Physiological effects of abiotic stress on crop yield and quality

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Agricultural yields are likely to decrease by 2050
Abiotic stress: Challenging Indian Agriculture

- Agriculture production has undergone drastic changes in recent years and is being seriously limited by various abiotic stresses.
- More than 50% of agricultural production loss is due to abiotic stresses, their intensity and adverse impact are likely to amplify with climate change.
- The major loss is due to high temperature (20%) followed by drought (9%), low temperature (7%), and other forms of stresses (4%).
"Globally-averaged temperatures in 2015 shattered the previous mark set in 2014 by 0.23 degrees Fahrenheit (0.13 Celsius). Only once before, in 1998, has the new record been greater than the old record by this much."

~ NASA Goddard Institute for Space Studies [NASA post of January 20, 2016]
Floods, droughts to be the norm

Kamcilla Pillay reports back from the annual briefing on climate change by India’s Centre for Science and Environment in New Delhi last week.

Extreme weather events brought on by climate change would hit developing nations the hardest, making it imperative for them to come together to find solutions.

Floods and droughts, like the one affecting KwaZulu-Natal, would affect food security, heighten poverty and result in deaths, said experts gathered at the annual media briefing on climate change, convened by the Centre for Science and Environment in New Delhi last week.

Emmanuel Olukayode Odipo, who is based at the Climate Change Network in Nigeria, said in his talk on drought response and disaster management that the situation for developing nations would become more challenging.

"From 2010 to 2035, droughts, according to the Climate Change Emergency Institute, are more likely than not. There will be more record hot weather. In fact, at present, we are experiencing between one and five days of extreme heat a year."

"As the Earth’s temperature increases by 2°C, we will experience 27 of these days. As we reach 3°C, the number will increase to 62." Southern Africa would experience an increase in temperature, general dryness and there would be "no coherent patterns" in rainfall trends. The region's problems would worsen in the coming years.

The Intergovernmental Panel on Climate Change said that droughts could intensify over the coming century in southern parts of the continent.

The Centre for Science and Environment said in a report that all types of natural disasters, including droughts, had increased from an average of 60 plus events during the 1970s to 350 in 2014.

Africa, on average, between 1970 and last year, experienced 60 natural disasters, affecting millions of people.

Early warning systems on the part of local governments were crucial but Odipo said, community-based systems such as those used in Nepal were also needed.

Rosa Perez, of the Philippine Climate Change Commission, agreed with Odipo and said these systems worked well with broad vulnerability and risk assessments.

She said tapping into indigenous knowledge and traditional methods while honing them with scientific methods would also help communities adapt to the changing climate.

Asia would also feel the effects of climate change.

Roxy Mathew Koil, a scientist at the Indian Institute of Tropical Meteorology, said one third of the past 15 years were afflicted by droughts in South Asia and that drought frequency was expected to increase.
Build up of atmospheric carbon dioxide and other GHGs over years

Source: National Oceanic and atmospheric administration
STRESS

Biotic Stress
(Pest & Disease)

Abiotic Stress

Light
- Low
- High

Temp
- Low
- High

Water
- Drought
- Flood

Chemicals
- Salts
- Pesticides
- Fungicides

Chilling
Freezing
ABIOTIC STRESS RESPONSES OF PLANTS

GROWTH
- Germination inhibition
- Growth reduction
- Premature senescence
- Reduction in productivity

PHYSIOLOGY
- Reduction in water uptake
- Altered transpiration rate
- Reduction in Photosynthesis
- Altered respiration
- Decrease in Nitrogen assimilation
- Metabolic toxicity
- Accumulation of growth inhibitors

MOLECULAR BIOLOGY
- Altered gene expression
- Breakdown of macromolecules
- Reduced activity of vital enzymes
- Decreased protein synthesis
- Disorganization of membrane systems
High Temperature

- Inhibition of seed germination
- Reduction of plant growth
- Improper development
- Alteration in photosynthesis
- Alteration in phenology
- Alteration in dry matter partitioning
- Water loss
- Yield reduction
- Oxidative stress
- Reduction of crop quality
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<td>Cowpea</td>
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<td>Flowering</td>
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<tr>
<td>Rice</td>
<td>34</td>
<td>Grain yield</td>
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</table>
Physiological effects of high temperature

1. Inhibition of metabolic activities due to enzyme denaturing
2. Simple proteins are less susceptible than complex ones
3. Changes in membrane fluidity
4. Rubisco activase is more sensitive than Rubisco
5. Respiration increases drastically than gross Pn at higher Temp.
6. More loss of C through photorespiration (30-80%)
7. Respiration rate is doubled for every 10°C increase in tissue temperature
Accumulation of Reactive Oxygen Species (ROS) as a result of high temperature is a major cause of crop yield loss

Apel & Hirt, 2004; Mahajan & Tuteja, 2005; Tuteja, 2007, 2010; Khan & Singh, 2008; Waraich et al., 2012

Reactive Oxygen Species (ROS) generation in chloroplasts, Mitochondria and Peroxisomes causing oxidative damage due to abiotic stresses
High temperature

Oxidative stress

Disruption of membrane properties, proteins/enzymes, and cellular homeostasis

Transcriptional factors

Signal sensing and transduction

Activation of stress responsive genes

Activation of antioxidant enzymes, free radical scavengers, signaling molecules, osmoprotectants

ROS detoxification, reactivation of protein and enzymes, re-establishment of cellular homeostasis

Development of heat tolerance
Adaptation to high temperature stress

- Signaling cascades and transcriptional control (T)
- Expression of stress proteins (T)
- Antioxidant defense (T)
- Osmo-protectants (T)
- Changing leaf orientation (A)
- Transpirational cooling (A)
- Early maturation (A)
- Leaf rolling (A)
- Alteration of membrane lipid compositions (A)
Physiological traits associated with heat tolerance/avoidance

1. CTD (Canopy cooling)
2. Photosynthetic rate
3. Cell membrane thermostability
4. Stomatal conductance
5. Chlorophyll fluorescence (Efficiency of photosystem II)
6. Leaf rolling and surface reflectance
7. Spikelets fertility
8. Pollen viability
Chilling injury

- Plants are seriously injured by temperature above 0°C, below 15°C.

Freezing injury

- As temperature decreases below 0°C, ice forms in the intercellular spaces of plant tissues.
- Low temperature damages plants both by a chilling effect, leading to physiological and developmental abnormalities, and by freezing, causing cellular damage directly or via cellular dehydration.
Effects of low temperature stress

- Flowering in rice are extremely sensitive to low temperatures and damage may occur at temperatures as low as 20°C.

- Visible symptoms of low-temperature injury
  - Wilting of leaves
  - Bleaching due to photo-oxidation of pigments
  - Water logging of the intercellular spaces
  - Browning
  - Leaf necrosis and plant death
WATER STRESS

The 75% of the earth’s surface is with water, but most is not available to plants.

- 97% saltwater
- 30.9% groundwater
- 68.7% snow and ice (including polar icecaps)
- 0.4% lakes and rivers
- <1% of Earth’s water is fresh and potentially available to plants
Water stress and drought are not synonyms

**Water stress:** short term effect (minutes to hours)

- Very frequent even in well irrigated plants
- Whenever evaporative demand is higher than the xylem capacity for refilling leaves.

eg. The incidence of dry wind can cause a temporary water deficit in the leaf.
Drought: Long term effect (days to months)

- When soil water depleted partially (or) totally (due to low precipitation).
- While the evaporative demand is high, a long term imbalance is produced between water demand and supply.
- Drought is usually accompanied by high irradiance and temperature.
DROUGHT STRESS

**Physiological Responses**
- Recognition of root signals
- Loss of turgar and osmotic adjustment
- Reduced leaf water potential ($\psi$)
- Decrease in stomatal conductance to $CO_2$
- Reduced internal $CO_2$ concentration
- Decline in net photosynthesis
- Reduced growth rates

**Biochemical Responses**
- Transient decrease in photochemical efficiency
- Decreased efficiency of Rubisco
- Accumulation of stress metabolites like MDHA, Glutathione, Pro, Glybet, Polyamines, and $\infty$-tocopherol
- Increase in antioxidative enzymes like SOD, CAT, APX, POD, GR and MDHAR
- Reduced ROS accumulation

**Molecular Responses**
- Stress responsive gene expression
- Increased expression in ABA biosynthetic genes
- Expression of ABA responsive genes
- Synthesis of specific proteins like LEA, DSP, RAB, dehydrins
- Drought stress tolerance
Plant’s response to water deficit

1. Decreases leaf area
2. Stimulates Leaf Abscission
3. Enhances Root Extension into soil
4. Stomata Closes in Response to Abscisic Acid
5. Limits Photosynthesis within the chloroplast
6. Increases Wax Deposition on the Leaf Surface
7. Alters Energy Dissipation from Leaves
8. Reduces Protein synthesis and enzyme levels
9. Reduces Nutrient uptake
10. Accumulates compatible solutes
How Water Deficit is related to Leaf Energy Balance?

When water deficit develops slowly enough to allow changes in developmental processes, water stress has several effects on growth.

- Water Deficit
- Stomatal Closure
- Reduced Transpiration
- Temperature elevation above normal
- Reduced PHOTOSYNTHESIS
Effect of drought intensity on photosynthesis

- **Mild stress**
  - Leaf $P_n$ / stomatal conductance is reduced
  - Stomata close to maintain high WUE by inhibiting transpiration

- **Severe stress**
  - Dehydration of mesophyll cells
  - Inhibit $P_n$, mesophyll metabolisms impaired, WUE decreases
  - Effects are more on stomatal conductance than $P_n$
Table I. Economic yield reduction by drought stress in some representative field crops.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Growth stage</th>
<th>Yield reduction</th>
<th>References</th>
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<tbody>
<tr>
<td>Barley</td>
<td>Seed filling</td>
<td>49–57%</td>
<td>Samarah (2005)</td>
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<tr>
<td>Maize</td>
<td>Grain filling</td>
<td>79–81%</td>
<td>Monneveux et al. (2005)</td>
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<td>63–87%</td>
<td>Kamara et al. (2003)</td>
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<td>70–47%</td>
<td>Chapman and Edmeades (1999)</td>
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<td>Atteya et al. (2003)</td>
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<td>53–92%</td>
<td>Lafitte et al. (2007)</td>
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<tr>
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<td>48–94%</td>
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<td>Common beans</td>
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<td>Cowpea</td>
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<td>Ogbonnaya et al. (2003)</td>
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<td>Sunflower</td>
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<td>Mazahery-Laghab et al. (2003)</td>
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<td>Canola</td>
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<td>30%</td>
<td>Sinaki et al. (2007)</td>
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<td>Potato</td>
<td>Flowering</td>
<td>13%</td>
<td>Kawakami et al. (2006)</td>
</tr>
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</table>
Accumulation of hormones - ABA and ethylene

ABA closes stomata during water stress

Diagram:
- Leaf water potential (MPa)
- Stomatal resistance (s cm⁻¹)
- Time (days)

Water withheld: Water potential decreases as soil dries out
Water provided: Stomatal resistance decreases

Graph:
- ABA content
- ABA (ng cm⁻²)
Plant adaptations to drought

1. **Resistance**
   Plants express pre-existing programme and able to maintain, more or less original growth and development e.g. Increased ABA and reduced growth promoters.

   Changes in phytohormones directly proportional to severity of stress and inversely to resistance ability.

2. **Adaptation**
   Initiate new developmental programme. Once adapted, growth recover even up to non stress condition.
Plants subjected to abiotic stresses produce ROS

- superoxide (O$_2^-$)
- hydrogen peroxide (H$_2$O$_2$)
- hydroxyl radicals (·OH)
- singlet oxygen (¹O$_2$)

These ROS may initiate destructive oxidative processes

- lipid peroxidation
- chlorophyll bleaching
- protein oxidation
- damage to nucleic acids
Antioxidant enzymes
- Superoxide dismutase (SOD)
- glutathione reductase (GR)
- Catalase
- Peroxidase

Low-molecular antioxidants
- ascorbic acid
- glutathione
- α-tocopherol, flavonoids and carotenoids play a key role in scavenging those activated species
Water stress

↑ JA roots

↑ ABA root/shoot

+ ↑ Ck leaves

+ Ax, Ck, BR

Change in sugar contents

↑ G protein

↑ cytosolic Ca²⁺

↑ ROS

Protein phosphorylation/ dephosphorylation

Stomatal closure

↓ stomata/mesophyll diffusion

↓ CO₂ assimilation

↓ ATP

↓ ribulose biphosphate

↓ Rubisco

↓ photosynthesis

↓ productivity

SOD, CAT, APX, GR synthesis

Oxidative stress control

Senescence control

Inhibition of ET accumulation

↓ chlorophyll a/b and carotenoids

↓ leaf area

Epinasty/hyponasty

↓ ratio root/shoot

↓ Number of leaves

Reduce transpiration/ higher water absorption

Deformation of tracheids/ ↓ mesophyll mitosis/ ↓ cell size/ ↓ number of stomata/ increase of starch granules/ more trichomes/ thicker palisade parenchyma
In rainfed lowland areas, submergence is a major problem during the monsoon periods.

≈9% of global rice area is flood-prone.

Total area affected due to submergence in Tamil Nadu – 5 lakh hectares of paddy with a production loss of Rs. 950 crores in samba and thaladi seasons.

Nagapattinam and Tiruvarur districts - 1.34 lakh hectares each, Thanjavur district - 1.26 lakh hectares.
Flooding

Flash flood
Short duration over a few weeks (2 weeks) and not very deep. Water level can reach 50 cm

Deep flooding
Lasts for a long time (several months).

Submergence tolerance
The ability of a rice plant to survive 10–14 d of complete submergence and renew its growth when the water subsides

Hattori et al., 2011
Impact of flooding

- Reduced movement of gases to and away from plant surfaces
- Reduced $O_2$ supply that limits respiration
- Reduced $CO_2$ supply that limits photosynthesis
- Reduced ethylene diffusion away from the plant which triggers chlorosis and excessive leaf elongation of intolerant cultivars
- Poor plant growth and survival during submergence

(Ella et al., 2003)
Alcoholic Fermentation

- Submergence can shift aerobic respiration to the less efficient anaerobic fermentation pathway.

- This pathway depends on continued supply of substrate (glucose) and the two key enzymes, alcohol dehydrogenase (ADH) and pyruvate decarboxylase (PDC).

- Alcoholic fermentation is the key catalytic pathway for recycling NAD to maintain glycolysis and substrate level phosphorylation in the absence of oxygen.

- Increased alcoholic fermentation is a way to alleviate the effect of anoxia on reduced production of energy for growth and maintenance.
Adaptations for Submergence Tolerance

- The presence of gas filled spaces, known as aerenchyma, in roots of numerous plant species is considered to be an important anatomical adaptation for survival under flooded conditions.

- Aerenchyma provides a diffusion path for the transport of oxygen from aerial plant parts to roots or rhizomes.
Physiology of submergence tolerance

Energy maintenance
• Conservation of carbohydrate during submergence
• Sustained sugar supply and energy metabolism
• Quick regeneration following submergence
• Efficient ROS scavenging

Submergence mediated by plant hormones
• Ethylene, GA and ABA play important roles
• Under anaerobic conditions, ethylene concentration increases in plant tissue because of both increased synthesis and entrapment
• Susceptible genotypes show a reduction in ABA concentration with a concomitant increase in GA resulting in enhanced shoot elongation
The presence of excessive amounts of soluble salts hinder or affect the normal functions of plant growth.

- 10% of global arable land - affected by salinity or sodicity
- Out of 1.5 billion ha of global cultivated land:
  - 23% - salinity and 37% - sodicity
- Salinity: Higher accumulation of Ca, Mg, Na and their SO₄, NO₃, CO₃, HCO₃ and Cl salts.
- Sodicity: Higher concentration of Na.
EFFECTS OF SALINITY ON CROP PLANTS

**Osmotic effect or water deficit**
Reduces the plant’s ability to take up water leading to slower growth

**Salt specific effect or Ion Excess**
Salts enter the transpiration stream and eventually injure cells in the transpiring leaves, further reducing growth.

**High salt concentration in the plant cause**
Chlorophyll degradation
Leaf edge burns
Necrotic spots on the leaf
Cell poisoning
Death of the plant
EVENTS THAT TAKE PLACE UNDER SALT STRESS AND PLANT RESPONSES

(Horie et al., 2012)
EFFECTS OF SALINITY ON CROP PLANTS

• Increased respiration
• Ion toxicity
• Changes in plant growth
• Mineral distribution
• Membrane permeability
• Decreased efficiency of photosynthesis
• Increased production of reactive oxygen species
Effects on growth and development

- Reduction in the rate of leaf surface expansion.
- Clear stunting of plants
- Decrease in the fresh and dry weights of leaves, stems, and roots.
- Sterility and lower seed set.
- Increased the number of sterile florets and
- Viability of pollen becoming more pronounced with increased salinity

Effects on leaf anatomy

- Epidermal thickness
- Mesophyll thickness
- Palisade cell length Increases
- Palisade diameter
- Spongy cell diameter
- Reduces intercellular spaces in leaves
MECHANISM OF SALT TOLERANCE

Avoidance

- Salt Exclusion
- Salt Extrusion
- Salt Dilution
- Compartmentation of ions

Tolerance

- Osmotic adjustment
- Hormone synthesis – ABA hardens plants against excess salts
- Homeostasis
- Detoxification
- Growth control
Consequences on postharvest produce quality

Climate change effects

CO₂
Temperature
Water stress
Salinity

Quality of fruits and vegetables

Vitamin C, Sugars and Acidity
Total phenols, Anthocyanin
Flavonoids
Lycopene and Carotenoids
Volatile aroma compounds
Mineral nutrients
Elevated CO$_2$ affect the mineral composition of fruits and vegetables.

Significant reduction of minerals like N, Ca, Fe, S, Mg and Zn (15–25%) is seen in many herbaceous and woody plants under high CO$_2$ concentrations (Loladze 2002)

Initial reduction in protein and mineral content could be overcome in long-term exposures to elevated CO$_2$ by the enhanced root growth and hence may maintain the quality of fruits and vegetables (Idso and Idso 2001)
High temperature reduce Starch, Vitamin C, Sugars, Acidity, Phenolics, Flavonoid

High temperatures reduce colour development. Night temperatures are more critical for the anthocyanin content than the day temperatures (Kentaro Mori et al., 2005).

- Increased day and night temperatures (30°C/25°C) reduced the soluble sugars, starch, AA and proteins in apple (Hsiao-hua Pan et al., 2007).
- Citrus fruits grown in hot tropical areas have lower levels of vitamin C compared to areas of cool nights (Njoku et al., 2011).
Many fruit crops are widely cultivated in semi-arid climates.

Water stress affects the sugar content of fruits to a greater extent than other quality parameters. In fruits, water stress reduces the juiciness, thereby increasing the sugar content. (Romero et al., 2006).

Deficit irrigation treatment is used in some of the fruit crops to increase the sugar content by imposing the treatment at later stages of fruit maturation.

Carotenoids, the naturally occurring isoprenoids with antioxidant properties, are the major pigments in many fruits and vegetables – influenced by water stress.
Salinity

Lycopene and Carotenoids

• Antioxidants like lycopene, carotenoids and ascorbic acid accumulated in tomato fruits during salt stress (D’Amico et al., 2003).

• However, in leaves of *Lycopersicon esculentum* plants under salt-stress condition shows a decreased expression of carotenoid biosynthetic genes (Merlene Ann Babu et al., 2011).

Phenols, Flavonoids and Anthocyanins

• The response of strawberry plants under salt-stress conditions revealed that the phenylpropanoids and flavonoid pathways are still intact and functioning, as indicated by higher contents of antioxidants (Neocleous and Vasilakakis 2007).
Approaches to improve abiotic stress tolerance

1. GERMPLASM IMPROVEMENT
2. IMPROVEMENT OF STRESS TOLERANCE THROUGH CONVENTIONAL BREEDING
3. IMPROVEMENT OF STRESS TOLERANCE THROUGH MARKER ASSISTED BACKCROSS BREEDING
4. IMPROVEMENT OF STRESS TOLERANCE THROUGH PLANT GENETIC ENGINEERING
5. HORMONAL REGULATION OF STRESS TOLERANCE
6. BIOSTIMULANTS AND BIOINCOLUNATS
Endogenous hormonal balance and adaptation to stress

- Hormonal balance is important than conc. of individual hormone
- Stress induces production of high ABA, low CK and Auxin and alter GA and ethylene level
- Increase in CK level- exceeding the pre stressed level cause improvement in yield
- Increased ABA during drought: induce cross tolerance. eg. salinity/cold tolerance
- Resistance to stress is linked with ability of plant to maintain the existing hormonal balance
Physiological role of PGRs in stress management

Water stress

Synthesis or degradation of growth regulators

- ABA
  - Involved in: Stomatal opening; Root permeability; Proline & glycine betaine content; Secondary metabolites

- Cytokinins
  - Involved in: Chloroplast biogenesis, assimilate-mobilization, stomatal functioning, root-shoot communication

- Ethylene
  - Involved in: Abscission; Lignification; Lipid turnover; Pigment bleaching

- Polyamines
  - Involved in: Stabilization of protein and membrane lipids; Reduction in ROS; Involvement in ionic balance

- Brassinosteroids
  - Involved in: Photosynthesis, nucleic and protein synthesis, root growth

Plant development
New generation PGRs

- Polyamines
- 1-MCP
- Salicylic Acid
- Jasmonic Acid
- Brassinosteroids
- AVG
- CPPU
SALICYLIC ACID

• SA is a phenolic phytohormone with high potential for stress tolerance
• Lower level of SA alleviate abiotic stress; at higher level it induces oxidative stress
  • Induce drought tolerance with an enhanced antioxidant system
  • Inhibits ethylene synthesis and antagonistic to Jasmonic acid
  • Triggers systemic acquired response (SAR)
  • Induces the pathogenesis related proteins PR-1, PR-2, PR-5
  • Improves stomatal regulation, maintains leaf chlorophyll content, increases WUE, and stimulates root growth

Anosheh et al., 2012
Jasmonic acid (JA) is an organic compound found in several plants. Cyclopentanone derivative synthesized from linolenic acid. Induces storage proteins, osmotin, thionin (antifungal) and defensin. The major function of JA and its various metabolites is regulating plant responses to abiotic and biotic stresses. It has an important role in response to wounding of plants and systemic acquired resistance.
Interaction of Ethylene, Jasmonic Acid & Salicylic acid with reference to stress condition

- Pathways do not function independently.

- Involved in a complex signaling network in different pathways influence positive and negative regulatory interactions.

- Hormones may interact with one another in regulating stress signaling and plant stress tolerance.

- Ethylene enhance ABA action in seeds (Gazzarrini and McCourt, 2001) but may counteract ABA effects in vegetative tissues under drought stress (Spollen et al., 2000).

- A. thaliana provide evidence for cross talk among the SA, JA and ET signaling pathways.
BRASSINOSTEROIDS

- Brassinosteroids - sixth group of phytohormones
- Significant growth promoting effects and essential for many processes in plant growth and development
- Participate in the processes of gene expression, transcription and translation in normal and stressed plants
- Induce the expression of antioxidant genes and enhance the activities of antioxidant enzymes
- Brassinosteroid-1μM alleviates drought induced oxidative stress

(Behnamnia, 2009)
1. Enhances the activities of superoxidase dimutase, catalase, ascorbate peroxidase and glutathione reductase

2. Enhances the level of ascorbic acid and carotenoids

3. Enhances the net photosynthetic rate

4. Enhances the level of ABA, proline and other osmolytes

5. Enhances the Glutathione and phytochelatins

6. Stimulates nitrogen metabolism

7. Enhances the level of heat shock proteins

8. Improves the pigment levels and nitrate reductase
Polyamines are small, positively charged, organic molecules that are ubiquitous in all living organisms.

Three types: Putrescine, spermidine, hermospermine according to structure, universal distribution in cellular compartments, and involvement in physiological activities.

Water stress leads to accumulation of free or conjugated polyamines. Differences in polyamine metabolism under stress depend upon plant species/cultivar, duration of stress, developmental stage, etc.

Polyamines have antioxidative, free radical scavenging effects and ABA synthesis and membrane stabilizing properties.

Liu et al, 2007
CCC/ CC/ MC and Paclobutrazol
Tolerance to water stress in many plant species

- Increased production of ABA by inhibiting gibberellin synthesis

- Increased ABA helps in plant water balance, growth reduction and increased antioxidant content/activity

- **Combination of triazole and strobilurins** help in abiotic stress tolerance
1-MCP increase the activity of glutathione reductase and superoxide dismutase in water stressed plants.

These effects significantly increased protein concentration and maintained cell membrane integrity.

Provide protection against ROS produced by plants under stress condition - *Eduardo M. Kawakami*, 2007
Effect of Ethrel and 1-MCP on Antioxidants in Mango

Postharvest loss due to high temperature
Accelerated ripening affects the quality and nutritional contents of fleshy fruits.

- 1-MCP is applied to delay ripening while ethrel is used to accelerate ripening of climacteric fruits.

- 1-MCP decreased $\text{H}_2\text{O}_2$ and lipid peroxidation with increased activities of CAT and SOD while ethrel behaved just opposite

- Activity of ascorbate peroxidase (APX) increased in the presence of Ethrel while 1-MCP led to marginal increase in APX.
Hypothetical scheme for adaptation to stressful environment

- Competence to withstand stress
- Abiotic stress
  - Signal
  - Signal transduction (multiple pathway)
  - Existing hormonal homeostasis, tissue sensitivity, receptor system

- Resistance (inherent defense system)
- Ontogenic stage
  - External environment

- Adaptation
  - Recovery in growth and development
  - Improved physiological functions
  - Resumption of photoaction
  - Membrane stability, low lipid peroxidation
  - Stress proteins
  - Antioxidants
  - Gene modulation/expression
  - Recovery from stress
  - Stress responses
  - Hormonal homeostasis, tissue sensitivity, receptor system

- Endogenous ABA/ETH↓, CK/IAA/GA↑
- Exogenous PGRs
- Endogenous ABA/ETH↑, CK/IAA/GA or modified
- Photoinhibition
- Impaired metabolism
- Increased lipid peroxidation, membrane injury
- Increased oxygen species

- Stress induced hormonal homeostasis, tissue sensitivity, receptor system
<table>
<thead>
<tr>
<th>CROPS</th>
<th>PGR</th>
<th>DOSE AND STAGE</th>
<th>BENEFITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunflower</td>
<td>Salicylic acid</td>
<td>200mg L⁻¹ Seed treatment</td>
<td>Increased germination percentage and vigour index</td>
</tr>
<tr>
<td>Wheat</td>
<td>Strobilurin</td>
<td>250g/L Vegetative stage</td>
<td>Increased water use efficiency , chlorophyll content and yield</td>
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<tr>
<td>Mustard</td>
<td>GA3</td>
<td>100 ppm</td>
<td>Increase in chlorophyll, proline content in leaves, and yield</td>
</tr>
<tr>
<td>Barley</td>
<td>Salicylic acid and potassium nitrate</td>
<td>0.5mM SA and 10 mM KNO₃ After three weeks</td>
<td>Low MDA contents and decreased Na+/K+ ratio in leaves.</td>
</tr>
<tr>
<td>Wheat</td>
<td>Strigolactone and salicylic acid</td>
<td>1 mM and 10 mM Tillering and anthesis stages</td>
<td>Lower electrolyte leakage, higher relative water content, membrane stability index and antioxidants</td>
</tr>
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<tr>
<td>Apple</td>
<td>Paclobutrazol</td>
<td>250ppm</td>
<td>Reduced water loss, ethylene production and polyamines</td>
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<tr>
<td>Brassica</td>
<td>Epibrassinolide</td>
<td>1 µM at seedling stage</td>
<td>Enhanced seedling tolerance to drought</td>
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<tr>
<td>French bean</td>
<td>Epibrassinolide</td>
<td>1 µm Prior to stress</td>
<td>Increased root nodulation in French bean, due to induction in CK synthesis and nitrogenase</td>
</tr>
<tr>
<td>Rice</td>
<td>Putrescine, spermidine, spermine</td>
<td>10 µM Four leaf stage</td>
<td>Improved net photosynthesis, water use efficiency, proline, anthocyanins and CMI</td>
</tr>
<tr>
<td>Cotton</td>
<td>GA3</td>
<td>200ppm Vegetative stage</td>
<td>Increased the net photosynthetic rate, stomatal conductance and transpiration rate</td>
</tr>
</tbody>
</table>
Biostimulants and bioinoculants in stress mitigation

Categories

- Humic substances
- Seaweed extracts
- Protein hydrolysates and amino acids
- Chitosan
- Beneficial fungi
- Beneficial bacteria
Aerial application

Mode of application of biostimulants

Aerial
Soil

Seed treatment
Seedling dip
Foliar spray

Effects

Growth responses
- Improved shoot and root growth
- Higher flowering and fruit set
- Better yield

Biotic stress resistance
- Resistance to fungal, bacterial and viral pathogens
- Resistance to insect pests

Abiotic stress resistance
- Salt and drought resistance
- Freezing and chilling resistance
- Enhanced photosynthesis

Nutrients
- Enhanced nutritional quality
Beneficial bacteria (PGPR)

- Pseudomonas
- Bacillus
- Enterobacter
- Burkholderia
- klebsiella
- Azospirillum
- Anthrobacter
- Azotobacter
Schematic representation of mechanisms by which PGPR affect nutrient availability in the rhizosphere (Etesami et al. 2015)

- **Bacterial IAA production**
  - Biomass production
  - Increasing root exudates
    - Reducing soil pH
    - Release of chelators
    - Redox changes
    - Increasing microbial activity
    - Altering the solubility and availability of nutrients

- **ACC deaminase producing bacteria**
  - Root elongation
  - Enhancing plant tolerance to stresses
  - Improving plant’s nutrient uptake and growth

- **Increased availability of Fe, P, …**
  - Phosphate solubilizing bacteria
  - Siderophore producing bacteria
  - Increasing more root exudates
  - Increasing microbial activity
Conclusion

- The concept of abiotic stress is not new to agriculture.

- The benefits of modern agriculture rarely reached ecologically challenged regions and that have huge potential for sustaining agricultural productivity.

- The current mitigation and adaptation options are insufficient to face the challenges for food security.

- There is a need to change the strategy for addressing abiotic stress in agriculture through research, management, capacity building and policy changes to promote innovative and rewarding technologies.
Thank you