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Effect of Terminal Heat Stress on Reproductive Stages and Yield in Wheat Crop

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Bread wheat (*Triticum aestivum* L.) is a significant staple and calorie food crop worldwide. The majority of the world's wheat-growing regions regularly experience high temperatures (above optimal), which considerably reduce grain yield. During the reproductive stage, 15–20°C is the optimum temperature for wheat growth and temperature above the optimal cause terminal heat stress in wheat. The reproductive stage of wheat is more sensitive than the vegetative stage, which significantly reduces the grain filling duration and shrunken the seed. Wheat yield reductions of 6.4 % to 27 % with a 1°C increase in temperature have been reported by a number of empirical and model-based studies. Heat stress had a detrimental effect on plant growth and development, including leaf photosynthesis, reactive oxygen species (ROS) production, decreased wheat grain yields due to reduced grain weights and shortened of grain-filling duration, reduction in floret fertility and reduced spike grain weights. In order to improve wheat's tolerance to heat stress, this article focusing on the effects of heat stress on flower development and fertilization, grain development and reproductive failure, and various management strategies including genetics/breeding and selection, genetic engineering, and molecular breeding.

Effects of Terminal Heat Stress

1) **On flower development and fertilization:** Heat stress has a significant negative impact on flower initiation and development. The growth of microspores and pollen cells is negatively impacted by heat stress, which have the largest influence on reproductive organ viability, especially during flower opening. Heat stress during gametogenesis in wheat results in irreversible morphological defects in stigmas, styles, pollen, and ovaries and negatively affects subsequent physiological processes, such as pollen tube growth, fertilization effectiveness, and pollen viability. Meiosis stage is highly sensitive resulted in pollen and ovule sterility, anther indehiscence, and 30°C temperatures for three days completely vanished embryo sacs.

Heat stress significantly reduced the viability, development, and fertilization of pollen, which resulted in the formation of pseudo- seeds. When developing wheat pollen, high temperatures (35/25°C) disrupted tapetal cells, resulting in collapsed and desiccated pollen grains with aberrant surface patterns. When tapetal cells are damaged due to high-temperature stress, nutrient translocation is inhibited and pollen viability is decreased. Terminal heat stress causes embryo abortion as ethylene production rises and kernel weight decreases. During anthesis heat stress reduced floret fertility by altering the morphology and functions of the pollen and pistil. Grain number and size varies according to the heat stress level. Heat stress at post-anthesis decreased wheat yields by shortening the grain-filling period and limiting resource allocation to grain. The pre-anthesis photo-assimilate supply and amount of assimilate reserve maintained in vegetative tissues are significant factors in heat-stressed wheat because floret onset and subsequent grain development are negatively impacted. Less pollen grains on the stigma under heat stress is the main cause of decreased fertilization. In conclusion, heat stress in wheat during pollination and fertilization decreases pollen viability by reducing the number of pollen grains.

2) **On grain development:** In wheat endosperm, starch and protein predominate, with starch accumulation making up 65 % of the dry weight of the seed. Due to the sensitivity of soluble starch synthase in growing wheat kernels, starch synthesis is more sensitive to heat stress than protein synthesis. The activity of soluble starch synthase decreased in wheat under heat stress, resulting in poor starch synthesis and grain growth. Wheat starch granules undergo morphology (size, shape, and structure) changes under heat stress (>25°C). Heat stress reduces the number of endosperm cells early in wheat grain formation; subsequently, it hinders starch synthesis by reducing the translocation of assimilates to grain. Heat stress during grain growth alters the total nitrogen content, which changes the makeup of storage proteins. Protein quality degrades in heat-stressed plants; for example, heat stress alters the aggregation qualities that lower dough quality by raising gliadin levels and lowering glutenin levels. As a result, heat stress reduces grain quality by limiting the enzymatic pathways necessary for protein and starch biosynthesis, which prevents protein and starch accumulation.

Wheat grain filling duration and grain-filling rate (growing degree days) are significantly affected by heat stress. The association between final grain weight and grain-filling rate is positive. The earlier stage of grain filling is thought to be more susceptible to heat stress than the later stage. Heat stress decreases the flag leaf's ability to assimilate, which can prevent the accumulation and transit of ^{14}C assimilate and drastically lower grain weight and quality. Temperatures greater than 20°C during spike formation and anthesis accelerate spike development but decrease grain quantity. Heat stress significantly decreases assimilate translocation through apoplastic and symplastic routes. Heat stress (above 30°C) considerably decreased the assimilate translocation from flag leaf to grain. Wheat stem's assimilate reserves are reduced by heat stress, which limits carbon assimilation during stem elongation.

As a result, due to the significant decline in cotyledon cell numbers and cell expansion, heat stress facilitates rapid grain maturity and shortens the grain-filling period, resulting in shrivelled grain with low weights.

Strategies to improve Terminal Heat Tolerance

Agronomic management includes adopting techniques that reduce water use (conservation agriculture), use fertilizer at critical growth stages, irrigate to cool soil surfaces, enhance antioxidant systems and osmolyte accumulation using osmoprotectants and cultivate improved heat-tolerant genotypes.

Breeding and selection have been employed from the early days to introduce desired traits in crop plants, and they might be used to create wheat cultivars resistant to terminal heat stress. Although there is little genetic variation in cultivated bread wheat germplasm for heat tolerance, their wild relatives, such as durum wheat (*Triticum turgidum subsp. durum* and *Aegilops tauschii*), have significant genetic variation for a number of desirable traits that could be used to improve terminal heat tolerance in hexaploid bread wheat. It may be feasible to produce high-yielding wheat genotypes under high-temperature stress by combining biotechnological and physiological tools with conventional breeding methods.

After introducing desired genes into the candidate genotype, transgenic techniques and genetic modification can improve wheat's terminal heat tolerance. For example, ZmPEPC (a maize phosphoenolpyruvate carboxylase gene) overexpression in wheat increased the

expression of genes related to photosynthesis, increased antioxidant and photochemical activities, altered the contents of proline and other metabolites, and postponed the degradation of chlorophyll, resulting in the development of heat tolerance.
Significant efforts have been undertaken to elucidate stress-responsive mechanisms and molecular pathways. The efficient selection of terminal heat tolerance traits is difficult for breeders because heat tolerance is quantitative and irregular. Utilizing marker-assisted selection, mapping QTL associated with heat stress tolerance has revealed the mechanisms behind heat tolerance in wheat grown in warm climates. In wheat, several QTL for heat tolerance during the reproductive phase have recently been discovered. For instance, Paliwal et al. (2012) reported QTL on chromosomes 2B, 7D, and 7B for 1000-grain weight, canopy temperature depression, and grain-filling duration, respectively.

Conclusion

Wheat is an important staple grain crop grown all over the world. High temperatures during the reproductive stage have a large effect on wheat yield. Heat stress during flowering inhibits the beginning of flowers, harms their reproductive organs, results in pollen abortion, creates malformed pollen tubes, and decreases grain production. Heat stress has a significant impact on the biosynthesis of protein and starch in wheat by decreasing enzyme activity and inhibiting metabolic pathways. Heat stress reduces the assimilation efficiency in flag leaves, shortening the grain-filling period and speeding up the grain-filling rate, leading to less remobilization to grain and fewer grains. Wheat performance under terminal heat stress may be improved through breeding and selection for characteristics such grain weight, grain number, stay-green trait, osmolyte accumulation, and production of antioxidant enzymes. Genetic engineering that finds heat-responsive genes, enhances osmolyte and antioxidant synthesis, and identifies QTL associated to terminal heat stress tolerance. Agronomic strategies might be helpful in the short term to reverse wheat yield losses caused by terminal heat.

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