ROLE OF MINERAL NUTRITION IN ALLEVIATING DETRIMENTAL EFFECTS OF ENVIRONMENTAL STRESSES ON CROP PRODUCTION

by Ismail CAKMAK
Sabanci University Istanbul, Turkiye
HUGE INCREASES IN WORLD POPULATION
FOOD SECURITY
The world population is expanding rapidly and will likely be 10 billion by the year 2050. Limited availability of additional arable land and water resources, and the declining trend in crop yields globally make food security a major challenge in the 21st century.

According to the projections, food production on presently used land must be doubled in the next two decades to meet food demand of the growing world population.

The projected increase in food production must be accomplished on the existing cultivated areas because the expansion of new land is limited.

“1 out of 4 people in line at a soup kitchen is a child.”
From Hunger in America 2001
WORLD HUNGER

Percentage of Undernourished Individuals (%)

- More than 30.0
- 20.0 - 30.0
- 10.0 - 20.0
- 5.0 - 10.0
- Less than 5.0
- unknown
- unclassified

http://www.feedingminds.org/level1/lesson1/worldhungermap.htm
Decreases in Record Yield Capacity of Crop Plants by Abiotic and Biotic Stress Factors

- **Losses by abiotic stress**
- **Present average yield**
- **Losses by biotic stress**

### Corn
- Present average yield: 10%
- Losses by abiotic stress: 66%
- Losses by biotic stress: 24%

### Wheat
- Present average yield: 5%
- Losses by abiotic stress: 82%
- Losses by biotic stress: 13%

### Soybean
- Present average yield: 9%
- Losses by abiotic stress: 69%
- Losses by biotic stress: 22%

**Record Yield:**
- **Corn:** 19.3 tons ha\(^{-1}\)
- **Wheat:** 14.5 tons ha\(^{-1}\)
- **Soybean:** 7.4 tons ha\(^{-1}\)

Source: Bray et al., 2000, In Molecular Biology and Biochemistry of Plants, ASPP
Photooxidative stress
Photooxidative Damage

a key process involved in cell damage and cell death in plants exposed to environmental stress factors
Mineral nutritional status of plants greatly influences occurrence of photooxidative damage in plants by causing impairments in photosynthetic electron transport and CO₂ fixation in various ways.

Photooxidative damage in nutrient deficient plants can be more serious when plants are simultaneously exposed to an environmental stress.
Photosynthetic Electron Transport and Superoxide Radical Generation

LIGHT

THYLAKOID

PSII  PSI

STROMA

O₂ → O₂⁻, H₂O₂, OH⁻
Toxic O₂ Species

O₂ → Sucrose

2H₂O  O₂  ATP

CO₂  Phloem Export

Stomatal CO₂ Flux
Photosynthetic Electron Transport and Superoxide Radical Generation

LIGHT

THYLAKOID

PSII

PSI

STROMA

O₂ → O₂⁻, H₂O₂, OH⁻
Toxic O₂ Species

O₂⁻, H₂O₂, OH⁻

NUTRIENT DEFICIENCY

CELL DAMAGE

2H₂O → O₂, ATP

CO₂ → Sucrose
Phloem Export

Stomatal CO₂ Flux
FREE RADICAL DAMAGE TO CRITICAL CELL CONSTITUENTS

O₂

h.v. e⁻

¹⁰₂ O₂⁻ H₂O₂ OH⁻

MEMBRANE DNA CHLOROPHYLL PROTEIN

LIPID PEROXIDATION MUTATION CHLOROSIS PROTEIN DAMAGE

CELL DEATH
Of the mineral nutrients, nitrogen plays a major role in utilization of absorbed light energy and photosynthetic carbon metabolism.

In N-deficient leaves an excess of non-utilized light energy can be expected leading to high risk for occurrence of photooxidative damage.
Photosynthetic characteristics in *C. album* leaves grown at high light

<table>
<thead>
<tr>
<th>Growth conditions</th>
<th>Chl (mmol m(^{-2}))</th>
<th>Photosynthetic rate (µmol m(^{-2}) s(^{-1}))</th>
<th>Electron transport rate (µmol m(^{-2}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deficient N</td>
<td>0.47</td>
<td>13</td>
<td>124</td>
</tr>
<tr>
<td>Adequate N</td>
<td>0.90</td>
<td>29</td>
<td>254</td>
</tr>
</tbody>
</table>

Kato et al., 2003, Plant Cell Physiol. 44:318-325
To avoid occurrence of photooxidative damage in response to excess light energy, thylakoid membranes have a protective mechanism by which excess energy is dissipated as heat.

Dissipation of excess light energy is associated with enhanced formation of xanthophyll pigment **zeaxanthin**.
Zeaxanthin is synthesized from violaxanthin in the light-dependent xanthophyll cycle to avoid excess energy.
Xanthophyll Cycle Composition in Relation to Leaf N of Fuji/M.26 Trees at Noon Under an Incident PFD of 1500 µmol m\(^{-2}\) s\(^{-1}\)

Verhoeven et al., Plant Physiol. 1997, 113: 817-824
Use of Absorbed Light Energy for Photochemistry

Verhoeven et al., Plant Physiol. 1997, 113: 817-824
Conversion State of Xanthophyll Cycle Pigments at Growth Irradiance in Spinach Leaves

Verhoeven et al., Plant Physiol. 1997, 113: 817-824
In plants suffering from N deficiency the conversion state of the xanthophyll cycle pigments zeaxanthin was enhanced together with chlorophyll bleaching particularly under high light intensity.

These results indicate impaired use of absorbed light energy in photosynthetic CO$_2$ fixation and thus enhanced demand for protection against excess light energy in N-deficient plants.
Nitrogen is involved in protection of plants from chilling stress

In studies with *Eucalyptus* seedlings it has been shown that seedlings with impaired N nutritional status were less susceptible to photooxidative damage in winter months.

Experiments were carried out to study the effect of low temperature stress on lipid peroxidation, antioxidants and defense enzymes in lemon that is very sensitive to low temperature.
Effect of Increasing Nitrogen Supply on Lipid Peroxidation at Normal and Low Temperature in Lemon

S. Eker, unpublished results
Effect of Increasing Nitrogen Supply on Prolin Concentration at Normal and Low Temperature in Lemon

S. Eker, unpublished Results
Effect of Increasing Nitrogen Supply on Superoxide Dismutase at Normal and Low Temperature in Lemon

S. Eker, unpublished Results
Yield of transgenic alfalfa in 3 years of field trials. Cuttings were planted in 1x3 m plots in replicated trials in spring 1992.
Effect of Increasing Nitrogen Supply on Ascorbate Peroxidase at Normal and Low Temperature in Lemon

S. Eker, unpublished Results
Effect of Increasing Nitrogen Supply on Glutathione Reductase at Normal and Low Temperature in Lemon

S. Eker, unpublished Results

<table>
<thead>
<tr>
<th>Nitrogen Supply</th>
<th>Glutathione Reductase (µmol g(^{-1}) DW min) at 24 °C</th>
<th>Glutathione Reductase (µmol g(^{-1}) DW min) at -3.5 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>low N</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>medium N</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>sufficient N</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
Effect of Increasing Nitrogen Supply on Catalase at Normal and Low Temperature in Lemon

S. Eker, unpublished Results
Catalase enzyme is highly sensitive to low temperature. Improved N nutrition protects catalase from inhibition/inactivation by low temperature stress.

The activity of most antioxidant enzymes is increased by low N supply, especially at low temperature. This lead to suggestion that N deficiency promotes increased production of reactive oxygen species.
POTASSIUM IN CROP PRODUCTION

Alleviation of Effects of Stress Factors

Water Regime

Photosynthesis

Protein Synthesis

Enzyme Activation

Meristematic Growth

Phloem Export of Photosynthates
K Deficiency - Enhanced Sensitivity to

- Diseases
- Low Temperature
- High Light
- Drought
- Fe toxicity
- Salinity
Effect of Varied K Supply on Photosynthesis in Cotton

Photosynthesis Rate (µmol m\(^{-2}\) s\(^{-1}\))

Days

13 19 26

adequate K

K deficiency

Bednarz and Oosterhuis, 1999 ; J. Plant Nutr.
Effect of Elevated CO\textsubscript{2} on Photosynthesis at Varied K Supply

Adequate K
Low K

Barnes et al., 1995, Plant Cell Environ.
Photosynthetic Electron Transport and Superoxide Radical Generation

LIGHT

PSII

STROMA

PHOTOSYNTHETIC ELECTRON TRANSPORT AND SUPEROXIDE RADICAL GENERATION

PHOTOSYNTHETIC ELECTRON TRANSPORT AND SUPEROXIDE RADICAL GENERATION

STROMA

PSI

2H2

O

O2

O2

H2O2, OH-

Reactive O2 Species

CELL DAMAGE

K Deficiency

CO2

Sucrose

Phloem Export

2H2

O

O2

Stomatal CO2 Flux

O2

-
Growth of bean plants with low K supply under low and high light intensity

Enhancement of leaf chlorosis by high light intensity is not related to differential K concentration in leaves.
Enhancement of leaf chlorosis in Mg-deficient leaves by high light intensity is not related to Mg concentration in leaves.

Partially shaded bean leaf at low Mg concentration.
Photooxidative damage to chloroplasts is a major contributing factor in development of K deficiency symptoms on leaves.

Plants grown under high light intensity require more K than plants grown under low light.
Enhancement of photooxidative damage in K-deficient leaves

Partially shaded K-deficient bean leaves
CARBOHYDRATE ACCUMULATION AND CHLOROSIS IN NUTRIENT-DEFICIENT LEAVES

Inhibitions in photosynthetic CO$_2$ reduction and phloem loading of sucrose play an important role in O$_2$ activation and occurrence of photooxidative damage, especially in Mg or K deficient leaves.

Leaf chlorosis and necrosis is common in Mg and K deficient leaves, but not in P deficient leaves.
PHLOEM TRANSPORT

K and Mg play critical role in phloem transport
Accumulation of Phosynthates in K-Deficient Source Leaves

Sucrose concentration
(mg Glucose equiv. g⁻¹ DW)

Control: 12
K Deficiency: 76
Sucrose concentration in source leaves

(mg Glucose equiv. g\(^{-1}\) DW)

Control: 12
Low K: 76
Low Mg: 108
Low P: 19
Decrease in Phloem Export of Sucrose by K-Deficiency

Control: 3.4
K Deficiency: 1.6

Phloem Export of Sucrose
(mg Glucose equiv. g⁻¹ DW 8 h⁻¹)
Export of sucrose from bean leaves
(mg Glucose equiv \cdot g^{-1} DW \cdot 8h^{-1})

Control: 3.4 ± 0.8
Low K: 1.6 ± 0.3
Low Mg: 0.7 ± 0.3
Low P: 2.8 ± 1.0
Relative distribution of total carbohydrates between shoot and roots (%)

Control: 84, 16
K Deficiency: 97, 3
Relative distribution of total carbohydrates between shoot and roots (%)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Carbohydrates (shoot)</th>
<th>Carbohydrates (roots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>84</td>
<td>16</td>
</tr>
<tr>
<td>Low K</td>
<td>97</td>
<td>3</td>
</tr>
<tr>
<td>Low Mg</td>
<td>99</td>
<td>1</td>
</tr>
<tr>
<td>Low P</td>
<td>77</td>
<td>23</td>
</tr>
</tbody>
</table>
Enzymes involved in H$_2$O$_2$ detoxification in chloroplasts

- AsA peroxidase
- MDAsA reductase
- DHAsA reductase
- Glutathione reductase

H$_2$O$_2$ → AsA → MDAsA → DHAsA → GSSG → GSH → NADPH

H$_2$O → non-enzymatic → NADH → NADPH → NADP$^+$
Ascorbate Peroxidase Activity of Source Leaves

Control: 4.7

(K Deficiency: 9.5

(μmol Ascorbate g⁻¹ FW min⁻¹)
Monodehydroascorbate Reductase Activity of Source Leaves

Control: 1.2 (µmol Ascorbate g\textsuperscript{-1} FW min\textsuperscript{-1})

K Deficiency: 3.5 (µmol Ascorbate g\textsuperscript{-1} FW min\textsuperscript{-1})
Potassium Improved Photosynthesis Under Drought Stress

Sen Gupta et al., 1988, Plant Physiol.
Effect of increasing K Supply on Percentage of Live Roots Under Varied Drought Treatments

Live root (%)

K supply to growing medium (mM)

- Non-drought stressed
- Drought Stressed

0 2.5 10

- Live root (%) increases with increasing K supply in both non-drought stressed and drought stressed conditions.
- Drought stressed conditions show a higher live root percentage compared to non-drought stressed conditions at all K supply levels.
Alleviation of Frost Damage by K Supply in Potato

Grewal, and Singh, 1980
Alleviation of Salt Stress by K Supply

Activity of **NADPH-oxidizing enzymes** play an important role in generation of superoxide radical production under drought, chilling, Zn deficiency, UV light, wounding, pathogenic infection, etc.
Stress stimulated NADPH oxidase and NADPH-dependent superoxide radical generation

Cakmak, 2003, in press
Increases in NADPH-Dependent $\text{O}_2^{-}$ Generation by K Deficiency in Bean Roots

<table>
<thead>
<tr>
<th>K supply (µmol)</th>
<th>$\text{O}_2^{-}$ generation (nmol $\text{O}_2^{-}$ FW min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>45 (124)</td>
</tr>
<tr>
<td>25</td>
<td>42 (117)</td>
</tr>
<tr>
<td>50</td>
<td>50 (139)</td>
</tr>
<tr>
<td>100</td>
<td>49 (136)</td>
</tr>
<tr>
<td>200</td>
<td>44 (122)</td>
</tr>
<tr>
<td>2000 (control)</td>
<td>36 (100)</td>
</tr>
</tbody>
</table>

S. Eker, unpublished results
K Deficiency-Induced Marked Increases in NADPH Oxidase Activity of Bean Roots

S. Eker, unpublished results
Chilling-Induced NADPH-Oxidation and NADPH-Dependent $\text{O}_2^-$ Generation in Leaves of Cucumber

Shen et al., 2000; Plant Physiol.
K Deficiency-Induced Biosynthesis of ABA (Abscisic Acid) in Roots

Peuke et al., 2002, J. Exp. Botany
NADPH oxidase and $O_2^-$ Production in Plants Treated with ABA and Drought

ABA: Abscisic Acid

Jiang and Zhang, 2002; Planta
Zn and B deficiencies also affect photosynthetic activities of plants in various ways.

• Both micronutrients exert marked influences on photosynthetic CO$_2$ fixation and translocation of photosynthates.

• Any disturbance in the adequate supply of plants with Zn and B is, therefore, potentially capable of inducing photooxidative damage
ALSO ZINC-DEFICIENT PLANTS ARE HIGHLY PHOTOSENSITIVE

Increases in light intensity rapidly cause development of chlorosis and necrosis in Zn-deficient plants.

Growth of Zn deficient bean plants at different light intensities:
- 22 W m\(^{-2}\)
- 53 W m\(^{-2}\)
- 127 W m\(^{-2}\)
Growth of Citrus Trees on a Zn-Deficient Soil

Cakmak et al., 1995
High light-induced damage in B-deficient plants.
Superoxide Generation and Photooxidative Damage

Photooxidative damage to membrane and chlorophyll can be expected in B-deficient leaves as a result of enhanced photogeneration of toxic oxygen free radicals caused by impaired utilization of light energy in photosynthesis.
O$_2$ - Production in Leaf Disks from B-Deficient Plants

![Graph showing nmol NO$_2$ 30 min$^{-1}$ for 4 leaf disks with different light intensities and B conditions.]

- +B
- -B
- -B, +SOD
Activity of NADPH-oxidizing enzymes play an important role in generation of superoxide radical under drought, chilling, Zn deficiency, UV light, wounding, pathogenic infection, etc.
NADPH Oxidase Activity in Isolated Tomato and Tobacco Membranes

Sagi and Fluhr, 2001, Plant Physiol. 126: 1281-1290
There is increasing evidence suggesting that Ca is involved in expression of high tolerance to heat stress in plants.

- Jiang and Huang (2001) showed that Ca treatment protects cool-season grass species from heat injury expressed as increased lipid peroxidation and chlorophyll degradation.

- Exposure of seedlings to heat stress at 40 °C induced lipid peroxidation and reduced survival of seedlings, and these effects of heat stress could be inhibited very significantly by Ca treatment.
Oxidative Damage and Survival in Response of Heating in Arabidopsis

Oxidative Damage and Survival in Response of Heating in Arabidopsis with and without Ca supply

Effect of Foliar Application of Ca on Lipid Peroxidation and Blossom-end

CONCLUSIONS
The existing data indicate that improving mineral nutritional status of plants under marginal environmental conditions is indispensable for sustaining survival and high yield.

Impairment in mineral nutritional status of plants, therefore, exacerbates adverse effects of environmental stress factors on plant performance.
Mineral at adequate levels nutrients supplied are essentially required for maintaining photosynthetic activities and utilization of light energy in CO$_2$ fixation.

Improving mineral nutrition of plants is, therefore, a major contributing factor to the protection of plants from photooxidative damage under marginal environmental conditions.
Remaining challenges include the better understanding the roles of mineral nutrients in

i) ROS formation during photosynthesis and plasma membrane-bound NADPH oxidase,
ii) signaling pathways affecting adaptive response of plants to environmental stresses and
iii) expression and regulation of genes induced by mineral nutrient deficiency.