Available online at
http://agrospheresmagazine.vitalbiotech.org/

ISSN (E): 2582 – 7022

Agrospheres:e- Newsletter, (2026) 7(6), 83-86

Article ID: 1000

Management of Heat Stress in Crops for Sustainable Crop Productivity in Variable Climatic Conditions

Ramanand Patel

Scientist (Agrometeorology), Regional Research Station Zone-|| Agwanpur -852202 Saharsa, Bihar, BAU Sabour

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*Corresponding Author
Ramanand Patel*

Article History
Received: 10.06.2026
Revised: 15.06.2026
Accepted: 20.06.2026

INTRODUCTION

Temperature is important for controlling various metabolic activities and the development and growth of plants. There is a specific optimum range of temperatures for all kinds of plants where they thrive best. If the temperature in the environment exceeds beyond the optimum range of temperature, the plant will suffer from heat stress and it will cause problems for the development of plants as well as irreversible damage to the cells. During the past few decades, global warming has caused frequent heat waves which have been quite challenging for sustainable agriculture. Crops such as wheat, rice, corn, and different types of vegetables have been more sensitive to heat stress during their growth stages of flowering and grain filling.

Heat stress has become one of the major abiotic stresses that pose limitations to the productivity of agriculture across the world in the current climate variability situation marked by an increase in temperature and heat waves. Increased temperatures have adverse effects on the growth, development, and productivity of plants due to interference in important physiological, biochemical, and molecular activities of plants. The level and time duration of heat stress will determine the level of damage that can be from reduced growth to total crop loss under extreme situations. This paper provides a detailed description of the impacts of heat stress on crops and different management techniques to cope with the problem.

2. Impact of Heat Stress on Crops

Heat stress impacts the crop plants in several ways such as physiological, morphological, biochemical, and reproductive functions of the plants causing decrease in yield of the plant.

Physiologically, heat stress increases respiration and decreases the efficiency of photosynthesis because heat stress causes damage to the chloroplast structure and enzymes needed for carbon assimilation. Due to increased respiration rates, stored carbohydrates of the plant get exhausted.

Morphologically, plant height is decreased along with smaller leaves. Heat stressed plants show symptoms of leaf scorching and senescence of the plants. Many plants fail to produce flowers and fruits under heat stress.

From the biochemical aspect, heat stress leads to protein denaturation and inactivation of enzymes, hence disrupting metabolic pathways. Moreover, heat stress leads to overproduction of reactive oxygen species (ROS) such as hydrogen peroxides and superoxide radicals that damage cellular components like lipids, proteins, and nucleic acids.

Processes like reproduction are highly affected by heat stress as high temperatures reduce viability of the pollen, stigma receptivity, and hinder fertilization. Ultimately, poor grain filling, reduced seed set, and low yields occur.

3. Most Critical Growth Stages Affected by Heat Stress

Various growth stages of crops are affected differently by heat stress, although some are highly sensitive than others.

At the germination and seedling stage, heat stress may hinder seed germination and development and early establishment of the plant. Nonetheless, the most sensitive growth stage to heat stress is reproductive stage, specifically at flowering and pollination where heat stress may lead to pollen sterility and fertilization failure.

Again, just like at the reproductive growth stage, heat stress at the stage of grain/fruit development hinders assimilates translocation and storage, hence leading to shrunken grains or fruits. Thus, heat stress during reproductive and grain filling growth stages may lead to yield losses.

4. Heat Stress Management Strategies

4.1 Agronomic Practices

Adoption of appropriate agronomic practices is one of the most effective ways to mitigate heat stress in crops. Adjusting the sowing time helps crops escape peak temperature periods, ensuring that critical growth stages do not coincide with extreme heat conditions. Early or timely sowing is particularly beneficial in regions prone to terminal heat stress.

Use of mulching practices is yet another method that assists in conserving soil moisture, decreasing soil temperature, and improving microclimatic conditions. Organic mulches such as straw, crop residues, and compost work effectively in improving soil condition.

Effective management of irrigation is another very important method of reducing heat stress, where adequate availability of water keeps the plants turgid and aids in evaporation.

Shade management through the use of shade nets and intercropping systems helps decrease the amount of direct solar radiation and canopy temperature, hence protecting the plants from excessive heat.

4.2 Soil and Nutrient Management

Healthy soils play an important role in improving the ability of the crops to withstand the effects of heat stress. Application of organic materials such as farm yard manure, compost, and green manure helps in improving soil structure and water holding capacity, and microbial activity.

Fertilizer management is very important as good fertilization improves the defense mechanisms of plants. Potassium helps in

ISSN (E): 2582 – 7022

regulation of stomata and maintenance of water balance, whereas zinc and boron are important nutrients for stress tolerance and successful reproduction.

4.3 Crop and Variety Selection

Selection of appropriate crops and varieties adapted to local climatic conditions is a crucial strategy for managing heat stress. Heat-tolerant and early-maturing varieties can escape or withstand high temperature conditions more effectively.

Plant breeding programs are increasingly focusing on developing heat-resilient varieties by incorporating traits such as improved membrane stability, efficient antioxidant systems, and better pollen viability under high temperatures.

4.4 Biotechnological Approaches

Recent innovations in the field of biotechnology have provided various approaches to increase heat tolerance in plants. Through the use of transgenic crops with genes that respond to heat, plants are able to cope well with high temperatures.

Marker-assisted molecular selection provides an efficient way to screen and breed heat-resistant genotypes with high efficiency. In addition, techniques such as CRISPR/Cas9 editing allow for the promising manipulation of heat resistance genes, leading to the creation of climate-resilient crops.

4.5 Plant Growth Regulators and Chemicals

Plant growth regulators (PGRs) have proven to be highly useful in coping with the effects of heat stress. Compounds such as salicylic acid, gibberellins, and abscisic acid regulate the physiological reactions of the plant, allowing it to resist the stress.

Anti-transpirants limit water loss by creating a protective layer around the leaves and thus increasing water efficiency at high temperatures. Foliar application of osmoprotectants such as proline and glycine betaine maintains cellular osmotic pressure.

4.6 Protective Cultivation

Techniques of protective cultivation include polyhouses, net houses, and greenhouses, which create a favorable environment protecting plants from the drastic variations in temperature. In addition, protective cultivation techniques allow regulating temperature, humidity, and light and thereby limit the negative impact of heat stress. These technologies are especially helpful when dealing with high value crops such as vegetables and flowers.

4.7 Water Management Technologies

Water management technologies play a vital role in dealing with heat stress since drip irrigation allows watering plants in the root zone minimizing water losses and ensuring the best soil moisture conditions.

Moreover, sprinkler irrigation can cool down canopy temperature due to evaporation of water. Fertigation is another technique providing fertilizers through irrigation systems and thus delivering nutrients effectively.

5. Climate-Smart Agriculture Role

Climate-smart agriculture (CSA) incorporates sustainable agricultural practices aimed at increasing efficiency, building up the ability to cope with climatic changes, and lowering greenhouse gas emissions.

CSA approaches not only help mitigate the impact of climate change but also ensure long-term sustainability of agricultural systems by promoting resource conservation and ecological balance.

6. Future Outlooks

The management of heat stress in agricultural plants is expected to employ the utilization of sophisticated technologies in the near future. The use of artificial intelligence and remote sensing techniques can provide an opportunity to monitor plant stress in a real-time and implement timely mitigation actions.

The development of climate resilient crops using advanced breeding techniques and biotechnology will also be important in terms of adaptation of agriculture to climatic changes. It is important to enhance awareness among the farmers with the help of extension and capacity building programs. Also, there is a need for supportive government policies and investments into R&D infrastructure in order to promote the application of climate resilient agricultural technologies.

CONCLUSION

The issue of heat stress presents a serious challenge to the world agricultural production and food security. The harmful impact that heat stress has on plant development, growth and reproduction requires a special approach to its management. It is possible to mitigate the negative impact of heat stress and preserve crop productivity through the use of agronomic practices in conjunction with biotechnology, precision agriculture and climate smart agricultural practices.

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