Heat Stress in Vegetable Crops: Impacts, Physiological Responses and Mitigation Strategies in a Changing Climate

Abhishek[1], Himanshu[2] and Romika Thakur[3]

[1]Department of Vegetable Science, Maharana Pratap Horticultural University, Karnal, 132117, India

[2]Department of Vegetable Science, CCS Haryana Agricultural University, Hisar, 125004, India

[3]Department of Seed Science and Technology, Dr. Y S Parmar University of Horticulture and Forestry, Nauni, Solan

Corresponding Author: himanshumehla1999@gmail.com

Abstract

Heat stress, primarily driven by climate change, presents a major challenge to global agriculture, especially the production of vegetable crops. Extended periods of high temperatures interfere with plant growth and development from germination to harvest by triggering morphological, physiological, and biochemical disruptions. These effects include disturbed water balance, decreased photosynthetic activity, hormonal imbalances, and damage to cell membranes, all of which contribute to lower yields and diminished crop quality. The specific symptoms vary among crops, influencing characteristics like fruit setting, tuber development, and leaf size. To cope with heat stress, plants employ various tolerance and avoidance mechanisms such as regulating stomatal activity, accumulating osmolytes, and producing heat shock proteins. Breeding methods—both traditional and modern techniques like QTL mapping and marker-assisted selection—show potential for creating heat-resistant crop varieties. Furthermore, agronomic strategies including the application of bio-stimulants, osmo-protectants, beneficial microbes, and improved soil practices help strengthen plant resilience. This article examines the adverse effects of heat stress on vegetable crops and presents integrated approaches to enhance their tolerance in a warming world.

Introduction

Heat stress is typically described as an increase in temperature beyond a certain critical point, sustained long enough to cause lasting harm to plant growth and development. Extremely high temperatures can lead to severe cellular damage or even cell death within minutes, largely due to the breakdown of cellular structures. Currently, Earth's surface temperature is about 1.2°C higher than it was in the late 1800s, before the industrial revolution, and warmer than at any point in the past 100,000 years. The period from 2011 to 2020 was the hottest decade on record, with each of the past four decades being warmer than the previous ones since 1850. Climate change, characterized by long-term changes in temperature and weather patterns, is a key contributor to heat stress. While some changes can occur naturally, human activities—especially the burning of fossil fuels like coal, oil, and gas—have been the dominant cause, releasing greenhouse gases that trap heat.

Temperature is a critical factor limiting the distribution and yield of many crops. Prolonged exposure to high temperatures can disrupt seed germination, hinder plant growth, cause flowers to drop, reduce pollen viability, and negatively impact fruit development, size, weight, and quality. Most vegetables thrive at temperatures between 10°C and 24°C. High temperatures can cause direct damage such as protein denaturation and membrane lipid fluidization. Indirect or delayed effects include enzyme inactivation in chloroplasts and mitochondria, reduced protein synthesis, protein breakdown, and deterioration of membrane stability.

Effects of heat stress on plants

Heat stress negatively impacts plants throughout their life cycle—from seedling emergence to harvest and even during storage. It disrupts seedling establishment, causes leaf margin drying and scorching, reduces overall plant growth, interferes with pollen formation, alters photosynthesis, decreases total biomass, leads to spikelet sterility, and affects the development and quality of grains and fruits.

A. Morphological and yield traits

At advanced stages, elevated temperatures can negatively impact processes such as photosynthesis, respiration, water balance, and membrane integrity. They can also alter hormone levels as well as the concentrations of primary and secondary metabolites. High heat may lead to significant damage both before and after harvest, including leaf and twig scorching, sunburn on foliage, branches, and stems, premature leaf aging and drop, suppression of shoot and root development, fruit discoloration and injury, and ultimately, reduced crop yield.

B. Physiological and biochemical traits

1. **Waters relations:** Under field conditions, high-temperature stress is frequently associated with reduced water availability
2. **Accumulation of compatible osmolytes:** An important adaptation in many plants exposed to abiotic stresses—such as salinity, drought, and extreme temperatures—is the buildup of specific low molecular weight organic compounds, commonly known as compatible osmolytes.
3. **Photosynthesis:** Any constraint in photosynthesis can limit plant growth at high temperatures.
4. **Assimilate partitioning:** Under conditions of mild to moderate heat stress, both the production (source) and utilization (sink) of plant resources may decline, resulting in substantial decreases in growth, crop yield, and harvest index. At elevated temperatures, the distribution of assimilates through both apoplastic and symplastic pathways greatly influences the transport and allocation processes within the plant.
5. **Cell membrane thermostability:** Heat stress accelerates the kinetic energy and movement of molecules across membranes thereby loosening chemical bonds within molecules of biological membranes.

C. Hormonal changes

Hormones play a pivotal role in regulating plant growth and development. Cross-talk between hormone signaling pathways enables plants to integrate multiple environmental and developmental signals, ensuring appropriate physiological responses. One notable example is ethylene, a gaseous hormone that influences nearly every stage of a plant's life cycle. Ethylene regulates processes ranging from seed germination, vegetative growth, and flowering, to fruit ripening and leaf senescence. It also plays a key role in mediating plant responses to biotic and abiotic stresses, including drought, flooding, and pathogen attack.

Table 1: Symptoms of heat stress on vegetable crops:

Crops	Symptoms
Brinjal	Reduced extension of main stem, reduced no. of branches per plant.
Amaranthus, Palak and Spinach	Reduce their water content thereby reduces their quality.
Potato	Sharp reduction in the potato tuber yield, at 30 ^{o}C complete inhibition of tuber formation occurs and decreased starch content.
Cauliflower	Ricey, leafy, loose, yellow, small and hard curds
Tomato	Fruit set failure at high temperatures involves bud drop, abnormal flower growth, poor pollen creation, poor inflorescence and viability, abortion of ovule and reduced carbohydrate existence.
Cassava	Reduction of leaf area
Lettuce	Bitter taste, accelerated development of tip burn
Spinach beet	Bolting rendering the plant unmarketable
Cowpea	Inhibition of floral bud development
Chilli	Reduced fruit width and fruit weight increased the proportion of abnormal seeds per fruit. Abortion of flower prior to anthesis and reduce fruit set.
Okra	Reduced yield, damages in pod quality parameters such as fibre content and break down of the Ca-pectate.

Mitigating strategies for heat stress

The negative impacts of heat stress can be reduced by enhancing crop plants' heat tolerance through different genetic strategies. Understanding metabolic pathways related to this stress can support the development of heat-resistant plants. Heat shock proteins, which are produced in response to stress, play a key role in this process and are controlled by specific transcription factors. High temperatures often lead to the production of reactive oxygen species (ROS), which can harm cellular components such as lipids, proteins, and nucleic acids.

Avoidance

Mechanisms for surviving which include long term evolutionary, phenological and morphological adaptations and short-term avoidance or acclimation mechanisms

- Leaf rolling
- Closure of stomata
- Increased stomatal and trachomatous densities
- Larger xylem vessels
- Waxy cuticle

Tolerance

Ability to grow and produce yield under high temperature.

1. **Breeding for heat stress tolerance in vegetable crops**

Breeding for heat stress in the vegetable can be done by two means. They are

1) Conventional breeding methods and
2) Advanced breeding methods.

- **Conventional breeding method:** Cultivating various heat-tolerant varieties by using techniques such as recurrent selection, the pedigree method, and selecting plants that possess heat tolerance traits.
- **Advanced breeding method**: It involves marker-assisted selection linked to QTLs, offering the benefit of greater stability and less environmental influence since the process targets the gene level.

Selection of heat-tolerant varieties

Sr. No.	Crop	Varieties
1	Tomato	Pusa Sadabahar and Pusa Hybrid-1
2	Radish	Pusa Chetki
3	Carrot	Pusa Vrishti
4	Cauliflower	Pusa Meghna

Developing and choosing heat-resistant plant varieties is a crucial approach to reduce the harmful impact of heat on plants. The heat-tolerant tomato variety exhibited only slight changes in gene activity and increased gene expression, whereas the heat-sensitive variety displayed decreased gene expression.

2. **The use of osmolytes aided in the protection of the defensive system**
    1. Ascorbic acid
    2. Abscisic Acid
    3. Citric acid
    4. Glycine betaine
    5. Nitric oxide
    6. Salicylic Acid
3. **Exogenous application of microbes:** Microbes enhance plant growth, productivity, and protection by forming a symbiotic relationship. They boost nutrient and water absorption, water use efficiency (WUE), resilience against damage, and the levels of internal hormones. For instance, arbuscular mycorrhizal fungi (AMF) serve as a good example.
4. **Use of organic amendments:** By combining low-oxygen biochar with mineral nutrients like phosphorus, plants may be better able to thrive under heat stress.
5. **Anti transpirant:** Kaolin (a white, non-reactive clay mineral) helps protect plants by reflecting infrared and ultraviolet light, which lessens the harmful impact of light and heat stress on plant health and product quality, while also improving the plant's water status.
6. **Biostimulants:** Any material or microorganism used on plants to improve nutrient use efficiency, tolerance to non-living stresses, and/or the quality of crops, regardless of whether it contains nutrients. Biostimulants influence various metabolic processes, including respiration, photosynthesis, nucleic acid production, and the absorption of ions.
7. **Use of inorganic amendments**
    - Calcium
    - Sulphur
    - Zinc
    - Silicon

8. **Soil management practices**
    - Mulching (straw mulch to enhance seedling survival)
    - Soil treated with inorganic nutrients (N, P, K, Ca, Zn) in combination with organic material, e.g., FYM and straw mulch
    - Proper crop rotation and adjusting N supply
    - Adjusting sowing date

Conclusion

Heat stress poses a significant challenge to agriculture globally, adversely affecting plant development and productivity by causing a range of morphological, physiological, and biochemical disturbances. To counteract heat damage, plants activate several adaptive strategies including stabilizing cell membranes, scavenging reactive oxygen species (ROS), producing antioxidants, and adjusting osmotic balance. Although these mechanisms help, the genetic foundations of heat tolerance are still not well understood. Nevertheless, QTL mapping has been valuable in enhancing our knowledge of the genetic components involved in stress tolerance.

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