ROLE OF FOLIAR AND SOIL APPLICATION OF POTASSIUM IN
SALT TOLERANCE AND QUALITY ENHANCEMENT OF TOMATO
(Lycopersicon esculentum)

By

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M.Sc. (Hons.) Agriculture

A thesis submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

IN

SOIL SCIENCE

INSTITUTE OF SOIL & ENVIRONMENTAL SCIENCES,
FACULTY OF AGRICULTURE,
UNIVERSITY OF AGRICULTURE FAISALABAD,
PAKISTAN
2013
Declaration
I hereby declare that the contents of the thesis, “Role of foliar and soil application of potassium in salt tolerance and quality enhancement of tomato (Lycopersicon esculentum) “are product of my own research and no part has been copied from any published source (except the references, standard mathematical or genetic models/ equations/ formulae/ protocols etc.). I further declare that this work has not been submitted for award of any other diploma/degree. The university may take action if the information provided is found inaccurate at any stage. (In case of any default the scholar will be proceeded against as per HEC plagiarism policy).

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We the Supervisory Committee, certify that the contents and form of this thesis submitted by MUHAMMAD AMJAD (Regd. # 2003-ag-1578) have been found satisfactory and recommend that it be processed for evaluation by the external examiner(s) for the award of the degree.

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DEDICATED TO

GREATEST REFORMER OF THE WORLD

PROPHET MUHAMMAD

(Peace Be Upon Him)
Acknowledgement

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Muhammad Amjad
<table>
<thead>
<tr>
<th>No</th>
<th>Title</th>
<th>Page No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Review of Literature</td>
<td>5</td>
</tr>
<tr>
<td>2.1</td>
<td>The problem of salinity</td>
<td>5</td>
</tr>
<tr>
<td>2.1.1</td>
<td>History of salinization</td>
<td>5</td>
</tr>
<tr>
<td>2.2</td>
<td>Salinity through natural processes and human activities</td>
<td>5</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Primary salinity</td>
<td>5</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Secondary salinity</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>Salinity in agriculture</td>
<td>6</td>
</tr>
<tr>
<td>2.4</td>
<td>Mechanisms of salinity action</td>
<td>7</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Salinity and plant phenology</td>
<td>7</td>
</tr>
<tr>
<td>2.4.2</td>
<td>Salinity and plant physiology</td>
<td>8</td>
</tr>
<tr>
<td>2.4.3</td>
<td>Salinity and oxidative stress</td>
<td>10</td>
</tr>
<tr>
<td>2.5</td>
<td>Plant responses to salinity stress</td>
<td>11</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Two phase model of plant response to salinity</td>
<td>11</td>
</tr>
<tr>
<td>2.5.2</td>
<td>Plant responses to osmotic stress (osmotic adjustment)</td>
<td>12</td>
</tr>
<tr>
<td>2.5.3</td>
<td>Plant response to ionic stress (ion homeostasis)</td>
<td>13</td>
</tr>
<tr>
<td>2.5.3.1</td>
<td>Role of calcium and ion pumps in ion homeostasis</td>
<td>14</td>
</tr>
<tr>
<td>2.5.3.2</td>
<td>Role ethylene in ion homeostasis</td>
<td>15</td>
</tr>
<tr>
<td>2.5.4</td>
<td>Plant responses to oxidative stress</td>
<td>16</td>
</tr>
<tr>
<td>2.5.4.1</td>
<td>ROS regulation in chloroplast</td>
<td>17</td>
</tr>
<tr>
<td>2.5.4.2</td>
<td>ROS regulation in peroxisomes</td>
<td>18</td>
</tr>
<tr>
<td>2.5.4.3</td>
<td>ROS regulation in mitochondria</td>
<td>18</td>
</tr>
<tr>
<td>2.5.4.4</td>
<td>ROS regulation in apoplast</td>
<td>19</td>
</tr>
<tr>
<td>2.6</td>
<td>Role of ABA in plants salinity stress response</td>
<td>20</td>
</tr>
<tr>
<td>2.7</td>
<td>Role of potassium in alleviating injurious effects of salinity stress</td>
<td>21</td>
</tr>
<tr>
<td>2.7.1</td>
<td>Fruit quality and potassium</td>
<td>23</td>
</tr>
<tr>
<td>2.8</td>
<td>Tomato and salinity</td>
<td>25</td>
</tr>
<tr>
<td>2.8.1</td>
<td>Germination</td>
<td>25</td>
</tr>
</tbody>
</table>
### 2.8.2 Root development 26
### 2.8.3 Shoot development 26
### 2.8.4 Fruit yield and quality 27

3 Results and Discussion 29

#### 3.1 Characterization of Comparative Response of Fifteen Tomato (*Lycopersicon esculentum*) Genotypes to NaCl Stress 29

##### 3.1.1 Introduction 29

##### 3.1.2 Materials and Methods 30

##### 3.1.2.1 Plant material and growth conditions 30

##### 3.1.2.2 Growth parameters 30

##### 3.1.2.3 Photosynthetic parameters 31

##### 3.1.2.4 Leaf sap analysis 31

##### 3.1.2.5 Ranking of genotypes for salt tolerance 31

##### 3.1.3 Results 32

##### 3.1.4 Discussion 38

#### 3.2 Antioxidative and physiologic response of salt-tolerant and salt-sensitive tomato (*Lycopersicon esculentum*) genotypes to potassium 42

##### 3.2.1 Introduction 42

##### 3.2.2 Materials and Methods 43

##### 3.2.2.1 Plant materials 43

##### 3.2.2.2 Growth conditions 43

##### 3.2.2.3 Gas exchange measurements 44

##### 3.2.2.4 Plant growth characteristics 44

##### 3.2.2.5 Photosynthetic pigments 44

##### 3.2.2.6 Membrane stability index (MSI) 45

##### 3.2.2.7 Leaf sap Na\(^+\) and K\(^+\) determination 45

##### 3.2.2.8 Determination of enzymatic activities 45

##### 3.2.2.9 Statistical analysis 46

##### 3.2.3 Results 47

##### 3.2.3.1 Effect of foliar and solution application of potassium on growth of four tomato genotypes under NaCl salinity 47

##### 3.2.3.2 Effect of foliar and solution application of potassium on gas exchange 54
characteristics and membrane stability index (MSI) of four tomato genotypes under NaCl salinity

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.3.3 Effect of foliar and solution application of potassium on leaf ionic parameters of four tomato genotypes under NaCl salinity</td>
<td>60</td>
</tr>
<tr>
<td>3.2.3.4 Effect of foliar and solution application of potassium on photosynthetic pigments and antioxidant enzymes activity of four tomato genotypes under NaCl salinity</td>
<td>64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.4 Discussion</td>
<td>72</td>
</tr>
</tbody>
</table>

3.3 Soil and foliar application of potassium enhances fruit yield and quality of tomato under salinity

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.1 Introduction</td>
<td>78</td>
</tr>
<tr>
<td>3.3.2 Materials and Methods</td>
<td>79</td>
</tr>
<tr>
<td>3.3.2.1 Experimental Setup</td>
<td>79</td>
</tr>
<tr>
<td>3.3.2.2 Plant biomass, fruit yield and quality</td>
<td>80</td>
</tr>
<tr>
<td>3.3.2.3 Fruit juice characteristics</td>
<td>81</td>
</tr>
<tr>
<td>3.3.2.4 Leaf sap ionic analysis</td>
<td>81</td>
</tr>
<tr>
<td>3.3.2.5 Statistical analysis</td>
<td>82</td>
</tr>
<tr>
<td>3.3.3 Results</td>
<td>82</td>
</tr>
<tr>
<td>3.3.3.1 Plant growth characteristics</td>
<td>82</td>
</tr>
<tr>
<td>3.3.3.2 Plant leaf ionic content</td>
<td>85</td>
</tr>
<tr>
<td>3.3.3.3 Fruit yield parameters</td>
<td>88</td>
</tr>
<tr>
<td>3.3.3.4 Fruit quality characteristics</td>
<td>88</td>
</tr>
<tr>
<td>3.3.3.4.1 Fruit diameter and height</td>
<td>88</td>
</tr>
<tr>
<td>3.3.3.4.2 Total Soluble Solids (TSS, Brix) and Fruit Dry matter (%)</td>
<td>91</td>
</tr>
<tr>
<td>3.3.4 Discussion</td>
<td>94</td>
</tr>
</tbody>
</table>

3.4 Enhanced levels of ethylene and ABA increase salt tolerance in tomato

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4.1 Introduction</td>
<td>98</td>
</tr>
<tr>
<td>3.4.2 Materials and Methods</td>
<td>99</td>
</tr>
<tr>
<td>3.4.2.1 Plant material and growth conditions</td>
<td>99</td>
</tr>
<tr>
<td>3.4.2.2 Chlorophyll content index (CCI) and Stomatal conductance</td>
<td>100</td>
</tr>
<tr>
<td>3.4.2.3</td>
<td>Leaf xylem sap analyses</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------</td>
</tr>
<tr>
<td>3.4.2.4</td>
<td>Leaf abaxial surface imprints</td>
</tr>
<tr>
<td>3.4.2.5</td>
<td>Leaf ethylene biosynthesis</td>
</tr>
<tr>
<td>3.4.2.6</td>
<td>Statistical analysis</td>
</tr>
<tr>
<td>3.4.3</td>
<td>Results</td>
</tr>
<tr>
<td>3.4.3.1</td>
<td>Chlorophyll content index (CCI) and stomatal conductance ($g_s$)</td>
</tr>
<tr>
<td>3.4.3.2</td>
<td>Stomatal morphology</td>
</tr>
<tr>
<td>3.4.3.3</td>
<td>Xylem sap ABA and leaf ethylene biosynthesis</td>
</tr>
<tr>
<td>3.4.3.4</td>
<td>Xylem sap ionic contents ($Na^+$, $K^+$, $K^+/Na^+$)</td>
</tr>
<tr>
<td>3.4.4</td>
<td>Discussion</td>
</tr>
<tr>
<td>4</td>
<td><strong>Summary</strong></td>
</tr>
<tr>
<td></td>
<td><strong>References</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Appendix</strong></td>
</tr>
</tbody>
</table>
### List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Review of published abstracts on the influence of K; effects by crops; K application, and K form on fruit attributes</td>
<td>24</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Salt tolerance indexes(^a) of growth and ionic characteristics in tomato genotypes under different levels of salinity</td>
<td>33</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Rankings of genotypes for their relative salt tolerance in terms of shoot fresh weight in a cluster analysis (Ward’s minimum variance analysis)</td>
<td>34</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Rankings of genotypes for their relative salt tolerance in terms of root fresh weight in a cluster analysis (Ward’s minimum variance analysis)</td>
<td>35</td>
</tr>
<tr>
<td>3.1.4</td>
<td>Rankings of genotypes for their relative salt tolerance in terms of shoot dry weight in a cluster analysis (Ward’s minimum variance analysis)</td>
<td>36</td>
</tr>
<tr>
<td>3.1.5</td>
<td>Rankings of genotypes for their relative salt tolerance in terms of root dry weight in a cluster analysis (Ward’s minimum variance analysis)</td>
<td>37</td>
</tr>
<tr>
<td>3.1.6</td>
<td>Rankings of genotypes for their relative salt tolerance in terms of K(^+)/Na(^+) in a cluster analysis (Ward’s minimum variance analysis)</td>
<td>38</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Shoot fresh weight (SFW, g) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress</td>
<td>48</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Shoot dry weight (SDW, g) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress</td>
<td>49</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Root fresh weight (RFW, g) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress</td>
<td>50</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Root dry weight (RDW, g) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress</td>
<td>51</td>
</tr>
<tr>
<td>3.2.5</td>
<td>Shoot length (SL, cm) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl</td>
<td>52</td>
</tr>
</tbody>
</table>
and potassium after 15 and 30 days of stress

3.2.6 Root length (RL, cm) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress

3.2.7 Photosynthetic rate (A, μmol m⁻² s⁻¹) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress

3.2.8 Transpiration rate (E, mmol m⁻² s⁻¹) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

3.2.9 Intercellular CO₂ concentration (Ci, mmol m⁻² s⁻¹) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

3.2.10 Stomatal conductance (gs, μmol mol⁻¹) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

3.2.11 Membrane stability index (MSI, %) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of potassium NaCl and after 15 and 30 days of stress

3.2.12 Leaf sap Na⁺ concentration (mol m⁻³) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

3.2.13 Leaf sap K⁺ concentration (mol m⁻³) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

3.2.14 Leaf sap K⁺/Na⁺ concentration in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

3.2.15 Plant leaf chlorophyll a (mg g⁻¹ FW) contents in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in
response to different levels of NaCl and potassium after 15 and 30 days of stress

3.2.16 Plant leaf chlorophyll b (mg g\(^{-1}\) FW) contents in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress 66

3.2.17 Plant leaf chlorophyll a+b contents in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress 67

3.2.18 Superoxide dismutase activity (SOD, Units mg Prot.\(^{-1}\) min\(^{-1}\)) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress 68

3.2.19 Catalase activity (CAT, mmol H\(_2\)O\(_2\) mg Prot.\(^{-1}\) min\(^{-1}\)) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress 69

3.2.20 Glutathione reductase activity (GR, µmol NADPH mg Prot.\(^{-1}\) min\(^{-1}\)) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress 70

3.2.21 Melondialdehyde contents (MDA, mmol g\(^{-1}\) FW) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress 71

3.3.1 Physical and chemical properties of soil and water used in the experiment 81

3.3.2 Plant height and dry weight of salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application 84

3.3.3 Plant leaf ionic concentration (Na\(^{+}\) and K\(^{+}\)) in salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress 86
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.4</td>
<td>Plant leaf $K^+/Na^+$ ratio in salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application</td>
<td>87</td>
</tr>
<tr>
<td>3.3.5</td>
<td>Fruit weight per plant and average fruit weight of salt tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application</td>
<td>89</td>
</tr>
<tr>
<td>3.3.6</td>
<td>Fruit diameter and height of salt tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application</td>
<td>90</td>
</tr>
<tr>
<td>3.3.7</td>
<td>Total soluble solids and fruit dry matter in salt tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application</td>
<td>92</td>
</tr>
<tr>
<td>3.3.8</td>
<td>Titratable acidity and fruit juice pH in salt tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application</td>
<td>93</td>
</tr>
</tbody>
</table>
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>A schematic summary of the stresses that plants suffer under high salinity growth condition and the corresponding responses that plants use in order to survive these detrimental effects</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>The growth response to salinity stress occurs in two phases: a rapid response to the increase in external osmotic pressure (the osmotic phase), and a slower response due to the accumulation of Na(^+) in leaves (the ionic phase). The solid line represents the change in the growth rate after the addition of NaCl. (a) The broken green line represents the hypothetical response of a plant with an increased tolerance to the osmotic component of salinity stress. (b) The broken red line represents the response of a plant with an increased tolerance to the ionic component of salinity stress. (c) The green-and-red line represents the response of a plant with increased tolerance to both the osmotic and ionic components of salinity stress</td>
<td>12</td>
</tr>
<tr>
<td>2.3</td>
<td>Regulation of ion homeostasis by various ion pumps. The salinity stress signal is perceived by a receptor or salt sensor present at the plasma membrane of the cell. This signal is responsible for activating various ion pumps present at plasma and vacuolar membranes. This signal also activates the SOS pathway, the components of which help in regulating some of these pumps. The various pumps/channels are the K(^+) inward-rectifying channel (KIRC), histidine kinase transporter (HKT), nonspecific cation channels (NSCC), K(^+) outward-rectifying channel (KORC), Na(^+)/H(^+) antiporters (SOS1), vacuolar Na(^+)/H(^+) exchanger (NHX), and H(^+)/Ca(^{2+}) antiporter (CAX1). Na(^+) extrusion from plant cells is powered by the electrochemical gradient generated by H(^+)-ATPases, which permits the Na(^+)/H(^+) antiporters to couple the passive movement of H(^+) inside along the electrochemical gradient and extrusion of Na(^+) out of the cytosol</td>
<td>16</td>
</tr>
<tr>
<td>2.4</td>
<td>Schematic representation of superoxide radical production in chloroplasts of K-deficient leaves ((\leaves) refers to the inhibition of the corresponding</td>
<td>20</td>
</tr>
</tbody>
</table>
reaction by K deficiency)

2.5 Model of the K-deficiency-induced NADPH oxidase, superoxide-radical production, and membrane damage in root cells

2.6 TSS, titratable acidity (TA) and relation between both parameters of vine riped fruits of `Daniela' cultivar grown at different salt concentrations in the substrate

3.1.1 Relationship between CO₂ assimilation rate (A), transpiration rate (B), stomatal conductance (C), intercellular CO₂ concentration (D) and shoot fresh weight of fifteen tomato genotypes/varieties after 30 days of imposition NaCl stress. All the values are mean of three replicates

3.2.1 Correlation between leaf K concentration and shoot dry weight, shoot fresh weight under NaCl stress and potassium application

3.2.2 Correlation between CO₂ assimilation rate, A (A), stomatal conductance, gs (B), transpiration rate, E (C), intercellular CO₂ concentration, Ci (D) and leaf K⁺ content under NaCl stress and potassium application

3.2.3 Correlation between membrane stability index (MSI) and melondialdehyde (MDA) under NaCl and potassium application

3.2.4 Correlation between total chlorophyll content and leaf K⁺ (A) and leaf Na⁺ (B) under NaCl stress and potassium application

3.3.1 Correlation coefficients between leaf sap ionic concentrations (Na⁺ and K⁺) and plant growth characteristics (plant height and plant dry weight). (A) relationship between leaf sap Na⁺ and plant height (B) relationship between leaf sap Na⁺ and plant dry weight (C) relationship between leaf sap K⁺ and plant height (D) relationship between leaf sap K⁺ and plant dry weight. All the values are means of three replicates

3.3.2 Correlation coefficients between leaf sap ionic concentrations (Na⁺ and K⁺) and fruit yield (fruit weight per plant and average fruit weight) and size (fruit diameter) characteristics. (A) relationship between leaf sap Na⁺ and fruit weight per plant (B) relationship between leaf sap Na⁺ and average fruit weight (C) relationship between leaf sap Na⁺ and fruit diameter (D) relationship between leaf sap K⁺ and fruit weight per plant (E) relationship

x
between leaf sap K⁺ and average fruit weight (F) relationship between leaf sap K⁺ and fruit diameter. All the values are mean of three replicates

3.4.1 Chlorophyll content index (CCI) of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). Error bars represents standard error of means (n=4)

3.4.2 Stomatal conductance (gₛ) of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). Error bars represents standard error of means (n=4)

3.4.3 Guard cell length (Lₛ) (A), guard cell pair width (Ws) (B), stomatal pore aperture length (La) (C) and stomatal pore aperture width (Wa) (D) in the abaxial leaf surface of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). The values represent the means of impression images from four replicates and 10 stomata from each leaf. Error bars represents standard error of means (n=4)

3.4.4 Stomatal density (SD) (A), stomatal aperture (SA) (B) in the abaxial leaf surface of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). The values represent the means of impression images from four replicates and 10 stomata from each leaf. Error bars represents standard error of means (n=4)

3.4.5 [ABA] xylem (A), leaf ethylene biosynthesis (B) of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). Error bars represents standard error of means (n=4)

3.4.6 Xylem sap K⁺ (A) xylem sap Na⁺ (B) xylem sap K⁺/ Na⁺ of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). Error bars represents standard error of means (n=4)
3.4.7 Correlation between A: stomatal density (SD) and stomatal conductance (gs), and B: stomatal aperture (SA) and gs. Each value represents mean of four replicates.

3.4.8 Correlation between ABA and stomatal conductance in tolerant (Indent-1) and sensitive (Red Ball) tomato genotypes. Each value represents mean of four replicates.
Role of foliar and soil application of potassium in salt tolerance and quality enhancement of tomato (*Lycopersicon esculentum*)

Abstract

Salinity is among major threats to crop production and food security worldwide. World population is increasing at an alarming rate especially in the third world countries like Pakistan. So it requires more food production to ensure food security for this ever increasing world population. As the area under cultivation is limited and cannot be increased, we must resort to extensive salt affected areas worldwide to ensure food security. To utilize these salt affected areas we must devise strategies to able the crop plants to tolerate salinity and give economical yields. To accomplish this current research was planned to identify salt tolerant genotypes and alleviating the salinity stress by potassium application. In the preliminary experiment two salt-tolerant (Indent-1 and Nagina) and two salt-sensitive (Peto-86 and Red Ball) tomato genotypes were identified from fifteen genotypes based on the higher growth, lower Na\(^+\) and higher K\(^+\) accumulation at three NaCl levels (Control, 75 and 150 mM) in hydroponics experiment. Subsequently in the second experiment, the alleviating effects of potassium in foliar and solution form (0, 4.5 and 9 mM) on salt tolerant and sensitive genotypes were studied at same NaCl levels combined with. Results showed that response of tolerant genotypes was higher to potassium application compared to sensitive genotypes. It can also be concluded that salt tolerance of Indent-1 and Nagina might be due to higher value of antioxidant enzymes (SOD, CAT, GR), photosynthetic gas exchange, membrane stability index (MSI), Chlorophyll contents (Chl a and b), K\(^+\), K\(^+\)/Na\(^+\) and lower values melon dialdehyde (MDA) and Na\(^+\). Third experiment was conducted in pots under control, 7.5 and 15 dS m\(^{-1}\) salinity and control, 180 and 360 kg ha\(^{-1}\) (in soil) and 4.5 and 9 mM (foliar) potassium treatments to check the interactive effect of salinity and potassium on tomato fruit quality and yield. Potassium treatments significantly increased the fruit yield in tomato genotypes with highly significant values in tolerant genotypes than sensitive genotypes. Both salinity and potassium positively affected the fruit quality characteristics (TSS, TA, pH, DM %) in both tolerant and sensitive genotypes, however the fruit quality was higher in tolerant compared to sensitive genotypes. In the fourth experiment involvement of phytohormones (ABA, ethylene) in salt tolerance of tomato genotypes and changes in
stomatal morphological characteristics in response to NaCl and potassium application were studied. The experiment was conducted under controlled conditions in a climatic chamber with three NaCl (0, 75 and 150 mM) and two potassium levels (0, 4.5 mM) in hydroponics using salt-tolerant (Indent-1) and salt-sensitive (Red Ball) genotypes. The results revealed that salt-tolerant genotype had higher values of ABA and ethylene and correspondingly higher growth, chlorophyll content index (CCI), stomatal conductance (gs), lower Na\textsuperscript{+} and higher K\textsuperscript{+} as compares salt-sensitive genotype. Stomatal density (SD) and stomatal aperture size (SA) were significantly decreased by NaCl, with non-significant differences between the salt tolerant and sensitive genotypes suggesting these characteristics were not genetically controlled rather influenced by the environment. Based on the results of this research it was concluded that application of potassium increases yield and quality of tomato fruits under soil salinity and it could be used as an effective practice to produce even a salt sensitive species like tomato under saline conditions.

**Keywords:** salinity, potassium, tomato, yield, quality
Soil salinity is a worldwide problem and a major abiotic stress that limits agricultural production in these salt affected areas. It has been estimated that salinity affects about 7% of the world’s total land and 20% (45 Mha) of irrigated land of the world (Yamaguchi and Blumwald, 2005; FAO, 2007). Soil salinity is present even before human existence and agriculture, but it is still increasing at an annual rate of 10% (Foolad, 2004). It is common in arid and semi-arid areas because of low rainfall, high temperature, high rates of evapotranspiration resulting in net upward movement of salts, salty parent material, poor quality irrigation water and poor management practices (Azevedo Neto et al., 2006).

In Pakistan salinity is one of the most serious environmental problems and is ranked eighth in terms of extent of salinized area (FAO, 2006). Of the total irrigated land of the country 25% is salt affected (3.9% of the world salt affected land) up to varying degrees and about 1.4 million ha has now been abandoned for agriculture (World Bank, 2006; FAO, 2006). The total annual cost of crop losses from the salt affected areas range between 15-55 billion rupees (A$340 million to A$1.2 billion), in addition to the Rs15 billion (A$340 million) estimated losses directly from the land that has been rendered unproductive. Taking average per year yield reduction in the country of Rs 35 billion, which was equivalent to 0.6% of the country’s gross domestic production in 2004 (World Bank, 2006; Corbishley and Pearce, 2007).

Considering the severity of problem, these salt affected areas should be utilized and managed in an effective manner to avoid desertification of fertile agricultural land, feed ever increasing world population and support the economy of the country. Previously used methods of reclaiming the salt affected soils included leaching of the saline soils and using amendments in sodic soils accompanied by heavy irrigation with good quality water. This practice of managing these soils is not economical due to significantly high cost of amendments, impractical due to large salt affected areas and unavailability of good quality irrigation water (Qureshi et al., 1990; Corbishley and Pearce, 2007). Effective approaches to utilize these problematic soils are the introduction and selection of salt tolerant species/genotypes and identifying and elucidate the mechanisms of inducing salinity tolerance in
genotypes and species (Blumwald et al., 2004). To accomplish this understanding of the mechanisms of salt stress and tolerance are very important.

Salinity negatively affects plant growth in a number of ways like osmotic stress created due to excess of salts in the root environment that results in loss of plants turgidity, deficiency of mineral elements (phosphorus, potassium, nitrate, and calcium) due to decreased water uptake from soil, specific ion toxicity (Na⁺, Cl⁻ and SO₄²⁻) (Xiong and Zhu, 2002; Shabala and Cuin, 2008; Rubio et al., 2010) and secondarily, salinity effect plant growth by the excessive formation of reactive oxygen species (ROS) like superoxide anions (O₂⁻), hydrogen peroxide (H₂O₂) and hydroxyl redicals (OH•). These ROS are generated under regular cellular processes however during stress ROS overcome the plants’ scavenging system that leads to oxidative damage to cellular membranes (Yang et al., 2007).

Salt tolerance of plants is the capacity to endure and sustain normal growth under salinity. Plant species/genotypes vary in their salt tolerance ability owing to differential salt tolerance mechanisms (Chinnusamy et al., 2006; Shabala and Cuin, 2008; Abogadallah et al., 2010). Different mechanisms are involved in plant salt tolerance like maintaining ion homeostasis by Na⁺ efflux, compartmentation and production of compatible solutes/osmoprotectants (Rubio et al., 2010) and detoxification by the enhanced activities of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), peroxidase (POD) and glutathione reductase (GR) to scavenge cytotoxic ROS (Apel and Hirt, 2004; Navrot et al., 2007).

Plants responses to abiotic stress are mediated by hormones. Under salt stress abscisic acid (ABA) and ethylene are very important that regulates plants physiological responses to salt stress. ABA has an essential role in long distance drought signaling in controlling the stomatal movements in water conservation (Davies and Zhang, 1991). Reports suggest that ABA acts as a mediator and also the major internal signal in plants (Keskin et al., 2010; Javid et al., 2011). Ethylene plays important role in ion homeostasis under salinity stress by regulating the H⁺-ATPase gene expression (Wang et al., 2009). Thus enhanced ethylene concentration is important in determining the salt tolerance of plants (Cao et al., 2006, 2007).
Improving plant nutritional status under salt stress has shown to be very effective in inducing salt tolerance in plants. Salinity causes K+ deficiency because of the excess of Na+ in the rooting medium that acts as antagonist and decreases the availability of potassium which might be one of the factors causing oxidative stress (Rodriguez-Navarro, 2000). Although potassium is not the part of any plant structure or bio-molecule yet it is has important role in many important physical and biochemical activities required for the growth, development, yield and quality of plants and it also able the plants to survive under environmental stress conditions, as stress affects negatively physiological processes of plants like root and shoot elongation, enzyme activity, water transport, synthesis of proteins, photosynthetic transport and chlorophyll content (Cakmak, 2005; Pettigrew, 2008; Gerardeaux et al., 2010). Hence, under salt stress improving the K+ nutritional status of the plants could be used as a tool to minimize oxidative cell damage, at least by the reduced formation of ROS during photosynthesis and by the inhibition of NADPH oxidase generating O$_2$– (Shen et al., 2000; Shin and Schachtman, 2004). Foliar application of K+ fertilizer could be effective in correcting the salinity induced K+ deficiency and also significantly decrease salinity induced damage to membranes, and increase biomass production in tomato and strawberry (Kaya et al., 2001a, 2003).

Tomato (Lycopersicon esculentum Mill currently named Solanum lycopersicum L.) is an important vegetable crop worldwide and is ranked second in terms of its consumption after potato. It is moderately tolerant to salinity and different species differ significantly for salt tolerance (Maggio et al., 2007; Lu et al., 2010). It is commonly cultivated in warm and dry areas where salinization is a major threat to its cultivation (Yurtseven et al., 2005). In Pakistan tomato is grown on an area of 49992 ha with a total production of 476826 tonnes (FAO, 2010). Thus there is a need for new salt tolerant genotypes to be introduced and identified for these areas.

In view of the above information regarding extent of problem of salinity, importance of tomato and ameliorative role of potassium, research work was carried out with the general objectives to study the response of tomato plants to NaCl stress based on growth, physiology and biochemistry of plants that would add to our knowledge for better comprehending the salt tolerance mechanisms and identifying the tolerant tomato genotypes for these saline
areas and to study the involvement of potassium in alleviating salt stress, inducing salt tolerance and fruit quality improvement in tomato. More specific objectives of the project were:

- To characterize the comparative response of different tomato genotypes to salt stress.
- To Study the interactive effect of potassium and salinity on physiologic, gas exchange, ionic characteristics in tomato plants and their involvement in salt tolerance.
- To understand the mechanism of salinity causing potassium deficiency and consequently the oxidative stress by measuring the effect of potassium on antioxidant enzymes under salinity.
- To assess the interacting effect of potassium and salt stress on ABA levels in contrasting tomato genotypes and role of ABA as a mediator in regulating the plants response to salt stress.
- To study the response of leaf ethylene biosynthesis to salt stress and potassium.
- To study the stomatal morphological changes in tomato genotypes in response to salinity and potassium application.
2.1 The problem of salinity

In agriculture, salinity is the extent of accumulation of dissolved salts in soil solution that inhibits plant growth and crop productivity (Gorham, 1992). According to estimates, about 7% (1000 million ha) of the total area of the world, 20% of the total cultivated area and 50% of the total irrigated land is salt affected (Flowers et al., 1997; Munns, 2002; Flowers, 2004). Soil salinity is present long before humans and agriculture, but it is still increasing at an alarming rate of 10% annually (Foolad, 2004).

In Pakistan 6.67 million ha area is salt affected which is 1/3rd of the total (Khan, 1998). It is a combination of both forms of salinity (primary and secondary), 26.2% of Pakistan’s irrigated area is severely affected by irrigation salinity (Kendirli, et al., 2005; Qadir et al., 2008). Widespread salinization in Pakistan is a result of combination of many factors like high evaporation, geological conditions, intensive irrigation, inappropriate use of low quality ground water, poor drainage, waterlogging, inefficient irrigation (Kahlown et al., 2003; Van Weert et al., 2009).

2.1.1 History of salinization

History of salinization is as old as the history of man and irrigation (6,000 years old). History teaches us that around 4000 and 2000 BC, demise of civilization of Mesopotamia occurred solely because of secondary salinization due to their irrigation practices, which first eradicated the production of wheat and consequently more salt-tolerant barley (Boyden, 1987; Läuchli, 1991; Ghassemi et al., 1995). In this century history has repeated itself in many countries.

2.2 Salinity through natural processes and human activities

There are two main forms of salinity; primary and secondary

2.2.1 Primary salinity

It occurs over a long period of time through natural processes of accumulation of salts in soil or groundwater in regions of the world where evapo-transpiration rate is high and rainfall is
insufficient to leach salts (McDowell, 2008). Two natural processes are responsible for this type of salinity; the weathering of salty parent material and oceanic salt deposition carried through wind and rain.

2.2.2 Secondary salinity

Secondary salinity results due to anthropogenic changes in the hydrological cycle either through excessive and inefficient use of salty irrigation water and having insufficient drainage or through the replacement of native vegetation with shallow-rooted vegetation (Beresford et al., 2001; Rose, 2004). Due to this injudicious use of land, salt affected area is increasing and is a major environmental concern (Bridgman et al., 2008). Global impact of secondary salinization estimated to be around 74 million hectares and of these 43 million hectares are of irrigated land (Rose, 2004).

2.3 Salinity in agriculture

Salinity poses a major threat to food production as it restricts crop yield and restricts the usage previously uncultivated land. In addition to the extent of salt affected area, salinity is also major threat because of the fact that only few crop species can survive or adapted to saline conditions. Salinity is threat to crop productivity as irrigated lands has double the productivity of rain-fed land and thus contributes 1/3rd of the world’s food production.

According to International data base (IDB) considering current growth trend, world population expected to reach 9 billion in 2040 coupled with augmented urbanization in developing countries (http://www.census.gov/ population /international/data/idb/information gateway.php) and agriculture will have enormous challenge ahead not only to increase our food production for ever-increasing population but also to maintain the current levels of production. Since the land under cultivation further cannot be increased, we must find ways to achieve this without resorting to the unsuitable agricultural practices that would further threaten forests and biodiversity. According to estimates productivity needs to be enhanced to 20% in developed and 60% in the developing countries. Considering these facts about demographic, ecological and agricultural issues, the threat posed by salinity is more alarming. Therefore limiting the spread of salinization, improving species or genotypes adaptation to salinity, enhancing the salt-tolerance of crops/genotypes are the important concerns of future.
2.4 Mechanisms of salinity action

In general, there are three major mechanisms by which plant growth can be inhibited by salinity (Bartels and Sunkar, 2005; Munns and Tester, 2008):

a) Physiological drought resulting from the elevated osmotic pressure of the soil solution;

b) Excessive uptake of either chloride or sodium ions leading to specific ion toxicity;

c) Nutrient ion imbalance due to a diminished uptake of $K^+$, $Ca^{2+}$, $NO_3^-$ or $P$ by the excessive uptake of $Na^+$ or $Cl^-$

In addition to these, secondary effect of salinity stress is the Oxidative damage due to excess formation of reactive oxygen species (ROS) resulting in oxidation of membranes and leakage of cellular contents

2.4.1 Salinity and plant phenology

Plants immediately respond to salinity by decreasing total leaf area because of loss of cell turgor pressure (Hu and Schmidhalter, 1998; Akhtar et al., 2010). In the glycophytes, which are not as efficient in salt exclusion from the transpiration stream as does the halophytes, salt will concentrate to toxic levels in the leaves, which result in death of old leaves and young leaves are injured and it causes succulence (Farooq et al., 2008). Thus the health and number of green leaves will decline, but this number of green leaves is still enough to supply necessary photosynthates to initiate flowering and seed production thus, seed size and seed number is reduced (Munns, 1993; Moradi and Ismail, 2007).

Indirectly salinity reduces the water availability, because increased salt concentration in soil solution decreases the soil water potential and less availability of water to plants (Chinnusamy et al., 2005). This decrease in leaf water potential is compensated by a decrease in leaf osmotic potential by which the leaf turgor pressure is maintained (Chinnusamy et al., 2005). Under saline conditions a decrease in cell’s turgor is the main reason causing inhibition of plant cell expansion (Greenway and Munns, 1980).

Although salinity can rapidly reduce the root growth (Neumann, 1995; Saqib et al., 2005), yet the decrease in shoot growth is more than the root growth, thereby the root/shoot ratio is
increased (Mass and Poss, 1989; Nasim et al., 2009). Salinity happens to significantly decrease the total dry matter, and the extent of decline depends on salt concentrations and genotypes (Nasim et al., 2007).

The response of phenological characteristics to salinity also varies with stage of development of plant (Neumann, 1995; Eker et al., 2006), crops show more sensitivity at seed germination, but lesser sensitive at later growth stages and vice versa. Mass and Poss (1989) showed that wheat, sorghum and cowpea were least tolerant at the vegetative and at early stage of reproduction, more tolerant at flowering, and most tolerant at the grain filling stage. Dasgan et al., (2002) reported that in tomato that at seedling stage, shoot-root dry weight related parameters were independent of salt tolerance. Hajer et al., (2006) reported that responses of tomato plant to NaCl varied at different growth stages and shoot growth is more affected by salinity than root growth; consequently root/shoot growth was increased in salt stressed plants. Hence, the knowledge of effect of salinity at different growth stage can help us in employing suitable management and genetic schemes for saline conditions.

2.4.2 Salinity and plant physiology

Salinity affects the basic metabolic pathways like photosynthesis and respiration. Salinity directly affects the functioning of respiratory enzymes (Moradi and Ismail, 2007; Ranjbarfordoei et al., 2002). It has often been stated that elevated level of salinity increases the rate of respiration. Salt sensitive species showed a greater increase in respiration than the salt tolerant ones (Fidalgo et al., 2004). While, high salt concentration also decreases the rate of photosynthesis by affecting photosynthetic enzymes, gas exchange and light reactions. It is evident from the results reported that salinity inhibits photosynthesis by two ways i.e. stomatal and non-stomatal factors (Desingh and Kanagaraj, 2007). Robinson et al., (1983) reported a 65% inhibition in the rate of photosynthesis and stomatal conductance under saline conditions, however, chlorophyll concentrations remained unchanged. Non-stomatal factors that inhibit photosynthesis may involve toxic ions. An antagonistic relationship was found between rate of photosynthesis and leaf Na⁺ content in a many crops like rice (Saqib et al., 2006), wheat (Saqib et al., 2012), tomato (Hjer et al., 2006) and leaf Cl⁻ content in citrus (Lu et al., 2010). Leaf total chlorophyll contents significantly reduce under saline conditions and the extent of reduction depends upon salt concentrations and salt tolerance of plant species.
Increase in chlorophyll contents was observed in salt-tolerant species, whereas it decreased in salt-sensitive species (Ashraf and McNeil, 1988; Bai et al., 2006). In salt-sensitive species chlorophyll content was significantly reduced due to Cl⁻ accumulation (Lu et al., 2010). In tomato, Azarmi et al., 2010, reported a significant reduction in plant growth, chlorophyll content (CCI), leaf number and stomatal conductance in response to NaCl stress.

Under saline soils, uptake and consumption of essential plant nutrients is impaired predominantly of K⁺ and Ca²⁺, which ultimately changes ionic ratios (K⁺/Na⁺ and Ca²⁺/Na⁺), consequently growth and yield of plants is further affected (Greenway and Munns, 1980; Zhu, 2001; Iqbal et al., 2007). The decreased K⁺ and Ca²⁺ acquisition could be the result of antagonism of Na⁺ and K⁺ or Ca²⁺ at roots uptake sites and transport into the xylem (Candan and Tarhan, 2003; Pervaiz et al., 2007) or it could be the indirect inhibition of the uptake process, e.g. H⁺-ATPase activity (Kaya et al., 2007). As Ca²⁺ has vital role in sustaining the selectivity and integrity of the cell membrane (Fageria, 1983), thus both selectivity and the stability of the membranes could be impaired by its deficiency and as a result Na⁺ may accumulate passively in plant tissue. Ca²⁺ is also necessary for selective transport of ions like K⁺ across membranes; Thus, Ca²⁺ can function to buffer the effect of salinity by accumulating other ions (Cramer, 2002).
Environmental stresses like salinity and drought disrupt this coordination between different cellular pathways (Mittler et al., 2006). This uncoupling of coordination pathways leads to transfer of high energy state electrons to $O_2$ and subsequently formation of reactive oxygen species (ROS) (Torres and Dangl, 2005). ROS include singlet oxygen ($^1O_2$), hydrogen peroxide ($H_2O_2$), superoxide ($O_2^-$) and hydroxyl radicle (HO’) are cytotoxic and have the ability to oxidize important biomolecules like DNA, proteins and lipids (Apel and Hirt, 2004). ROS are the products of normal metabolism and generated at low concentrations in mitochondria, peroxisomes and chloroplasts however under stress conditions ROS generation is intensely enhanced. Accumulation of ROS depends upon the equilibrium between their

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**Figure 2.1:** A schematic summary of the stresses that plants suffer under high salinity growth condition and the corresponding responses that plants use in order to survive these detrimental effects (Horie et al., 2012).

### 2.4.3 Salinity and oxidative stress

Environmental stresses like salinity and drought disrupts this coordination between different cellular pathways (Mittler et al., 2006). This uncoupling of coordination pathways leads to transfer of high energy state electrons to $O_2$ and subsequently formation of reactive oxygen species (ROS) (Torres and Dangl, 2005). ROS include singlet oxygen ($^1O_2$), hydrogen peroxide ($H_2O_2$), superoxide ($O_2^-$) and hydroxyl radicle (HO’) are cytotoxic and have the ability to oxidize important biomolecules like DNA, proteins and lipids (Apel and Hirt, 2004). ROS are the products of normal metabolism and generated at low concentrations in mitochondria, peroxisomes and chloroplasts however under stress conditions ROS generation is intensely enhanced. Accumulation of ROS depends upon the equilibrium between their
formation and detoxification (Mittler et al., 2004) which is ultimately governed by the harshness and period of exposure to stress and the growth conditions.

In addition to the toxic effects of ROS causing oxidative damage cells under abiotic stresses, recent reports suggest that these toxic ROS also have an important role in signal transduction that mediate plant responses to environmental stresses, pathogen infection, and different developmental stimuli and programmed cell death (Apel and Hirt, 2004; Torres and Dangl, 2005). This rapid and excessive generation of ROS under stress is known as “the oxidative burst” and is reported to be necessary for many vital signal transduction pathways and membrane-associated NADPH oxidases (Torres and Dangl, 2005). The contrasting dual role of ROS emphasizes the necessity to regulate the equilibrium state of ROS under non-stressed as well as stress conditions. Thus elucidating the control mechanism of ROS signaling under stress conditions could be an effective strategy to enhance tolerance of crops against different types of abiotic stresses.

2.5 Plant responses to salinity stress

Plant salt-tolerance is a complex phenomenon; various components are involved in imparting salt tolerance. Plants respond at cellular level or as a whole organism and possess a number of adaptations to sustain their growth.

2.5.1 Two phase model of plant response to salinity

Based on the response of plants to salinity stress, Munns and Tester, 2008 presented two phase model of plant growth under salinity stress. Plants respond to salinity stress by reduction in shoot growth that occurs in two distinct phases. Firstly rapid response to increase in external osmotic pressure and secondly the slower response to accumulation of Na\(^+\) in leaves. In the first phase salt concentration around the roots increases to threshold, and immediate response is the significant decrease in growth. Most plants have threshold level of approximately 40 mM NaCl and sensitive species like rice and arabidopsis have less threshold level. This rapid response of plant is mainly (but not entirely) due to the osmotic effect of the salt beyond threshold around the roots.

The second phase (ionic specific) starts when salt accumulation in the old leaves reaches to a toxic level consequently they die. If the rate of dying of older leaves exceeds the rate of new
leaves formation, photosynthesis will no longer be able to supply sugars to younger leaves which further results in reduced growth rate of these leaves. In addition to immediate effect of osmotic stress, it also greatly reduces the growth rate than the ionic stress. Impact of ionic stress is delayed one with less effect than osmotic stress. At high salinity levels and in salt-sensitive species ion stress dominates the osmotic stress.

![Figure 2.2](image)

**Figure 2.2:** The growth response to salinity stress occurs in two phases: a rapid response to the increase in external osmotic pressure (the osmotic phase), and a slower response due to the accumulation of Na$^+$ in leaves (the ionic phase). The solid line represents the change in the growth rate after the addition of NaCl. (a) The broken green line represents the hypothetical response of a plant with an increased tolerance to the osmotic component of salinity stress. (b) The broken red line represents the response of a plant with an increased tolerance to the ionic component of salinity stress (c) The green-and-red line represents the response of a plant with increased tolerance to both the osmotic and ionic components of salinity stress. (Based on Munns et al., 1995)

### 2.5.2 Plant responses to osmotic stress (osmotic adjustment)

Osmotic stress due to salinity reduces water uptake in plant roots. Sufficient amount of water availability is indispensible for important cellular functions like metabolism and photosynthesis and to maintain their growth. For this plants have to regulate water transport under salinity stress (Munns and James, 2003; Eker et al., 2006). Evaporation is the key driving force in the long distance transport from roots to shoots especially through the apoplastic pathway. Salinity induced osmotic stress induces the closure of stomata either directly or indirectly via hormonal regulation which results in reduced evaporation and overall water transport (Jia et al., 2002; Moradi and Ismail, 2007; Horie et al., 2012).
Apart from apoplastic and symplastic pathways, transcellular pathway is also very important. Water potential ($\Psi$) has an important role in forcing the water movement across the membranes (Horie et al., 2012). Under normal conditions (non-saline) intracellular $\Psi$ is normally less than that of the soil solution that creates a gradient between water potential in plant roots and soil solution which causes the water influx into the roots. If this $\Psi$ gradient is reversed due to excessive salts in the soil solution, water efflux from roots can occur, that results in dehydration (Horie et al., 2012). Plants respond to this osmotic stress by osmotic adjustment via accumulation of solutes.

Osmotic adjustment is important regulatory mechanism against salinity induced osmotic stress. During salinity stress cellular osmotic potential ($\Psi_{osm}$) in the roots must be reduced against an osmotic gradient between the root cells and the outer environment by the accumulation of solutes to restore water uptake (Greenway and Munns, 1980; Hanson and Burnet, 1994). Plant cells accumulate different types of ionic and organic solute in the cytosol and vacuole for osmotic adjustment. Potassium ($K^+$) as an osmoticum is mostly accumulated in the cell cytosol whereas $Na^+$ in the vacuole (mostly in salt-tolerant cultivars and halophytes) (Gorham, 1992). In addition to these ions, organic molecules are also accumulated in the cytosol for osmotic adjustment; these organic molecules are called compatible solutes (Munns, 1993; Bohnert and Shen, 1999). Compatible solutes are nontoxic compounds even at high levels of accumulation in the cytosol and apart from the role in osmotic adjustment they also serve as membrane structures and as scavengers of ROS under stress condition including the salt stress (Bohnert and Shen, 1999). Compatible solutes include the molecules like proline, free amino acids, sugars and glycine betaine (GB). Amini Ehsanpour (2005) reported the differential increase in soluble protein contents with the increase in growth media in two tomato cultivars (Isfahani cv. and Shirazy cv.) conversely decrease in soluble protein in tomato was observed by Mohamed and Ismail (2011) whereas increase in carbohydrate and proline concentration.

### 2.5.3 Plant response to ionic stress (ion homeostasis)

Salinity stress results in the over-accumulation of $Na^+$ in cytoplasm that is cytotoxic and interrupts vital metabolic processes like protein synthesis, enzyme activation and photosynthesis in case of cells of source organs (Blaha et al., 2000). Overall at whole plant
level salinity results in excessive accumulation of Na\(^+\) in shoots especially in older leaves and plants capability to check this accumulation of Na\(^+\) is linked to salt-tolerance in barley, wheat (Garthwaite et al., 2005) and tomato (Hajer et al., 2006). Consequently ionic stress prematurely forces senescence in older leaves with necrosis and chlorosis symptoms (Munns et al., 2006).

Hence, for glycophytes keeping low levels of Na\(^+\) in cytosol and shoot at cellular or whole plant level respectively whereas acquisition and maintenance of K\(^+\) is an effective strategy for salt tolerance (Zhu et al., 1998). Thus maintaining high levels of K\(^+\)/ Na\(^+\) in plant tissues particularly in shoot is supposed to be a key factor for salt tolerance in glycophytes (Yamaguchi and Blumwald, 2005; Hauser and Horie, 2010). Significant increase in Na\(^+\) and decrease in K\(^+\) accumulation under NaCl stress was reported in tomato and the difference was significant difference between the cultivars (Mohamed and Ismail, 2011). Maggio et al, (2007) also found significant decrease in K\(^+\) and increase in Na\(^+\) contents in young and mature tomato plants.

The fundamental mechanism of entries of Na\(^+\) into roots through both symplastic and apoplastic pathways are largely unknown. Four distinct mechanisms of salt entry can be assumed (Yeo et al., 1987): (a) selective transport of Na\(^+\) via ion channels/transporters at the plasma membrane (PM) of root epidermis, (b) non-selective ion channels/transporters at the plasma membrane of root epidermis, (c) symplastic intrusion of Na\(^+\) due to direct leakage or injury in bilayer membranes and (d) non-selective apoplastic intrusion into xylem from outside environment. There are three independent levels of selectivity at three different membranes during the intrusive Na\(^+\) entry into the roots: at the PM of epidermal cells, at the root and shoot tonoplast and at the PM of the xylem parenchyma cell.

2.5.3.1 Role of calcium and ion pumps in ion homeostasis

In plants imbalance in sodium ions homeostasis due to high salinity is regulated by the coordinated activities of different ion pumps, Ca\(^{2+}\) sensors, and its interacting partners that leads to efflux of excessive Na\(^+\) from tissues (Tuteja, 2007). There are specific channels that are more selective to K\(^+\) than Na\(^+\) like potassium inward-rectifying channel that facilitate the influx of K\(^+\) and discriminate the accumulation of K\(^+\) over Na\(^+\) ions. Similarly histidine kinase transporter (HKT) a low-affinity Na\(^+\) transporter and a key determinant of plant salt
tolerance checks the entry of Na\(^{+}\) into the cytosol (Platten et al., 2006). There is a voltage-independent nonspecific cation channel that acts as a gate for the entrance of Na\(^{+}\) into plant cells. Furthermore, there is a potassium outward-rectifying channel that mediates the efflux of K\(^{+}\) and influx of Na\(^{+}\) that results in excess accumulation of Na\(^{+}\) in the cytosol. Efflux of Na\(^{+}\) from plant cells is driven by the electrochemical gradient created by H\(^{+}\)-ATPase, which allows the vacuolar Na\(^{+}\)/H\(^{+}\) exchanger (NHX) to couple the passive movement of H\(^{+}\) into the vacuole and efflux of Na\(^{+}\) out of cytosol. Another pump, the H\(^{+}\)/Ca\(^{2+}\) antiporter (CAX1), mediates Ca\(^{2+}\) homeostasis (Zhu, 2002; Zhang et al., 2004; Desai et al., 2006; Mahajan et al., 2006).

Calcium is one of the major functional components in the “signaling web” and plays a vital role in stress signaling and imparting salt tolerance in plants (Tuteja, 2007). High levels of salinity stress result in enhanced levels of cytosolic Ca\(^{2+}\), which starts the stress signal transduction pathways for stress tolerance. The high levels of Ca\(^{2+}\) in the cytosol is the result of either its release from an extracellular source (apoplastic space) or can be the result of activity of phospholipase C which results in the hydrolysis of phosphatidylinositol bisphosphate to inositol trisphosphate and consequently release of Ca\(^{2+}\) from intracellular Ca\(^{2+}\) sources (Tuteja, 2007).

### 2.5.3.2 Role of ethylene in ion homeostasis

Ethylene as a gaseous hormone involved in plant responses to different stresses and has long been regarded as stress hormone apart from its role in fruit ripening, senescence, germination and pathogen response (Chen et al., 2005; Chen and Zhang, 2006). Under salinity stress plasma membrane H\(^{+}\)-ATPase plays a vital role in ion homeostasis by forcing the Na\(^{+}\)/H\(^{+}\) antiporters to efflux Na\(^{+}\) (Shi et al., 2000). Ethylene as stress hormone plays important role in expressing the H\(^{+}\)-ATPase gene and thus crucial for ion homeostasis (Waters et al., 2007; Wang et al., 2009). Extensive studies on ethylene under salinity stress revealed its role in salt tolerance of plants (Cao et al., 2006, 2007). Alvarez et al., (2003) reported that salt adapted calli has shown significantly higher ethylene production compared to control and salt-sensitive calli. Ethylene signaling might be necessary for salt tolerance of plants as ethylene-insensitive mutants were more sensitive to salinity stress (Cao et al., 2006, 2007). Thus
ethylene as stress hormone is important component of salt stress tolerance in plant by regulating H⁺-ATPase gene expression and in signal transduction.

**Figure 2.3:** Regulation of ion homeostasis by various ion pumps. The salinity stress signal is perceived by a receptor or salt sensor present at the plasma membrane of the cell. This signal is responsible for activating various ion pumps present at plasma and vacuolar membranes. This signal also activates the SOS pathway, the components of which help in regulating some of these pumps. The various pumps/channels are the K⁺ inward-rectifying channel (KIRC), histidine kinase transporter (HKT), nonspecific cation channels (NSCC), K⁺ outward-rectifying channel (KORC), Na⁺/H⁺ antiporters (SOS1), vacuolar Na⁺/H⁺ exchanger (NHX), and H⁺/Ca²⁺ antiporter (CAX1). Na⁺ extrusion from plant cells is powered by the electrochemical gradient generated by H⁺-ATPases, which permits the Na⁺/H⁺ antiporters to couple the passive movement of H⁺ inside along the electrochemical gradient and extrusion of Na⁺ out of the cytosol (Tuteja, 2007).

### 2.5.4 Plant responses to oxidative stress

It is evident from the previous findings that exposure of plants to biotic as well as abiotic stress such as drought, salinity, high light intensity, etc. induces the generation of reactive oxygen species (ROS), which include hydrogen peroxide (H₂O₂), superoxide (O₂⁻) and hydroxyl radical (HO') (Quiles and Lopez, 2004; Esfandiari et al., 2007). Under both biotic
and abiotic stresses, ROS are considered to be as the main source of destruction to cells (Candan and Tarhan, 2003; Bor et al., 2003; Gara et al., 2003). ROS are produced as a result of incomplete reduction of atmospheric oxygen in vital processes such as photosynthesis, respiration and photorespiration (Mittler, 2002; Uchida et al., 2002; Esfandiari et al., 2007). For perfect reduction of oxygen in these processes, four electrons are required, but ROS are generated by the incomplete reduction of O2 (Mittler, 2002; Esfandiari et al., 2007). These ROS are extremely cytotoxic and can cause lipid peroxidation, DNA mutation and protein denaturing by reacting with lipids, proteins and nucleic acids respectively (Quiles and Lopez, 2004). ROS causes peroxidation of plasmalemma by reacting with unsaturated fatty acids (Karabal et al., 2003; Esfandiari et al., 2007), by which cellular contents may leak and result in rapid desiccation and ultimately death of the cell.

For detoxification of these cytotoxic ROS under normal metabolism antioxidant like ascorbic acid (AsA) and glutathione (GSH), and antioxidant enzymes such as ascorbate peroxidase (APX), glutathione peroxidase (GPX), catalase (CAT) and superoxide dismutase (SOD) (Apel and Hirt, 2004; Mittler et al., 2004; Dietz et al., 2006). These detoxification mechanisms are existent in all cellular organelles, depicting the importance of detoxification of ROS for cellular survival (Mittler et al., 2004).

2.5.4.1 ROS regulation in chloroplast

In chloroplast, ROS generation is dependent on the intensity of photon which in drought and salinity stress conditions is excess of that required for CO2 assimilation because of closure of stomata, consequently, results in transfer of excessive electron to O2 and production of superoxide at photosystem-I (PSI) (Asada, 2006). In the vicinity of PSI there is a membrane attached Cu/ZnSOD that converts O2•− to H2O2, which, in turn, is converted to water by a membrane-bound thylakoid-ascorbate peroxidase (tylAPX) (Asada, 2006: Sano et al., 2005). While 1O2 is formed by the over-reduction of electron transport chain at photosystem-II (PSII) (Asada, 2006). Hydrogen peroxide (H2O2) stimulate the oxidation of quinone A (QA), the primary plastoquinone (PQ) electron acceptor that enhances the flow of photosynthetic electron transport and thus less production of 1O2 under stress conditions (Asada, 2006; Moller et al., 2007). Conversely 1O2 cytotoxicity can cause lipid peroxidation and extensive tissue damage in leaves that could result in cellular death (Karpinska et al., 2000; Moller et
Thus in chloroplast controlling the production and scavenging of ROS is indispensible for stress tolerance as shown in transgenic plants and in drought or salinity tolerant cultivars (Hernandez et al., 2001; Mittler and Berkowitz, 2001; Tseng et al., 2007) and incompetence of ROS-scavenging mechanisms in chloroplast resulted in sensitivity to both salinity and drought (Serrato et al., 2004; Wang et al., 2005; Wang et al., 2008). Higher activity of SOD, CAT, APX and GR was observed in salsola (Stenoptera) and tomato chlorophyll was observed and also the activity was higher in upper younger leaves than the older leaves (Doğan, 2012).

2.5.4.2 ROS regulation in peroxisomes

ROS generation in peroxisomes depend on delicate balance between its production and scavenging. As salinity stress is accompanied by decreased water availability and closure of stomata, it reduces the CO$_2$ to O$_2$ ratio in mesophyll cells subsequently increased photorespiration and production of glycolate in chloroplasts (Corpas et al., 2001). Glycolate is oxidized by glycolate-oxidase and in turn produce H$_2$O$_2$ which is major source of H$_2$O$_2$ during photorespiration (Karpinski et al., 2003). Catalases (CATs) are the main antioxidative enzymes that detoxify the H$_2$O$_2$ and are mainly localized in peroxisomes, ascorbate peroxidase (APX) and AsA–GSH cycle may also be involved in scavenging the H$_2$O$_2$ (Mittler et al., 2004; Vandenabeele et al., 2004). SOD converts O$_2^-$ (generated by xanthine oxidase, XOD) to O$_2$ and H$_2$O$_2$ (Corpas et al., 2001). Abiotic stresses like salinity and drought disturb the oxidation state, obstruct antioxidative defense system and thus increased ROS formation (Nyathi and Baker, 2006). Mittova et al., (2003, 2004) showed that salt stress decreased the AsA and GSH contents in peroxisomes and resulted in induced lipid peroxidation in tomato.

2.5.4.3 ROS regulation in mitochondria

Abiotic stresses especially salinity and drought increases the ROS generation in mitochondria (Bartoli et al., 2004; Pastore et al., 2007). Mitochondria are regarded as the source of ROS formation, though in lesser quantity compared to peroxisomes and chloroplasts (Rhoads et al., 2006). Mitochondrial electron transport chain (mtETC), complex I and III are the main sites of ROS generation (Rhoads et al., 2006; ´Moller et al., 2007). During water stress enhanced mitochondrial respiration could add to the production of ROS via transference of
electrons to O$_2$ from cytochrome (Norman et al., 2004). It has been suggested that increased respiration rate in the mitochondria under severe drought results in over production of ROS, because of the increased demand of ATP from mitochondria and decreased rate of ATP synthesis in the chloroplast (Atkin and Macherel, 2009). In mitochondria alternative oxidase (AOX) and Mn-SOD are the major scavenging enzymes that control this signaling pathway and scavenge ROS (Foyer and Noctor, 2005). In the initial step of ROS detoxification O$_2^-$ is converted to H$_2$O$_2$ and O$_2$ by Mn-SOD while AOX lower the production of ROS (Rhoads et al., 2006). Mittova et al., (2003, 2004) found decrease in H$_2$O$_2$ and lipid peroxidation and higher activities of antioxidant enzymes (SOD, POD, GSH and APX) in mitochondria in response to salinity in wild tomato species Lycopersicon pennellii whereas contrasting trend was observed in cultivated tomato Lycopersicon esculentum.

2.5.4.4 ROS regulation in apoplast

Apoplast serve as a vital source of H$_2$O$_2$ formation in response to severe abiotic stresses like salinity and drought, also in response to abscisic acid (ABA) (Hu et al., 2006; Jubany-Marí et al., 2009). In Arabidopsis, AtRbohD and AtRbohF encode two NADPH oxidases and shown to be responsible for ROS production in apoplast necessary for ABA-induced closure of stomata (Torres and Dangl, 2005). In addition to NADPH oxidases, there are other enzymes involved in ROS formation like peroxidases, polyamine oxidases and cell wall-associated oxidases (Moschou et al., 2008). Apoplastic H$_2$O$_2$ is supposed to have role in plants adaptation to salt and drought stress such as cell wall strengthening and maintaining sufficient growth rate for plant survival (Jubany-Marí et al., 2009). In maize, Rodriguez et al., (2004) showed that under NaCl stress; high levels of apoplastic of ROS have positive effect on leaf elongation and lower levels of apoplastic ROS production was associated with a decrease in leaf elongation.
2.6 Role of ABA in plants salinity stress response

Plants ability to cope with salinity stress depends on its sensitivity to incoming stresses and in response adjusts their physiology to adapt to stress (Zhang et al., 2006). Such regulations require feed-forward mechanism for stress adaption, such as the ability of plants to control water loss by partially closing stomata or by reducing leaf development, long before irreversible damage to inner membrane systems and loss of leaf turgor (Davies and Zhang, 1991).

Abscisic acid (ABA) plays a vital role in plants regulated physiological responses. Because of rapid accumulation and involvement of ABA in mediating stress responses that help plants to survive under stress conditions, it is called stress hormone. There are two pre-requisites that its production should be rapidly and sensitively activated to evade plant growth inhibition and function under normal (non-stressed) conditions, secondly it should be rapidly deactivated and degraded after the stress condition is relaxed so that plant can resume normal growth and functioning (Zhang et al., 2006). Recent reports have suggested that ABA plays a dual physiological role in plants regulation under stress conditions (Finkelstein et al., 2002). It has inhibitive role when accumulated in large amounts under stress conditions and promoting role at low concentration under normal conditions has been reported important for
vegetative growth in many organs like primary root growth (Spollen et al., 2000) and in seedling development after germination (Cheng et al., 2002).

ABA plays an essential role in long distance drought signaling in controlling the stomatal movements in water conservation (Davies et al., 2002). It is produced in dehydrated roots and translocated to xylem and control leaf growth and opening of stomata (Zhang and Davies, 1990a, 1990b). This regulatory mechanism is prone to changes by xylem pH and ionic conditions (Wilkinson et al., 1998). Xylem pH changes play a pivotal role in redistribution of ABA in leaf tissues and regulation of stomata when there is no significant changes in xylem ABA concentrations (Hartung et al., 2002). It has also been shown that ABA is involved in ROS network genes expression and activation like (GR1), APX1, CAT1, (Zhang et al., 2006), APX and GR in maize leaves as well as Cu/ZnSOD in the cytosol (Hu et al., 2005).

2.7 Role of potassium in alleviating injurious effects of salinity stress

Potassium (K) is one of the major macro nutrients necessary for plant growth and development. In plants between 2-10% of plant dry weight (Tisdale et al., 1993) and its optimum concentration in the cytosol is maintained about 100 mM for proper functioning of enzymes whereas its vacuolar contents are commonly found in the range 20–200 mM and variable depending upon availability of potassium and tissue type (Walker et al., 1996). Potassium is the major cation in plant cells and have vital roles in metabolism like water and assimilate transport, protein synthesis and activation of enzymes apart from its role in growth and development (Pettigrew, 2008). It has been shown that supplementary potassium has significant role in the physiology and biochemistry of plants and its appropriate levels effectively increase the plant productivity (Chartzoulakis et al., 2006) whereas its deficiency results in reduced chlorophyll contents and thus decrease in photosynthetic rate (Gerardeaux et al., 2010), consequently, root and shoot elongation is inhibited (Kanai et al., 2007).

Evidence suggests that abiotic stresses increases the plants internal K+ requirement and also causes the oxidative damage to cells by the formation of ROS particularly during photosynthesis (Cakmak, 2005; Foyer, 2005;). Enhanced K requirement of plants under environmental stresses might be due to the fact that it is required during photosynthetic CO₂ fixation. Salinity and drought stress are accompanied by partial closure of stomata and thus
reduced CO₂ fixation (Cakmak, 2005). High levels of ROS formation in stressed plants impair photosynthesis and related disturbances in carbohydrate metabolism (Jiang and Zhang, 2002). These facts indicate that ROS generation could be additionally enhanced if abiotic stress is accompanied by K deficiency, at least due to disturbances in water relations, photosynthesis and stomatal functioning (Mengel and Kirkby, 2001).

![Figure 2.5: Model of the K-deficiency-induced NADPH oxidase, superoxide-radical production, and membrane damage in root cells.](image)

As it has been discussed in the above sections that high concentrations of NaCl in the growth media impair K nutrition and it might be a contributory factor to oxidative damage and associated cell damage (Cakmark, 2005). Therefore under salt stress improving the K nutritional status of plants could be essential to lessen the oxidative damage especially by decreasing ROS production during photosynthesis and inhibiting NADPH oxidase involved in generating O₂•⁻ (Shen et al., 2000). This is supported by the experiment on tomato by Kaya et al., (2001) showing that foliar application of K fertilizer (KH₂PO₄) significantly reduced the membrane damage and thus increased the biomass production. It has also been shown that salinity caused P deficiency in addition to K and foliar application of K effectively corrected the deficiency of both the nutrients. As salt-stressed plants are characterized by accumulation of Na⁺ and impairment of K⁺ nutrition therefore plants K⁺: Na⁺ is considered a useful tool to assess plant salt tolerance. Thus selecting or breeding species/genotypes with
high $K^+ : Na^+$ ratio is an effective approach to minimize the decrease in growth in salt affected soils (Santa-Maria and Epstein, 2001).

### 2.7.1 Fruit quality and potassium

Although is not the constituent of any plant structure or organic molecules yet it still has important role in physiological and biochemical processes related to growth, yield, quality and stress in plants (Marschner, 1995; Cakmak, 2005). It has significant effect on quality characteristics of fruits and vegetables related human health. Apart from its involvement in photosynthesis and stomatal regulation, K is also involved in translocation of photosynthates from source to sink via phloem, stress tolerance, enzyme activation and turgor maintenance (Marschner, 1995; Pettigrew, 2008). Adequate potassium nutrition increases the fruit quality characteristics in many horticultural crops like improved fruit color, increased soluble solids, ascorbic acid contents, shelf life, shipping quality and yield (Lester et al., 2005, 2007; Kanai et al., 2007). Previous reports in different fruiting crops (cucumber, tomato, mango, and muskmelon) showed that foliar application of potassium improved the fruit quality when compared to soil application whereas soil application had little or no effect (Demiral and Koseoglu, 2005; Lester et al., 2005; Jifon and Lester, 2009). Table 2.1 shows the review of potassium on fruit quality of different crops.
Table 1. Review of published abstracts on the influence of K: effects by crop, K application, and K form on fruit attributes.

<table>
<thead>
<tr>
<th>Crop (Scientific Name)</th>
<th>K application</th>
<th>K form(s)</th>
<th>Attributes (improved)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple (Malus × domestica)</td>
<td>Soil</td>
<td>KCl, K2SO4</td>
<td>Color, firmness, sugar; Wt. yield, firmness, sugars</td>
<td>Nova (2009);</td>
</tr>
<tr>
<td></td>
<td>Foliar</td>
<td>Unknown; KCl</td>
<td>Size, color, firmness, sugars; Wt. yield, firmness, sugars</td>
<td>El-Gazzar (2000);</td>
</tr>
<tr>
<td>Banana (Musa sp.)</td>
<td>Soil</td>
<td>KCl</td>
<td>Size, sugars, acid; Wt. yield, firmness, sugars; Quality</td>
<td>Asadola (1998);</td>
</tr>
<tr>
<td></td>
<td>Foliar</td>
<td>KCl</td>
<td>Size, sugars, acid; Wt. yield, firmness, sugars; Quality</td>
<td>Wijit (2009); Suresh (2002); Nareesh (1999)</td>
</tr>
<tr>
<td>Citrus (Citrus sinensis)</td>
<td>Foliar</td>
<td>KCl, KNO3</td>
<td>Yield, quality; Appearance, quality; Yield, quality</td>
<td>Hoggog (1990); Dutta (2003); Duensing (1990)</td>
</tr>
<tr>
<td></td>
<td>Foliar</td>
<td>Unknown; KCl</td>
<td>Yield, quality; Appearance, quality; Yield, quality</td>
<td>Hoggog (1990); Dutta (2003); Duensing (1990)</td>
</tr>
<tr>
<td>Citrus (Citrus reticulata)</td>
<td>Soil</td>
<td>Unknown; KCl</td>
<td>Yield, quality; Appearance, quality; Yield, quality</td>
<td>Lin (2009);</td>
</tr>
<tr>
<td></td>
<td>Foliar</td>
<td>Unknown; KCl</td>
<td>Yield, quality; Appearance, quality; Yield, quality</td>
<td>Lin (2009);</td>
</tr>
<tr>
<td>Citrus (Citrus reticulata)</td>
<td>Foliar</td>
<td>KCl &gt; KNO3</td>
<td>Peel thickness, quality; Color, firmness, sugar; Amino acids, quality</td>
<td>Gill (2005); Gun (2004);</td>
</tr>
<tr>
<td>Cucumber (Cucumis sativus)</td>
<td>Soil</td>
<td>KCl, K2SO4 &gt; KCl</td>
<td>No change; Wt. yield, firmness, sugars; Quality</td>
<td>Khanna (2003);</td>
</tr>
<tr>
<td>Cucumber (Cucumis sativus)</td>
<td>Foliar</td>
<td>KCl, K2SO4 &gt; KCl</td>
<td>No change; Wt. yield, firmness, sugars; Quality</td>
<td>Khanna (2003);</td>
</tr>
<tr>
<td>Cucumber (Cucumis sativus)</td>
<td>Soil</td>
<td>KCl, K2SO4 &gt; KCl</td>
<td>No change; Wt. yield, firmness, sugars; Quality</td>
<td>Khanna (2003);</td>
</tr>
<tr>
<td>Guava (Psidium guajava)</td>
<td>Soil</td>
<td>Unknown; KCl</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Guava (Psidium guajava)</td>
<td>Foliar</td>
<td>KCl &gt; KCl</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Kiwi-fruit (Actinidia deliciosa)</td>
<td>Soil</td>
<td>KCl, KNO3</td>
<td>Yield, weight, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Litchi (Litchi chinensis)</td>
<td>Foliar</td>
<td>KNO3</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Mango (Mangifera indica)</td>
<td>Soil</td>
<td>KNO3</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Mango (Mangifera indica)</td>
<td>Foliar</td>
<td>KNO3</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Muskmelon (Cucumis melo)</td>
<td>Soil</td>
<td>Unknown; KNO3</td>
<td>Yield, weight, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Muskmelon (Cucumis melo)</td>
<td>Foliar</td>
<td>Unknown; KNO3</td>
<td>Yield, weight, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Nectarine (Prunus persica)</td>
<td>Soil</td>
<td>KCl, K2SO4 &gt; KCl</td>
<td>No change; Wt. yield, firmness, sugars; Quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Okra (Abelmoschus esculentus)</td>
<td>Foliar</td>
<td>Unknown; KNO3</td>
<td>Yield, weight, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Passionfruit (Passiflora edulis)</td>
<td>Hydroponic</td>
<td>KCl, K2SO4 &gt; KCl</td>
<td>No change; Wt. yield, firmness, sugars; Quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Papaya (Carica papaya)</td>
<td>Soil</td>
<td>Unknown; KCl</td>
<td>Weight, sugars, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Pears (Pyrus communis)</td>
<td>Soil</td>
<td>KCl</td>
<td>Weight, sugars, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Peach (Prunus persica)</td>
<td>Soil</td>
<td>KCl</td>
<td>Weight, sugars, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Pepper (Capsicum annuum)</td>
<td>Soil</td>
<td>KCl, K2SO4 &gt; KCl</td>
<td>No change; Wt. yield, firmness, sugars; Quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Pepper (Capsicum annuum)</td>
<td>Foliar</td>
<td>KNO3</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
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<td>Pepper (Capsicum annuum)</td>
<td>Foliar</td>
<td>KNO3</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
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<td>Foliar</td>
<td>KNO3</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
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<td>Weight, yield, quality; Firmness, quality</td>
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<td>Weight, yield, quality; Firmness, quality</td>
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<td>Weight, yield, quality; Firmness, quality</td>
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<td>KNO3</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
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<td>Pepper (Capsicum annuum)</td>
<td>Foliar</td>
<td>KNO3</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
<tr>
<td>Pepper (Capsicum annuum)</td>
<td>Foliar</td>
<td>KNO3</td>
<td>Weight, yield, quality; Firmness, quality</td>
<td>Bash (1997); Sastry (2001);</td>
</tr>
</tbody>
</table>

Sources from different studies are separated by a semicolon; K form attributing to improved quality greater than another K form is indicated by the > symbol.

References from different studies are separated by a semicolon, and only first author names are listed for brevity.

(Source: Lester et al., 2010)
2.8 Tomato and salinity

Tomato (Solanum lycopersicum L., previously named Lycopersicon esculentum Mill.) is an important crop in several parts of the world, including in regions suffering from drought and soil salinity, such as the Mediterranean region, where these aspects have been studied (Savic et al., 2009; Jensen et al., 2010; Lu et al., 2010). It is moderately tolerant to salinity and is commonly cultivated in salinized areas (Cuartero and Fernandez, 1999; Lu et al., 2010). Salt stress seriously disrupts tomato crop growth at all stages of growth especially at germination, vegetative and reproductive growth stages, so it results loss in economic yield (Del Amor et al., 2001), but it may enhance the quality by increasing sugar concentration and dry matter content (Yurtseven et al., 2005). Effect of salinity on tomato plants at different developmental stages is given below:

2.8.1 Germination

There are two ways of tomato seeding; it may be transplanted or may be directly seeded to final cropping positions. In the latter case there is no problem of salinity as both the substrate and irrigation water have no salts in them, but in the former case (direct sowing) salinity problem results in poor germination and emergence would economically threaten the viability of the crop. Relatively low levels of NaCl reduce the tomato seed germination. Cuartero and Fernández-Munäoz (1999) reported that NaCl concentration of 80 mM decreased the germination percentage in most cultivars and at 190 mM germination percentage is drastically decreased for direct-sown crop. Very few genotypes are able to germinate at higher salt concentration that is also with low percentage, this suggests that genotypes vary in their ability to germinate at moderate salinity levels within Lycopersicon esculentum, and could be used selection tool for cultivated tomato genotypes for salt tolerance (Cuartero and Fernández-Munäoz, 1999).

Salinity not only lowers the germination percentage but also lengthen the time required for completing the germination (Kaveh et al., 2011). Not all the seeds unable to germinate under high salinity, if somehow salt concentration is lowered by environmental factors like high rainfall or irrigation with good quality water, more than half of the seeds would still be able to germinate (Yokas et al., 2008; Kaveh et al., 2011 ). The main effect of salinity on seed
germination is restricting the water uptake in the first phase of germination and the seeds that have not entered cell division phase still have the capability to germinate.

2.8.2. Root development

Roots are the plant organs that are in immediate contact with soil and any changes in soil directly changes the growth, physiology and morphology of roots and consequently disturbs the ion and water uptake and hormones which can communicate with shoot. The changes in the root growth and physiology ultimately affect the whole plant.

Salt stress decreases the root biomass in tomato and upper limit of salt stress after which root biomass is significantly decreases is between 6 and 4 dS m\(^{-1}\) (Papadopoulos and Rendig, 1983). It has been reported that NaCl stress decreases the root biomass in tomato and increased the root appearing time compared to without salt (Cuartero and Fernández-Munáoz, 1999; Hajer et al., 2006). Reduced root growth under salt stress could be due to low water potential of root environment, cell growth restriction, nutritional imbalance due to excessive saline ions and ionic toxicity resulting in cell death. Salinity induced reduction in root biomass is variable among tomato genotypes. Decrease in root biomass under saline conditions in *Lycopersicon esculentum* is more than several accessions of *Lycopersicon peruvianum* and *Lycopersicon pennellii* (Abrisqueta et al., 1991) and within L. esculentum, different cultivars also differs at moderate salinity levels 5±7 dS m\(^{-1}\) (Cruz, 1990; Snapp and Shennan, 1994) and these differences are not apparent at higher salinity levels of 13 dS m\(^{-1}\) or above (Cruz, 1990).

2.8.3. Shoot development

Salt stress slows down the shoot growth in tomato plants and it has been observed that growth of older leaves is less affected than the younger leaves. Tomato plants can withstand greater levels of salt stress at the flowering and fruiting stages than at the seedling stages (Cruz and Cuartero, 1990; Maggio et al., 2007). Under saline conditions both stem and dry weight are decreased, but in the cultivated tomato decrease in leaf dry weight is more than stem dry weight (Cruz and Cuartero, 1990; Hajer et al., 2006) while in wild relatives (*Lycopersicon pimpinellifolium*, *Lycopersicon peruvianum*, *Lycopersicon hirsutum* and *Lycopersicon pennellii*) the decrease is similar in stem and leaf dry weight (Bolarin et al.,
1995). The reduction leaf dry weight might be due to reduction in leaf area rather than decreased leaf number (Hajer et al., 2006).

Reduced leaf growth under salt stress has been attributed to reduction in cell wall rheological characteristics, cell turgor and photosynthetic rate. Salinity happen to cause a rapid decrease in leaf water potential and slower decrease in osmotic potential is unable to counterbalance this change in water potential (Yeo et al., 1991; Stirzaker et al., 1997). However after few hours changes in osmotic potential can counter the impact of salinization and thus turgor is established at lower level (Alarcoăn et al., 1994) comparable to control (Yang et al., 1990). Though turgor is necessary for growth, the rate of cell expansion is also affected by cell wall rheological properties (Munns, 1993). A new stabilized growth rate is established at 100 mM NaCl but lower than non-stressed plants (Sacher and Staples, 1985; Stirzaker et al., 1997). Salinity induced water stress would limit the growth of plants whereas salt-specific effects would results in injuries in leaf tissues (Munns, 1993; Alarcoăn et al., 1994). Thus plant species/ genotypes that are able absorb more water under conditions of low water potential from soil would adapt better to saline stress.

2.8.4. Fruit yield and quality

Tomato is moderately tolerant to salinity and can tolerate salinity up to 2.5 dS m\(^{-1}\) level without any yield loss (Maas, 1986). Thus a small increase in salinity of irrigation water is likely to produce yield loss (Cuartero and Soria, 1997). The reduction in yield is less in field cultivation than in hydroponics for the same irrigation water (Mitchell et al., 1991) this might be due to delay in the buildup of salinity in soil. This reduction in yield is due to reduced mean fruit weight rather than fruit number, as salinity caused reduced water availability, biochemical and physiological disturbances in the rooting medium (Azarmi et al., 2010; Cuartero et al., 2006).

It is generally believed that soil salinity improves tomato fruit quality. For tomato fruit quality is somewhat ambiguous term and should be precisely defined depending on its usage and consumer. The tomato fruit quality characteristics improved by salinity treatment include sugars, acidity, soluble solids and fruit juice pH which are important for both its processing as well as for fresh market, while others (as taste and shelf life) are important for fresh market only (Azarmi et al., 2010; Yesterven et al., 2005). Salinity also produces blossom
end rot which makes tomato fruits unacceptable for both processing industry and fresh market (Cuartero and Fernández-Munáoz, 1999). The improvement in fruit quality characteristics (TSS, dry matter percent, titratable acidity and pH) in response to salinity stress had been reported because of decreased fruit water content and increased concentrations of reducing sugars and acids as compared to non-saline conditions (Leonardi et al., 2004). The accumulation of reducing sugars and organic acids is responsible for increased the titratable acidity and decreased the pH of the fruit juice.

Figure 2.6: TSS, titratable acidity (TA) and relation between both parameters of vine ripe fruits of ‘Daniela’ cultivar grown at different salt concentrations in the substrate. (Saranga et al., 1991)
Chapter-3

RESULTS AND DISCUSSION

Study-1

3.1 Characterization of Comparative Response of Fifteen Tomato 
(Lycopersicon esculentum) Genotypes to NaCl Stress

3.1.1 Introduction

The main impediments of growing media salinity on growth and yield of plants are osmotic effect, specific ion toxicity, nutritional imbalance and above all production of reactive oxygen species (ROS), which ultimately bring out disturbances in photosynthesis and physiology of the plants (Telesiński et al., 2008; Zhao et al., 2007).

Previous methods used for assessing the salt tolerance of plants on yield response were not very effective because of excess amount of time they take and expensiveness (Gama et al., 2009). However physiological characters can be used to assess the salt tolerance of plants, such as photosynthesis can provide us a guess of salt stress tolerance (Gama et al., 2009); while chlorophyll fluorescence is the quantitative indicative of the photosynthesis (Zhao et al., 2007; Ehsanzadeh et al., 2009).

Potassium is very important plant nutrient that take part in important physiological processes like photosynthesis, assimilative transport and activation of enzymes, especially under stress conditions such as drought (Liebersbach et al., 2004) and salinity (Qi and Spalding, 2004). Considerable differences exist among different species and genotypes such as wheat (Damon and Rengel, 2007), potato (Trehan et al., 2005; Arvin and Donnelly, 2008), canola (Damon et al., 2007), rice (Yang et al., 2004), cotton (Zhang et al., 2007) and tomato (Ezin et al., 2010). Therefore, the knowledge of K⁺ uptake and accumulation for biomass production under saline stress conditions can be used to assess the salt-tolerance of different genotypes and the mechanism of salinity tolerance.

Tomato is moderately salt-tolerant and is commonly cultivated in salinized areas (Lu et al., 2010). Use of salt-tolerant species/ varieties is one of the most feasible and effective option to tackle salinity (Yilmaz, 2004). The plant species or varieties may differ significantly for
salt tolerance due to their genetic makeup (Kausar et al., 2012). Therefore, the current study was conducted with the objective to assess the effect of different salinity levels on growth, physiology and phenotype of tomato genotypes that may lead to screen salt-tolerant and salt-sensitive tomato genotypes.

3.1.2 Materials and Methods

3.1.2.1 Plant material and growth conditions

Twelve tomato (Lycopersicon esculentum Mill.) genotypes (Indent-1, Indent-2, Roma, 1211, 127, Pakit, Nagina, VCT-1, Riogrande, Estra-229, LA-3847, LA-0716) and three varieties (Peto-86, Red Ball, Titano) were obtained from National Agricultural Research Council (NARC), Islamabad and Department of Plant Breeding and Genetics, University of Agriculture Faisalabad.

The experiment was conducted in a wire house during spring 2010 (February, March) at University of Agriculture Faisalabad (Latitude = 31°- 26’ N, Longitude = 73°- 06’ E, Altitude = 184.4 m), average minimum and maximum temperature was 9.5-30.4 °C and relative humidity 57.5-62.7%. Healthy seeds of each genotype/variety were surface sterilized with 1% sodium hypochlorite solution and sown in polythene lined iron trays having two inches layer of acid washed quartz sand. After germination, seedlings were irrigated with ½ strength Hoagland’s nutrient solution (Hoagland and Arnon, 1950). At two leaf stage, uniform seedlings were randomly transferred to foam plugged holes (2 cm diameter) in polystyrene sheet suspended over ½ strength Hoagland’s nutrient solution (Hoagland and Arnon, 1950). After one week of transplanting, three levels of NaCl salinity (control; 0.9 dS m⁻¹, 75 and 150 mM) were maintained with three replicates according to completely randomized design by stepwise increment of i.e. 1/3rd of total salt for three consecutive days (25 and 50 mM respectively) by lab grade NaCl. Aeration was given with air pumps for 8 hours a day, pH was maintained daily at 6.0-6.5, and nutrient solution was changed after every 10 days.

3.1.2.2 Growth parameters

To assess the effect of NaCl on plant growth, after 30 days of stress three seedlings of each genotype were collected, root and shoot were separated and used for measurement of shoot and the longest root lengths and fresh weights, whereas shoot and root dry weights were
measured after drying them in an oven at 65 ± 5 °C in hot air oven (Model DHG-9053A, R and M Marketing, Sussex, UK) till constant weight.

3.1.2.3 Photosynthetic parameters

After 30 days of salt stress before harvesting, photosynthetic parameters: transpiration rates, stomatal conductance, CO₂ assimilation rate, intercellular CO₂ concentration was recorded with portable Infra-red gas analyzer (LCA4 - ADC Bioscientific).

3.1.2.4 Leaf sap analysis

Two or 3 youngest fully expanded leaves of tomato genotypes were detached after 30 days of salt treatment, rinsed quickly in distilled water, blotted dry with tissue paper and stored in separate Eppendorf tubes at freezing temperature for leaf sap extraction to determine Na⁺ and K⁺. Frozen leaf samples were thawed and crushed using a stainless steel rod with tapered end. The sap was collected in Eppendorf tubes by Gilson pipette and centrifuged at 6500 x g for 10 minutes (Gorham, 1984). The leaf sap was diluted as required by adding distilled water and Na⁺ and K⁺ were determined using flame photometer (Sherwood Flame photometer, Model-410; Sherwood Scientific, Ltd, Cambridge UK) with the help of standard solutions using reagent grade salts of NaCl and KCl.

3.1.2.5 Ranking of genotypes for salt tolerance

All the data of the measured characteristics were converted to relative values (relative to control, 0 mM) for cluster analysis. Cluster analysis followed the methods described by Jolliffe et al., (1989) and Khrais et al., (1998). Cluster group rankings were obtained based on Ward’s minimum variance cluster analysis on the means of the salt tolerance indexes for shoot and root fresh and dry weights and also ionic characteristics (K⁺/Na⁺). The distance between two clusters was calculated as the ANOVA sum of squares between the two clusters in all the parameters analyzed. The clusters were merged in each generation to minimize the within-cluster sum of squares. The procedures are described in the “IBM SPSS Statistics”. The cluster groups were identified in dendrograms. The number of cluster groups was determined by calculating the pseudo $t^2$ which reached a local maximum. The cluster group rankings were obtained from the averages of means over multiple parameters in each cluster group, i.e., cluster mean, in order from highest to lowest averages. A sum was obtained by
adding the numbers of cluster group ranking at each salt level in each genotype. The genotypes were finally ranked based on the sums in order that those with the smallest sums were ranked as the most tolerant and those with the largest sums were ranked as the least tolerant in terms of relative salt tolerance (Zeng et al., 2002).

3.1.3 Results

Increasing salt concentration in the rooting medium caused significant decrease in plant growth (shoot fresh weight, SFW; root fresh weight, RFW; shoot dry weight, SDW; root dry weight, RDW) in all the tomato genotypes, however the genotypes differed significantly regarding the plant growth and ions (K⁺/Na⁺) accumulations indicated by the salt tolerance indexes. Highest salt tolerance indexes were found in Indent-1 and Nagina whereas lowest in Peto-86 and Red Ball in all the growth and ionic characteristics (Table 3.1.1). The genotypes was ranked based on growth (shoot/ root fresh and dry weights) and ionic (K⁺/Na⁺) characteristics, simultaneous analysis of the means was done for these parameters using single-linked cluster analysis, the genotypes were divided into four cluster groups at 75 mM NaCl level and five cluster groups at higher level of NaCl (150 mM). The overall ranking of the genotypes considering the growth and accumulation of ions revealed that Indent-1 and Nagina were ranked as salt tolerant having highest indexes for growth and accumulation K⁺/Na⁺ whereas the genotypes Peto-86 and Red Ball as salt sensitive having lowest indexes for these parameters (Tables 3.1.2-3.1.6). The other genotypes had intermediate level of salt tolerance and were ranked accordingly by the analysis of the means as presented in the tables.
Table 3.1.1. Salt tolerance indexes\(^a\) of growth and ionic characteristics in tomato genotypes under different levels of salinity

<table>
<thead>
<tr>
<th>Salt tolerance index</th>
<th>NaCl (mM)</th>
<th>SFW</th>
<th>RFW</th>
<th>SDW</th>
<th>RDW</th>
<th>K(^+)/Na(^+)</th>
</tr>
</thead>
<tbody>
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<td>Peto-86</td>
<td>75</td>
<td>0.54</td>
<td>0.57</td>
<td>0.57</td>
<td>0.61</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
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<td>0.33</td>
<td>0.40</td>
<td>0.47</td>
<td>0.11</td>
</tr>
<tr>
<td>Red Ball</td>
<td>75</td>
<td>0.55</td>
<td>0.47</td>
<td>0.56</td>
<td>0.54</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>150</td>
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<td>0.37</td>
<td>0.38</td>
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</tr>
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<td>0.69</td>
<td>0.65</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>150</td>
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<td>0.52</td>
<td>0.47</td>
<td>0.54</td>
<td>0.14</td>
</tr>
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<td>0.73</td>
<td>0.64</td>
<td>0.65</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
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<td>127</td>
<td>75</td>
<td>0.75</td>
<td>0.69</td>
<td>0.63</td>
<td>0.69</td>
<td>0.30</td>
</tr>
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<td></td>
<td>150</td>
<td>0.56</td>
<td>0.59</td>
<td>0.45</td>
<td>0.61</td>
<td>0.12</td>
</tr>
<tr>
<td>Indent-1</td>
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<td>0.81</td>
<td>0.81</td>
<td>0.84</td>
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<tr>
<td></td>
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<td>0.69</td>
<td>0.54</td>
<td>0.71</td>
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<tr>
<td>Indent-2</td>
<td>75</td>
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<td>0.24</td>
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<td>0.41</td>
<td>0.46</td>
<td>0.52</td>
<td>0.13</td>
</tr>
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<td>75</td>
<td>0.70</td>
<td>0.64</td>
<td>0.60</td>
<td>0.62</td>
<td>0.22</td>
</tr>
<tr>
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<td>150</td>
<td>0.53</td>
<td>0.40</td>
<td>0.48</td>
<td>0.52</td>
<td>0.12</td>
</tr>
<tr>
<td>Nagina</td>
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<td>0.85</td>
<td>0.76</td>
<td>0.73</td>
<td>0.76</td>
<td>0.39</td>
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<td>0.67</td>
<td>0.59</td>
<td>0.67</td>
<td>0.25</td>
</tr>
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<td>VCT-1</td>
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<td>0.71</td>
<td>0.61</td>
<td>0.61</td>
<td>0.69</td>
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</tr>
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<td>0.59</td>
<td>0.42</td>
<td>0.54</td>
<td>0.15</td>
</tr>
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<td>Rio Grande</td>
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<td>0.73</td>
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<td>0.62</td>
<td>0.70</td>
<td>0.29</td>
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<td>0.40</td>
<td>0.40</td>
<td>0.56</td>
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<td>Titano</td>
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<td>0.66</td>
<td>0.69</td>
<td>0.28</td>
</tr>
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<td>0.56</td>
<td>0.42</td>
<td>0.45</td>
<td>0.49</td>
<td>0.12</td>
</tr>
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<td>0.62</td>
<td>0.25</td>
</tr>
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<td>0.52</td>
<td>0.42</td>
<td>0.40</td>
<td>0.51</td>
<td>0.14</td>
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<td>0.59</td>
<td>0.66</td>
<td>0.27</td>
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<td>0.42</td>
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<td>0.51</td>
<td>0.13</td>
</tr>
</tbody>
</table>

\(^a\) Salt tolerance index was defined as the observations under salinity divided by the means of the controls
Table 3.1.2 Rankings of genotypes for their relative salt tolerance in terms of shoot fresh weight in a cluster analysis (Ward’s minimum variance analysis)

<table>
<thead>
<tr>
<th>Genotype</th>
<th>75 mM</th>
<th>150 mM</th>
<th>Sum b</th>
<th>Genotype rank c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indent-1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Nagina</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Roma</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
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<td>127</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Titano</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>1211</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Estra-229</td>
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<td>5</td>
<td>3</td>
</tr>
<tr>
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</tr>
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<td>LA-0716</td>
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<td>5</td>
<td>3</td>
</tr>
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<td>Indent-2</td>
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<td>6</td>
<td>4</td>
</tr>
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<td>Pakit</td>
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<td>3</td>
<td>6</td>
<td>4</td>
</tr>
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<td>VCT-1</td>
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<td>4</td>
</tr>
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<td>Riogrande</td>
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<td>Red Ball</td>
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<td>8</td>
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</tr>
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<td>Peto-86</td>
<td>4</td>
<td>5</td>
<td>9</td>
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a Cluster groups were obtained from Ward’s minimum-variance cluster analysis on the means of the salt tolerance indexes in shoot fresh weight. Genotypes were divided into four cluster groups at 75 mM NaCl and five cluster groups at 150 mM. The cluster group rankings were obtained from cluster means (data not shown) in the order from the highest to the lowest cluster means.

b Sums were obtained from the cluster group rankings by adding the ranking numbers at the two salt levels in each genotype.

c Genotypes were finally ranked based on the sums with the smallest sum being the most relatively tolerant.
Table 3.1.3 Rankings of genotypes for their relative salt tolerance in terms of root fresh weight in a cluster analysis (Ward’s minimum variance analysis)

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Cluster groups</th>
<th>75 mM</th>
<th>150 mM</th>
<th>Sum b</th>
<th>Genotype rank c</th>
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<td>Nagina</td>
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<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>127</td>
<td></td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
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<tr>
<td>VCT-1</td>
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<td>3</td>
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<td>4</td>
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<tr>
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</table>

a Cluster groups were obtained from Ward’s minimum-variance cluster analysis on the means of the salt tolerance indexes in shoot fresh weight. Genotypes were divided into four cluster groups at 75 mM NaCl and five cluster groups at 150 Mm. The cluster group rankings were obtained from cluster means (data not shown) in the order from the highest to the lowest cluster means.

b Sums were obtained from the cluster group rankings by adding the ranking numbers at the two salt levels in each genotype.

c Genotypes were finally ranked based on the sums with the smallest sum being the most relatively tolerant.
Table 3.1.4 Rankings of genotypes for their relative salt tolerance in terms of shoot dry weight in a cluster analysis (Ward’s minimum variance analysis)

<table>
<thead>
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<th>Genotype</th>
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a Cluster groups were obtained from Ward’s minimum-variance cluster analysis on the means of the salt tolerance indexes in shoot fresh weight. Genotypes were divided into four cluster groups at 75 mM NaCl and five cluster groups at 150 Mm. The cluster group rankings were obtained from cluster means (data not shown) in the order from the highest to the lowest cluster means.

b Sums were obtained from the cluster group rankings by adding the ranking numbers at the two salt levels in each genotype.

c Genotypes were finally ranked based on the sums with the smallest sum being the most relatively tolerant.
Table 3.1.5 Rankings of genotypes for their relative salt tolerance in terms of root dry weight in a cluster analysis (Ward’s minimum variance analysis)

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a Cluster groups were obtained from Ward’s minimum-variance cluster analysis on the means of the salt tolerance indexes in shoot fresh weight. Genotypes were divided into four cluster groups at 75 mM NaCl and five cluster groups at 150 Mm. The cluster group rankings were obtained from cluster means (data not shown) in the order from the highest to the lowest cluster means.

b Sums were obtained from the cluster group rankings by adding the ranking numbers at the two salt levels in each genotype.

c Genotypes were finally ranked based on the sums with the smallest sum being the most relatively tolerant.
### Table 3.1.6 Rankings of genotypes for their relative salt tolerance in terms of K⁺/Na⁺ in a cluster analysis (Ward’s minimum variance analysis)

<table>
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*a Cluster groups were obtained from Ward’s minimum-variance cluster analysis on the means of the salt tolerance indexes in shoot fresh weight. Genotypes were divided into four cluster groups at 75 mM NaCl and five cluster groups at 150 Mm. The cluster group rankings were obtained from cluster means (data not shown) in the order from the highest to the lowest cluster means.

*b Sums were obtained from the cluster group rankings by adding the ranking numbers at the two salt levels in each genotype.

*c Genotypes were finally ranked based on the sums with the smallest sum being the most relatively tolerant.

### 3.1.4 Discussion

There was an overall reduction in tomato plant growth with the elevated levels of NaCl as compared to non-saline conditions. There are two reasons for the inhibition of plant growth: firstly, because of reduced water availability to the plants due to excess of NaCl in the nutrient solution and secondly due to specific ion toxicity (Munns et al., 2006). This was in accordance with the previous findings by Kumar et al., (2005) who ascribed the reduced plant growth to decreased water absorption due to osmotic effects, deficiency of nutrients as
a consequence of the ionic imbalance and decrease in many metabolic activities. Hence, different plant species have evolved different strategies to tackle with these deleterious effects of excess salts in the rooting medium (Munns et al., 2006; Yokas et al., 2008; Tantawy et al., 2009). Results from this study are consistent with previous ones represented by; plant height (root and shoot length) is reduced under saline conditions.

The shoot and root fresh and dry weights were decreased due to the exposure of tomato to the increasing concentration of NaCl (75 and 150 mM). Similar results were also found earlier by Oztekin and Tuzel (2011) in tomato cultivars. Salinity stress changed the morphology, growth and physiology of the roots that altered the water and ion uptake, consequently the whole plant growth is affected. A similar trend was also documented by other authors (Li et al., 2004; Akhtar et al., 2010). Finally, saline conditions resulted in a clear stunting of plant growth, as a result the shoot and root length, fresh and dry weights were considerably decreased in all the genotypes. In this study, shoot and root length, fresh and dry weight reduction in Indent-1 and Nagina genotypes was less while in Peto-86 and Red Ball these parameters were severely reduced as compared to other genotypes/varieties. This indicates that Indent-1 and Nagina were more tolerant to the increasing salinity and could better cope with reduced water availability.

It is evident from the previous findings that under salt stress, stomata were closed due to decreased water availability and uptake by the roots (Christina et al., 2010). Due to the closing of stomata, stomatal conductance, and internal CO₂ concentration were decreased, as a result plant’s net photosynthetic and transpiration rate were also decreased and consequently, the growth of plants. Significant positive correlation coefficients were found between leaf gas exchange parameters and shoot fresh weight indicating the importance of these gas exchange parameters under NaCl stress (Figure 3.1.1). This disruption in stomatal regulation under saline conditions was attributed to the decreased level of K⁺ in plants. This could be due to the fact that K⁺ had a significant role as osmoticum in vacuole to maintain high tissue water content under stress condition (Marschner, 1995). Many reports depict the importance of K⁺ in regulating the photosynthesis and maintaining the water balance of plants (Stepien and Klbus, 2006; Athar and Ashraf, 2005). In present work, NaCl stress led to the significant decrease in all the gas exchange parameters in all the fifteen genotypes. Since growth of plants directly correlated to these gas exchange parameters, thus the genotypes,
Indent-1 and Nagina maintained higher values of these attributes and produced more biomass as compared to other varieties/genotypes, whereas Peto-86 and Red Ball produced less biomass because of lower values of these attributes.

The results showed an increase in leaf Na\(^+\) concentration while decrease in leaf K\(^+\) concentration decreased with the increasing NaCl concentration in the nutrient solution. Under saline conditions, more accumulation of Na\(^+\) resulted in ionic imbalance, as a consequence plant uptake of K\(^+\) was decreased which is apparent by the depressed growth at higher NaCl concentrations (Sairam et al., 2002; Dadkhah, 2011). The deficiency of K\(^+\) under salinized conditions was inversely correlated to the increased accumulation of Na\(^+\), which indicates a competition between Na\(^+\) and K\(^+\) ions which might be due to the fact that these two ions share the same transport system at the root surface (Rus et al., 2001). When large amounts of Na\(^+\) get absorbed and accumulated by plants, it becomes highly toxic at different levels of physiology. Physiologically, Na\(^+\) toxicity impairs disruption of K\(^+\) nutrition, induction of water stress and oxidative cell damage (Aktas et al., 2006). The restricted absorption and accumulation of Na\(^+\) and maintenance of high K\(^+\)/Na\(^+\) ratios may enhance salt tolerance and K\(^+\)/Na\(^+\) ratio has served as a nutritional indicator to select salt tolerant genotypes/ varieties in tomato crop (Juan et al., 2005; Dasgan et al., 2002). In tomato leaves, high K\(^+\)/Na\(^+\) is a better indicator of the ability of the plants to select and use K\(^+\) under NaCl salinity, and maintenance of high K\(^+\)/Na\(^+\) ratio is also important for salt tolerance of tomato plants (Santa-Cruz et al., 2002). In the present study, the result for the K\(^+\)/Na\(^+\) ratio was comparable to those results earlier documented by other authors. Highest leaf K\(^+\)/Na\(^+\) ratio values were observed in the Indent-1 and Nagina, which were less affected by salinity and the lowest in Peto-86 and Red Ball, which were more affected by salinity.

Based on the results it is concluded that salinity severely affected tomato plant physiological processes and thus resulted in decreased plant growth. Considering the genotypes, Indent-1 and Nagina were characterized as salt-tolerant and Peto-86 and Red Ball as salt-sensitive under saline conditions. The results obtained in this study are important for the region and also useful for others working on tomato breeding for salt tolerance.
Figure 3.1.1 Relationship between CO₂ assimilation rate (A), transpiration rate (B), stomatal conductance (C), intercellular CO₂ concentration (D) and shoot fresh weight of fifteen tomato genotypes/varieties after 30 days of imposition NaCl stress. All the values are mean of three replicates.
Study-2

3.2 Antioxidative and physiological response of salt-tolerant and salt-sensitive tomato (*Lycopersicon esculentum*) genotypes to potassium

3.2.1 Introduction

The detrimental effects of salt stress include: an immediate one osmotic effect which decreases the water availability to plants, a long term ionic imbalance which causes the accumulation and toxicity of salts especially Na\(^+\) and Cl\(^-\), which ultimately induces the deficiency of other nutrients like K\(^+\) and Ca\(^{2+}\) (Shabala and Cuin, 2008; Abogadallah *et al.*, 2010). Since the roots are the plant organs that are directly exposed to environment, therefore growth is restricted due to decreased water availability, this ultimately limits the nutrient uptake and translocation to the shoot especially K\(^+\) (Rubio *et al.*, 2010).

Plants subjected to salinity shows K\(^+\)-deficiency and stunted growth mainly because of the decreased photosynthetic capacity (Cakmak, 2005). Plant genotypes respond differently to this decrease in photosynthesis rate, generally salt-tolerant genotypes were less affected in terms of net photosynthetic rate and stomatal conductance than the salt sensitive ones (Naumann *et al.*, 2007; Zhao *et al.*, 2007; Lopez-Climent *et al.*, 2008). The limitation of photosynthesis under saline conditions may be due to stomatal and/or non-stomatal limitation (Debez *et al.*, 2008). Under salinity stress light energy absorbed by the photosynthetic pigments remains in excess due to restricted photosynthetic CO\(_2\) fixation (Foyer and Noctor, 2005). This excess amount of energy may damage PSII via generating reactive oxygen species (ROS) (Yang *et al.*, 2007). ROS includes singlet oxygen (\(^1\)O\(_2\)), hydroxyl radicals (OH\(^-\)), superoxide (O\(_2^-\)) and hydrogen peroxide (H\(_2\)O\(_2\)). These ROS severely damages the important biological molecules like protein, nucleic acids and lipids (Mittler, 2002).

There are number of proposed pathways in plants that collaborate to protect this oxidative damage like cyclic electron flows through either PSI or PSII, xanthophyll cycle-dependent energy dissipation, photorespiration and antioxidant system (Asada, 2006). Apart from chloroplast ROS are also being generated in mitochondria and peroxisome (Dat *et al.*, 2000; Navrot *et al.*, 2007). The antioxidative defense system is an important scavenger of these ROS, and comprised of low molecular mass antioxidants and antioxidant enzymes like superoxide dismutase (SOD), catalase (CAT), glutathione reductase (GR), guaiacol
peroxidase (GPOD), ascorbate peroxidase (APX) and dehydro ascorbate reductase (DHAR) (Apel and Hirt, 2004; Noctor and Foyer, 1998).

Since potassium is a major inorganic osmolyte and has high concentration in chloroplast and cytoplasm (100-200 mM) tends to stabilize the pH between 7-8, plays an important ameliorative role under stress conditions in physiology of the plants especially under salt stress in enzyme activation, regulation of osmotic pressure, maintenance of membrane potential and turgor, opening and closing of stomata and tropism (Abogadallah et al., 2010; Lester, 2005). In alleviating salinity, preventing Na⁺ accumulation in shoot is not so important rather maintaining K⁺ homeostasis and K⁺/Na⁺ ratio is more important by preventing K⁺ loss by Na⁺ (Shabala and Cuin, 2008; Rubio et al., 2010).

Salt tolerance of tomato (Lycopersicon esculentum) varies among different species and genotypes (Tester and Davenport, 2003; Maggio et al., 2007), thus there is a need that new cultivars continuously be evaluated against salinity. In study-1 salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) genotypes were identified from a set of fifteen tomato genotypes against three levels of NaCl (control, 75 and 150 mM). In the present study, we exposed these salt-tolerant and salt-sensitive tomato genotypes to different levels of potassium (both foliar and solution form) to same levels of NaCl stress to investigate the role potassium in alleviating the detrimental effects of NaCl stress. Also to understand the mechanisms involved in ameliorating the salt stress by the application of potassium.

3.2.2 Materials and Methods

3.2.2.1 Plant materials

Four tomato genotypes were used in this experiment Indent-1 and Nagina (salt-tolerant) and Red Ball and Peto-86 (salt-sensitive) identified for salt-tolerance in Study-1.

3.2.2.2 Growth conditions

The experiment was carried out in a wire house of the Saline Agriculture Research Centre, Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad, Pakistan. Healthy seeds of these genotypes were surface sterilized with 1 % sodium hypochlorite solution, rinsed thoroughly with deionized water for 5 minutes and germinated in sand filled
iron trays lined with polythene sheets. The seedlings at two leaf stage were transferred to Hoagland’s nutrient solution (Hoagland and Arnon, 1950) in 100 L iron containers lined with polythene sheets, having 2 levels of potassium (4.5 and 9 mM) both in the solution and foliar form. Foliar application of potassium was done using KNO₃ salt at three weeks interval by a hand sprayer. After three days of transplantation, two levels of NaCl salinity (75 and 150 mM) were developed by stepwise increment in three equal doses along with a control (EC 0.9 dS m⁻¹, having only nutrient solution). The pH of the solutions was maintained between 6.0-6.5 throughout the experiment by 1M HCl/NaOH and the solutions were continuously aerated with aeration pumps. The experiment was designed according to a completely randomized design with three NaCl treatments, two potassium levels, four varieties and three replicates.

3.2.2.3 Gas exchange measurements

After 15 and 30 days of salt treatment, leaf gas exchange characteristics were measured by pre-calibrated open system portable Infra-Red Gas Analyzer (LCA4 - ADC Bioscientific) from youngest fully expanded leaves. Net photosynthetic rate (A), stomatal conductance (gs), intercellular CO₂ concentration (Ci) and transpiration rate (E) were determined between 8:00 and 11:00 AM.

3.2.2.4 Plant growth characteristics

Plant samples were collected after 15 and 30 days of salt treatment, shoot and root fresh weight and length were measured. Plant dry weight measured after drying them in an oven at 65 ± 5 °C in hot air oven (Model DHG-9053A, R and M Marketing, Sussex, UK) till constant weight.

3.2.2.5 Photosynthetic pigments

For measuring the photosynthetic pigments 0.2 g of fresh leaf was extracted overnight with 80% acetone at -4°C. The extract was centrifuged at 10,000× g for 5 minutes. Absorbance of the supernatant was recorded at 645 and 663 nm using a spectrophotometer (Hitachi-220, Japan). The chlorophyll a and b were calculated by the following Arnon (1949) formula:

\[
\text{Chl a (mg g}^{-1}\text{ f.wt.) = [12.7(OD 663)-2.69(OD 645) \times V/1000\times W]}
\]

\[
\text{Chl b (mg g}^{-1}\text{ f.wt.) = [22.9(OD 645)-4.68(OD 663) \times V/1000\times W]}
\]
Where \( V \) = volume of the sample, \( W \) = weight of fresh tissue.

### 3.2.2.6 Membrane stability index (MSI)

The membrane stability index (MSI) was determined according to Sairam *et al.*, (2002). Fresh plant material (0.1 g of leaf) was taken in 10 ml of double distilled water in two sets. One set was kept at 40 °C temperature in water bath for 30 min and its electrical conductivity was recorded (EC1) using an electrical conductivity meter (Model 315i, WTW instruments Wilhelm, Germany). A second set was kept in a boiling water bath (100 °C) for 10 min and its electrical conductivity was also recorded (EC2). MSI was calculated as below:

\[
MSI = [1 - (C1/C2)] \times 100
\]

### 3.2.2.7 Leaf sap Na\(^+\) and K\(^+\) determination

Leaf sap Na\(^+\) and K\(^+\) ions were measured according to Gorham *et al.*, 1984. Frozen leaves were thawed and crushed with stainless steel rod and sap was collected in eppendorf tubes and centrifuged at 6500 rpm for 10 minutes. The supernatant was used for the determination of Na\(^+\) and K\(^+\) ions by flame photometer (Sherwood Flame photometer, Model-410; Sherwood Scientific, Ltd, Cambridge UK) using standards of NaCl and KCl.

### 3.2.2.8 Determination of enzymatic activities

For the determination of antioxidant enzymes 0.5 g of leaf sample was homogenized with pre-chilled mortar and pestle in 0.1 M phosphate buffer (pH=7.5) having 0.5 mM EDTA. Then the homogenate was centrifuged for 15 min at 15000×g at 4°C in Beckman refrigerated centrifuge. The supernatant thus obtained was collected and used for the determination of SOD, CAT and GR activity (Esfandiari *et al.*, 2007).

SOD activity was assayed by noting the ability of photochemical inhibition of nitro blue tetrazolium (NBT) (Sen Gupta *et al.*, 1993). About 3 ml of reaction mixture, containing 0.1ml of 200mM methionine, 0.01 ml of 2.25 mM nitro-blue tetrazolium (NBT), 0.1 ml of 3 mM EDTA, 1.5 ml of 100 mM potassium phosphate buffer, 1ml distilled water and 0.05 ml of enzyme extraction, were taken in test tubes in duplicate from each enzyme sample. Two tubes without enzyme extract were taken as control. The reaction was started by adding 0.1 ml riboflavin (60 µM) and placing the tubes below a light source of two 15 W florescent lamps for 15 min. Reaction was stopped by switching off the light and covering the tubes
with black cloth. Tubes without enzyme developed maximal colour. A non-irradiated complete reaction mixture which did not develop colour served as blank. Absorbance was recorded at 560 nm and one unit of enzyme activity was taken as the quantity of enzyme which reduced the absorbance reading of samples to 50% in comparison with tubes lacking enzymes.

CAT activity was measured according to Aebi (1984). About 3 ml reaction mixture containing 1.5 ml of 100 mM potassium phosphate buffer (pH=7), 0.5 ml of 75 mM H₂O₂, 0.05 ml enzyme extraction and distilled water to make up the volume to 3 ml. Reaction started by adding H₂O₂ and decrease in absorbance recorded at 240 nm for 1 min. Enzyme activity was computed by calculating the amount of H₂O₂ decomposed.

GR activity was assayed by recording the increase in absorbance in the presence of oxidized glutathione (GSSG) and 5, 5-dithiobis-2-nitrbenzoic acid (DTNB) (Sairam et al., 2002). The reaction mixture contained 1 ml of 0.2 M potassium phosphate buffer (pH=7.5) containing 0.1 mM EDTA, 0.5 ml of 3 mM DTNB in 0.01 M potassium phosphate buffer (pH=7.5), 0.1 ml of 2 mM NADPH, 0.1 ml enzyme extract and distilled water to make up a final volume of 2.9 ml. Reaction initiated by adding 0.1 ml of 2 mM GSSG. The increase in absorbance at 412 nm recorded at 25°C over a period of 5 min on a spectrophotometer.

Malondialdehyde (MDA) was measured by colorimetric method (Stewart and Bewley, 1980). 0.5 g of leaf samples were homogenized in 5 ml of distilled water. An equal volume of 0.5% thiobarbituric acid (TBA) in 20% trichloroacetic acid solution was added and the sample incubated at 95°C for 30 min. The reaction stopped by putting the reaction tubes in the ice bath. The samples then centrifuged at 10000×g for 30 min. The supernatant removed, absorption read at 532 nm, and the amount of nonspecific absorption at 600 nm read and subtracted from this value. The amount of MDA present calculated from the extinction coefficient of 155 mM⁻¹cm⁻¹.

3.2.2.9 Statistical analysis

Data are presented as the mean of three replicates. Three way analysis of variance (ANOVA) test was employed to check the statistical significance of different variables using “Statistix 8.0” software. Comparisons with P values < 0.05 were considered significantly different.
3.2.3 Results

3.2.3.1 Effect of foliar and solution application of potassium on growth of four tomato genotypes under NaCl salinity

Data regarding growth parameters are statistically analyzed and results revealed that effect of treatments, genotypes and their interaction was highly significant at p < 0.05 (see ANOVA Appendix 14-19 ab).

Tomato plant growth characteristics; shoot fresh weight, root fresh weight, shoot dry weight, root dry weight, shoot length and root length are shown in figures 3.2.1-3.2.6. Generally, NaCl stress significantly decreased all the measured growth characteristics in both the salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) genotypes compared to respective control irrespective of time (after 15 and 30 days). Highest values of these parameters were observed at control in both the salt sensitive and tolerant genotypes and these values significantly decreased at 75 and 150 mM NaCl level. However salt-tolerant genotypes maintained higher growth at all NaCl levels than the salt-sensitive genotypes. After 15 and 30 days of salt stress the highest values of shoot fresh weight (34.6, 55.4), root fresh weight (1.9, 3.9), shoot dry weight (2.1, 3.3), root dry weight (0.30, 0.52), shoot length (25.4, 47.1) and root length (36, 49) was in salt tolerant genotype Indent-1 and minimum values of shoot fresh weight (11.5, 21.5), root fresh weight (0.7, 1.53), shoot dry weight (0.8, 1.2), root dry weight (0.10, 0.21), shoot length (8.9, 18.4) and root length (11.1, 19.8) in salt-sensitive genotype Red Ball at 150 mM NaCl (0 mM K).

The potassium treatments (both foliar and solution) had a significant effect on all these growth parameters and significantly decreased the negative effects of NaCl stress especially at 9 mM K⁺ compared to zero potassium at both the time periods. The difference between the solution and foliar potassium application was non-significant, although the effect was more pronounced in solution form of potassium application. The response of genotypes to potassium treatments was more pronounced in tolerant (Indent-1 and Nagina) than sensitive genotypes (Peto-86 and Red Ball).
Table: 3.2.1 Shoot fresh weight (SFW, g) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>57.6 ± 1.2</td>
<td>89.7 ± 2.6</td>
<td>51.3 ± 1.7</td>
<td>75.3 ± 2.2</td>
<td>29.4 ± 1.4</td>
<td>44.7 ± 1.7</td>
<td>28.6 ± 0.7</td>
<td>42.6 ± 1.2</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>61.3 ± 1.1</td>
<td>94.1 ± 2.1</td>
<td>55.4 ± 1.7</td>
<td>80.4 ± 1.6</td>
<td>33.2 ± 0.8</td>
<td>50.5 ± 1.5</td>
<td>33.7 ± 2.1</td>
<td>48.4 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>66.4 ± 1.6</td>
<td>99.7 ± 1.7</td>
<td>60.1 ± 2.2</td>
<td>87.6 ± 1.4</td>
<td>39.5 ± 2.0</td>
<td>57.6 ± 1.4</td>
<td>38.4 ± 0.4</td>
<td>53.8 ± 0.9</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>60.5 ± 1.7</td>
<td>92.4 ± 1.7</td>
<td>53.9 ± 2.6</td>
<td>78.5 ± 1.7</td>
<td>32.6 ± 1.2</td>
<td>47.6 ± 1.7</td>
<td>31.4 ± 0.9</td>
<td>45.7 ± 1.3</td>
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<td>9</td>
<td>64.7 ± 1.8</td>
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<td>58.7 ± 1.6</td>
<td>85.1 ± 1.1</td>
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<td>55.1 ± 0.9</td>
<td>36.2 ± 1.5</td>
<td>50.4 ± 1.1</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>52.1 ± 1.7</td>
<td>80.8 ± 1.9</td>
<td>47.3 ± 1.4</td>
<td>67.4 ± 1.1</td>
<td>21.3 ± 1.2</td>
<td>38.5 ± 0.9</td>
<td>24.8 ± 0.9</td>
<td>37.3 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>58.6 ± 2.0</td>
<td>87.6 ± 1.7</td>
<td>50.4 ± 1.5</td>
<td>76.8 ± 1.4</td>
<td>26.6 ± 0.4</td>
<td>43.7 ± 0.9</td>
<td>29.5 ± 0.5</td>
<td>40.7 ± 1.0</td>
</tr>
<tr>
<td>75 mM NaCl</td>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>34.6 ± 1.0</td>
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<td>50.2 ± 1.5</td>
<td>11.5 ± 0.3</td>
<td>21.5 ± 0.9</td>
<td>12.4 ± 0.5</td>
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<td>44.7 ± 1.2</td>
<td>72.8 ± 2.0</td>
<td>41.7 ± 1.8</td>
<td>67.1 ± 1.6</td>
<td>19.4 ± 0.7</td>
<td>29.7 ± 0.8</td>
<td>15.6 ± 0.7</td>
<td>28.6 ± 0.9</td>
</tr>
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<td></td>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>52.6 ± 1.5</td>
<td>75.8 ± 1.4</td>
<td>43.9 ± 1.1</td>
<td>72.3 ± 2.3</td>
<td>22.1 ± 0.7</td>
<td>33.7 ± 0.8</td>
<td>21.8 ± 0.6</td>
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<td>150 mM NaCl</td>
<td>Solution K (mM)</td>
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<td>18.0 ± 0.9</td>
<td>27.5 ± 1.2</td>
<td>13.7 ± 0.4</td>
</tr>
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<td>9</td>
<td>49.7 ± 1.4</td>
<td>73.5 ± 1.9</td>
<td>42.6 ± 1.2</td>
<td>71.5 ± 2.7</td>
<td>20.5 ± 0.6</td>
<td>32.3 ± 1.1</td>
<td>20.1 ± 0.7</td>
<td>30.7 ± 1.0</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.2 Shoot dry weight (SDW, g) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>Indent-1 15 days</th>
<th>Indent-1 30 days</th>
<th>Nagina 15 days</th>
<th>Nagina 30 days</th>
<th>Peto-86 15 days</th>
<th>Peto-86 30 days</th>
<th>Red Ball 15 days</th>
<th>Red Ball 30 days</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15 days</td>
<td>30 days</td>
<td>15 days</td>
<td>30 days</td>
<td>15 days</td>
<td>30 days</td>
<td>15 days</td>
<td>30 days</td>
</tr>
<tr>
<td>Control</td>
<td>0</td>
<td>3.27 ± 0.08</td>
<td>5.63 ± 0.28</td>
<td>2.96 ± 0.10</td>
<td>4.56 ± 0.18</td>
<td>1.57 ± 0.07</td>
<td>2.76 ± 0.24</td>
<td>1.45 ± 0.04</td>
<td>2.62 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>3.36 ± 0.12</td>
<td>5.68 ± 0.28</td>
<td>3.01 ± 0.10</td>
<td>5.60 ± 0.34</td>
<td>1.61 ± 0.06</td>
<td>2.80 ± 0.19</td>
<td>1.47 ± 0.05</td>
<td>2.67 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>3.34 ± 0.09</td>
<td>5.66 ± 0.31</td>
<td>2.98 ± 0.12</td>
<td>4.57 ± 0.41</td>
<td>1.59 ± 0.06</td>
<td>2.78 ± 0.20</td>
<td>1.46 ± 0.05</td>
<td>2.65 ± 0.24</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>0</td>
<td>3.44 ± 0.16</td>
<td>5.73 ± 0.49</td>
<td>3.09 ± 0.10</td>
<td>4.66 ± 0.23</td>
<td>1.64 ± 0.08</td>
<td>2.85 ± 0.23</td>
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<td>2.70 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>3.40 ± 0.12</td>
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<td>1.60 ± 0.07</td>
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<td>2.68 ± 0.12</td>
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<tr>
<td></td>
<td>9</td>
<td>2.62 ± 0.07</td>
<td>4.54 ± 0.09</td>
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<td>3.47 ± 0.10</td>
<td>1.13 ± 0.06</td>
<td>1.92 ± 0.11</td>
<td>1.03 ± 0.05</td>
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<tr>
<td>75 mM NaCl</td>
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<td>2.70 ± 0.17</td>
<td>4.58 ± 0.32</td>
<td>2.54 ± 0.07</td>
<td>3.52 ± 0.23</td>
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<td>1.09 ± 0.03</td>
<td>2.10 ± 0.36</td>
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<tr>
<td></td>
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<td>2.65 ± 0.10</td>
<td>4.57 ± 0.39</td>
<td>2.51 ± 0.07</td>
<td>3.50 ± 0.28</td>
<td>1.16 ± 0.06</td>
<td>1.94 ± 0.12</td>
<td>1.06 ± 0.05</td>
<td>2.07 ± 0.14</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>0</td>
<td>2.76 ± 0.06</td>
<td>4.61 ± 0.29</td>
<td>2.60 ± 0.06</td>
<td>3.58 ± 0.30</td>
<td>1.20 ± 0.04</td>
<td>2.01 ± 0.08</td>
<td>1.11 ± 0.04</td>
<td>2.13 ± 0.12</td>
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<td>4.5</td>
<td>2.73 ± 0.08</td>
<td>4.60 ± 0.37</td>
<td>2.59 ± 0.07</td>
<td>3.54 ± 0.38</td>
<td>1.18 ± 0.05</td>
<td>1.99 ± 0.13</td>
<td>1.08 ± 0.06</td>
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<tr>
<td></td>
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<td>2.14 ± 0.06</td>
<td>3.31 ± 0.24</td>
<td>1.97 ± 0.09</td>
<td>2.73 ± 0.24</td>
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<td>1.40 ± 0.13</td>
<td>0.75 ± 0.04</td>
<td>1.21 ± 0.11</td>
</tr>
<tr>
<td>Solution K (mM)</td>
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<td>2.19 ± 0.07</td>
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<td>2.79 ± 0.24</td>
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<td>1.45 ± 0.12</td>
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<td>2.23 ± 0.08</td>
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<td>2.83 ± 0.18</td>
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<td>1.48 ± 0.12</td>
<td>0.82 ± 0.04</td>
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<td>2.80 ± 0.20</td>
<td>0.88 ± 0.03</td>
<td>1.45 ± 0.13</td>
<td>0.80 ± 0.04</td>
<td>1.28 ± 0.07</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.3 Root fresh weight (RFW, g) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>3.81 ± 0.17</td>
<td>7.63 ± 0.04</td>
<td>3.28 ± 0.14</td>
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<td>1.86 ± 0.09</td>
<td>3.83 ± 0.33</td>
<td>1.78 ± 0.04</td>
<td>3.67 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>3.94 ± 0.13</td>
<td>7.86 ± 0.33</td>
<td>3.41 ± 0.10</td>
<td>6.57 ± 0.08</td>
<td>1.98 ± 0.07</td>
<td>3.97 ± 0.56</td>
<td>1.85 ± 0.10</td>
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<tr>
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<td>3.89 ± 0.22</td>
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<td>6.53 ± 0.45</td>
<td>1.96 ± 0.10</td>
<td>3.92 ± 0.16</td>
<td>1.81 ± 0.07</td>
<td>3.75 ± 0.21</td>
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<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>3.99 ± 0.13</td>
<td>7.94 ± 0.34</td>
<td>3.52 ± 0.12</td>
<td>6.68 ± 0.27</td>
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<td>1.24 ± 0.05</td>
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<td>4.96 ± 0.15</td>
<td>1.32 ± 0.06</td>
<td>2.52 ± 0.12</td>
<td>1.38 ± 0.05</td>
<td>2.33 ± 0.29</td>
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<td>2.85 ± 0.16</td>
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<td>2.44 ± 0.07</td>
<td>4.91 ± 0.15</td>
<td>1.29 ± 0.05</td>
<td>2.50 ± 0.32</td>
<td>1.35 ± 0.08</td>
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</tr>
<tr>
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<td>2.58 ± 0.10</td>
<td>5.06 ± 0.07</td>
<td>1.41 ± 0.05</td>
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<td>1.48 ± 0.09</td>
<td>2.44 ± 0.16</td>
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<tr>
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<td>2.94 ± 0.10</td>
<td>5.44 ± 0.30</td>
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<td>4.99 ± 0.18</td>
<td>1.39 ± 0.06</td>
<td>2.53 ± 0.22</td>
<td>1.44 ± 0.11</td>
<td>2.40 ± 0.15</td>
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<td>3.94 ± 0.13</td>
<td>1.52 ± 0.05</td>
<td>3.76 ± 0.19</td>
<td>0.78 ± 0.04</td>
<td>1.61 ± 0.17</td>
<td>0.69 ± 0.02</td>
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</tr>
<tr>
<td></td>
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<td>1.94 ± 0.09</td>
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<td>1.69 ± 0.07</td>
<td>3.97 ± 0.17</td>
<td>0.90 ± 0.03</td>
<td>1.71 ± 0.10</td>
<td>0.83 ± 0.03</td>
<td>1.70 ± 0.08</td>
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<tr>
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<td>4.11 ± 0.12</td>
<td>1.64 ± 0.07</td>
<td>3.93 ± 0.24</td>
<td>0.86 ± 0.02</td>
<td>1.67 ± 0.11</td>
<td>0.80 ± 0.04</td>
<td>1.67 ± 0.11</td>
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</table>

Each value is mean of three replicates ± SE
Table: 3.2.4 Root dry weight (RDW, g) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>Indent-1</th>
<th>Nagina</th>
<th>Peto-86</th>
<th>Red Ball</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15 days</td>
<td>30 days</td>
<td>15 days</td>
<td>30 days</td>
</tr>
<tr>
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<td></td>
<td>15 days</td>
<td>30 days</td>
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<td>30 days</td>
</tr>
<tr>
<td>0</td>
<td>0.422 ± 0.019</td>
<td>0.757 ± 0.057</td>
<td>0.365 ± 0.012</td>
<td>0.653 ± 0.035</td>
<td>0.216 ± 0.010</td>
</tr>
<tr>
<td>4.5</td>
<td>0.449 ± 0.021</td>
<td>0.797 ± 0.040</td>
<td>0.403 ± 0.011</td>
<td>0.713 ± 0.050</td>
<td>0.227 ± 0.005</td>
</tr>
<tr>
<td>9</td>
<td>0.424 ± 0.010</td>
<td>0.783 ± 0.078</td>
<td>0.372 ± 0.031</td>
<td>0.680 ± 0.036</td>
<td>0.235 ± 0.010</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>0.486 ± 0.020</td>
<td>0.833 ± 0.071</td>
<td>0.444 ± 0.015</td>
<td>0.737 ± 0.051</td>
</tr>
<tr>
<td>0</td>
<td>0.456 ± 0.013</td>
<td>0.790 ± 0.087</td>
<td>0.414 ± 0.010</td>
<td>0.703 ± 0.050</td>
<td>0.245 ± 0.014</td>
</tr>
<tr>
<td></td>
<td>75 mM NaCl</td>
<td>4.5</td>
<td>0.356 ± 0.016</td>
<td>0.687 ± 0.042</td>
<td>0.352 ± 0.011</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.348 ± 0.017</td>
<td>0.677 ± 0.040</td>
<td>0.324 ± 0.023</td>
<td>0.593 ± 0.035</td>
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<td>0.338 ± 0.016</td>
<td>0.743 ± 0.076</td>
<td>0.383 ± 0.054</td>
<td>0.633 ± 0.101</td>
<td>0.215 ± 0.007</td>
</tr>
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<td>0.368 ± 0.020</td>
<td>0.713 ± 0.081</td>
<td>0.362 ± 0.027</td>
<td>0.607 ± 0.045</td>
<td>0.202 ± 0.006</td>
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<tr>
<td>9</td>
<td>0.303 ± 0.006</td>
<td>0.520 ± 0.036</td>
<td>0.268 ± 0.016</td>
<td>0.443 ± 0.067</td>
<td>0.134 ± 0.009</td>
</tr>
<tr>
<td>0</td>
<td>0.337 ± 0.017</td>
<td>0.560 ± 0.062</td>
<td>0.313 ± 0.008</td>
<td>0.487 ± 0.057</td>
<td>0.155 ± 0.009</td>
</tr>
<tr>
<td>4.5</td>
<td>0.306 ± 0.010</td>
<td>0.537 ± 0.055</td>
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<td>0.460 ± 0.036</td>
<td>0.140 ± 0.009</td>
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<td>9</td>
<td>0.338 ± 0.018</td>
<td>0.603 ± 0.086</td>
<td>0.318 ± 0.015</td>
<td>0.513 ± 0.065</td>
<td>0.203 ± 0.006</td>
</tr>
<tr>
<td>0</td>
<td>0.338 ± 0.021</td>
<td>0.577 ± 0.091</td>
<td>0.318 ± 0.015</td>
<td>0.513 ± 0.065</td>
<td>0.165 ± 0.027</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.5 Shoot length (SL, cm) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indent-1</td>
<td>Nagina</td>
<td>Peto-86</td>
<td>Red Ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>Solution K (mM)</td>
<td>4.5 41.3 ± 1.2 66.3 ± 1.7 37.8 ± 1.2 57.9 ± 2.6 21.3 ± 1.4 37.3 ± 1.6 20.5 ± 0.9 35.1 ± 1.0</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>Control</td>
<td>46.1 ± 1.3 72.2 ± 1.6 43.1 ± 1.4 62.7 ± 1.6 24.7 ± 1.0 40.9 ± 1.1 23.8 ± 0.7 39.6 ± 1.1</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>9</td>
<td>Foliar K (mM)</td>
<td>4.5 44.5 ± 1.5 68.7 ± 1.7 41.5 ± 1.8 60.6 ± 1.5 23.4 ± 0.9 39.2 ± 1.1 22.2 ± 0.9 37.2 ± 1.2</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>4.5 51.6 ± 2.4 77.3 ± 2.9 47.3 ± 1.7 68.2 ± 2.2 28.6 ± 1.1 44.6 ± 1.5 27.5 ± 0.7 43.8 ± 1.4</td>
<td></td>
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</tr>
<tr>
<td>75 mM NaCl</td>
<td>9 67.0 ± 2.6 94.0 ± 2.5 57.6 ± 1.8 75.7 ± 2.3 35.8 ± 1.6 62.6 ± 2.2 26.3 ± 1.3 33.6 ± 1.2</td>
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</tr>
<tr>
<td>9</td>
<td>Foliar K (mM)</td>
<td>4.5 45.4 ± 1.2 66.2 ± 1.8 41.7 ± 1.2 57.6 ± 2.0 18.2 ± 0.5 34.1 ± 1.1 19.1 ± 0.6 33.6 ± 1.3</td>
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</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>9 42.1 ± 1.4 62.6 ± 2.4 38.6 ± 1.0 55.6 ± 2.0 16.5 ± 0.7 30.5 ± 1.0 16.7 ± 0.7 30.1 ± 0.6</td>
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</tr>
<tr>
<td>150 mM NaCl</td>
<td>0 25.4 ± 0.9 47.1 ± 1.2 23.6 ± 0.8 41.1 ± 1.3 9.5 ± 0.4 20.7 ± 0.4 8.9 ± 0.3 18.3 ± 0.4</td>
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</tr>
<tr>
<td>4.5</td>
<td>Solution K (mM)</td>
<td>9 29.7 ± 1.0 52.3 ± 2.1 27.4 ± 0.9 44.9 ± 1.5 12.3 ± 0.4 24.4 ± 1.0 12.1 ± 0.3 23.9 ± 0.6</td>
<td></td>
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</tr>
<tr>
<td>9</td>
<td>Foliar K (mM)</td>
<td>4.5 27.5 ± 1.2 50.4 ± 1.8 25.3 ± 0.9 43.1 ± 1.7 11.5 ± 0.4 22.5 ± 0.9 10.9 ± 0.5 21.7 ± 1.0</td>
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</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>9 34.6 ± 1.2 58.9 ± 1.7 31.5 ± 1.2 50.5 ± 1.2 14.2 ± 0.5 28.6 ± 0.8 14.4 ± 0.4 27.8 ± 0.6</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>Foliar K (mM)</td>
<td>9 32.1 ± 1.4 55.4 ± 2.0 29.5 ± 1.0 47.6 ± 1.5 12.9 ± 0.5 25.1 ± 0.6 12.7 ± 0.6 24.6 ± 0.5</td>
<td></td>
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</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.6 Root length (RL, cm) response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indent-1</td>
<td>Nagina</td>
<td>Peto-86</td>
<td>Red Ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0</td>
<td>47.5 ± 1.4</td>
<td>80.6 ± 2.6</td>
<td>42.3 ± 1.6</td>
<td>66.1 ± 2.8</td>
<td>23.5 ± 0.9</td>
<td>39.4 ± 1.2</td>
<td>21.5 ± 0.8</td>
<td>36.8 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>52.2 ± 1.7</td>
<td>84.7 ± 2.4</td>
<td>45.8 ± 2.1</td>
<td>71.2 ± 2.6</td>
<td>25.8 ± 1.0</td>
<td>42.5 ± 1.6</td>
<td>23.3 ± 1.0</td>
<td>39.3 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>50.6 ± 2.3</td>
<td>82.1 ± 3.4</td>
<td>44.2 ± 1.7</td>
<td>68.7 ± 2.5</td>
<td>24.5 ± 0.9</td>
<td>41.3 ± 1.1</td>
<td>22.5 ± 0.8</td>
<td>37.7 ± 0.7</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>57.4 ± 1.9</td>
<td>89.3 ± 3.1</td>
<td>50.4 ± 1.8</td>
<td>73.8 ± 2.2</td>
<td>29.1 ± 0.9</td>
<td>45.4 ± 1.3</td>
<td>26.1 ± 1.3</td>
<td>42.3 ± 1.5</td>
</tr>
<tr>
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<td>9</td>
<td>55.1 ± 1.6</td>
<td>86.7 ± 3.6</td>
<td>47.6 ± 1.7</td>
<td>70.4 ± 2.2</td>
<td>26.7 ± 1.1</td>
<td>43.5 ± 1.1</td>
<td>23.8 ± 0.8</td>
<td>40.6 ± 1.1</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>40.6 ± 1.5</td>
<td>67.1 ± 2.5</td>
<td>33.5 ± 1.3</td>
<td>53.4 ± 2.3</td>
<td>19.4 ± 0.8</td>
<td>27.5 ± 1.2</td>
<td>16.7 ± 0.6</td>
<td>30.2 ± 1.6</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>46.7 ± 1.7</td>
<td>74.5 ± 2.8</td>
<td>36.2 ± 1.4</td>
<td>56.8 ± 1.5</td>
<td>22.5 ± 1.0</td>
<td>29.4 ± 0.9</td>
<td>18.6 ± 0.6</td>
<td>34.7 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>44.2 ± 1.4</td>
<td>72.1 ± 2.4</td>
<td>34.9 ± 1.0</td>
<td>55.5 ± 1.9</td>
<td>21.2 ± 1.0</td>
<td>28.5 ± 1.6</td>
<td>17.5 ± 0.6</td>
<td>32.6 ± 1.9</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>51.3 ± 1.8</td>
<td>77.3 ± 3.1</td>
<td>39.5 ± 1.2</td>
<td>60.2 ± 2.1</td>
<td>24.9 ± 1.0</td>
<td>32.6 ± 1.3</td>
<td>21.1 ± 0.7</td>
<td>36.4 ± 1.5</td>
</tr>
<tr>
<td>75 mM NaCl</td>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>48.6 ± 1.3</td>
<td>76.4 ± 2.2</td>
<td>37.4 ± 1.2</td>
<td>58.6 ± 4.2</td>
<td>23.4 ± 0.9</td>
<td>30.7 ± 1.4</td>
<td>19.7 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>53.1 ± 1.3</td>
<td>53.1 ± 2.1</td>
<td>35.6 ± 1.3</td>
<td>43.4 ± 2.5</td>
<td>14.7 ± 0.6</td>
<td>23.1 ± 1.5</td>
<td>13.4 ± 0.6</td>
<td>22.4 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>43.7 ± 1.2</td>
<td>57.2 ± 1.8</td>
<td>38.7 ± 1.2</td>
<td>46.2 ± 1.2</td>
<td>16.5 ± 0.6</td>
<td>26.5 ± 1.7</td>
<td>16.3 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>41.6 ± 1.4</td>
<td>54.3 ± 2.1</td>
<td>35.6 ± 1.5</td>
<td>44.1 ± 2.3</td>
<td>14.8 ± 0.4</td>
<td>25.1 ± 1.6</td>
<td>14.4 ± 0.5</td>
<td>22.7 ± 1.4</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
3.2.3.2 Effect of foliar and solution application of potassium on gas exchange characteristics and membrane stability index (MSI) of four tomato genotypes under NaCl salinity

Generally the effect of treatments and genotypes was highly significant as indicated by the ANOVA (Appendix 20—23 ab). The higher NaCl concentration (75 and 150 mM) caused significant reduction in all the measured gas exchange characteristics as compared to control (figures: 3.2.7-3.2.10) namely; photosynthetic rate (A), transpiration rate (E), intercellular CO₂ concentration (Ci) and stomatal conductance (gs) in all the four tomato genotypes. The salt-tolerant genotypes Indent-1 and Nagina showed higher values of these parameters than the salt-sensitive genotypes Peto-86 and Red Ball, while the difference within the salt-tolerant and salt-sensitive genotypes was non-significant. Also the effect of NaCl treatments was similar after both the times (15 and 30 days). However potassium application (both solution and foliar) had significantly (p < 0.05) increased the values of these parameters at higher concentrations (4.5 and 9 mM) especially in tolerant genotypes. The solution form of potassium had non-significant higher effect on these characteristics than foliar form potassium at both the time intervals.

Membrane stability index was measured to assess the damage of membranes by salt stress and on an overall average basis; the effect of different treatments and genotypes was highly significant as evident from the analysis of variance table (Appendix 24). A significant decrease in membrane stability index was observed at 75 and 150 mM NaCl compared to control in both the salt tolerant and sensitive genotypes at both the time intervals (Figure: 3.2.11). The differences between the salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) genotypes were highly significant especially at 75 and 150 mM NaCl, however, the difference within the two salt-tolerant and salt-sensitive genotypes were non-significant. The salt sensitive genotypes (Peto-86 and Red Ball) showed significantly higher decrease in the MSI at both the NaCl levels (75 and 150 mM) than the salt tolerant genotypes; which maintained a fairly high MSI. The effect of application of potassium was significant (P < 0.05) and it positively affected MSI compared to subsequently lower levels of salinity at the same potassium level; however the effect was non-significant within the same salinity level in all the four genotypes.
Table: 3.2.7 Photosynthetic rate (A, μmol m⁻² s⁻¹) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>2.79 ± 0.12</td>
<td>5.30 ± 0.24</td>
<td>2.61 ± 0.15</td>
<td>4.95 ± 0.23</td>
<td>1.50 ± 0.05</td>
<td>2.84 ± 0.20</td>
<td>1.44 ± 0.07</td>
<td>2.74 ± 0.25</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>2.70 ± 0.12</td>
<td>5.11 ± 0.44</td>
<td>2.52 ± 0.06</td>
<td>4.77 ± 0.40</td>
<td>1.42 ± 0.08</td>
<td>2.69 ± 0.35</td>
<td>1.35 ± 0.04</td>
<td>2.55 ± 0.35</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>3.13 ± 0.12</td>
<td>5.93 ± 0.22</td>
<td>2.87 ± 0.13</td>
<td>5.44 ± 0.41</td>
<td>1.73 ± 0.07</td>
<td>3.29 ± 0.08</td>
<td>1.67 ± 0.05</td>
<td>3.16 ± 0.24</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>2.93 ± 0.14</td>
<td>5.55 ± 0.34</td>
<td>2.77 ± 0.09</td>
<td>5.25 ± 0.24</td>
<td>1.62 ± 0.06</td>
<td>3.07 ± 0.12</td>
<td>1.56 ± 0.05</td>
<td>2.97 ± 0.23</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>2.38 ± 0.05</td>
<td>4.51 ± 0.25</td>
<td>2.13 ± 0.08</td>
<td>4.03 ± 0.32</td>
<td>1.00 ± 0.07</td>
<td>1.90 ± 0.13</td>
<td>1.01 ± 0.13</td>
<td>1.92 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>2.26 ± 0.07</td>
<td>4.29 ± 0.16</td>
<td>2.04 ± 0.08</td>
<td>3.86 ± 0.27</td>
<td>0.93 ± 0.05</td>
<td>1.77 ± 0.17</td>
<td>0.92 ± 0.06</td>
<td>1.74 ± 0.18</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>2.75 ± 0.09</td>
<td>5.22 ± 0.29</td>
<td>2.53 ± 0.09</td>
<td>4.79 ± 0.21</td>
<td>1.10 ± 0.06</td>
<td>2.09 ± 0.09</td>
<td>1.16 ± 0.03</td>
<td>2.20 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>2.55 ± 0.10</td>
<td>4.84 ± 0.28</td>
<td>2.34 ± 0.11</td>
<td>4.44 ± 0.29</td>
<td>1.00 ± 0.06</td>
<td>1.90 ± 0.13</td>
<td>1.01 ± 0.09</td>
<td>1.92 ± 0.10</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>1.80 ± 0.10</td>
<td>3.41 ± 0.23</td>
<td>1.66 ± 0.06</td>
<td>3.15 ± 0.15</td>
<td>0.75 ± 0.06</td>
<td>1.41 ± 0.16</td>
<td>0.73 ± 0.09</td>
<td>1.39 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1.67 ± 0.07</td>
<td>3.16 ± 0.16</td>
<td>1.53 ± 0.10</td>
<td>2.91 ± 0.16</td>
<td>0.70 ± 0.05</td>
<td>1.32 ± 0.18</td>
<td>0.66 ± 0.04</td>
<td>1.25 ± 0.12</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>2.10 ± 0.08</td>
<td>3.96 ± 0.13</td>
<td>1.91 ± 0.09</td>
<td>3.62 ± 0.22</td>
<td>0.86 ± 0.06</td>
<td>1.63 ± 0.15</td>
<td>0.87 ± 0.03</td>
<td>1.66 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1.95 ± 0.08</td>
<td>3.69 ± 0.16</td>
<td>1.79 ± 0.08</td>
<td>3.39 ± 0.10</td>
<td>0.78 ± 0.07</td>
<td>1.48 ± 0.06</td>
<td>0.77 ± 0.04</td>
<td>1.46 ± 0.06</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.8 Transpiration rate (E, mmol m$^{-2}$ s$^{-1}$) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>Indent-1 15 days</th>
<th>Indent-1 30 days</th>
<th>Nagina 15 days</th>
<th>Nagina 30 days</th>
<th>Peto-86 15 days</th>
<th>Peto-86 30 days</th>
<th>Red Ball 15 days</th>
<th>Red Ball 30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>2.24 ± 0.10</td>
<td>4.05 ± 0.34</td>
<td>1.89 ± 0.09</td>
<td>3.41 ± 0.17</td>
<td>1.04 ± 0.06</td>
<td>1.96 ± 0.13</td>
<td>1.07 ± 0.05</td>
<td>2.03 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>2.30 ± 0.09</td>
<td>4.10 ± 0.06</td>
<td>1.93 ± 0.11</td>
<td>3.46 ± 0.21</td>
<td>1.07 ± 0.07</td>
<td>2.01 ± 0.08</td>
<td>1.10 ± 0.05</td>
<td>2.07 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>2.27 ± 0.11</td>
<td>4.08 ± 0.16</td>
<td>1.92 ± 0.11</td>
<td>3.43 ± 0.28</td>
<td>1.05 ± 0.07</td>
<td>1.98 ± 0.14</td>
<td>1.09 ± 0.06</td>
<td>2.06 ± 0.18</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>2.34 ± 0.09</td>
<td>4.15 ± 0.18</td>
<td>1.98 ± 0.09</td>
<td>3.51 ± 0.23</td>
<td>1.11 ± 0.06</td>
<td>2.05 ± 0.12</td>
<td>1.14 ± 0.05</td>
<td>2.12 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>2.31 ± 0.12</td>
<td>5.12 ± 0.35</td>
<td>1.96 ± 0.10</td>
<td>3.47 ± 0.36</td>
<td>1.09 ± 0.08</td>
<td>2.02 ± 0.08</td>
<td>1.13 ± 0.04</td>
<td>2.09 ± 0.11</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>1.85 ± 0.10</td>
<td>3.37 ± 0.12</td>
<td>1.39 ± 0.08</td>
<td>2.74 ± 0.13</td>
<td>0.73 ± 0.02</td>
<td>1.37 ± 0.12</td>
<td>0.79 ± 0.04</td>
<td>1.45 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1.88 ± 0.04</td>
<td>3.41 ± 0.25</td>
<td>1.43 ± 0.08</td>
<td>2.78 ± 0.18</td>
<td>0.78 ± 0.03</td>
<td>1.41 ± 0.08</td>
<td>0.84 ± 0.04</td>
<td>1.50 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>1.90 ± 0.09</td>
<td>3.43 ± 0.21</td>
<td>1.47 ± 0.09</td>
<td>2.82 ± 0.18</td>
<td>0.81 ± 0.03</td>
<td>1.44 ± 0.15</td>
<td>0.89 ± 0.05</td>
<td>1.54 ± 0.12</td>
<td>1.54 ± 0.12</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>1.93 ± 0.09</td>
<td>3.46 ± 0.25</td>
<td>1.47 ± 0.09</td>
<td>2.82 ± 0.18</td>
<td>0.81 ± 0.03</td>
<td>1.44 ± 0.15</td>
<td>0.89 ± 0.05</td>
<td>1.54 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1.90 ± 0.09</td>
<td>3.43 ± 0.21</td>
<td>1.44 ± 0.07</td>
<td>2.79 ± 0.13</td>
<td>0.79 ± 0.05</td>
<td>1.42 ± 0.10</td>
<td>0.85 ± 0.04</td>
<td>1.51 ± 0.07</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>1.43 ± 0.08</td>
<td>2.85 ± 0.10</td>
<td>1.01 ± 0.08</td>
<td>2.05 ± 0.11</td>
<td>0.47 ± 0.03</td>
<td>1.02 ± 0.06</td>
<td>0.55 ± 0.03</td>
<td>1.04 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1.47 ± 0.08</td>
<td>2.89 ± 0.14</td>
<td>1.08 ± 0.07</td>
<td>2.10 ± 0.10</td>
<td>0.50 ± 0.04</td>
<td>1.06 ± 0.07</td>
<td>0.60 ± 0.04</td>
<td>1.09 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>1.45 ± 0.08</td>
<td>2.86 ± 0.11</td>
<td>1.05 ± 0.07</td>
<td>2.07 ± 0.10</td>
<td>0.48 ± 0.03</td>
<td>1.04 ± 0.07</td>
<td>0.57 ± 0.04</td>
<td>1.06 ± 0.09</td>
<td>1.06 ± 0.09</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>1.51 ± 0.07</td>
<td>2.95 ± 0.18</td>
<td>1.14 ± 0.07</td>
<td>2.14 ± 0.12</td>
<td>0.54 ± 0.04</td>
<td>1.11 ± 0.13</td>
<td>0.63 ± 0.03</td>
<td>1.14 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1.49 ± 0.06</td>
<td>2.90 ± 0.15</td>
<td>1.10 ± 0.06</td>
<td>2.11 ± 0.05</td>
<td>0.51 ± 0.03</td>
<td>1.07 ± 0.10</td>
<td>0.59 ± 0.04</td>
<td>1.10 ± 0.07</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.9 Intercellular CO\textsubscript{2} concentration (Ci, mmol m\textsuperscript{-2} s\textsuperscript{-1}) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

| Salinity | Potassium (mM) | Indent-1 15 days | Indent-1 30 days | Nagina 15 days | Nagina 30 days | Peto-86 15 days | Peto-86 30 days | Red Ball 15 days | Red Ball 30 days |
|----------|----------------|------------------|------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Control  | 0              | 139.4 ± 5.0      | 170.5 ± 6.6      | 125.7 ± 7.1    | 149.6 ± 9.2    | 64.1 ± 2.9      | 85.7 ± 5.1      | 61.6 ± 2.4      | 81.9 ± 3.6      |
| Solution | 4.5            | 149.3 ± 5.3      | 179.5 ± 8.4      | 133.6 ± 5.9    | 158.3 ± 5.6    | 68.4 ± 3.2      | 91.5 ± 4.3      | 67.1 ± 2.8      | 87.4 ± 3.9      |
|          | 9              | 144.7 ± 7.2      | 174.3 ± 8.1      | 129.1 ± 5.4    | 154.7 ± 7.0    | 66.3 ± 2.9      | 89.3 ± 4.4      | 64.4 ± 2.4      | 84.8 ± 3.0      |
| Foliar K | 4.5            | 155.1 ± 7.1      | 186.4 ± 10.3     | 141.7 ± 5.2    | 166.5 ± 7.4    | 74.2 ± 3.0      | 97.6 ± 4.6      | 73.5 ± 3.6      | 93.7 ± 4.0      |
|          | 9              | 150.8 ± 5.9      | 178.9 ± 8.9      | 138.3 ± 5.3    | 160.2 ± 10.2   | 70.5 ± 2.2      | 93.4 ± 4.8      | 68.1 ± 1.9      | 88.7 ± 4.1      |

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium (mM)</th>
<th>Indent-1 15 days</th>
<th>Indent-1 30 days</th>
<th>Nagina 15 days</th>
<th>Nagina 30 days</th>
<th>Peto-86 15 days</th>
<th>Peto-86 30 days</th>
<th>Red Ball 15 days</th>
<th>Red Ball 30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 mM NaCl</td>
<td>0</td>
<td>114.7 ± 4.9</td>
<td>141.3 ± 7.8</td>
<td>102.3 ± 3.5</td>
<td>123.7 ± 8.1</td>
<td>47.7 ± 2.7</td>
<td>59.9 ± 2.7</td>
<td>44.9 ± 1.7</td>
<td>63.4 ± 2.2</td>
</tr>
<tr>
<td>Solution</td>
<td>4.5</td>
<td>124.8 ± 6.0</td>
<td>149.7 ± 6.3</td>
<td>110.2 ± 4.2</td>
<td>129.2 ± 5.2</td>
<td>52.3 ± 1.7</td>
<td>65.7 ± 4.0</td>
<td>50.3 ± 1.6</td>
<td>68.7 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>118.4 ± 5.5</td>
<td>145.1 ± 6.1</td>
<td>108.1 ± 5.5</td>
<td>126.1 ± 5.6</td>
<td>50.4 ± 2.4</td>
<td>63.1 ± 3.7</td>
<td>47.5 ± 2.2</td>
<td>65.4 ± 2.6</td>
</tr>
<tr>
<td>Foliar K</td>
<td>4.5</td>
<td>132.5 ± 4.5</td>
<td>157.8 ± 8.3</td>
<td>116.4 ± 6.0</td>
<td>137.6 ± 6.6</td>
<td>59.7 ± 2.5</td>
<td>71.0 ± 2.6</td>
<td>56.8 ± 2.2</td>
<td>72.8 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>126.7 ± 5.3</td>
<td>150.4 ± 8.3</td>
<td>112.9 ± 4.7</td>
<td>132.1 ± 7.6</td>
<td>54.2 ± 2.2</td>
<td>67.4 ± 1.7</td>
<td>52.1 ± 2.1</td>
<td>68.6 ± 2.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium (mM)</th>
<th>Indent-1 15 days</th>
<th>Indent-1 30 days</th>
<th>Nagina 15 days</th>
<th>Nagina 30 days</th>
<th>Peto-86 15 days</th>
<th>Peto-86 30 days</th>
<th>Red Ball 15 days</th>
<th>Red Ball 30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 mM NaCl</td>
<td>0</td>
<td>94.3 ± 3.5</td>
<td>119.8 ± 9.7</td>
<td>87.6 ± 3.2</td>
<td>110.2 ± 5.6</td>
<td>36.4 ± 1.7</td>
<td>48.1 ± 3.3</td>
<td>35.1 ± 1.1</td>
<td>44.5 ± 1.9</td>
</tr>
<tr>
<td>Solution</td>
<td>4.5</td>
<td>102.1 ± 5.0</td>
<td>126.7 ± 7.7</td>
<td>95.1 ± 4.5</td>
<td>117.8 ± 5.0</td>
<td>40.7 ± 1.4</td>
<td>53.2 ± 2.2</td>
<td>39.7 ± 1.7</td>
<td>48.2 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>98.3 ± 4.5</td>
<td>124.3 ± 6.7</td>
<td>92.4 ± 3.3</td>
<td>115.1 ± 5.8</td>
<td>38.6 ± 1.6</td>
<td>51.7 ± 1.9</td>
<td>38.6 ± 1.7</td>
<td>46.7 ± 1.5</td>
</tr>
<tr>
<td>Foliar K</td>
<td>4.5</td>
<td>111.2 ± 5.8</td>
<td>135.2 ± 7.4</td>
<td>101.3 ± 4.5</td>
<td>125.3 ± 6.2</td>
<td>45.1 ± 1.9</td>
<td>60.5 ± 2.3</td>
<td>43.7 ± 1.5</td>
<td>53.7 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>105.6 ± 4.9</td>
<td>128.9 ± 6.2</td>
<td>98.7 ± 4.3</td>
<td>120.7 ± 5.9</td>
<td>42.3 ± 1.2</td>
<td>54.6 ± 1.5</td>
<td>40.5 ± 1.3</td>
<td>49.6 ± 1.3</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.10 Stomatal conductance ($g_s$, $\mu$mol mol$^{-1}$) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>Solution K (mM)</td>
<td>Foliar K (mM)</td>
<td>Control</td>
<td>Solution K (mM)</td>
<td>Foliar K (mM)</td>
<td>Control</td>
<td>Solution K (mM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.5</td>
<td>9</td>
<td></td>
<td>4.5</td>
<td>9</td>
<td></td>
<td>4.5</td>
</tr>
<tr>
<td>0</td>
<td>0.368 ± 0.020</td>
<td>0.459 ± 0.037</td>
<td>0.322 ± 0.010</td>
<td>0.395 ± 0.035</td>
<td>0.207 ± 0.009</td>
<td>0.224 ± 0.024</td>
<td>0.195 ± 0.011</td>
<td>0.214 ± 0.015</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>0.401 ± 0.015</td>
<td>0.475 ± 0.055</td>
<td>0.348 ± 0.019</td>
<td>0.411 ± 0.025</td>
<td>0.227 ± 0.011</td>
<td>0.239 ± 0.020</td>
<td>0.220 ± 0.014</td>
<td>0.223 ± 0.014</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.382 ± 0.023</td>
<td>0.469 ± 0.025</td>
<td>0.337 ± 0.020</td>
<td>0.405 ± 0.029</td>
<td>0.218 ± 0.013</td>
<td>0.236 ± 0.017</td>
<td>0.207 ± 0.013</td>
<td>0.218 ± 0.013</td>
<td></td>
</tr>
<tr>
<td>0.269 ± 0.014</td>
<td>0.270 ± 0.016</td>
<td>0.223 ± 0.010</td>
<td>0.225 ± 0.009</td>
<td>0.116 ± 0.007</td>
<td>0.118 ± 0.007</td>
<td>0.105 ± 0.004</td>
<td>0.110 ± 0.006</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.11 Membrane stability index (MSI, %) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of potassium NaCl and after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>Indent-1 15 days</th>
<th>Indent-1 30 days</th>
<th>Nagina 15 days</th>
<th>Nagina 30 days</th>
<th>Peto-86 15 days</th>
<th>Peto-86 30 days</th>
<th>Red Ball 15 days</th>
<th>Red Ball 30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>4.5</td>
<td>9</td>
<td>0</td>
<td>4.5</td>
<td>9</td>
<td>0</td>
<td>4.5</td>
</tr>
<tr>
<td>Control</td>
<td>Solution K (mM)</td>
<td>89.4 ± 3.8</td>
<td>90.7 ± 3.5</td>
<td>90.2 ± 4.5</td>
<td>91.8 ± 3.8</td>
<td>91.0 ± 3.6</td>
<td>80.7 ± 4.3</td>
<td>83.4 ± 3.3</td>
<td>82.5 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>90.1 ± 3.2</td>
<td>91.4 ± 2.9</td>
<td>90.7 ± 2.4</td>
<td>92.3 ± 1.8</td>
<td>91.5 ± 2.1</td>
<td>82.3 ± 2.1</td>
<td>85.6 ± 2.0</td>
<td>84.3 ± 2.3</td>
</tr>
<tr>
<td>75 mM NaCl</td>
<td>Solution K (mM)</td>
<td>87.3 ± 4.0</td>
<td>89.6 ± 3.9</td>
<td>88.7 ± 4.2</td>
<td>91.4 ± 3.5</td>
<td>90.5 ± 2.3</td>
<td>78.4 ± 3.7</td>
<td>81.2 ± 3.3</td>
<td>80.4 ± 3.4</td>
</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>90.5 ± 2.2</td>
<td>91.7 ± 3.1</td>
<td>91.1 ± 2.0</td>
<td>92.1 ± 1.8</td>
<td>91.6 ± 2.3</td>
<td>81.6 ± 1.9</td>
<td>83.1 ± 2.3</td>
<td>81.7 ± 2.3</td>
</tr>
<tr>
<td>150 mM NaCl</td>
<td>Solution K (mM)</td>
<td>86.6 ± 2.2</td>
<td>88.7 ± 3.9</td>
<td>89.5 ± 2.9</td>
<td>92.7 ± 2.9</td>
<td>90.5 ± 2.9</td>
<td>70.8 ± 1.8</td>
<td>72.4 ± 2.0</td>
<td>71.5 ± 1.8</td>
</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>90.0 ± 1.7</td>
<td>90.5 ± 1.7</td>
<td>90.5 ± 1.7</td>
<td>90.0 ± 2.6</td>
<td>89.6 ± 2.6</td>
<td>60.5 ± 1.6</td>
<td>62.7 ± 1.7</td>
<td>61.5 ± 1.4</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
3.2.3.3 Effect of foliar and solution application of potassium on leaf ionic parameters of four tomato genotypes under NaCl salinity

Analysis of variance regarding plant leaf ionic contents is presented in Appendix 25-27ab, which showed a significant difference between the tolerant and sensitive genotypes and the effects of different treatments were highly significant as well. The interactive effect of genotypes and treatments was highly significant as well except K⁺ in which it was non-significant.

With the increasing NaCl concentration in the growth medium significant differences in leaf Na⁺ and K⁺ concentration between salt-tolerant and salt-sensitive genotypes were observed (figures 3.2.12-3.2.14). The concentration of Na⁺ increased with increasing solution NaCl concentration (75 and 150 mM) compared to control, but the increase was more in salt sensitive genotypes (Peto-86 and Red Ball) than the salt tolerant genotypes (Indent-1 and Nagina). An opposite trend was found in case of K⁺ concentration, and a significant reduction was found at 150 mM NaCl concentration compared to control and 75 mM NaCl in all the four tomato genotypes, and consequently K⁺/Na⁺. The salt-tolerant genotypes (Indent-1 and Nagina) maintained fairly high K⁺ concentration than the salt-sensitive genotypes (Peto-86 and Red Ball) and thus higher K⁺/Na⁺ as well. The application of potassium (both solution and foliar) significantly reduced leaf Na⁺ concentration and increased leaf K⁺ concentration, and consequently K⁺/Na⁺ ratio in all the genotypes especially at 9 mM K⁺. The salt-tolerant genotypes responded to potassium application significantly than salt-sensitive genotypes. The effect of foliar and solution form of potassium application was non-significant, however the effect was more when K⁺ was applied to the growth media compared to foliar application.
Table: 3.2.12 Leaf sap Na\(^+\) concentration (mol m\(^{-3}\)) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>Indent-1 15 days</th>
<th>Indent-1 30 days</th>
<th>Nagina 15 days</th>
<th>Nagina 30 days</th>
<th>Peto-86 15 days</th>
<th>Peto-86 30 days</th>
<th>Red Ball 15 days</th>
<th>Red Ball 30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>34.3 ± 1.7</td>
<td>37.8 ± 1.8</td>
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Each value is mean of three replicates ± SE
Table: 3.2.13 Leaf sap K⁺ concentration (mol m⁻³) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

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<td>Peto-86</td>
<td>Red Ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>195.8 ± 11.3</td>
<td>213.1 ± 9.8</td>
<td>174.4 ± 9.6</td>
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<td>105.8 ± 4.1</td>
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Each value is mean of three replicates ± SE
Table: 3.2.14 Leaf sap K⁺/Na⁺ concentration in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

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<th>Peto-86 30 days</th>
<th>Red Ball 15 days</th>
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</table>

Each value is mean of three replicates ± SE
3.2.3.4 Effect of foliar and solution application of potassium on photosynthetic pigments and antioxidant enzymes activity of four tomato genotypes under NaCl salinity

Analysis of variance table showed highly significant effect of treatments and genotypes whereas the interaction between treatments and genotypes was non-significant for photosynthetic pigments (CHL a, CHL b and total CHL) (Appendix 28-30ab). The effect of NaCl on photosynthetic pigments (CHL a, CHL b) differed significantly in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) tomato genotypes (Figures 3.2.15-3.2.17), while difference within same salt-tolerance group was non-significant at both the time periods. Higher levels of NaCl (75 and 150 mM) in the growing solution caused a significant decrease in photosynthetic pigments compared to control with higher values in salt tolerant genotypes than the salt sensitive genotypes regardless of time. Potassium application (foliar and solution) significantly increased the chlorophyll content especially at highest concentrations (9 mM). Among the genotypes the salt tolerant genotypes responded more to the application of potassium both in solution and foliar application than the salt sensitive genotypes. The response of potassium was similar at both the time periods (15 and 30 days) in all the genotypes.

Antioxidative enzymes were significantly affected by different treatments and the genotypes also differed significantly with respect to the activity of antioxidant enzymes (Appendix 31-34ab). The activity of antioxidant enzymes; superoxide dismutase (SOD), catalase (CAT), glutathione reductase (GR) and melon dialdehyde (MDA) was determined under NaCl (control, 75 and 150 mM) and potassium (4.5 and 9 mM) treatments after 15 and 30 days (Figures 3.2.18-3.2.21). It has been observed that increasing NaCl concentration caused a significant increase in all antioxidant enzymes after both the time periods. The salt-tolerant genotypes (Indent-1 and Nagina) showed a significantly higher antioxidants (SOD, CAT, GR) activity and lower MDA contents than the salt-sensitive genotypes (Peto-86 and Red Ball) at higher NaCl levels. The effect of time was non-significant in all genotypes and in all the three NaCl levels. The potassium application (both solution and foliar) significantly decreased the antioxidants activity in all the four tomato genotypes; however the salt tolerant genotypes responded significantly better than the salt sensitive genotypes. The difference between the responses of antioxidants to forms of potassium was also non-significant.
Table: 3.2.15 Plant leaf chlorophyll a (mg g⁻¹ FW) contents in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>4.5</td>
<td>9</td>
<td>4.5</td>
<td>9</td>
<td>4.5</td>
<td>9</td>
<td>4.5</td>
</tr>
<tr>
<td>Control</td>
<td>Solution K (mM)</td>
<td>5.76 ± 0.16</td>
<td>6.17 ± 0.14</td>
<td>5.91 ± 0.22</td>
<td>6.68 ± 0.17</td>
<td>6.39 ± 0.23</td>
<td>4.81 ± 0.12</td>
<td>5.23 ± 0.14</td>
<td>5.07 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>6.43 ± 0.12</td>
<td>6.86 ± 0.17</td>
<td>6.73 ± 0.11</td>
<td>7.37 ± 0.13</td>
<td>7.18 ± 0.30</td>
<td>5.52 ± 0.32</td>
<td>6.22 ± 0.31</td>
<td>6.10 ± 0.20</td>
</tr>
<tr>
<td>75 mM NaCl</td>
<td>Solution K (mM)</td>
<td>5.53 ± 0.16</td>
<td>5.89 ± 0.18</td>
<td>5.73 ± 0.17</td>
<td>6.10 ± 0.09</td>
<td>5.95 ± 0.15</td>
<td>4.65 ± 0.12</td>
<td>4.95 ± 0.09</td>
<td>4.82 ± 0.12</td>
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<tr>
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<td>Foliar K (mM)</td>
<td>6.15 ± 0.13</td>
<td>6.86 ± 0.15</td>
<td>6.27 ± 0.06</td>
<td>7.06 ± 0.32</td>
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<td>5.08 ± 0.17</td>
<td>5.79 ± 0.70</td>
<td>5.37 ± 0.38</td>
</tr>
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<td>150 mM NaCl</td>
<td>Solution K (mM)</td>
<td>4.31 ± 0.11</td>
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<td>4.63 ± 0.15</td>
<td>5.20 ± 0.14</td>
<td>4.89 ± 0.13</td>
<td>3.50 ± 0.11</td>
<td>3.83 ± 0.09</td>
<td>3.71 ± 0.10</td>
</tr>
<tr>
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<td>Foliar K (mM)</td>
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<td>6.53 ± 0.33</td>
<td>6.13 ± 0.62</td>
<td>4.47 ± 0.54</td>
<td>4.89 ± 0.29</td>
<td>4.68 ± 0.41</td>
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</table>

Each value is mean of three replicates ± SE
Table: 3.2.16 Plant leaf chlorophyll b (mg g⁻¹ FW) contents in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
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<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indent-1</td>
<td>Nagina</td>
<td>Peto-86</td>
<td>Red Ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 mM NaCl</td>
<td>0</td>
<td>8.34 ± 0.23</td>
<td>9.35 ± 0.26</td>
<td>8.00 ± 0.25</td>
<td>8.95 ± 0.27</td>
<td>6.24 ± 0.15</td>
<td>8.18 ± 0.60</td>
<td>6.70 ± 0.20</td>
<td>8.30 ± 0.44</td>
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<td>4.5</td>
<td>8.93 ± 0.19</td>
<td>9.98 ± 0.18</td>
<td>8.52 ± 0.28</td>
<td>9.98 ± 0.25</td>
<td>7.05 ± 0.18</td>
<td>8.80 ± 0.37</td>
<td>7.40 ± 0.22</td>
<td>8.95 ± 0.50</td>
</tr>
<tr>
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<td>8.55 ± 0.30</td>
<td>9.79 ± 0.16</td>
<td>8.29 ± 0.24</td>
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<td>6.70 ± 0.21</td>
<td>8.53 ± 0.74</td>
<td>7.13 ± 0.13</td>
<td>8.66 ± 0.66</td>
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<td>5.02 ± 0.21</td>
<td>5.63 ± 0.23</td>
<td>3.99 ± 0.13</td>
<td>4.69 ± 0.11</td>
<td>3.92 ± 0.14</td>
<td>4.86 ± 0.13</td>
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<td>5.97 ± 0.15</td>
<td>7.14 ± 0.60</td>
<td>5.81 ± 0.16</td>
<td>6.92 ± 0.10</td>
<td>4.67 ± 0.16</td>
<td>5.53 ± 0.18</td>
<td>4.54 ± 0.09</td>
<td>5.33 ± 0.26</td>
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<td>9</td>
<td>5.89 ± 0.18</td>
<td>6.72 ± 0.11</td>
<td>5.76 ± 0.15</td>
<td>6.50 ± 0.06</td>
<td>4.44 ± 0.14</td>
<td>4.95 ± 0.16</td>
<td>4.26 ± 0.14</td>
<td>4.67 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>15 days</td>
<td>6.99 ± 0.16</td>
<td>7.42 ± 0.35</td>
<td>6.71 ± 0.16</td>
<td>7.19 ± 0.29</td>
<td>5.09 ± 0.13</td>
<td>5.96 ± 0.28</td>
<td>5.00 ± 0.15</td>
<td>5.64 ± 0.13</td>
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<td>6.66 ± 0.21</td>
<td>7.06 ± 0.14</td>
<td>6.12 ± 0.15</td>
<td>6.96 ± 0.32</td>
<td>4.76 ± 0.14</td>
<td>5.52 ± 0.09</td>
<td>4.48 ± 0.09</td>
<td>5.08 ± 0.18</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.17 Plant leaf chlorophyll a+b contents in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indent-1</td>
<td>Nagina</td>
<td>Peto-86</td>
<td>Red Ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0</td>
<td>14.10 ± 0.39</td>
<td>15.78 ± 0.63</td>
<td>13.53 ± 0.41</td>
<td>15.10 ± 0.29</td>
<td>10.55 ± 0.26</td>
<td>13.81 ± 0.20</td>
<td>11.33 ± 0.34</td>
<td>14.01 ± 0.23</td>
</tr>
<tr>
<td>Solution K (mM) 4.5</td>
<td>15.10 ± 0.33</td>
<td>16.84 ± 0.44</td>
<td>14.41 ± 0.46</td>
<td>16.84 ± 0.33</td>
<td>11.92 ± 0.30</td>
<td>14.85 ± 0.21</td>
<td>12.51 ± 0.37</td>
<td>15.10 ± 0.21</td>
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</tr>
<tr>
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<td>14.46 ± 0.52</td>
<td>16.52 ± 0.38</td>
<td>14.02 ± 0.42</td>
<td>15.39 ± 0.35</td>
<td>11.33 ± 0.37</td>
<td>14.39 ± 0.24</td>
<td>12.06 ± 0.23</td>
<td>14.61 ± 0.24</td>
</tr>
<tr>
<td>Foliar K (mM) 4.5</td>
<td>16.35 ± 0.42</td>
<td>18.10 ± 0.43</td>
<td>14.93 ± 0.22</td>
<td>17.34 ± 0.37</td>
<td>12.73 ± 0.34</td>
<td>16.04 ± 0.23</td>
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<td>16.48 ± 0.36</td>
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<td>15.59 ± 0.59</td>
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<td>16.68 ± 0.46</td>
<td>11.93 ± 0.29</td>
<td>15.06 ± 0.25</td>
<td>12.61 ± 0.27</td>
<td>15.35 ± 0.34</td>
</tr>
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<td>75 mM NaCl</td>
<td>0.92</td>
<td>12.59 ± 0.27</td>
<td>15.12 ± 0.65</td>
<td>11.92 ± 0.15</td>
<td>11.65 ± 0.47</td>
<td>9.22 ± 0.17</td>
<td>11.89 ± 0.35</td>
<td>10.04 ± 0.12</td>
<td>12.14 ± 0.45</td>
</tr>
<tr>
<td>Solution K (mM) 4.5</td>
<td>12.21 ± 0.27</td>
<td>14.97 ± 0.81</td>
<td>11.60 ± 0.27</td>
<td>13.18 ± 0.54</td>
<td>8.93 ± 0.09</td>
<td>11.48 ± 0.31</td>
<td>9.49 ± 0.16</td>
<td>11.67 ± 0.50</td>
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</tr>
<tr>
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<td>9</td>
<td>13.99 ± 0.31</td>
<td>16.02 ± 0.65</td>
<td>13.07 ± 0.37</td>
<td>15.16 ± 0.49</td>
<td>10.26 ± 0.25</td>
<td>12.55 ± 0.37</td>
<td>11.27 ± 0.27</td>
<td>13.20 ± 0.57</td>
</tr>
<tr>
<td>Foliar K (mM) 4.5</td>
<td>13.48 ± 0.43</td>
<td>15.70 ± 0.80</td>
<td>12.39 ± 0.32</td>
<td>14.35 ± 0.71</td>
<td>9.84 ± 0.23</td>
<td>12.04 ± 0.50</td>
<td>10.29 ± 0.27</td>
<td>12.53 ± 0.44</td>
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</tr>
<tr>
<td>150 mM NaCl</td>
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<td>9.07 ± 0.20</td>
<td>10.40 ± 0.96</td>
<td>8.58 ± 0.35</td>
<td>9.52 ± 0.92</td>
<td>6.82 ± 0.22</td>
<td>7.93 ± 0.54</td>
<td>6.70 ± 0.24</td>
<td>8.22 ± 0.59</td>
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<tr>
<td>Solution K (mM) 4.5</td>
<td>10.20 ± 0.25</td>
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<td>11.70 ± 1.42</td>
<td>7.89 ± 0.28</td>
<td>9.35 ± 0.79</td>
<td>7.67 ± 0.14</td>
<td>9.01 ± 0.96</td>
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<tr>
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<td>9.95 ± 0.31</td>
<td>11.36 ± 1.24</td>
<td>9.73 ± 0.24</td>
<td>10.99 ± 0.69</td>
<td>7.50 ± 0.25</td>
<td>8.37 ± 0.69</td>
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<tr>
<td>Foliar K (mM) 4.5</td>
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<td>9.61 ± 0.65</td>
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<td>11.33 ± 0.36</td>
<td>12.03 ± 1.73</td>
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<td>11.86 ± 0.92</td>
<td>8.10 ± 0.23</td>
<td>9.41 ± 0.76</td>
<td>7.62 ± 0.15</td>
<td>8.66 ± 0.99</td>
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</table>

Each value is mean of three replicates ± SE
Table: 3.2.18 Superoxide dismutase activity (SOD, Units mg Prot.\(^{-1}\) min\(^{-1}\)) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity Potassium</th>
<th>Indent-1 15 days</th>
<th>Indent-1 30 days</th>
<th>Nagina 15 days</th>
<th>Nagina 30 days</th>
<th>Peto-86 15 days</th>
<th>Peto-86 30 days</th>
<th>Red Ball 15 days</th>
<th>Red Ball 30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12.39 ± 0.60</td>
<td>13.24 ± 0.63</td>
<td>10.28 ± 0.38</td>
<td>11.12 ± 0.29</td>
<td>6.93 ± 0.20</td>
<td>7.49 ± 0.20</td>
<td>7.38 ± 0.17</td>
<td>8.54 ± 0.23</td>
</tr>
<tr>
<td>4.5</td>
<td>14.25 ± 0.57</td>
<td>15.89 ± 0.44</td>
<td>12.14 ± 0.43</td>
<td>14.52 ± 0.33</td>
<td>7.69 ± 0.23</td>
<td>8.94 ± 0.21</td>
<td>8.62 ± 0.38</td>
<td>9.49 ± 0.21</td>
</tr>
<tr>
<td>9</td>
<td>13.59 ± 0.61</td>
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<td>11.69 ± 0.27</td>
<td>12.91 ± 0.35</td>
<td>7.27 ± 0.21</td>
<td>8.41 ± 0.24</td>
<td>8.12 ± 0.25</td>
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</tr>
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<td>16.82 ± 0.50</td>
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<td>16.34 ± 0.46</td>
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<td>10.17 ± 0.25</td>
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<tr>
<td>Foliar K (mM)</td>
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<td>20.57 ± 0.41</td>
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<td>26.16 ± 0.48</td>
<td>28.69 ± 0.65</td>
<td>21.15 ± 0.52</td>
<td>22.89 ± 0.47</td>
<td>16.14 ± 0.33</td>
<td>17.33 ± 0.35</td>
<td>15.52 ± 0.46</td>
</tr>
<tr>
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<td>75 mM NaCl</td>
<td>25.64 ± 0.75</td>
<td>27.72 ± 0.81</td>
<td>20.07 ± 0.60</td>
<td>20.87 ± 0.54</td>
<td>15.35 ± 0.52</td>
<td>16.14 ± 0.31</td>
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<td>27.83 ± 0.92</td>
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<td>36.43 ± 1.66</td>
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<td>29.79 ± 0.69</td>
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<td>20.06 ± 0.69</td>
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<td>150 mM NaCl</td>
<td>39.29 ± 1.26</td>
<td>42.73 ± 1.08</td>
<td>33.53 ± 1.31</td>
<td>36.27 ± 1.01</td>
<td>21.29 ± 0.65</td>
<td>23.34 ± 1.06</td>
<td>24.52 ± 0.97</td>
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<td>4.5</td>
<td>38.45 ± 1.48</td>
<td>39.89 ± 1.73</td>
<td>31.37 ± 0.98</td>
<td>34.19 ± 0.92</td>
<td>20.66 ± 0.61</td>
<td>21.45 ± 0.76</td>
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<td></td>
<td>9</td>
<td>38.45 ± 1.48</td>
<td>39.89 ± 1.73</td>
<td>31.37 ± 0.98</td>
<td>34.19 ± 0.92</td>
<td>20.66 ± 0.61</td>
<td>21.45 ± 0.76</td>
<td>23.04 ± 0.88</td>
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</tbody>
</table>

Each value is mean of three replicates ± SE
<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
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<th>30 days</th>
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<tr>
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<td>Solution K (mM)</td>
<td>0.744 ± 0.061</td>
<td>0.789 ± 0.065</td>
<td>0.657 ± 0.036</td>
<td>0.726 ± 0.036</td>
<td>0.553 ± 0.043</td>
<td>0.597 ± 0.039</td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td>0.780 ± 0.031</td>
<td>0.810 ± 0.046</td>
<td>0.694 ± 0.014</td>
<td>0.757 ± 0.028</td>
<td>0.595 ± 0.025</td>
<td>0.664 ± 0.026</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.764 ± 0.048</td>
<td>0.804 ± 0.043</td>
<td>0.671 ± 0.020</td>
<td>0.740 ± 0.033</td>
<td>0.580 ± 0.022</td>
<td>0.634 ± 0.025</td>
</tr>
<tr>
<td>4.5</td>
<td>Foliar K (mM)</td>
<td>0.826 ± 0.022</td>
<td>0.872 ± 0.018</td>
<td>0.747 ± 0.037</td>
<td>0.815 ± 0.036</td>
<td>0.646 ± 0.036</td>
<td>0.728 ± 0.040</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.804 ± 0.044</td>
<td>0.863 ± 0.028</td>
<td>0.722 ± 0.032</td>
<td>0.798 ± 0.041</td>
<td>0.634 ± 0.028</td>
<td>0.702 ± 0.032</td>
</tr>
<tr>
<td>0</td>
<td>Solution K (mM)</td>
<td>1.034 ± 0.022</td>
<td>1.135 ± 0.034</td>
<td>0.965 ± 0.029</td>
<td>1.048 ± 0.050</td>
<td>0.723 ± 0.034</td>
<td>0.822 ± 0.039</td>
</tr>
<tr>
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<td>1.107 ± 0.041</td>
<td>1.187 ± 0.042</td>
<td>1.063 ± 0.041</td>
<td>1.123 ± 0.043</td>
<td>0.772 ± 0.037</td>
<td>0.858 ± 0.035</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>1.065 ± 0.059</td>
<td>1.162 ± 0.030</td>
<td>1.029 ± 0.027</td>
<td>1.096 ± 0.027</td>
<td>0.750 ± 0.021</td>
<td>0.841 ± 0.029</td>
</tr>
<tr>
<td>4.5</td>
<td>Foliar K (mM)</td>
<td>1.184 ± 0.061</td>
<td>1.256 ± 0.037</td>
<td>1.128 ± 0.042</td>
<td>1.196 ± 0.034</td>
<td>0.854 ± 0.046</td>
<td>0.918 ± 0.033</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>1.138 ± 0.058</td>
<td>1.200 ± 0.036</td>
<td>1.091 ± 0.062</td>
<td>1.175 ± 0.036</td>
<td>0.812 ± 0.029</td>
<td>0.877 ± 0.023</td>
</tr>
<tr>
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<td>Solution K (mM)</td>
<td>1.831 ± 0.099</td>
<td>1.966 ± 0.066</td>
<td>1.681 ± 0.052</td>
<td>1.848 ± 0.038</td>
<td>1.044 ± 0.040</td>
<td>1.173 ± 0.025</td>
</tr>
<tr>
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<td></td>
<td>1.896 ± 0.099</td>
<td>2.050 ± 0.070</td>
<td>1.753 ± 0.106</td>
<td>1.898 ± 0.063</td>
<td>1.103 ± 0.034</td>
<td>1.236 ± 0.033</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>1.856 ± 0.101</td>
<td>2.043 ± 0.080</td>
<td>1.720 ± 0.080</td>
<td>1.868 ± 0.050</td>
<td>1.065 ± 0.064</td>
<td>1.203 ± 0.042</td>
</tr>
<tr>
<td>4.5</td>
<td>Foliar K (mM)</td>
<td>1.967 ± 0.112</td>
<td>2.095 ± 0.104</td>
<td>1.822 ± 0.105</td>
<td>1.994 ± 0.082</td>
<td>1.163 ± 0.049</td>
<td>1.288 ± 0.036</td>
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<tr>
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<td></td>
<td>1.943 ± 0.107</td>
<td>2.059 ± 0.113</td>
<td>1.782 ± 0.077</td>
<td>1.937 ± 0.051</td>
<td>1.115 ± 0.074</td>
<td>1.235 ± 0.029</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.20 Glutathione reductase activity (GR, µmol NADPH mg Prot.\(^{-1}\) min\(^{-1}\)) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
<th>15 days</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indent-1</td>
<td>Nagina</td>
<td>Peto-86</td>
<td>Red Ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0</td>
<td>4.47 ± 0.21</td>
<td>4.68 ± 0.21</td>
<td>3.71 ± 0.13</td>
<td>3.88 ± 0.12</td>
<td>2.50 ± 0.06</td>
<td>2.62 ± 0.08</td>
<td>2.66 ± 0.06</td>
<td>2.78 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>5.14 ± 0.23</td>
<td>5.38 ± 0.24</td>
<td>4.38 ± 0.15</td>
<td>4.58 ± 0.18</td>
<td>2.78 ± 0.07</td>
<td>2.90 ± 0.08</td>
<td>3.11 ± 0.08</td>
<td>3.25 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>4.91 ± 0.13</td>
<td>5.13 ± 0.16</td>
<td>4.22 ± 0.11</td>
<td>4.41 ± 0.13</td>
<td>2.62 ± 0.08</td>
<td>2.74 ± 0.09</td>
<td>2.93 ± 0.08</td>
<td>3.06 ± 0.10</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>6.26 ± 0.19</td>
<td>6.54 ± 0.24</td>
<td>5.69 ± 0.12</td>
<td>5.94 ± 0.15</td>
<td>3.34 ± 0.10</td>
<td>3.49 ± 0.12</td>
<td>3.84 ± 0.09</td>
<td>4.01 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>6.07 ± 0.17</td>
<td>6.35 ± 0.19</td>
<td>5.15 ± 0.13</td>
<td>5.38 ± 0.17</td>
<td>3.13 ± 0.10</td>
<td>3.27 ± 0.12</td>
<td>3.39 ± 0.09</td>
<td>3.54 ± 0.11</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>6.03 ± 0.11</td>
<td>6.18 ± 0.16</td>
<td>5.67 ± 0.21</td>
<td>5.82 ± 0.19</td>
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<td>4.04 ± 0.08</td>
<td>4.14 ± 0.13</td>
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<tr>
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<td>9</td>
<td>6.49 ± 0.20</td>
<td>6.66 ± 0.22</td>
<td>6.20 ± 0.14</td>
<td>6.36 ± 0.16</td>
<td>4.50 ± 0.12</td>
<td>4.62 ± 0.13</td>
<td>4.39 ± 0.13</td>
<td>4.50 ± 0.13</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>6.26 ± 0.18</td>
<td>6.42 ± 0.18</td>
<td>6.03 ± 0.19</td>
<td>6.18 ± 0.19</td>
<td>4.39 ± 0.12</td>
<td>4.50 ± 0.12</td>
<td>4.15 ± 0.10</td>
<td>4.26 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>6.90 ± 0.18</td>
<td>7.08 ± 0.22</td>
<td>6.61 ± 0.18</td>
<td>6.78 ± 0.17</td>
<td>4.97 ± 0.10</td>
<td>5.10 ± 0.12</td>
<td>4.74 ± 0.10</td>
<td>4.86 ± 0.11</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>6.67 ± 0.20</td>
<td>6.84 ± 0.22</td>
<td>6.38 ± 0.17</td>
<td>6.54 ± 0.18</td>
<td>4.74 ± 0.10</td>
<td>4.86 ± 0.10</td>
<td>4.56 ± 0.12</td>
<td>4.68 ± 0.11</td>
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<td>7.14 ± 0.22</td>
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<td>6.55 ± 0.19</td>
<td>6.72 ± 0.07</td>
<td>4.95 ± 0.11</td>
<td>5.03 ± 0.16</td>
<td>4.64 ± 0.18</td>
<td>5.12 ± 0.13</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>7.41 ± 0.21</td>
<td>7.60 ± 0.23</td>
<td>6.83 ± 0.17</td>
<td>7.00 ± 0.16</td>
<td>5.37 ± 0.19</td>
<td>5.37 ± 0.19</td>
<td>5.13 ± 0.13</td>
<td>5.48 ± 0.14</td>
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<td>7.25 ± 0.22</td>
<td>7.44 ± 0.24</td>
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<td>6.88 ± 0.18</td>
<td>5.29 ± 0.11</td>
<td>5.29 ± 0.16</td>
<td>4.98 ± 0.19</td>
<td>5.40 ± 0.22</td>
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<tr>
<td>Foliar K (mM)</td>
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<td>7.68 ± 0.22</td>
<td>7.88 ± 0.16</td>
<td>7.10 ± 0.27</td>
<td>7.28 ± 0.20</td>
<td>5.87 ± 0.14</td>
<td>5.93 ± 0.11</td>
<td>5.49 ± 0.19</td>
<td>6.02 ± 0.18</td>
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<td>7.76 ± 0.20</td>
<td>6.94 ± 0.21</td>
<td>7.12 ± 0.15</td>
<td>5.73 ± 0.16</td>
<td>5.85 ± 0.10</td>
<td>5.29 ± 0.18</td>
<td>5.92 ± 0.10</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
Table: 3.2.21 Melondialdehyde contents (MDA, mmol g⁻¹ FW) in salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes in response to different levels of NaCl and potassium after 15 and 30 days of stress

<table>
<thead>
<tr>
<th>Salinity</th>
<th>Potassium</th>
<th>Indent-1 15 days</th>
<th>Nagina 15 days</th>
<th>Peto-86 15 days</th>
<th>Red Ball 15 days</th>
<th>Indent-1 30 days</th>
<th>Nagina 30 days</th>
<th>Peto-86 30 days</th>
<th>Red Ball 30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>4.47 ± 0.21</td>
<td>3.71 ± 0.13</td>
<td>2.50 ± 0.06</td>
<td>2.66 ± 0.08</td>
<td>2.78 ± 0.07</td>
<td>7.12 ± 0.15</td>
<td>5.73 ± 0.16</td>
<td>5.29 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>5.14 ± 0.23</td>
<td>4.38 ± 0.15</td>
<td>2.78 ± 0.07</td>
<td>2.90 ± 0.08</td>
<td>3.11 ± 0.08</td>
<td>6.26 ± 0.17</td>
<td>5.69 ± 0.12</td>
<td>3.34 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>4.91 ± 0.13</td>
<td>4.41 ± 0.13</td>
<td>2.62 ± 0.08</td>
<td>2.74 ± 0.09</td>
<td>2.93 ± 0.08</td>
<td>6.49 ± 0.19</td>
<td>5.94 ± 0.15</td>
<td>3.49 ± 0.12</td>
</tr>
<tr>
<td>Control</td>
<td>4.5</td>
<td>6.26 ± 0.19</td>
<td>5.69 ± 0.12</td>
<td>3.34 ± 0.10</td>
<td>3.49 ± 0.12</td>
<td>3.84 ± 0.09</td>
<td>6.25 ± 0.17</td>
<td>5.94 ± 0.15</td>
<td>3.49 ± 0.12</td>
</tr>
<tr>
<td></td>
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<td>6.07 ± 0.17</td>
<td>5.15 ± 0.13</td>
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<td>3.27 ± 0.12</td>
<td>3.39 ± 0.09</td>
<td>6.54 ± 0.24</td>
<td>6.59 ± 0.12</td>
<td>3.49 ± 0.12</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>6.03 ± 0.11</td>
<td>5.67 ± 0.19</td>
<td>4.21 ± 0.12</td>
<td>4.32 ± 0.15</td>
<td>4.04 ± 0.08</td>
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<td>6.26 ± 0.19</td>
<td>4.39 ± 0.12</td>
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<td>6.49 ± 0.20</td>
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<td>4.97 ± 0.12</td>
<td>4.50 ± 0.13</td>
<td>6.42 ± 0.18</td>
<td>6.18 ± 0.19</td>
<td>4.50 ± 0.12</td>
</tr>
<tr>
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<td>6.90 ± 0.18</td>
<td>6.61 ± 0.18</td>
<td>5.10 ± 0.12</td>
<td>5.27 ± 0.12</td>
<td>4.74 ± 0.10</td>
<td>7.08 ± 0.22</td>
<td>6.78 ± 0.17</td>
<td>5.49 ± 0.11</td>
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<td>4.86 ± 0.10</td>
<td>4.56 ± 0.12</td>
<td>6.84 ± 0.22</td>
<td>6.54 ± 0.18</td>
<td>4.86 ± 0.10</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>7.14 ± 0.22</td>
<td>6.55 ± 0.19</td>
<td>4.95 ± 0.11</td>
<td>5.03 ± 0.16</td>
<td>4.64 ± 0.18</td>
<td>7.32 ± 0.18</td>
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<td>5.37 ± 0.19</td>
<td>5.37 ± 0.19</td>
<td>5.13 ± 0.13</td>
<td>7.60 ± 0.23</td>
<td>7.00 ± 0.16</td>
<td>5.37 ± 0.19</td>
</tr>
<tr>
<td>Solution K (mM)</td>
<td>4.5</td>
<td>7.25 ± 0.22</td>
<td>6.71 ± 0.25</td>
<td>5.29 ± 0.11</td>
<td>5.29 ± 0.16</td>
<td>4.98 ± 0.19</td>
<td>7.44 ± 0.24</td>
<td>6.88 ± 0.18</td>
<td>4.98 ± 0.19</td>
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<td>7.68 ± 0.22</td>
<td>7.10 ± 0.27</td>
<td>5.87 ± 0.14</td>
<td>5.93 ± 0.11</td>
<td>5.49 ± 0.19</td>
<td>7.88 ± 0.16</td>
<td>7.28 ± 0.20</td>
<td>5.93 ± 0.11</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td>4.5</td>
<td>7.57 ± 0.28</td>
<td>6.94 ± 0.21</td>
<td>5.73 ± 0.16</td>
<td>5.85 ± 0.10</td>
<td>5.29 ± 0.18</td>
<td>7.76 ± 0.20</td>
<td>7.12 ± 0.15</td>
<td>5.73 ± 0.16</td>
</tr>
</tbody>
</table>

Each value is mean of three replicates ± SE
3.2.4 Discussion

Salt stress is a complicated phenomenon that induces other stresses as well like osmotic, specific ion toxicity and nutrient deficiency, thereby affecting different biochemical and physiological mechanisms linked to plant growth and development (Sairam et al., 2002).

In the current experiment increasing NaCl concentrations reduced the growth of the tomato plants in both the salt tolerant and sensitive genotypes (Figure 3.2.1-3.2.7), this might be due to the decreased water availability and toxicity of ions (Na\(^+\) and Cl\(^-\)) in the rooting medium (Chen et al., 2007). However, potassium application positively affected the growth of the plants (Figure 3.2.22), which might be due to antagonistic effect between Na\(^+\) and K\(^+\) uptake in the rooting medium. The uptake of potassium varied among tomato genotypes resulting in varied growth response of these genotypes under salt stress. The salt tolerant genotypes (Indent-1 and Nagina) maintained higher levels of K\(^+\) and thus showed better growth than the salt sensitive genotypes (Red Ball and Peto-86). The results in the present experiment were consistent with the previous findings in different crops, rice (Ikeda et al., 2004), tomato (Kaya et al., 2001; Azarmi et al., 2010), cucumber, pepper and strawberry (Kaya et al., 2001b, 2003).

Photosynthesis in crop plants is directly related to dry-matter production and seed yield and it is being controlled by both the stomatal and non-stomatal factors (Natr and Lawlor, 2005). The concentration of K\(^+\) plays an important role in the opening and closing of stomata, and thus it also controls the rate of photosynthesis (Shabala et al., 2002). In the current experiment, application of potassium (both solution and foliar) significantly increased the rate of stomatal conductance (gs), photosynthesis (A) and related gas exchange characteristics i.e. transpiration rate (E), intercellular CO\(_2\) concentration (Ci) in all the four tomato genotypes in both the saline and non-saline conditions. Highly significant positive correlation coefficients were found between leaf tissues K\(^+\) contents and gas exchange characteristics showing that potassium has direct role in the photosynthesis and ultimately plant survival under salt stress (Figure 3.2.23). However, the effect of potassium on the photosynthesis was more pronounced in the salt tolerant genotypes than the salt sensitive. Apart from the role of potassium in stomatal conductance, it is also reported in number of previous studies that optimum concentration of potassium can also enhance chlorophyll
content and activity of photophosphorylase and maintains proton gradient in the chloroplast and thylakoid membranes (Véry and Sentenac, 2003; Yurtseven et al., 2005; Chartzoulakis et al., 2006; Hermans et al., 2006).

Figure 3.2.1 Correlation between leaf K+ concentration and shoot dry weight, shoot fresh weight under NaCl stress and potassium application

Figure 3.2.2 Correlation between CO2 assimilation rate, A (A), stomatal conductance, gs (B), transpiration rate, E (C), intercellular CO2 concentration, Ci (D) and leaf K+ content under NaCl stress and potassium application
Decrease in MSI with increasing salt stress in all the genotypes could be the result of oxidative damage to membranes due to excessive generation of ROS, which resulted in leakage of cellular contents (Gomathi and Rakkiyapan, 2011), as it is evident from the significant correlation between MDA and MSI (Figure 3.2.24). However, significantly higher values of MSI in tolerant genotypes (Indent-1 and Nagina) compared to sensitive, could be attributed to enhanced activities of antioxidant enzymes in these tolerant genotypes (Sairam and Saxena, 2000; Sairam and Tyagi, 2004). Potassium as an ameliorative agent decreased the negative effects of salinity and lower levels of ROS and thus less damage to membranes. Higher MSI and lower lipid peroxidation results were also found by other authors in tolerant genotypes of rice (Tijen and Ismail, 2005), sugarcane (Gomathi and Rakkiyapan, 2011) and wheat (Saqib et al., 2012).

![Figure 3.2.3 Correlation between membrane stability index (MSI) and melon dialdehyde (MDA) under NaCl and potassium application.](image)

Soil salinity destroys the chlorophyll pigments and also causes the instability of pigment protein complex that results in the reduction of chlorophyll a, b and total chlorophyll contents (Azooz et al., 2004; Jaleel et al., 2008). In the current experiment, increasing NaCl concentration in the rooting medium significantly decreased the chlorophyll contents in both salt tolerant and sensitive genotypes. This decrease in chlorophyll content could also been attributed to intervention of salt ions with normal processes of de novo protein synthesis and structural components of chlorophyll instead of chlorophyll destruction (Jaleel et al., 2007; Molazem et al., 2010). The increase in chlorophyll content with application of potassium compared to control treatment (0 mM K+) might be due to decreased tissue Na⁺ contents,
which might be due to the amelioration of negative effects of salt stress and consequently less destruction to chlorophyll contents due to excess of Na\(^+\). The significant correlation coefficient between total chlorophyll content and leaf Na\(^+\) (R\(^2\) = 0.7889), leaf K\(^+\) (R\(^2\) = 0.5721) is indicative of this fact (Figure 3.2.25). Effects of salt stress on chlorophyll content are consistent with the previous findings of Dag\(\text{a}\) et al., (2004), Azooz et al., (2004), Jaleel et al., (2007, 2008), Molazem et al., (2010).

**Figure 3.2.4 Correlation between total chlorophyll content and leaf K\(^+\) (A) and leaf Na\(^+\) (B) under NaCl stress and potassium application**

Exposure of plants to salt stress causes oxidative stress by generating reactive oxygen species (ROS) mainly because of stomatal closure that ultimately decreases the gas exchange, ionic toxicity and K\(^+\) deficiency. Salt tolerant genotypes counteract this oxidative stress by increasing their antioxidative defense capacity by producing antioxidant enzymes like SOD, CAT and GR (Sudhakar et al., 2001; Zhu, 2001; Xu et al., 2011). In this experiment, with increasing NaCl concentration (75 and 150 mM) antioxidant enzymes (SOD, CAT and GR)
activity increased significantly in all the four genotypes, however salt tolerant genotypes (Indent-1 and Nagina) exhibited a significantly higher levels of these antioxidant enzymes than the salt-sensitive genotypes (Red Ball and Peto-86) and thus the lower values of MDA in these genotypes as well. Also the higher levels of K+ application reduced the activity of these antioxidant enzymes. The results in this experiment support the idea that plants exposed to salt stress show oxidative damage while activation of antioxidative defense system played a crucial role in the salt tolerance of plants and decreased the activity of these enzymes with enhanced application of potassium which could be attributed to ameliorative effects of potassium against salt stress. Our results are in conformity with previous findings of Hernandez et al., (2000), Sudhakar et al., (2001) and Xu et al., 2011. It is a well-established fact that plants exposed to NaCl stress show decreased K+ uptake and it is supposed that K+ deficiency at the cellular level might be one of the factors responsible for oxidative stress and cellular damage as evident in this experiment from MDA concentration showing higher contents in potassium deficient plants. Hence improved K+ nutrition under salt stress could be indispensible to minimize this oxidative damage by reducing the formation of ROS and by inhibition of generation of O2− and thus the NADPH oxidase (Shen et al., 2000; Cakmak, 2005; Xu et al., 2011). The findings of Kaya et al., (2001) are consistent with our findings that the foliar application of K+ in the form of KH2PO4 significantly inhibited the decrease in biomass production, chlorophyll and membrane damage and also corrected the K+ deficiency.

Salt-stressed plants are characterized by accumulation of Na+ and impairment of K+-nutrition (Shannon and Grieve 1999; Cakmak, 2005) this might be due to excessive generation of reactive oxygen species (ROS) that causes the lipid peroxidation resulting in the activation of K+ efflux channels and thus the leakage of K+ from the cells (Cuin and Shabala, 2007; Xu et al., 2011). Thus under salt stress optimal level of K+/Na+ ratio becomes a crucial attribute to assess the salt tolerance of species/genotypes (Tester and Davenport, 2003; Shabala et al., 2010). The increasing concentration of NaCl in the growing medium in this study had significantly increased the Na+ concentration in the plant leaves and consequently decreased the K+ concentration at both the time intervals (15 and 30 days) of salt treatments. This decrease in leaf K+ concentration could be the result of antagonism between Na+ and K+ at roots uptake sites and effect of Na+ on the transport of K+ into the xylem (Davenport et al., 2007). However, application of Potassium both in the solution and/or foliar significantly
decreased the leaf Na\textsuperscript{+} content in all the four tomato genotypes. The decreased leaf Na\textsuperscript{+} content might be result of a competition for binding sites on the plasma membrane between K\textsuperscript{+} and Na\textsuperscript{+} which resulted in the suppression of Na\textsuperscript{+} influx from the external solution (Al-Uqaili, 2003; Kusvuran et al., 2007).

It becomes evident from results that salt stress significantly affected the physiology of tomato plants that resulted in the decreased growth; however salt tolerant genotypes maintained better growth. Application of potassium alleviated the toxic effects of NaCl and resulted in low levels of tissue Na\textsuperscript{+} and antioxidant enzymes and improved photosynthetic characteristics and consequently, enhanced growth of plants. The better growth of tolerant genotypes could be attributed to the enhanced uptake/accumulation of potassium in these genotypes and it could also be the result of enhanced activities of antioxidant enzymes. So higher levels of potassium application could be used as a good ameliorative agent against salt stress and as an effective practice for crop production of sensitive species/varieties.
3.3 Soil and foliar application of potassium enhances fruit yield and quality of tomato under salinity

3.3.1 Introduction

Soil salinity not only affects plant growth but also the developmental processes like seed germination, seedling vigour, flower and seed setting, primarily because of hyperosmotic stress and ionic imbalance (Sairam and Tyagi 2004). The increased osmotic pressure in the root environment decreases the availability of water to plants and its movement to reproductive organs such as fruits, and as a result fruit size is decreased as seen in tomato and other crops (Mavrogianopoulos et al., 2002).

Tomato is an important crop in several parts of the world, including in regions suffering from drought and soil salinity, such as the Mediterranean region, where these aspects have been studied (Savic et al., 2009; Jensen et al., 2010). Tomato is tolerant to abiotic stress factors, but these stresses such as salinity may enhance the quality by increasing sugar concentration and dry matter content (Yurtseven et al., 2005).

Potassium is among the important macro-nutrients required for the growth, development, yield and quality of plants and it also plays a key role in the survival of plants under abiotic stress conditions, as stress negatively affects the physiological processes like root and shoot elongation, enzyme activity, water and assimilate transport, synthesis of protein, photosynthetic transport and chlorophyll content (Yin and Vyn, 2003; Véry and Sentenac, 2003; Pettigrew, 2008; Gerardeaux et al., 2010). Under saline field condition, plants suffer a deficiency of potassium mainly because of the excess of Na⁺ in the rooting medium that acts as antagonist and decreases the availability of potassium (Niu et al., 1995; Rodriguez-Navarro, 2000), thus under salinity stress plants face the problem of K⁺ deficiency. Therefore, improving the K-nutritional status of plants under salinity stress alleviate the detrimental effects of Na⁺ by different mechanisms including K⁺=Na⁺ discrimination (Rodriguez-Navarro, 2000; Rubio et al., 2009).

As higher levels of NaCl cause K⁺ deficiency, salt might be one of the factors to oxidative stress. Hence, under salt stress improvement in K⁺ nutritional status of the plants could be used as a tool to minimize oxidative cell damage, at least by the reduced formation of ROS.
during photosynthesis and by the inhibition of NADPH oxidase generating $\text{O}_2^\cdot$ (Shen et al., 2000; Shin and Schachtman, 2004). Foliar application of $\text{K}^+$ fertilizer could be effective in correcting the salinity induced $\text{K}^+$-deficiency and also significantly decrease salinity induced damage to membranes, and increase biomass production in tomato and strawberry (Kaya et al., 2001, 2003).

Tomato production in the field is mainly concentrated in the warm and dry areas of the world where irrigation is a necessary practice. Natural and anthropogenic processes in these areas often create soil salinization (Iqbal et al., 2007), which is a major constraint to tomato production (Yurtseven et al., 2005). Salt-affected soils can be utilized for crop production by: leaching of salts below the root zone so that it may not hamper crop production, selection and introduction of salt tolerant cultivars and species, and by the use of soil amendments to alleviate the detrimental effects of salt stress (Yurtseven et al., 2005; Lu et al., 2010)). Under current circumstances it is not feasible to leach salts because of limited supply of fresh water, so developing techniques to enhance salt tolerance is inevitable, and the application of potassium is a feasible choice not only to enhance salt tolerance but also to improve tomato quality.

In this experiment four tomato genotypes differing in salt tolerance (identified in previous experiments) were used with the objective to study the effect of application of potassium (soil and foliar) on enhancing salt tolerance and improving tomato fruit yield and quality. The differential response of salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes to potassium under salt stress was evaluated.

### 3.3.2 Materials and Methods

#### 3.3.2.1 Experimental Setup

A pot experiment was conducted in the glass house of Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan, between 5 October 2011 and 21 February 2012. Two sets of tomato (Solanum lycopersicum L.) varieties (salt tolerant and salt sensitive), namely Indent-1 and Nagina (salt tolerant), Peto-86 and Red Ball (Salt sensitive) were used in this experiment. These varieties were screened for salt tolerance in previous experiments (Study-1) based on different growth, physiological, gas exchange and ionic characteristics.
The experiment was conducted according to completely randomized design (CRD) with three replicates using factorial arrangement. Seeds of these four genotypes were surface sterilized with 1% sodium hypochlorite solution, germinated in polythene lined iron trays filled with quartz sand. Plants at the five leaves stage were transferred to ceramic pots having 12 kg of soil. Sandy loam soil was collected from the upper surface of soil (0-15 cm), air dried, grounded and sieved through 2 mm mesh screen and analyzed for different physio-chemical characteristics (Table 3.3.1). Before pot filling different levels of salinity (0, 7.5 and 15 dS m\(^{-1}\)) were developed in soil by mixing calculated amount of NaCl in a mechanical mixer based original ECe and saturation percentage. Whereas potassium levels (0, 180 and 360 kg ha\(^{-1}\)) were developed by KNO\(_3\) along with two levels of foliar potassium (4.5 and 9 mM) at 25 day’s interval. For potassium, KNO\(_3\) was used because other forms like KCl could change the salinity levels with their anions. Recommended doses of fertilizer (210-125-180 kg ha\(^{-1}\)) were applied and the amount N added in the form of KNO\(_3\) was taken into consideration while making final calculations. Plants were irrigated with tap water with characteristics given in Table 3.3.1 as per plant requirement.

3.3.2.2 Plant biomass, fruit yield and quality

Plants were harvested when 90% of the total fruits turned red. Before harvesting plant height was measured with a meter rod and number of fruits per plant was counted. For plant dry weight measurement plants were placed in a forced draft oven at 65±5 °C till constant weight. For fruit yield and size parameters ten fruits per replicate was selected at random and fruit yield parameters; fruit weight per plant and average fruit weight were measured with electronic balance and fruit size parameters fruit diameter, fruit height were measured with measuring tape. Fruit dry matter was measured by drying them in at 65 ± 5 °C in a hot air oven (Model DHG-9053A, R and M Marketing, Sussex, UK) till constant weight and expressed as percentage.
Table: 3.3.1 Physical and chemical properties of soil and water used in the experiment

<table>
<thead>
<tr>
<th>Soil characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>pHs</td>
<td>7.59</td>
</tr>
<tr>
<td>Sodium Adsorption Ratio (SAR)</td>
<td>2.98</td>
</tr>
<tr>
<td>EC (dS m$^{-1}$)</td>
<td>1.37</td>
</tr>
<tr>
<td>N (mmol kg$^{-1}$)</td>
<td>96</td>
</tr>
<tr>
<td>P (mmol kg$^{-1}$)</td>
<td>1.14</td>
</tr>
<tr>
<td>K (mmol kg$^{-1}$)</td>
<td>1.7</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td>1.04</td>
</tr>
<tr>
<td>Texture (%)</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>Sand</td>
<td>58</td>
</tr>
<tr>
<td>Clay</td>
<td>20</td>
</tr>
<tr>
<td>Silt</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Irrigation water characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Conductivity (EC)</td>
<td>0.79 (dS m$^{-1}$)</td>
</tr>
<tr>
<td>pH</td>
<td>7.06</td>
</tr>
<tr>
<td>Residual Sodium Concentration (RSC)</td>
<td>1.12 mmolc L$^{-1}$</td>
</tr>
</tbody>
</table>

3.3.2.3 Fruit juice characteristics

Ten fruits per plant were used for the measurement of fruit juice characteristics like pH, total soluble solids (Brix) and titratable acidity (TA).

Brix was measured with a digital hand-held "Pocket" refractometer (PAL-Alpha; Cat. No. 3840). Titratable acidity of fruit juice was measured by titration method according to American Association of Analytical Chemists (AOAC) (2000) using 0.1 M NaOH. To 9 ml of filtered fruit juice 1 ml of distilled water was added and it was titrated against 0.1M NaOH using phenolphthalein as indicator.

3.3.2.4 Leaf sap ionic analysis

For leaf ionic analysis (Na$^+$ and K$^+$) fresh leaves were frozen and thawed. Thawed leaves were crushed with stainless steel rod in micro centrifuge tubes and leaf sap was collected. The leaf sap was then centrifuged at 6500 rpm for 10 minutes; supernatant was collected and used for Na$^+$ and K$^+$ determination (Gorham, 1984). The concentration of Na$^+$ and K$^+$ was determined with flame photometer (Sherwood Flame photometer, Model-410; Sherwood Scientific, Ltd, Cambridge UK) using standard curve made by different concentrations readings of NaCl and KCl.
3.3.2.5 Statistical analysis

Data were analyzed for analysis of variance (ANOVA) with up to three way interaction (salinity*potassium*genotypes) by “Statistix 8.0” software and presented as mean of three replicates ± SE and significance checked at \( P \leq 0.05 \).

3.3.3 Results

3.3.3.1 Plant growth characteristics

Plants were harvested when 90% of the fruits had turned red and plant height was recorded in response to different treatments of salinity (7.5 and 15 dS m\(^{-1}\)) and potassium both in the form of soil (180 and 360 kg ha\(^{-1}\)) and foliar (4.5 and 9 mM) in salt tolerant and salt sensitive genotypes (Table 3.3.2).

Analysis of variance has shown that treatment effect was highly significant and also the genotypes differed significantly as well for plant growth characteristics (Appendix 35-36ab). Increasing salinity (7.5 and 15 dS m\(^{-1}\)) levels significantly (\( P \leq 0.05 \)) reduced plant height in all the four genotypes, however a significant difference in plant height between salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes was recorded both in the control and salt stressed plants. The decrease in plant height was significantly higher in salt sensitive genotypes as compared to salt tolerant genotypes. Application of potassium both in the soil and foliar form alleviated the negative effects of salinity and resulted in a significant increase in plant height of both salt tolerant and salt sensitive genotypes as compared to respective controls. The effect of potassium was much more pronounced in the salt stressed than the non-stressed plants, but the effect of soil and foliar application of potassium was not significant.

A significant difference in plant dry weight was observed in all the four tomato genotypes (Table 3.3.2). Although at higher levels of salt stress (7.5 and 15 dS m\(^{-1}\)) plant dry weight significantly decreased in both salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes but it was significantly higher (\( P \leq 0.05 \)) in salt tolerant genotypes than the salt sensitive genotypes at all the salinity levels. Potassium application (soil and foliar) positively affected the plant dry weight, and it was significantly increased in response to both levels of potassium application at 15 dS m\(^{-1}\) as compared to control, however at 7.5
dS m⁻¹ it was only significant at higher potassium concentration (360 kg ha⁻¹ and 9 mM). There was no significant difference between soil and foliar applications of potassium and between the levels of potassium.
Table: 3.3.2 Plant height and dry weight of salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application

<table>
<thead>
<tr>
<th>Soil K (kg ha⁻¹)</th>
<th>Foliar K (mM)</th>
<th>Plant Height (cm)</th>
<th>Plant dry weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indent-1</td>
<td>Nagina</td>
</tr>
<tr>
<td>0</td>
<td>4.5</td>
<td>96.4 ± 1.47</td>
<td>84.8 ± 1.65</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>105.2 ± 3.00</td>
<td>94.9 ± 1.82</td>
</tr>
<tr>
<td>180</td>
<td>0</td>
<td>79.2 ± 1.91</td>
<td>71.1 ± 1.29</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>93.0 ± 2.18</td>
<td>82.3 ± 1.48</td>
</tr>
<tr>
<td>360</td>
<td>0</td>
<td>98.2 ± 2.89</td>
<td>91.2 ± 1.95</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>15.28 ± 0.49</td>
<td>12.33 ± 0.64</td>
</tr>
<tr>
<td>150 mM NaCl</td>
<td>4.5</td>
<td>81.9 ± 1.85</td>
<td>73.5 ± 1.80</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>81.3 ± 2.61</td>
<td>71.6 ± 1.62</td>
</tr>
</tbody>
</table>

Each value represents the mean of replicates ± SE.
3.3.3.2 Plant leaf ionic content

On an overall average basis the effect of treatments and genotypes was highly significant as shown in analysis of variance table (Appendix 37-39ab). With increasing salinity from control to higher levels (7.5 and 15 dS m\(^{-1}\)) leaf Na\(^+\) concentration significantly increased whereas K\(^+\) concentration significantly decreased in both the salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) groups (Table 3.3.3). However salt-tolerant group had significantly lower values of Na\(^+\) and higher values of K\(^+\) concentration than salt-sensitive group. Potassium application was effective and significantly increased the leaf K\(^+\) and decreased the leaf Na\(^+\) concentration with more pronounced effects in salt-tolerant genotypes as compared to salt-sensitive genotypes. With these antagonistic effects between salinity and potassium application, the ratio between leaf K\(^+\) and Na\(^+\) (K\(^+\)/Na\(^+\)) decreased with increasing salinity (7.5 and 15 dS m\(^{-1}\)) and it increased with increasing potassium application (both in soil and foliar) in both the salt-tolerant and salt-sensitive groups with significantly higher values in the salt-tolerant group (Table 3.3.4).
Table: 3.3.3 Plant leaf ionic concentration (Na\(^+\) and K\(^+\)) in salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application

<table>
<thead>
<tr>
<th></th>
<th>Leaf Na(^+) (mol m(^{-3}))</th>
<th>Leaf K(^+) (mol m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indent-1</td>
<td>Nagina</td>
</tr>
<tr>
<td><strong>Soil K (kg ha(^{-1}))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>41.0 ± 2.1</td>
<td>43.0 ± 1.9</td>
</tr>
<tr>
<td>180</td>
<td>36.9 ± 1.8</td>
<td>38.6 ± 2.2</td>
</tr>
<tr>
<td>360</td>
<td>32.7 ± 2.1</td>
<td>34.6 ± 1.5</td>
</tr>
<tr>
<td><strong>Foliar K (mM)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>38.8 ± 1.9</td>
<td>40.6 ± 1.7</td>
</tr>
<tr>
<td>9</td>
<td>35.3 ± 1.9</td>
<td>37.4 ± 1.5</td>
</tr>
<tr>
<td><strong>Soil K (kg ha(^{-1}))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 mM NaCl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>74.1 ± 3.2</td>
<td>85.6 ± 3.5</td>
</tr>
<tr>
<td>180</td>
<td>69.9 ± 3.5</td>
<td>79.6 ± 3.6</td>
</tr>
<tr>
<td>360</td>
<td>47.1 ± 3.3</td>
<td>74.8 ± 2.9</td>
</tr>
<tr>
<td><strong>Foliar K (mM)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>70.8 ± 3.3</td>
<td>81.0 ± 3.1</td>
</tr>
<tr>
<td>9</td>
<td>68.7 ± 3.2</td>
<td>76.7 ± 3.1</td>
</tr>
<tr>
<td><strong>Soil K (kg ha(^{-1}))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 mM NaCl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>114.3 ± 3.0</td>
<td>119.7 ± 4.2</td>
</tr>
<tr>
<td>180</td>
<td>106.1 ± 2.3</td>
<td>113.1 ± 2.2</td>
</tr>
<tr>
<td>360</td>
<td>100.6 ± 3.5</td>
<td>105.9 ± 2.4</td>
</tr>
<tr>
<td><strong>Foliar K (mM)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>111.2 ± 2.2</td>
<td>114.5 ± 2.5</td>
</tr>
<tr>
<td>9</td>
<td>104.5 ± 2.3</td>
<td>109.5 ± 2.5</td>
</tr>
</tbody>
</table>

Each value represents the mean of replicates ± SE.
Table: 3.3.4 Plant leaf K⁺/Na⁺ ratio in salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application

<table>
<thead>
<tr>
<th></th>
<th>Leaf K⁺/Na⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indent-1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td></td>
</tr>
<tr>
<td>Soil K (kg ha⁻¹)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>5.26 ± 0.05</td>
</tr>
<tr>
<td>180</td>
<td>6.26 ± 0.54</td>
</tr>
<tr>
<td>360</td>
<td>7.62 ± 0.27</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>5.84 ± 0.14</td>
</tr>
<tr>
<td>9</td>
<td>6.86 ± 0.34</td>
</tr>
<tr>
<td>75 mM NaCl</td>
<td></td>
</tr>
<tr>
<td>Soil K (kg ha⁻¹)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.04 ± 0.13</td>
</tr>
<tr>
<td>180</td>
<td>2.49 ± 0.25</td>
</tr>
<tr>
<td>360</td>
<td>2.91 ± 0.17</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>2.38 ± 0.18</td>
</tr>
<tr>
<td>9</td>
<td>2.75 ± 0.14</td>
</tr>
<tr>
<td>150 mM NaCl</td>
<td></td>
</tr>
<tr>
<td>Soil K (kg ha⁻¹)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.98 ± 0.08</td>
</tr>
<tr>
<td>180</td>
<td>1.20 ± 0.08</td>
</tr>
<tr>
<td>360</td>
<td>1.43 ± 0.09</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>1.12 ± 0.07</td>
</tr>
<tr>
<td>9</td>
<td>1.33 ± 0.04</td>
</tr>
</tbody>
</table>

Each value represents the mean of replicates ± SE
3.3.3.3 Fruit yield parameters

Analysis of variance table showed that fruit yield and quality parameters are significantly affected by different treatments and genotypes also differed significantly in terms of these parameters (Appendix 35-46ab). Fruit yield parameters measured in terms of fruit weight per plant and average fruit weight are presented in Table 3.3.5. Generally with increasing salinity stress (7.5 and 15 dS m\(^{-1}\)) fruit weight per plant and average fruit weight decreased significantly (P \(\leq 0.05\)) in both the salt tolerant (Indent-1 and Nagina) and salt sensitive (Peto-86 and Red Ball) genotypes. However salt-tolerant genotypes maintained significantly higher values for these fruit yield characteristics than the salt-sensitive genotypes in both the salt-stressed and non-stressed plants.

Application of potassium had a significant positive effect on the fruit yield of tomato plants both at control as well as under salt-stressed plants. The effect of potassium was much more pronounced in salt tolerant genotypes than salt sensitive genotypes. The form of application of potassium (soil and foliar) also differed non-significantly at all the salt treatments in all the genotypes.

3.3.3.4 Fruit quality characteristics

3.3.3.4.1 Fruit diameter and height

At harvesting average fruit diameter and height were measured in response to different levels of salinity and potassium in both the salt-tolerant and salt-sensitive genotypes and presented in table 3.3.6. A significant decrease (P \(\leq 0.05\)) in fruit diameter and height was observed with the increasing soil salinity (7.5 and 15 dS m\(^{-1}\)) in both the salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) groups. However higher levels of potassium application both to soil (180 and 360 kg ha\(^{-1}\)) and leaves (4.5 and 9 mM) significantly decreased the negative effects of potassium and induced a significant increase in fruit diameter and height. Also significant differences were observed in the forms of application of potassium (soil and foliar) in all the genotypes and in all the salt treatments. Among the genotypes salt-tolerant genotypes (Indent-1 and Nagina) performed better and had higher fruit diameter and height both in the control and salt-treated plants as compared to salt sensitive genotypes (Peto-86 and Red Ball).
Table: 3.3.5 Fruit weight per plant and average fruit weight of salt tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application

<table>
<thead>
<tr>
<th>Soil K (kg ha⁻¹)</th>
<th>Foliar K (mM)</th>
<th>Fruit weight per plant (g)</th>
<th>Average fruit weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indent-1</td>
<td>Nagina</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>616.3 ± 17.4</td>
<td>592.1 ± 17.0</td>
</tr>
<tr>
<td>180</td>
<td>4.5</td>
<td>632.4 ± 23.7</td>
<td>613.5 ± 18.7</td>
</tr>
<tr>
<td>360</td>
<td>9</td>
<td>684.1 ± 24.4</td>
<td>636.7 ± 16.3</td>
</tr>
<tr>
<td>0</td>
<td>75 mM NaCl</td>
<td>514.8 ± 13.9</td>
<td>498.0 ± 12.9</td>
</tr>
<tr>
<td>180</td>
<td>4.5</td>
<td>551.8 ± 11.1</td>
<td>522.5 ± 13.9</td>
</tr>
<tr>
<td>360</td>
<td>9</td>
<td>613.8 ± 14.8</td>
<td>573.3 ± 18.2</td>
</tr>
<tr>
<td>0</td>
<td>150 mM NaCl</td>
<td>362.7 ± 7.9</td>
<td>343.5 ± 13.9</td>
</tr>
<tr>
<td>180</td>
<td>4.5</td>
<td>408.1 ± 10.1</td>
<td>397.2 ± 10.8</td>
</tr>
<tr>
<td>360</td>
<td>9</td>
<td>472.1 ± 10.5</td>
<td>453.7 ± 11.1</td>
</tr>
<tr>
<td>0</td>
<td>9</td>
<td>398.0 ± 12.4</td>
<td>388.9 ± 9.7</td>
</tr>
</tbody>
</table>

Each value represents the mean of replicates ± SE
Table: 3.3.6 Fruit diameter and height of salt tolerant (Indent-I and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application

<table>
<thead>
<tr>
<th></th>
<th>Fruit diameter (cm)</th>
<th>Fruit height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indent-I</td>
<td>Nagina</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil K (kg ha⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>4.55 ± 0.15</td>
<td>4.72 ± 0.22</td>
</tr>
<tr>
<td>180</td>
<td>5.94 ± 0.13</td>
<td>5.16 ± 0.13</td>
</tr>
<tr>
<td>360</td>
<td>6.36 ± 0.24</td>
<td>5.61 ± 0.18</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>5.65 ± 0.14</td>
<td>4.98 ± 0.12</td>
</tr>
<tr>
<td>9</td>
<td>6.12 ± 0.23</td>
<td>5.35 ± 0.17</td>
</tr>
<tr>
<td>75 mM NaCl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil K (kg ha⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>4.29 ± 0.16</td>
<td>3.42 ± 0.15</td>
</tr>
<tr>
<td>180</td>
<td>4.77 ± 0.18</td>
<td>3.63 ± 0.10</td>
</tr>
<tr>
<td>360</td>
<td>4.94 ± 0.20</td>
<td>3.85 ± 0.14</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>4.61 ± 0.15</td>
<td>3.54 ± 0.12</td>
</tr>
<tr>
<td>9</td>
<td>4.89 ± 0.14</td>
<td>3.75 ± 0.27</td>
</tr>
<tr>
<td>150 mM NaCl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil K (kg ha⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3.26 ± 0.09</td>
<td>2.95 ± 0.09</td>
</tr>
<tr>
<td>180</td>
<td>4.34 ± 0.12</td>
<td>3.95 ± 0.09</td>
</tr>
<tr>
<td>360</td>
<td>4.46 ± 0.08</td>
<td>4.26 ± 0.14</td>
</tr>
<tr>
<td>Foliar K (mM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>4.21 ± 0.09</td>
<td>3.84 ± 0.15</td>
</tr>
<tr>
<td>9</td>
<td>4.33 ± 0.12</td>
<td>4.20 ± 0.16</td>
</tr>
</tbody>
</table>

Each value represents the mean of replicates ± SE.
3.3.3.4.2 Total Soluble Solids (TSS, Brix) and Fruit Dry matter (%)

Total soluble solids and fruit dry matter as a measure of tomato fruit quality increased significantly from control to salt stress (7.5 and 15 dS m\(^{-1}\)) in both the salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) genotypes (Table 3.3.7). Plants in the control treatment (0 mM K\(^{+}\)) showed significantly lower values of these fruit quality characteristics than the K\(^{+}\) treated plants at all the three saline levels (control, 7.5 and 15 dS m\(^{-1}\)). Application of potassium both to soil (180 and 360 kg ha\(^{-1}\)) and leaves (4.5 and 9 mM) had significant differences within different concentrations; and significantly increased the TSS and fruit dry matter in all the genotypes compared to control (no added K). Among the genotypes salt-tolerant genotypes had higher percentage of TSS and fruit dry matter in all the saline treatments than the salt-sensitive genotypes. The response of salt-tolerant genotypes to different concentrations of potassium was significantly higher than the salt-sensitive group.

3.3.3.4.3 Titratable acidity and pH of fruit juice

Titratable acidity and pH of the fruit juice were measured as indicators of sourness of tomato are presented in Table 3.3.8. Generally with increasing concentration of salinity (7.5 and 15 dS m\(^{-1}\)) and potassium both in soil (180 and 360 kg ha\(^{-1}\)) and foliar (4.5 and 9 mM) caused a significant (P \(<\) 0.05) increase in the titratable acidity of the tomato fruit juice as compared to respective control in all the genotypes. However the salt tolerant genotypes (Indent-1 and Nagina) showed significantly higher values of titratable acidity than the salt sensitive genotypes (Peto-86 and Red Ball). There were non-significant differences between different potassium concentrations within in the same salinity treatment in all the genotypes.

In case of pH of the fruit juice, soil salinity (7.5 and 15 dS m\(^{-1}\)) caused significant decrease in all the genotypes as compared to control. Whereas potassium application had no effect on pH of fruit juice within all the saline levels, but it significantly decreased the pH at higher salinity levels (7.5 and 15 dS m\(^{-1}\)) in all the genotypes, when compared to control at the respective potassium. Among the tomato genotypes; salt-tolerant genotypes (Indent-1 and Nagina) had significantly lower values of fruit juice pH than the salt-sensitive (Peto-86 and Red Ball) genotypes at all the saline and potassium levels, however the values were non-significant within the salt-tolerant and salt-sensitive groups.
<table>
<thead>
<tr>
<th>Foliar K (mM)</th>
<th>Control</th>
<th>75 mM NaCl</th>
<th>150 mM NaCl</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.04 ± 0.23</td>
<td>8.52 ± 0.18</td>
<td>10.22 ± 0.33</td>
</tr>
<tr>
<td>4.5</td>
<td>6.47 ± 0.12</td>
<td>7.36 ± 0.17</td>
<td>9.07 ± 0.24</td>
</tr>
<tr>
<td>9</td>
<td>6.47 ± 0.12</td>
<td>7.36 ± 0.17</td>
<td>9.07 ± 0.24</td>
</tr>
</tbody>
</table>

Each value represents the mean of replicates ± SE
Table: 3.3.8 Titratable acidity and fruit juice pH in salt tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes in response to salinity stress and potassium application

<table>
<thead>
<tr>
<th></th>
<th>Titratable acidity (mg/100 g)</th>
<th>Fruit juice pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indent-1</td>
<td>Nagina</td>
</tr>
<tr>
<td>Soil K (kg ha⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0</td>
<td>1242 ± 35</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>1354 ± 54</td>
</tr>
<tr>
<td></td>
<td>360</td>
<td>1433 ± 39</td>
</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>75 mM NaCl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil K (kg ha⁻¹)</td>
<td>0</td>
<td>1423 ± 47</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>1499 ± 48</td>
</tr>
<tr>
<td></td>
<td>360</td>
<td>1568 ± 58</td>
</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>150 mM NaCl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil K (kg ha⁻¹)</td>
<td>0</td>
<td>1630 ± 74</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>1722 ± 79</td>
</tr>
<tr>
<td></td>
<td>360</td>
<td>1872 ± 77</td>
</tr>
<tr>
<td></td>
<td>Foliar K (mM)</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

Each value represents the mean of replicates ± SE
3.3.4 Discussion

In the current study, salt-stress (7.5 and 15 dS m$^{-1}$) significantly decreased the growth of the tomato plants measured in terms of plant height and plant dry weight as evident from the correlation coefficients between leaf sap Na$^+$ and plant dry weight ($r^2 = 0.7394$) and plant height ($r^2 = 0.624$) (Figure 3.3.14). This could be the result of osmotic effect due to excess amounts of salts in the root zone which leads to the reduced photosynthetic capacity or toxicity of salts in the plant tissues (Sairam et al., 2002; Natr and Lawlor, 2005; Neocleous and Vasilakakis, 2007). The increase in these growth parameters with the application of potassium could be the result of antagonism between K$^+$ and Na$^+$ ions in the root zone (Chen et al., 2007). A significant relationship between leaf sap K$^+$ and plant dry weight ($r^2 = 0.9092$) and plant height ($r^2 = 0.9138$). It is consistent with previous findings in rice (Ikeda et al., 2004), tomato (Kaya et al., 2001; Azarmi et al., 2010), cucumber, and pepper (Kaya et al., 2003).

In this experiment results showed that with increasing salinity yield of tomato declined in both the salt-tolerant and salt-sensitive genotypes. This reduction in yield is reported to be caused by reduced mean fruit weight rather than fruit number because of reduced water availability, biochemical and physiological disturbances due to salinity in the rooting medium (Azarmi et al., 2010; Cuartero et al., 2006). Application of potassium increased the yield under salt-stress as it reduced the negative effects of salinity. Soil salinity and application of potassium increased the fruit quality of tomato fruits in all genotypes supported by the previous findings of Azarmi et al., (2010); Yesterven et al., (2005). All the fruit quality characteristics like TSS, dry matter percent, titratable acidity, pH of fruit juice positively affected by salinity and potassium except the fruit size (height and diameter), which decreased with increasing salinity and increased with increasing potassium concentration as shown by the correlation coefficients between leaf ionic concentration (Na$^+$, K$^+$) and fruit yield (average fruit weight, fruit weight per plant) and fruit diameter (Figure 3.3.15). Reduction in fruit size attributed to the decreased water uptake by roots and transport to fruit due to excess amounts of salts in the rooting medium (Leonardi et al., 2004; Neocleous and Vasilakakis 2007). The improvement in fruit quality characteristics (TSS, dry matter percent, titratable acidity and pH) in response to salinity stress had been reported because of decreased fruit water content and increased concentrations of reducing sugars and
acids as compared to non-saline conditions (Leonardi et al., 2004). The accumulation of reducing sugars and organic acids is responsible for increased titratable acidity and decreased pH of the fruit juice.

Increasing salinity levels caused an increase in Na\(^+\) concentration of leaf tissues and a decrease in K\(^+\) concentration. As a result, growth and yield of tomato plants in both salt-tolerant and salt-sensitive genotypes decreased due to higher concentration of salt in the rooting medium and its accumulation in the tissues. Higher concentrations of salts in the apoplast of cells negatively affect survival, growth and development of cells and ultimately whole plant primarily by ionic toxicity and hyper-osmolarity. Saline soils are dominated by Na\(^+\) and Cl\(^-\); both of these ions have inhibitory effect on the processes going on in cytosol and other organelles of cells (Niu et al., 1995; Serrano et al., 1999; Hasegawa et al., 2000; Kato et al., 2001; Zhu, 2002). Wyn Jones and Pollard (1983) reported that salt concentration > 0.4 M causes the inhibition of enzymes by disturbing hydrophobic–electrostatic balance necessary to maintain protein structure. Salinity also affects the growth of plants by disturbing the K\(^+\)-nutrition, impairing photosynthesis, membrane dysfunction and generation of reactive oxygen species (ROS) (Hasegawa et al., 2000; Rodriguez-Navarro, 2000; Zhu, 2003). K\(^+\) is among the important macro-nutrients required for the growth, development, yield and quality of plants, and Na\(^+\) has antagonistic effect on the uptake of K\(^+\) into the cells particularly at higher concentrations (Niu et al., 1995; Rodriguez-Navarro, 2000), thus under salinity stress plants face the problem of K\(^+\) deficiency. Therefore improving the K\(^+\)-nutritional status of plants alleviate the detrimental effects of Na\(^+\) by different mechanisms including K\(^+\)=Na\(^+\) discrimination (Rodriguez-Navarro, 2000; Rubio et al., 2009). As was the case in this experiment, salinity caused a significant decrease in plant growth and yield by excess of Na\(^+\) but application of potassium both in soil and foliar form alleviated these toxic effects of salinity and induced a significant increase in the growth, yield and fruit quality of tomato.
Figure 3.3.1 Correlation coefficients between leaf sap ionic concentrations (Na$^+$ and K$^+$) and plant growth characteristics (plant height and plant dry weight). (A) relationship between leaf sap Na$^+$ and plant height (B) relationship between leaf sap Na$^+$ and plant dry weight (C) relationship between leaf sap K$^+$ and plant height (D) relationship between leaf sap K$^+$ and plant dry weight. All the values are means of three replicates.
Figure 3.3.2 Correlation coefficients between leaf sap ionic concentrations (Na$^+$ and K$^+$) and fruit yield (fruit weight per plant and average fruit weight) and size (fruit diameter) characteristics. (A) relationship between leaf sap Na$^+$ and fruit weight per plant (B) relationship between leaf sap Na$^+$ and average fruit weight (C) relationship between leaf sap Na$^+$ and fruit diameter (D) relationship between leaf sap K$^+$ and fruit weight per plant (E) relationship between leaf sap K$^+$ and average fruit weight (F) relationship between leaf sap K$^+$ and fruit diameter. All the values are mean of three replicates.
3.4 Enhanced levels of ethylene and ABA increase salt tolerance in tomato

3.4.1 Introduction

The response of plants to adverse effects of salinity is regulated by different external and internal factors (Chinnusamy et al., 2006; Tuteja, 2007; Cao et al., 2007). Among the internal plant factors phytohormones have important roles in salt stress tolerance and adaptation (Shaterian et al., 2005; Tuteja, 2007). The phytohormones; abscisic acid (ABA) and ethylene has long been regarded as stress hormones and has specific role in regulating tolerance and adaptation to salt stress (Zhang et al., 2006; Javid et al., 2011).

The plant stress hormone ABA plays a central role in long distance drought signaling in controlling the stomatal movements in water conservation (Davies and Zhang, 1991; Davies et al., 2002). It has been proposed that ABA acts as a mediator and also the major internal signal in plant response to abiotic stresses (Keskin et al., 2010; Javid et al., 2011). Endogenous ABA concentration increases proportionally with salt stress related to leaf or soil water potential suggesting that increased ABA concentration is due to water deficit created by the excess of salts rather than salt specific effect (Davies et al., 2002). This higher ABA concentration reduces the loss of water as transpiration by the closure of stomata under stressful conditions (Zhang et al., 2006; Cabot et al., 2009; Hariadi et al., 2011). It is different from the prolonged increase in ABA level as result of slow increase in salinity in field or natural conditions (Etehadnia et al., 2008). There are two prerequisites for an ABA mediated regulation under stress; firstly its production should be triggered rapidly to avoid inhibition of plant growth and functioning, secondly it should be rapidly degraded and deactivated after the stress is relieved so that plant can resume normal growth and functioning (Shaterian et al., 2005; Zhang et al., 2006).

Plants salt tolerance is dependent upon its ability to maintain ion homeostasis i.e. maintaining low Na\(^+\) and high K\(^+\) and K\(^+\)/Na\(^+\) concentrations (Jeschke 1984; Inan et al., 2004). Cells adapt to salt stress by maintaining low cytosol Na\(^+\) concentration, by controlling the movement of this ions across plasma membrane and tonoplast (Niu et al., 1995; Rausch et al., 1996). It has been reported that H\(^+\)-ATPase located in the plasma membrane plays an important role in this by forcing the Na\(^+\)/H\(^+\) antiporters to efflux Na\(^+\) (Shi et al., 2000).
Ethylene as stress hormone plays important role in ion homeostasis under salinity stress by regulating the H\(^+\)-ATPase gene expression (Lucena et al., 2006; Waters et al., 2007; Wang et al., 2009). Thus enhanced ethylene concentration plays an important role in determining the plant salt tolerance (Cao et al., 2006, 2007). A significant increase in ethylene production has been reported in salt-adapted calli over salt-sensitive calli and control (Alvarez et al., 2003). It has also been reported that ethylene signaling might also be required for salt-tolerance as ethylene insensitive mutant showed more salt sensitivity (Cao et al., 2006, 2007).

Under salinity stress K\(^+\) nutritional status is very important, it not only acts a Na\(^+\) competitor in the rooting medium but also it has important role in stress signaling (Jung et al., 2009; Wang and Wu 2010; Römheld and Kirkby, 2010). According to a hypothetical model showing molecular changes in Arabidopsis in response to K\(^+\) deficiency, drought induced ABA may produce reactive oxygen species (ROS) which, in turn, trigger the flow of a second messenger (Ca), consequently K\(^+\) uptake by roots and regulation of stomatal guard cells. Ethylene production in K\(^+\)-deprived plants has also been reported in this model, subsequently, production of ROS and changes in root morphology and thus better tolerance to low potassium supply (Cheong et al., 2007; Jung et al., 2009).

It was hypothesized that salt stress will cause a differential increase in concentration of stress hormones in salt tolerant and sensitive tomato genotypes and elevated levels of these stress hormones could be responsible for salt-tolerance of tolerant tomato genotype, also higher potassium in the growth medium will lower the concentration of hormones by ameliorating salt stress. The experiment was conducted with the objectives to study the hormonal mechanisms involved in salt tolerance of tomato and also to study the interaction between stress hormones and potassium under saline conditions.

### 3.4.2 Materials and Methods

#### 3.4.2.1 Plant material and growth conditions

Two contrasting tomato genotypes Indent-1 (salt tolerant) and Red Ball (salt-sensitive) were identified in experiment-1 based on different growth, physiologic and ionic characteristics.

Experiment was conducted under controlled conditions (day/night air temperature 25/18 ± 2 °C, 60% relative humidity, 400 µmol m\(^{-2}\) s\(^{-1}\) light intensity) in a climatic chamber at Department of Plant and Environmental Sciences, University of Copenhagen, Taastrup,
Denmark, during November-December 2012. Seeds of these salt-tolerant and salt-sensitive genotypes were sown in small pots with peat. After two weeks, healthy seedlings were transferred to vermiculite for 10 days to get uniform stand of seedlings for the experiment.

At fifth leaf stage, uniform seedlings were transferred to modified Hoagland’s nutrient solution (Hoagland and Arnon, 1950) in plastic containers of 1.9 liters capacity (26 cm depth, 14 cm diameter) after carefully washing off the vermiculite from the roots. After three days of transplanting, different salinity (0, 75 and 150 mM NaCl) and potassium (0, 4.5 mM) treatments were applied. Salinity treatments were divided into three equal doses i. e. 25 and 50 mM NaCl, and applied in three consecutive days with control treatment getting no NaCl. Potassium nitrate was used as a source of potassium, and it was applied along with the salinity treatments. The amount of potassium and nitrate applied in the form KNO₃ was adjusted in the Hoagland’s solution. The plant roots were supplied with oxygen by an air pumping system throughout the experimental period and pH of the nutrient solution was maintained daily between 6.0-6.5 by the additions of 0.1M either HCl or NaOH.

3.4.2.2 Chlorophyll content index (CCI) and Stomatal conductance measurements

Chlorophyll content from leaf tissues was measured from different positions of two upper youngest fully expanded leaves using a portable Chlorophyll Content Meter, CCM-200 (Optisciences, MA, USA)

Stomatal conductance was measured by the SC-1 Leaf Porometer from the youngest fully expanded leaves (Decagon Devices, Inc., WA, USA).

3.4.2.3 Leaf xylem sap analyses

For the measurement of ions (Na⁺, K⁺) and ABA concentration, xylem sap was collected using a Scholander-type pressure chamber (Plant Moisture Systems, Santa Barbara, CA, USA). Stem was cut about 5 cm from the root-shoot junction with a sharp blade, washed with distilled water and dried with blotting paper. Then the remaining part was put in Scholander-type pressure chamber and pressure was increased gradually to collect the sap. The collected sap was frozen immediately at -80 °C and stored for further analysis of ABA and ions (Na⁺ and K⁺). Xylem sap ABA concentration was measured according to Asch (2000) by enzyme linked immunosorbent assay (ELISA), whereas ions in the xylem sap were determined by ion
chromatography (Metrohm AG, Herisau, Switzerland). Metrosep C4-100 analytical column was used for the determination of these cations (43125 mm, 1.7 mM nitric acid/0.7 mM dipicolinic acid (DPA) eluent). No cross-reaction of the antibody with other compounds in xylem sap was detected when tested according to Quarrie et al., (1988).

3.4.2.4 Leaf abaxial surface imprints

For leaf abaxial surface imprints, leaf surface was cleaned; a thin layer of nail polish was applied on the lower surface of leaves and allowed to dry for 10-15 minutes. Then transparent solution tape was adhered to the respective area, carefully drawn off and adhered to microscopic slides.

Imprints were photographed using a Leitz DMRD light microscope (Leica Mikroskopie and System GmbH, Wetzlar, Germany) with an associated camera (Leica DFC 420). For measuring stomata density, stomatal size and percent leaf area covered by stomata, a grid of 1 mm² was superimposed. Stomata density was measured by counting the number of stomata per mm² and stomata size measured as stomatal length x width, percent leaf area covered by stomata was calculated as the product of stomatal size and density per unit leaf area.

3.4.2.5 Leaf ethylene biosynthesis

Leaf ethylene biosynthesis was measured from uppermost fully expanded leaves from each plant according to Fišerová et al., (2008). Leaves (5-7) were detached, weighed and put into 100 ml vessels, sealed with special lids for collecting the gas samples and placed them at room temperature for 48 hours. For measuring the ethylene concentration, about 1 ml of gas sample was collected with a syringe (Braun Melsungen AG) and samples were analyzed by gas chromatography using ethylene standards of different concentrations. Final concentration of ethylene biosynthesis was presented as µmol g⁻¹ FW h⁻¹.

3.4.2.6 Statistical analysis

The experiment was conducted using completely randomized design with four replicates per treatment. To check the effect of salinity, potassium and varieties data was analyzed by ANOVA using linear model. All the data analysis was done in analytical software “Statistix 9.0” (Analytical Software, 2008; http://www.statistix.com).
3.4.3 Results

3.4.3.1 Chlorophyll content index (CCI) and stomatal conductance (gs)

On an overall mean basis, the effect of treatments was highly significant for both CCI and gs however, the genotypic effect was significant for gs but it was non-significant for CCI as shown by analysis of variance table (Appendix 46-47). Chlorophyll content index in response to salinity significantly decreased as compared to control, however there was non-significant difference between the genotypes under salinity (Figure 3.4.1). There were no significant differences between genotypes, with and without the application of potassium at three salinity levels.

NaCl (75 and 150 mM) significantly decreased stomatal conductance (gs) in salt-sensitive genotype (Red Ball), whereas the effect of NaCl was significant in salt-tolerant genotype (Indent-1) without potassium (Figure 3.4.2). Without potassium there was no difference between the two genotypes at NaCl levels (75 and 150 mM), however it was significant at potassium level (4.5 mM). Effect of potassium was highly significant in only salt-tolerant genotype.
Figure 3.4.1 Chlorophyll content index (CCI) of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). Error bars represents standard error of means (n=4).

Figure 3.4.2 Stomatal conductance ($g_s$) of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). Error bars represents standard error of means (n=4).

3.4.3.2 Stomatal morphology

The overall effect of treatments was highly significant for both the stomatal density and aperture but the genotypic effect was significant only for stomatal aperture (Appendix 49-
Stomatal morphological features were measured in terms of guard cell length (Ls), guard cell pair width (Ws), stomatal pore aperture length (La), stomatal pore aperture width (Wa), stomatal density (SD) and stomatal aperture (SA) (Figures 3.4.3 and 3.4.4). Increasing NaCl concentration in the growth medium caused a significant decrease in all the stomatal morphological features in both the salt-tolerant (Indent-1) and salt-sensitive (Red Ball) genotypes, except Ls which only decreased at the highest level of NaCl (150 mM) in Indent-1. There was no difference between the genotypes without NaCl, however the effect was significant when adding NaCl especially in case of Ls, Ws, La and Wa, whereas this effect was non-significant across all the NaCl levels in case of SD and SA. Potassium application had a non-significant effect on all the measured stomatal morphological features in both the genotypes.

3.4.3.3 Xylem sap ABA and leaf ethylene biosynthesis

Analysis of variance has shown that both the treatment and genotypic effects were highly significant for ABA whereas this was non-significant for ethylene biosynthesis (Appendix 51-52). Xylem sap ABA and leaf ethylene in response to NaCl and potassium are shown in Figure 3.4.5. Both parameters followed the same trend, increasing significantly with increasing NaCl levels in the growth medium in both the salt-tolerant (Indent-1) and salt-sensitive (salt-sensitive) genotypes. There was non-significant difference between salt-tolerant and salt-sensitive genotypes. Increasing potassium concentration (4.5 mM) in the growth medium had a significant negative effect on ABA and ethylene concentrations at 75 and 150 mM NaCl, however there was no significant effect without NaCl.

3.4.3.4 Xylem sap ionic contents (Na⁺, K⁺, K⁺/ Na⁺)

Xylem sap ionic contents were statistical analyzed by analysis of variance shown in Appendix 53-54, shown that the treatment and genotypic effects were highly significant whereas the interactive effect of treatment and genotypes was significant only for Na⁺. An opposite trend between xylem sap Na⁺ and K⁺ concentration was observed with increasing NaCl concentration in the growth medium, Na⁺ concentration significantly increased whereas K⁺ decreased in both genotypes (Figure 3.4.6). Subsequently xylem sap K⁺/ Na⁺ was significantly decreased at higher levels of growth medium NaCl compared to control. Highly significant differences between salt-tolerant (Indent-1) and salt-sensitive (Red Ball)
genotypes were observed at saline levels (75 and 150 mM) in xylem sap Na\(^+\) and K\(^+\) concentrations, whereas this difference was non-significant at 0 mM NaCl and also in case K\(^+\)/Na. Potassium application had a significant positive effect on xylem sap K\(^+\) and K\(^+\)/Na\(^+\) concentration and negative effect on Na\(^+\) concentration across all NaCl levels.

Figure 3.4.3 Guard cell length (Ls) (A), guard cell pair width (Ws) (B), stomatal pore aperture length (La) (C) and stomatal pore aperture width (Wa) (D) in the abaxial leaf surface of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). The values represent the means of impression images from four replicates and 10 stomata from each leaf. Error bars represent standard error of means (n=4).
Figure 3.4.4 Stomatal density (SD) (A), stomatal aperture (SA) (B) in the abaxial leaf surface of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). The values represent the means of impression images from four replicates and 10 stomata from each leaf. Error bars represents standard error of means (n=4)
Figure 3.4.5 [ABA] xylem (A), leaf ethylene biosynthesis (B) of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). Error bars represents standard error of means (n=4).
Figure 3.4.6 Xylem sap K$^+$ (A) xylem sap Na$^+$ (B) xylem sap K$^+$/Na$^+$ of salt-tolerant (Indent-1) and salt-sensitive (Red Ball) tomato genotypes exposed to different levels of NaCl (0, 75 and 150 mM) and potassium (0 and 4.5 mM). Error bars represents standard error of means (n=4).
3.4.4 Discussion

Plants exposed to environmental stresses have evolved special mechanisms by which they sensibly perceive incoming stresses and regulate their physiology accordingly (Zhang et al., 2006; Javid et al., 2011). In this respect stress hormones (abscisic acid (ABA) and ethylene), plant tissue ionic contents and stomatal morphology play an important role in perceiving incoming stress and regulating physiology. We studied the effect of potassium (0, 4.5 mM) on hormonal and stomatal morphological changes under different levels of salt (NaCl) stress.

Chlorophyll content index is a good measure of photosynthesis activity especially in salt stressed plants and previously it has been used as a good indicator of salt tolerance in different species like cotton (Saleh, 2012), rice (Ali et al., 2004), soybean (Ghassemi-Golezani et al., 2012), wheat (Saqib et al., 2012), quinoa (Adolf et al., 2012), and radish (Jamil et al., 2007). In the current experiment, reduced CCI in tomato genotypes could be the result of enhanced activity of chlorophyllase (Jamil et al., 2007; Ghassemi-Golezani et al., 2012), which is involved in destroying the chloroplast structure and instability of pigment protein complex (Singh and Dubey, 1995). Difference of CCI between the two genotypes is indicative of the fact that genetic constitution could be involved in expression of this trait (Ghassemi-Golezani et al., 2012). Increase in CCI at higher level of potassium could be due to decrease in activity of chlorophyllase as a result of alleviating effect of potassium resulting from antagonism between K⁺ and Na⁺ in the nutrient solution.

Salinity stress is accompanied by physiological water deficit similar to drought stress in different plant organs (Chaves et al., 2009). In addition physiological water deficit plants have to face hyper-ionic and hyper-osmotic stress as well under prolonged salt stress (Munns, 2002; Chaves et al., 2003; Sanchez et al., 2007). So as a result leaf tissues faces water deficit not only because of low soil water content but also by high vapour pressure deficit of the atmosphere due to arid and semi-arid climates. The effect of this water deficit causes the closure of stomata mediated by shoot and root generated hormones, which ultimately limits the photosynthesis by decreasing stomatal conductance (Lawlor and Cornic, 2002; Flexas et al., 2004; Kusvuran, 2012). Similar was the case in our experiment where increasing salt (NaCl) concentration in the root medium caused a significant decrease in the stomatal
conductance, and application of potassium increased the stomatal conductance especially in salt-tolerant genotypes (Indent-1). Increase in stomatal conductance with the application of potassium could be due to the increased potassium content in the plant tissues, since potassium serve as a major osmoticum in vacuole and important for maintaining tissue water content under stressful conditions (Marschner, 1995). Consistent with our results Fanaei et al., (2009), Zhu et al., (2012) found increase in stomatal conductance with enhanced levels of potassium in oilseeds and sweet potato respectively.

There are two views about the stomatal density and aperture. According to first, stomatal density increases with increasing abiotic stress (Yang and Wang, 2001; Zhang et al., 2006; Wang and Gao, 2003; Yang et al., 2007), because cells become smaller in size due to the reduced cell growth rate, it results in the large number of cells in the per surface area thus it increases the stomatal density (Karimi et al., 2005; Boughalleb et al., 2009). According to second point of view that stomatal density decreases with increasing stress (Nautiyal et al., 1994; Kumari et al., 1999; Klamkowski and Treder, 2006), the reason presented is that decreased stomatal density could be the direct result of leaf succulency and an increase in the size of the pavement cells, plants not only improve water use efficiency but also provide additional space for Na+ sequestration in leaf epidermis under salinity stress (Shabala et al., 2013). Adolf et al., (2012) hypothesized that stomatal density increases at mild stress up to a maximum and decreases again at higher stress. As is the case in the current study, higher levels of salt stress significantly decreased the stomatal density and stomatal aperture in both the salt-tolerant and salt-sensitive tomato genotypes. Furthermore high values of SD and SA in tolerant tomato genotypes resulted in higher stomatal conductance (Figure 3.4.7). However there may exist differences in stomatal density because of different types of abiotic stresses and also there may be the effect of plant species/varieties (Maherali et al., 2002; Liu et al., 2006). The results showed that effect of potassium had non-significant effect on SD and SA consistent with finding of Kostopoulou et al., (2012), in citrus aurantium seedlings with application of potassium nitrate exposed to salinity stress. Nevertheless, to reach at a conclusion, still needs some conclusive evidence.
Figure 3.4.7 Correlation between A: stomatal density (SD) and stomatal conductance (gs), and B: stomatal aperture (SA) and gs. Each value represents mean of four replicates.

Abscisic acid (ABA) is proposed to have role of a mediator in plant responses to a range of abiotic stresses including salt and drought (Keskin et al., 2010). In the current study, xylem sap ABA concentration increased significantly with increasing NaCl stress, and this was more pronounced in salt-tolerant genotype Indent-1 than in the salt sensitive one Red Ball. These results are consistent with those of Ghanem et al., (2008) and Babu et al., (2012) in tomato and De Costa et al., (2007) in maize. Zörb et al., (2013) reported enhanced concentration of ABA in maize leaves with increasing salinity stress in salt-tolerant compared to a salt-sensitive hybrid, as is the case in the present study higher ABA contents in tolerant genotype and stronger relation with stomatal conductance than the sensitive genotype (Figure 3.4.8). It has been reported that higher concentration of ABA in leaves under stress might be the result of de novo biosynthesis of ABA in roots that enters the
apoplast through transpiration stream and ultimately controls stomatal movements (Wilkinson and Davies, 2002) and this higher concentration is related to salt stress (Fricke et al., 2004; Javid et al., 2011). As was the case in the current experiment, ABA concentration in the xylem sap was significantly higher in salt-tolerant genotype than the salt sensitive genotype.

![Graph showing correlation between ABA and stomatal conductance in tolerant (Indent-1) and sensitive (Red Ball) tomato genotypes.](image)

**Figure 3.4.8** Correlation between ABA and stomatal conductance in tolerant (Indent-1) and sensitive (Red Ball) tomato genotypes. Each value represents mean of four replicates.

Ethylene is a gaseous hormone and regarded as stress hormone as it is involved in plant stress responses (Cao et al., 2007). It has a role not only in plant growth and development but also in plant responses to abiotic stress like heat stress, Fe-deficiency, wounding, ozone stress and salt stress (Guo and Ecker, 2004; Chen et al., 2005; Chen and Zhang, 2006). According to Cao et al., (2006, 2007) ethylene signaling might be necessary for salt-tolerance as ethylene-insensitive arabidopsis mutants were more sensitive to salt stress. Significantly higher
ethylene production was observed in salt-tolerant calli compared to control and salt-sensitive calli of sunflower (Alvarez et al., 2003). In agreement with this, in the current experiment leaf ethylene biosynthesis was significantly higher under NaCl (75 and 150 mM) stress compared to control (0 mM) especially without adding potassium to the nutrient solution, and it was significantly higher in salt-tolerant tomato (Indent-1) than in the salt sensitive genotype (Red Ball). This has also been supported by the findings of Wang et al., (2009), who observed enhanced ethylene production and decrease in salt induced Na⁺ concentration to the application of ethylene precursor 1-Aminocyclopropane-l-carboxylic acid (ACC) under salinity stress, and they reported that ethylene might be involved ion homeostasis under salinity stress by increasing plasma membrane H⁺-ATPase activity. Application of potassium in the growth medium decreased the ethylene concentration because K⁺ has antagonistic role to Na⁺ in the growth medium.

In the current study of increasing salt stress, xylem sap Na⁺ content increased and K⁺ decreased, and as a result K⁺/Na⁺ declined sharply under salt stress. It has been reported previously that control and uptake of Na⁺ and maintaining higher levels of K⁺/Na⁺ is one of the key factors responsible for salinity tolerance (Shabala et al., 2010; 2013; Shi et al., 2002; Zhu, 2003). In our experiment salt-tolerant Indent-1 had lower value of xylem sap Na⁺, higher values of K⁺ and K⁺/Na⁺ than the salt sensitive Red Ball. Decrease in Na⁺ and increase in K⁺ content with potassium application in the nutrient solution, especially in salt-tolerant genotype could be attributed to competition between K⁺ and Na⁺ for binding sites on the plasma membrane which decreases the influx of Na⁺ (Al-Uqaili 2003; Davenport et al., 2007). This increase in xylem K⁺ content could be responsible for enhanced stomatal conductance and decreased levels of ABA and ethylene, which enhanced growth of the whole plant because potassium is very important for many physiological processes like maintenance of turgor, photosynthesis, enzyme activation, and limiting excess uptake of ions such as Na⁺ and Fe³⁺ especially under salinity stress (Cakmak, 2005; Kusvuran et al., 2007; Shabala et al., 2010).

Salt stress decreased CCI, gs, xylem sap K⁺, K⁺/Na⁺, and increased xylem sap Na⁺ and plant hormone concentration (ABA, ethylene). ABA appears to increase water productivity under salt stress by regulating stomatal conductance through stomatal movements, improving water uptake by the root. Ethylene increases the K⁺/Na⁺ ratio by increasing plasma membrane H⁺-
ATPase activity. Potassium application had an ameliorative effect under salt stress as evident from these measured parameters. The difference in salt-tolerance between the genotypes (Indent-1, Red Ball) could be the result of difference between the concentrations of these endogenous hormones.
Chapter-4

SUMMARY

Soil salinity poses a severe threat to the world food security by reducing the crop productivity. To meet the food requirements of the world population in the future years, it not only demands to sustain the current food production but also to increase it. This increased demand of food has exerted a definite pressure on agriculture and it has been pushed to marginal salt affected lands. This scenario of looming food crisis in the coming years puts serious challenges for the agricultural scientists to breed salt tolerant species/genotypes and develop such techniques that can induce salt tolerance in plants or able the plants to survive under salt stress conditions and produce economical yields. Plants nutritional status is critical under stress conditions to able them to survive and maintain their growth. Potassium as a mineral nutrient is among the macro nutrients and very important for plant growth and quality of the product. It becomes even more important under stress conditions considering its role in important physiological processes especially in enzyme activation. So, under salinity stress improving the potassium nutritional status of plants is an effective approach to alleviate stress and also to increase food quality. Tomato is important vegetable crop and ranked second worldwide in terms of its consumption. It is moderately sensitive to salt stress and is mostly cultivated in arid and semi-arid areas of the world where salinity is a common limiting factor for its production. Based on these facts present research work was done to achieve the objective:

 ✓ To characterize the comparative response of different tomato genotypes to salt stress.
 ✓ To Study the interactive effect of potassium and salinity on physiologic, gas exchange, ionic characteristics in tomato plants and their involvement in salt tolerance.
 ✓ To understand the mechanism of salinity causing potassium deficiency and consequently the oxidative stress by measuring the effect of potassium on antioxidant enzymes under salinity.
✓ To assess the interacting effect of potassium and salt stress on ABA levels in contrasting tomato genotypes and role of ABA as a mediator in regulating the plants response to salt stress.
✓ To study the response of leaf ethylene biosynthesis to salt stress and potassium.
✓ To study the stomatal morphological changes in tomato genotypes in response to salinity and potassium application.

To accomplish these objectives, four experiments were conducted in the wire house of Saline Agriculture Research Centre (SARC), University of Agriculture, Faisalabad and Department of Plant and Environmental Sciences, University of Copenhagen, Denmark.

The preliminary experiment was conducted in solution culture to evaluate the salinity tolerance of 15 tomato genotypes in Hoagland’s nutrient solution with three levels of NaCl (0, 75 and 150 mM). The experiment was conducted in completely randomized design with three replicates. After 30 days of imposition of salt stress, gas exchange parameters: transpiration rate, stomatal conductance, CO₂ assimilation rate, intercellular CO₂ concentration were recorded and harvested plants were characterized for growth (shoot/longest root lengths and fresh/dry weights), and ionic characteristics (Na⁺, K⁺ and K⁺/Na⁺ ratio) parameters. All growth and gas exchange parameters were decreased with increasing NaCl concentrations. However this decrease was less in salt-tolerant genotypes as compared to salt-sensitive genotypes. It was also determined that with the increasing NaCl concentration in the rooting medium, the amount of Na⁺ in the plant tissues increased and, the amount of K⁺ ion decreased. Thus, it was concluded that the plants with more K⁺ absorbing ability, with high K⁺/Na⁺ ratio and higher growth were more salt-tolerant. It was also concluded that fresh and dry weights, gas exchange characteristics and K⁺/Na⁺ ratio were very effective in determining the salt-tolerance. Considering the genotypes, Indent-1 and Nagina were characterized as salt-tolerant and the Red Ball and Peto-86 as salt-sensitive under saline conditions.

In the second experiment differential response of salt-tolerant (Indent-1 and Nagina) and salt-sensitive (Peto-86 and Red Ball) tomato genotypes was studied to the application of different levels of potassium (control, 4.5 and 9 mM) in solution and foliar under NaCl-stress (control, 75 and 150 mM). Different growth, physiologic, antioxidative and ionic characteristics were
measured at two time intervals (15 and 30 days) in all the genotypes. The results showed that NaCl-stress decreased the growth of plants in both the tolerant and sensitive genotypes; however tolerant genotypes maintained significantly higher growth than the sensitive genotypes. Increasing concentration of salt severely affected the physiology of plants and caused a significant decrease in all the genotypes with more significant decrease in salt-sensitive genotypes than the salt tolerant genotypes in leaf gas exchange characteristics; photosynthetic rate (A), transpiration rate (E), stomatal conductance (gs), inter-cellular CO2 concentration (Ci), membrane stability index (MSI) and photosynthetic pigments; chlorophyll a and chlorophyll b. Increasing NaCl concentration in the growth medium caused a significant increase in the activity of antioxidant enzymes (SOD, CAT, GR) and decrease in MDA in both salt-tolerant and salt-sensitive groups. Application of potassium alleviated the effects of NaCl stress by the decreased tissue Na⁺, increased K⁺ and K⁺/Na⁺, positively affected the physiology of plants and resulted in better growth of plants especially in salt-tolerant group. There was not much of difference between the solution and foliar forms of application of potassium. The enhanced application of potassium could be used as an efficient tool to ameliorate the negative effects of salt stress and increasing salt tolerance in tomato to get better crop yields under saline soils.

Third experiment was conducted in pots to study the effect of potassium to soil (180 and 360 kg ha⁻¹) and leaves (4.5 and 9 mM) on tomato yield and quality under three salinity treatments (control 0, 7.5 and 15 dS m⁻¹), using two salt-tolerant (Indent-1 and Nagina) and two salt-sensitive (Peto-86 and Red Ball) genotypes in a pot experiment. Fruits were harvested when 90% of them turned red. Plant height, dry weight, fruit yield and quality characteristics, both physical (fruit diameter and height, fruit dry matter) and chemical (fruit juice total soluble solids (TSS), titratable acidity (TA, pH) were measured. Results showed that salinity decreased growth and yield of all genotypes, however, salt tolerant genotypes maintained better growth and produced higher yield than the salt-sensitive genotypes across all the three salinity levels. Potassium application mitigated the negative effects of salinity, and positively affected plant growth and yield, especially in salt tolerant genotypes. Fruit quality characteristics (TSS, TA, pH, DM %) were significantly improved by increasing salinity, but not fruit size. Potassium also had significant effect on the fruit quality as they all characteristics increased at higher K⁺ concentrations under salinity treatments. There were no
significant differences between K⁺ soil and foliar applications. Based on the results it was concluded that application of potassium increases yield and quality of tomato fruits under soil salinity and it could be used as an effective practice to produce even a salt sensitive species like tomato under saline conditions.

In the last experiment, the involvement of phytohormones in salt tolerance of tolerant tomato genotype and also the interaction between potassium and phytohormones under salt stress in relatively salt-tolerant (Indent-1) and salt-sensitive (Red Ball) genotypes was studied at three levels of NaCl (0, 75, 150 mM) combined with two levels of K (0, 4.5 mM) under controlled conditions in a climatic chamber. Results showed that the salt-tolerant genotype had significantly higher concentrations of ABA and ethylene under saline conditions compared to control, and higher than the salt-sensitive genotype. The concentration of these hormones was significantly higher without K⁺ indicating that K⁺ reduced the stress. Enhanced concentration of hormones in salt tolerant genotypes resulted in better chlorophyll content index (CCI), stomatal conductance and ion homeostasis that is higher K⁺/Na⁺ ratio. Salt stress altered the stomatal morphology and significantly decreased the stomatal density (SD) and stomatal aperture (SA) in both genotypes. It was concluded that under salt stress enhanced phytohormone concentration positively affected the tomato plant physiology in salt-tolerant genotype and this could be one of the factors responsible for its better salt tolerance. Potassium application served as ameliorant and reduced the negative effects of salt stress and could be used as an effective tool for crop production.

The results from this research depict that potassium served as a good ameliorant agent under salinity stress could be used as an effective strategy for crop production even with salt sensitive species like tomato.
References


Läuchli, A. 1991. The social and scientific relevance of salt tolerance studies. In: Workshop on Salt Tolerance in Microorganisms and Plants: Physiological and Molecular


Lu, S.W., T. Li and J. Jing. 2010. Effects of tomato fruit under Na\textsuperscript{+} -salt and Cl\textsuperscript{−} salt stresses on sucrose metabolism. African J. Agric. Res. 5(16): 2227-2231.


APPENDIX

In Appendix “G” represents Genotype, “K” Potassium and “NaCl” Treatments

Appendix-1: Analysis of Variance Table for Shoot Length

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Grand Mean 39.637 CV 7.68

Appendix-2: Analysis of Variance Table for Root Length

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Grand Mean 43.829 CV 9.14

Appendix-3: Analysis of Variance Table for Shoot Fresh Weight

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Grand Mean 50.404 CV 9.14

Appendix-4: Analysis of Variance Table for Root Fresh Weight

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Grand Mean 3.6644 CV 6.92
### Appendix-5: Analysis of Variance Table for Shoot Dry Weight

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Grand Mean 2.7364  CV 7.72

### Appendix-6: Analysis of Variance Table for Root Dry Weight

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Grand Mean 0.3964  CV 7.68

### Appendix-7: Analysis of Variance Table for CO₂ assimilation rate

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Grand Mean 2.9649  CV 9.14

### Appendix-8: Analysis of Variance Table for Transpiration Rate

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Grand Mean 2.2021  CV 7.68
### Appendix-9: Analysis of Variance Table for Stomatal conductance

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Grand Mean 0.2697    CV 7.68

### Appendix-10: Analysis of Variance Table for intercellular CO₂ concentration

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Grand Mean 96.035    CV 7.69

### Appendix-11: Analysis of Variance Table for Na⁺

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Grand Mean 50.370    CV 10.27

### Appendix-12: Analysis of Variance Table for K⁺

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Grand Mean 250.19    CV 9.31
### Appendix-13: Analysis of Variance Table for K⁺/Na⁺

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Grand Mean 7.8020    CV 14.44

### Appendix-14a: Analysis of Variance Table for Shoot Fresh Weight after 15 days

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Grand Mean 38.385    CV 6.03

### Appendix-14b: Analysis of Variance Table for Shoot Fresh Weight after 30 days

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Grand Mean 58.552    CV 4.46
### Appendix-15a: Analysis of Variance Table for Root Fresh Weight after 15 days

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Grand Mean 2.0299  CV 4.34

### Appendix-15b: Analysis of Variance Table for Root Fresh Weight after 30 days

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Grand Mean 4.0487  CV 5.27

### Appendix-16a: Analysis of Variance Table for Shoot dry Weight after 15 days

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Grand Mean 1.9027  CV 3.95
Appendix-16a: Analysis of Variance Table for Shoot dry Weight after 30 days

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Grand Mean 3.0783    CV 7.78

Appendix-17a: Analysis of Variance Table for Root dry Weight after 15 days

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Grand Mean 0.2791    CV 5.61

Appendix-17b: Analysis of Variance Table for Root dry Weight after 30 days

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Grand Mean 0.4854    CV 10.35
Appendix-18a: Analysis of Variance Table for Shoot length after 15 days

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Grand Mean 27.339    CV 6.52

Appendix-18b: Analysis of Variance Table for Shoot length after 30 days

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Grand Mean 44.534    CV 6.00

Appendix-19a: Analysis of Variance Table for Root length after 15 days

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Grand Mean 31.183    CV 6.71
Appendix-19b: Analysis of Variance Table for Root length after 30 days

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Appendix-20a: Analysis of Variance Table for photosynthetic rate (A) after 15 days

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Appendix-20b: Analysis of Variance Table for photosynthetic rate (A) after 30 days

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### Appendix-21a: Analysis of Variance Table for transpiration rate \((E)\) after 15 days

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Grand Mean 1.2476  CV 5.45

### Appendix-21b: Analysis of Variance Table for transpiration rate \((E)\) after 15 days

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Grand Mean 2.3384  CV 6.69

### Appendix-22b: Analysis of Variance Table for intercellular CO\(_2\) concentration \((Ci)\) after 30 days

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Grand Mean 85.954  CV 8.09
### Appendix-23a: Analysis of Variance Table for stomatal conductance (gs) after 15 days

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Grand Mean 0.2358    CV 5.66

### Appendix-23b: Analysis of Variance Table for stomatal conductance (gs) after 30 days

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Grand Mean 0.2516    CV 8.29

### Appendix-24a: Analysis of Variance Table for Membrane stability index after 15 days

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Grand Mean 77.891    CV 6.82
### Appendix-24b: Analysis of Variance Table for Membrane stability index after 30 days

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Grand Mean: 79.496, CV: 4.92

### Appendix-25a: Analysis of Variance Table for leaf sap Na⁺ contents after 15 days

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Grand Mean: 19.927, CV: 6.42

### Appendix-25b: Analysis of Variance Table for leaf sap Na⁺ contents after 30 days

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Grand Mean: 82.354, CV: 7.46
### Appendix-26a: Analysis of Variance Table for leaf sap K⁺ contents after 15 days

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Grand Mean 130.02 \ CV 8.90

### Appendix-26b: Analysis of Variance Table for leaf sap K⁺ contents after 30 days

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Grand Mean 141.50 \ CV 8.66

### Appendix-27a: Analysis of Variance Table for leaf sap K⁺/ Na⁺ contents after 15 days

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Grand Mean 2.4421 \ CV 12.37
### Appendix-27b: Analysis of Variance Table for leaf sap K+/ Na+ contents after 30 days

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Grand Mean 2.4810    CV 12.60

### Appendix-28a: Analysis of Variance Table for leaf CHL a contents after 15 days

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Grand Mean 4.5763    CV 4.82

### Appendix-28b: Analysis of Variance Table for leaf CHL a contents after 30 days

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Grand Mean 5.3130    CV 10.45
### Appendix-29a: Analysis of Variance Table for leaf CHL b contents after 15 days

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Grand Mean 6.5501   CV 4.90

### Appendix-29b: Analysis of Variance Table for leaf CHL b contents after 30 days

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Grand Mean 7.6922   CV 9.49

### Appendix-30a: Analysis of Variance Table for SOD activity after 15 days

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Grand Mean 19.927   CV 6.42
Appendix-30a: Analysis of Variance Table for SOD activity after 30 days

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Grand Mean 21.345    CV 5.53

Appendix-31a: Analysis of Variance Table for CAT activity after 15 days

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Grand Mean 1.0229    CV 5.38

Appendix-31b: Analysis of Variance Table for CAT activity after 30 days

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Grand Mean 1.1134    CV 3.97
### Appendix-32a: Analysis of Variance Table for GR activity after 15 days

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Grand Mean 5.7034    CV 5.45

### Appendix-32b: Analysis of Variance Table for GR activity after 30 days

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Grand Mean 5.9307    CV 5.12

### Appendix-33a: Analysis of Variance Table for MDA contents after 15 days

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Grand Mean 29.314    CV 6.32
### Appendix-33b: Analysis of Variance Table for MDA contents after 30 days

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Grand Mean 32.993 CV 6.99

### Appendix-34: Analysis of Variance Table for Plant height

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Grand Mean 4.0345 CV 6.37

### Appendix-35: Analysis of Variance Table for Plant dry weight

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Grand Mean 6.8913 CV 8.67
### Appendix-36: Analysis of Variance Table for leaf sap Na\(^+\) contents

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Grand Mean 83.460 CV 6.35

### Appendix-37: Analysis of Variance Table for leaf sap K\(^+\) contents

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Grand Mean 129.57 CV 9.06

### Appendix-38: Analysis of Variance Table for leaf sap K\(^+\)/Na\(^+\) contents

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Grand Mean 2.2036 CV 13.40
### Appendix-39: Analysis of Variance Table for fruit weight per plant

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Grand Mean 476.15  CV 4.92

### Appendix-40: Analysis of Variance Table for average fruit weight

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Grand Mean 19.399  CV 4.43

### Appendix-41: Analysis of Variance Table for fruit diameter

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Grand Mean 3.7723  CV 6.25
### Appendix-42: Analysis of Variance Table for fruit height

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<td>NACL</td>
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<td>K</td>
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Grand Mean 4.0345  CV 6.37

### Appendix-43: Analysis of Variance Table for fruit juice total soluble solids

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Grand Mean 6.8458  CV 5.51

### Appendix-44: Analysis of Variance Table for fruit dry matter %

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Grand Mean 6.7690  CV 5.29
Appendix-45: Analysis of Variance Table for fruit juice Titratable acidity

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Grand Mean 1326.2  CV 7.10

Appendix-46: Analysis of Variance Table for chlorophyll content index

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Grand Mean 43.453  CV 10.17

Appendix-47: Analysis of Variance Table for stomatal conductance

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Grand Mean 173.58  CV 10.10
Appendix-48: Analysis of Variance Table for stomatal density

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Grand Mean 287.00    CV 9.64

Appendix-49: Analysis of Variance Table for stomatal aperture size

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Grand Mean 59.776    CV 9.61

Appendix-50: Analysis of Variance Table for xylem ABA

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Grand Mean 208.50    CV 32.39
Appendix-51: Analysis of Variance Table for leaf ethylene biosynthesis

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Grand Mean 1.2581    CV 58.34

Appendix-52: Analysis of Variance Table for xylem Na⁺ contents

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Grand Mean 115.83    CV 22.92

Appendix-53: Analysis of Variance Table for xylem K⁺ contents

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</tbody>
</table>

Grand Mean 325.11    CV 11.15
### Appendix-54: Analysis of Variance Table for xylem K⁺/Na⁺ contents

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<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
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Grand Mean 10.070  CV 33.21