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Advancements in Breeding for Heat Stress Tolerance, Strategies, Challenges and Future Directions

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As global temperatures continue to rise due to climate change, farmers around the world are grappling with the detrimental effects of heat stress on their crops. Heat stress can significantly reduce crop yields, threaten food security, and diminish farmers' livelihoods. In response to this challenge, scientists and agricultural experts are increasingly turning to breeding techniques to develop crops with enhanced heat stress tolerance. In hot environments, maintenance of plant productivity requires that limiting plant processes are not irreversibly damaged by heat. All plant processes are irreversibly damaged if it is hot enough for a sufficient time. Consequently, in designing breeding programs to incorporate heat tolerance, answers are needed to the following questions: a) What types of hot weather are occurring in production environments, considering day and night temperatures at different times during the season; and, to what extent are they causing reductions in yield? This information is useful for establishing the priority to be given to breeding heat tolerance into cultivars for different target environments. b) What stages of plant development and plant processes are most sensitive to high' temperatures and are responsible for the reductions in yield? This information would facilitate the development of efficient techniques for screening germplasm for heat tolerance. It would also be useful to know whether other correlated factors such as evaporative demander day length influence plant response to hot weather. c) How is heat tolerance inherited, and are there any other characters associated with heat tolerance through genetic linkage or pleiotropy that influence crop adaptation or suitability as a cultivar? This information is useful for developing effective breeding strategies. I will describe studies that have enabled us to incorporate heat tolerance into crop.

A) Breeding strategies for heat stress tolerance involves implementing various strategies to identify, select, and develop individuals with enhanced resilience to high temperatures. Here are some key breeding strategies for heat stress tolerance in plants. (Lamba *et al.*,2023).

1.Trait Identification

Feature identification for heat tolerance contains classifying specific characteristics or attributes that enable plants or animals to withstand high temperatures. These traits play a crucial role in determining the heat tolerance of individuals and are embattled in breeding programs to develop heat-tolerant varieties. Heat traits are as follow.

a. **Heat Shock Proteins:** Molecular chaperones are heat shock proteins that help protect cells from heat-induced damage by facilitating proper protein folding and preventing protein aggregation. Plants and animals that produce higher levels of HSPs in response to heat stress tend to exhibit greater heat tolerance. Heat stress can prime to the accrual of reactive oxygen species in cells, causing oxidative damage. Antioxidant enzymes such as superoxide, dismutase, catalase and peroxidase scavenge ROS and mitigate oxidative stress, thereby enhancing heat tolerance.

b. **Membrane Stability**: Cellular membranes disrupt by high temperatures conciliatory their integrity and function. Plants and animals with stable cell membranes under heat stress exhibit greater heat tolerance. Membrane stability is often assessed by measuring electrolyte leakage or lipid peroxidation levels. Photosynthesis can impair from heat stress, leading to reduced carbon assimilation and growth. Plants with enhanced photosynthetic efficiency under high temperatures exhibit greater heat tolerance. Traits such as higher chlorophyll content, stomatal conductance, and photosystem stability contribute to maintaining photosynthetic activity.

c. **Reproductive Success:** Reproductive development can impair heat stress and reduce seed set or fertility in plants, as well as decrease reproductive performance in animals. Individuals that maintain reproductive success under heat stress exhibit greater heat tolerance. Root traits is influenced from heat tolerance that affect water and nutrient uptake, as well as root system architecture (Fig.1). Plants with deeper, well-developed root systems can access water from deeper soil layers and exhibit greater heat tolerance.

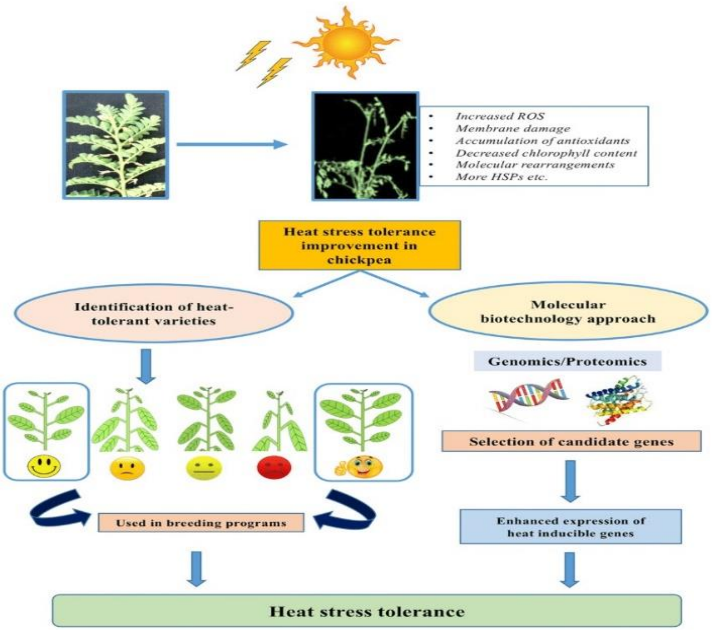

Fig: 01. Effect of heat stress and approaches for heat stress tolerance

Source: Molecular Biology Reports (2020)

2. Genetic Diversity

Utilizing genetic diversity within crop is essential for breeding resilient varieties. Breeders seek out wild relatives and landraces with natural heat tolerance traits to introduce genetic variability into breeding programs.

a) **Natural Variation:** Indoors populations of a species, there exists natural genetic variation for traits related to heat stress tolerance. This variation arises from mutations, genetic recombination, and historical adaptation to diverse environments. Accessing and utilizing this natural genetic diversity is essential for breeding programs aiming to enhance heat stress tolerance. Wild relatives of cultivated plants often exhibit adaptations to extreme environments, including heat stress. These wild relatives harbour valuable genes and alleles for heat tolerance traits that can be introgress into crop varieties through breeding. Similarly, landraces, which are traditional varieties adapted to local conditions, may possess unique genetic variations for heat stress tolerance.

b) **Genetic Resources Collections**: Gene banks and genetic resources collections preserve diverse genetic material from a wide range of plant and animal species. These collections serve as repositories of genetic diversity and provide breeders with access to valuable genetic resources for breeding heat-tolerant varieties. Introgression breeding involves transferring specific genes or genomic regions from wild relatives or exotic germplasm into elite breeding lines. This approach allows breeders to introduce novel alleles associated with heat stress tolerance into cultivated varieties while retaining desirable agronomic traits.

c) **Genome-Wide Association Studies:** GWAS enables the identification of genetic variants associated with heat stress tolerance by analysing natural variation within populations. By correlating genotype data with phenotypic traits under heat stress conditions, researchers can pinpoint candidate genes and genomic regions involved in heat tolerance. Population genetics studies provide insights into the patterns and distribution of genetic diversity within and among populations. By characterizing genomic diversity, researchers can identify hotspots of diversity, population structure, and genetic differentiation associated with adaptation to heat stress.

3. Marker-Assisted Selection (MAS)

Molecular markers linked to heat tolerance traits enable more efficient selection of desirable individuals in breeding populations. MAS facilitates the identification of heat-tolerant genotypes at early stages, accelerating the breeding process. Here are some examples of molecular markers commonly associated with heat tolerance traits.

a) **Single Nucleotide Polymorphisms**: SNPs are the most abundant type of genetic variation in the genome and serve as valuable molecular markers for identifying genomic regions associated with heat tolerance. Genome-wide association studies (GWAS) and linkage mapping can identify SNPs that are correlated with heat tolerance traits, enabling marker-assisted selection (MAS) in breeding programs. SSRs, also known as microsatellites, are tandemly repeated DNA sequences that exhibit high levels of polymorphism. SSR markers linked to heat tolerance traits can be used for genetic mapping and marker-assisted selection in crops. Indels are genomic variations resulting from the insertion or deletion of nucleotide sequences. They can serve as informative molecular markers for detecting genetic variation associated with heat tolerance traits and facilitating marker-assisted selection in breeding programs.

b) **Gene-Based Markers:** Gene-based markers, such as single-strand conformation polymorphisms (SSCPs) and cleaved amplified polymorphic sequences (CAPS), are designed based on sequence variations within candidate genes known to be involved in heat tolerance pathways. These markers enable targeted selection of alleles associated with heat tolerance traits in breeding programs.QTL mapping identifies genomic regions associated with quantitative traits, including heat tolerance. Molecular markers linked to QTLs for heat tolerance traits provide breeders with targets for marker-assisted selection to enhance heat tolerance in breeding populations

Challenges: Breeding for heat stress tolerance faces several challenges, which can impede the development of resilient crops varieties. Some of the key challenges include are

Complexity of Heat Stress Response: Heat stress tolerance is a complex trait influenced by multiple genetic and environmental factors. Understanding the underlying mechanisms of heat stress response remains a challenge for breeders. Heat stress triggers a wide range of physiological, biochemical, and molecular responses in organisms. These responses involve complex interactions among various cellular pathways, including those related to heat shock proteins, antioxidant defence mechanisms, osmotic regulation, and metabolic adjustments. Multiple genes controlled heat stress tolerance by small to moderate effects, as well as regulatory elements and epigenetic mechanisms. Genetic variation within and among populations further adds to the complexity, as individuals may exhibit diverse responses to heat stress due to their genetic backgrounds.

Trade-offs with Other Traits: Breeding for heat stress tolerance may result in trade-offs with other desirable traits, such as yield potential or disease resistance. Balancing multiple trait objectives is crucial for developing high-performing varieties. Breeding for heat stress tolerance may sometimes lead to a reduction in yield potential under optimal conditions. This trade-off occurs because genetic traits that confer heat tolerance, such as early flowering or increased transpiration efficiency, may not necessarily be advantageous under non-stress conditions. Breeders must balance heat tolerance with maintaining or improving yield potential to ensure the overall agronomic performance of varieties.

Environmental Variation: Heat stress tolerance must be evaluated under diverse environmental conditions to ensure its effectiveness across different agroecosystems. Field trials conducted in various locations and under different heat stress scenarios are necessary but resource-intensive.

Future Directions: The future direction for enhancing heat stress tolerance involves integrating cutting-edge technologies, interdisciplinary approaches, and innovative strategies to address the complex challenges associated with climate change.

a. **Climate-Smart Breeding:** Implementation of climate-smart breeding approaches that consider the dynamic interactions between genotype, phenotype, and environment will enhance the resilience of crops to heat stress (Hossain et al.,2013). Breeding programs will incorporate genomic selection, genomic prediction, and multi-environment trials to develop varieties adapted to changing climatic conditions and extreme heat events. Integration of multiple heat tolerance traits with other desirable agronomic traits, such as yield potential, disease resistance, and nutritional quality, will optimize breeding outcomes and mitigate potential trade-offs. Trait stacking through marker-assisted selection or gene editing will enable the simultaneous improvement of multiple traits to enhance overall resilience and performance under heat stress conditions.

b. **Collaborative Research and Knowledge Sharing**: Collaboration between researchers, breeders, policymakers, and stakeholders will foster interdisciplinary research efforts and facilitate knowledge sharing and technology transfer. Collaborative initiatives, such as public-private partnerships, international consortia, and open-access data repositories, will accelerate innovation and dissemination of heat stress tolerance technologies globally. Continued advancements in genomics, including high-throughput sequencing, genome editing CRISPR-Cas, and functional genomics, will accelerate the identification and characterization of genes and molecular pathways underlying heat stress tolerance. Integration of genomic information into molecular breeding programs will enable targeted manipulation of heat tolerance traits and facilitate the development of resilient varieties.

Conclusions

In conclusion, by embracing these future directions and leveraging emerging technologies and collaborative approaches, we can accelerate progress towards developing heat-tolerant crops varieties capable of withstanding the challenges of climate change and ensuring food security and agricultural sustainability in a warming world. In India develop heat tolerant variety of Tomato Arka Vikas (Sel 22) hybrid variety released by IIHR, Bangalore. Plants semi-determinate with dark green foliage. Fruits oblate, medium large (80-90 g.) with light green shoulder. Suitable for table purpose. Tolerant to heat and moisture stress. Crop is cultivated in Kharif/Rabi season and matures in 140 days. Average yield is 35-40 t/ha. The varieties of Indian mustard (NRCDR 02, NRCDR 601, DRMR150-35) have been developed by Rapeseed-Mustard Varieties developed by ICAR-DRMR. These variety have the characteristic Tolerant to high temperature and salinity at the time of sowing. Low incidence of white rust, (stag head), Alternaria blight and Sclerotium rot.

The wheat varieties DBW187 and DBW222 have been found superior over HD-3086 as far as heat tolerance is concerned. The wheat varieties DBW187 and DBW222 have been found superior over HD-3086 as far as heat tolerance is concerned. The ICAR-IIWBR Karnal has initiated a specific research project entitled "Breeding high yielding wheat genotypes for stress conditions of warmer regions of India" on heat tolerant varieties. Besides, ICAR-IIWBR Karnal is also collaborating with International Maize and Wheat Improvement Centre (CIMMYT), Mexico on development of climate resilient wheat varieties.

The variety PBW 803 developed by the Punjab Agricultural University (PAU), Ludhiana is suitable for irrigated timely sown condition and resistant to brown rust as well as moderately resistant to stripe rust. This variety is not recommended as heat-tolerant variety. Overall, investing in the development and adoption of heat stress-tolerant crop varieties can offer significant benefits to farmers, helping them adapt to climate change and sustainably increase agricultural productivity.

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