, increasing evidence suggests that maintenance of the K status of plants plays a critical role in increasing both crop productivity and resistance to environmental stress, including salinity [13,37]. K has been shown to play a significant role in a large range of metabolic functions in plants, including growth, photosynthesis, enzyme activation and osmotic potential [27] in addition to lowering the ROS production by reducing activity of NAD(P)H oxidases and maintaining photosynthetic electron transport [13]. In this context, we have shown that the addition of K to the NaCl-treated plants proved to be effective in protecting *B. campestris* plants against NaCl-caused oxidative stress by decreasing Na^+ and Cl^- content and increasing K^+ in leaves. The antagonistic effect of K^+ and Na^+ on uptake of each other is well documented and reported in both saline and sodic conditions [10,27,39,40]. Added K also improved AsA and GSH contents, and further enhanced the activity of APX and GR, whereas the activity of SOD dropped with K-supplementation to the NaCl-treated plants.

In fact, the generation of ROS is an important consequence of a number of stress factors including salinity stress in plants [6]. ROS are metabolised by an efficient antioxidant defence system wherein the enzymatic antioxidants SOD dismutase $O_2^{\bullet-}$ to H_2O_2, which is further detoxified by APX and/or catalase (data not shown), whereas non-enzymatic antioxidants AsA and GSH have a tight control over the generation and scavenging of ROS [6,39]. AsA-GSH-cycle metabolism is an essential mechanism of plant resistance under stressful conditions [38,41]. Glutathione removes excess H_2O_2 [42] and lipid peroxides keep ROS under control [43]. APX detoxifies H_2O_2 into water using AsA as the major substrate where GSH continuously regenerates AsA from DHA, the oxidized form, *via* the AsA-GSH cycle. In this process GSH is oxidised into GSSG, which is subsequently recycled by GR [42]. In the present study, K-supplementation to NaCl-treated plants further enhanced the GR activity (maximally at 40 mM NaCl) and thus maintained coordination between the enzymatic (SOD, APX and GR) and non-enzymatic (AsA, GSH) antioxidants. Earlier, increased glutathione content due to sulphur application had been found to protect dry mass and photosynthesis in cadmium-treated mustard (*Brassica campestris*) plants [43]. In addition to other physiological effects of nutrition in plants, glutathione maintains the endogenous level of K^+ in plant tissues and reduces the excess uptake and translocation of undesirable ions including Na^+ and Cl^- [13,14]. K^+ is the most prominent competitor in the uptake of Na^+ under salt stress [44]. K nutrition ameliorated to a great extent the Na^+ and Cl^- - accrued decrease in reducing equivalents viz., AsA and GSH which, in turn, had a tight control over the balance between production and scavenging of H_2O_2 and stabilized the cell membrane by decreasing TBARS content through coordination with other components of the AsA-GSH cycle. Our findings that K nutrition improves the leaf K^+ and decreases the Na^+ and Cl^- contents confirm those of Qadar and Azam [10], Zheng *et al.* [40,45] and More and Manchanda [39].

5. Conclusions

NaCl stress severely retarded plant growth and photosynthesis, increased the ion toxicity in terms of increasing leaf Na^+ and Cl^- contents, induced lipid peroxidation (TBARS), caused oxidative stress (H_2O_2) and modulated the plant antioxidant system to a great extent. K nutrition exhibited an antagonistic effect on Na^+ and Cl^- accumulation, controlled the SOD and APX activities required for the removal of H_2O_2 and TBARS, and up-regulated GR activity to improve the cellular reducing equivalents AsA and GSH in order to protect plants from NaCl-caused oxidative stress. A protocol for the application of an optimal level of K to the NaCl-affected soil may be developed to achieve increased crop productivity in a sustainable way.

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