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Terminal Heat Stress in Wheat: Adaptation for Sustainable Production

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INTRODUCTION

Wheat (Triticum aestivum L.) is one of the most important cereal crops worldwide and plays a fundamental role in ensuring global food and nutritional security. However, increasing global temperatures, irregular rainfall patterns, and frequent heat waves associated with climate change are creating substantial challenges for wheat production. Among various abiotic stresses, terminal heat stress has emerged as a major constraint, particularly in regions where elevated temperatures coincide with the reproductive and grain-filling stages.

Terminal heat stress generally occurs during the later stages of crop development, particularly from heading and anthesis to physiological maturity. Exposure to high temperatures during these sensitive stages accelerates plant development, shortens the grain-filling period, impairs reproductive processes, and reduces individual grain weight. Consequently, substantial reductions in grain yield and quality may occur.

The development and adoption of integrated management strategies are therefore essential to improve wheat resilience under changing climatic conditions. Combining heat-tolerant cultivars with appropriate agronomic practices, efficient irrigation, balanced nutrient management, conservation agriculture, and exogenous application of protective substances offers a promising approach to sustainable wheat production.

2. Understanding Terminal Heat Stress

Terminal heat stress refers to exposure of wheat plants to excessively high temperatures during reproductive development, particularly between heading and maturity. The optimum temperature for wheat grain setting and grain filling is approximately 19–22°C. Temperatures exceeding the optimum range can adversely affect physiological and biochemical processes.

Heat exposure during anthesis reduces pollen viability, fertilization efficiency, and grain number. During grain filling, elevated temperatures accelerate senescence, reduce photosynthetic activity, and disturb assimilate partitioning between source and sink tissues.

Research indicates that every 1°C increase in temperature may shorten the grain-filling duration by approximately 2.8 days, potentially reducing grain production by around 6%. Furthermore, terminal heat stress has been associated with reductions in plant height, fertile tillers, grain weight per spike, test weight, and overall grain yield.

The severity of yield reduction depends on genotype, duration and intensity of heat exposure, crop developmental stage, soil moisture availability, and prevailing environmental conditions.

3. Major Effects of Terminal Heat Stress on Wheat

Terminal heat stress affects wheat growth through several interconnected physiological and biochemical mechanisms.

3.1 Reproductive Damage: High temperatures during anthesis adversely affect pollen development, pollen viability, fertilization, and grain setting. This results in fewer grains per spike and reduced reproductive efficiency.

3.2 Reduced Photosynthetic Efficiency: Heat stress damages photosynthetic machinery, alters stomatal behaviour, and reduces carbon assimilation. Reduced assimilate availability negatively affects grain development.

3.3 Accelerated Leaf Senescence: Elevated temperatures promote premature leaf ageing and chlorophyll degradation, shortening the period of active photosynthesis and reducing carbohydrate accumulation.

3.4 Oxidative Stress: High temperatures stimulate the generation of reactive oxygen species (ROS), which cause oxidative damage to cellular membranes, proteins, and other cellular components. Malondialdehyde (MDA), an indicator of lipid peroxidation, increases under oxidative stress.

3.5 Reduced Grain Filling and Yield: Heat exposure accelerates physiological maturity and reduces grain-filling duration, resulting in smaller grains, lower thousand-grain weight, and reduced final productivity.

4. Integrated Strategies for Mitigating Terminal Heat Stress

4.1 Selection and Development of Heat-Tolerant Varieties

Genetic improvement is an important long-term strategy for mitigating terminal heat stress. The selection of early-maturing, heat-tolerant, and environmentally adaptable wheat genotypes can help plants complete critical reproductive stages before the onset of severe temperature stress.

Genotypes such as GW 190, HI 1418, HUA 543, Raj 4014, Raj 4000, Raj 4027, HD 2285, and PBW 497 have been identified as promising under heat-stress conditions. PBW-343 and DBW-17 have also demonstrated adaptability under different sowing conditions.

Breeding programmes should emphasize traits such as stable grain filling, maintenance of chlorophyll content, antioxidant capacity, membrane stability, effective tillering, and high grain weight under elevated temperatures.

4.2 Optimization of Sowing Time

Timely sowing is among the most economical and practical approaches for reducing terminal heat stress. Early planting allows wheat to complete flowering and grain filling before temperatures rise substantially during late winter and early summer.

In the northern Indian wheat-growing region, sowing between 25 October and 15 November is suggested in the reviewed literature, depending on cropping-system conditions and cultivar duration.

Delayed sowing exposes reproductive stages to elevated temperatures, resulting in shortened grain filling and reduced grain weight. Research has reported substantial yield reductions under delayed planting, emphasizing the importance of timely field preparation and sowing.

4.3 Conservation Agriculture, Zero Tillage and Mulching

Conservation agriculture provides an effective strategy for improving soil-water relations and reducing temperature-related crop damage. Zero tillage, minimum tillage, and crop-residue retention help maintain soil moisture, regulate soil temperature, and improve soil physical conditions.

In rice–wheat cropping systems of the Indo-Gangetic Plains, retention of rice residues has been reported to reduce wheat canopy temperature by approximately 1–4°C during the reproductive period.

Surface mulching also reduces evaporation, conserves available soil moisture, and supports root development. Technologies such as Happy Seeder. Super Seeder, and Smart Seeder facilitate wheat establishment under residue-retained conditions.
These practices can improve water-use efficiency, reduce cultivation costs, and contribute to climate-resilient agriculture.

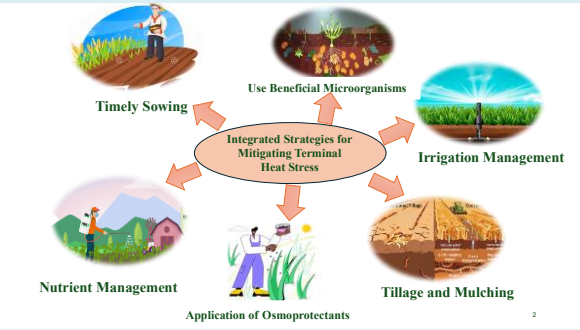
4.4 Efficient Irrigation Management

Water availability plays a critical role in regulating crop temperature through transpiration. Under adequate soil moisture conditions, wheat plants maintain transpiration and evaporative cooling, thereby reducing the harmful effects of high atmospheric temperatures.

Water deficiency causes stomatal closure, decreases photosynthetic activity, and limits evaporative cooling, making plants more vulnerable to heat injury.

Timely irrigation during critical growth stages, particularly anthesis and grain filling, is therefore essential. Sprinkler, drip, and appropriately scheduled surface irrigation can help maintain crop water status during periods of increasing temperature.

The combination of early sowing and timely irrigation is particularly useful for minimizing terminal heat-induced yield losses.



4.5 Application of Osmoprotectants and Plant Bioregulators

Exogenous application of osmoprotectants and plant bioregulators can improve wheat tolerance to high-temperature stress by regulating physiological and biochemical responses.

Important compounds include:

- **Potassium nitrate (KNO_3):** Supports photosynthesis, carbohydrate metabolism, and plant-water relations.
- **Salicylic acid:** Helps regulate antioxidant defence and may delay premature senescence.
- **Thiourea:** Contributes to improved metabolic activity and stress tolerance.
- **Sodium nitroprusside:** Acts as a nitric oxide donor and can regulate stress-responsive physiological processes.
- **Calcium chloride ($CaCl_2$):** Supports membrane stability and cellular signalling.
- **Zinc and silicon:** Contribute to antioxidant defence, water relations, and physiological stability under stress.

Reported research findings indicate that foliar application of sodium nitroprusside, 2% potassium nitrate, and 20 mM thiourea increased wheat grain yield by approximately 18.8%, 17.9%, and 14.9%, respectively, under the experimental conditions reported by Suryavanshi and Buttar (2016).

These responses should be interpreted in relation to cultivar, application stage, concentration, environmental conditions, and experimental methodology.

4.6 Balanced Nutrient Management

Balanced fertilization is essential for maintaining wheat growth and productivity under heat stress. Nitrogen supports chlorophyll formation, photosynthesis, and vegetative growth, whereas potassium regulates stomatal activity, enzyme function, and carbohydrate transport.

Phosphorus contributes to energy transfer and reproductive development. Zinc and magnesium support enzymatic and photosynthetic functions, while calcium contributes to membrane stability and cellular regulation.

Appropriate nutrient application, particularly during critical growth stages, can help maintain physiological activity and improve crop performance under adverse environmental conditions. However, nutrient application should be guided by soil testing, crop requirements, and locally recommended fertilizer practices.

4.7 Role of Beneficial Microorganisms

Plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi offer promising biological approaches for improving wheat resilience under heat stress.

These beneficial microorganisms can promote root development, improve nutrient acquisition, enhance antioxidant defence, and regulate plant growth through the production of biologically active compounds.

Seed inoculation and soil application of suitable microbial formulations may therefore complement conventional agronomic management while supporting environmentally sustainable crop production.

5. Integrated Climate-Smart Management Approach

No single management practice can completely eliminate the adverse effects of terminal heat stress. Therefore, an integrated approach combining genetic, agronomic, physiological, and biological interventions is essential.

A practical management framework includes:

1. Selection of suitable heat-tolerant and early-maturing wheat varieties.
2. Timely sowing according to regional agroclimatic conditions.
3. Adoption of zero tillage and residue-retention practices.
4. Maintenance of adequate soil moisture during anthesis and grain filling.
5. Balanced application of essential plant nutrients.
6. Use of scientifically validated osmoprotectants and plant bioregulators.
7. Integration of beneficial microorganisms to improve plant stress resilience.

Combining these interventions may provide greater benefits than implementing individual practices independently. However, their effectiveness should be evaluated through multi-location and multi-season field experiments.

6. Future Research Perspectives

Future research should focus on identifying physiological, biochemical, and molecular traits associated with terminal heat tolerance. Advanced

breeding approaches, genomic selection, molecular markers, and high-throughput phenotyping may accelerate the development of climate-resilient wheat cultivars.

Further investigation is also required to standardize the concentration, timing, and frequency of foliar applications of osmoprotectants under different agroecological conditions. Integrating precision irrigation, weather-based advisory systems, and conservation agriculture could further improve resource-use efficiency and yield stability.

CONCLUSION

Terminal heat stress represents a significant challenge to wheat productivity and global food security under changing climatic conditions. Its adverse effects on reproductive development, photosynthesis, grain filling, and assimilate partitioning necessitate the adoption of integrated management strategies.

The combined application of heat-tolerant varieties, timely sowing, conservation agriculture, efficient irrigation, balanced nutrient management, osmoprotectants, and beneficial microorganisms offers a scientifically supported pathway towards climate-resilient wheat production.

Key Message: Integrated crop management is essential for protecting wheat productivity against terminal heat stress and ensuring sustainable food production under a warming climate.

Towards Climate-Resilient Agriculture, Sustainable Wheat Production and Global Food Security.