Review Article

Terminal Heat Stress and its Mitigation options Through Agronomic Interventions in wheat crop: A Review

ABSTRACT

Climate change will be one of the most critical dangers to agriculture in the coming years. On average, abiotic stresses account for 50% of the production losses in agricultural production. Terminal stress is a major environmental issue limiting wheat production in the majority of wheat-growing regions across the world. The term "terminal heat stress" refers to a rise in temperature (> 30 °C) after anthesis during grain development which impairs the process of grain filling in wheat. Rising temperatures shorten the vegetative and reproductive periods of the wheat crop, but the reproductive stage is more vulnerable than the vegetative.The major portion of India, including the north-eastern plain zone, the central zone, and the peninsular zone, experienced terminal stress over the summer. There are numerous solutions available for mitigating the harmful effects of terminal heat stress on wheat crops.Adjusting sowing time is one of the most impactful agronomic techniques. Wheat planting methods such as conservation tillage, bed sowing, conventional tillage plus mulch, and surface residue preservation are considered suitable alternatives for mitigating terminal stress. Moreover, irrigation at a critical period reduces terminal heat stress and boosts wheat grain development. Foliar spraying of osmoprotectants such as KNO_3, Thiourea, Zn, and many others during anthesis and post-anthesis can also help in alleviating the effects of high-temperature stress on wheat crops.

Keywords: Wheat, Terminal Heat Stress, Agronomic measures, SowingTime, Tillage, Mulching, irrigation management

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Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops on the planet. It is the primary source of nutrition for more than 35% of the world's population. Wheat is farmed on over 219 million hectares worldwide (FOA, 2015). It is cultivated on 31.19 million hectares in India and produces 95.85 million tonnes, making it the country's 2nd largest wheat producer after rice (Shabnam *et al*., 2019). Unfavorable environmental circumstances (biotic and abiotic stress) viz, high temperatures, soil moisture shortages, and low light intensity pose significant challenges to wheat crop growth and yield, while high-temperature stress is the most severe one (Trnka *et al*., 2004; Modarresi *et al*., 2010). Global warming is being caused by climate change, which may have a negative impact on agricultural crop regional distribution and planting circumstances. The air temperature has gradually risen in recent decades and is anticipated to climb significantly higher in the future (IPCC, 2018). A rise in air temperature, along with an increase in volatility, will result in more recurring heat waves and heat records (IPCC, 2001; Porter and Semenov, 2005). Wheat crops are often susceptible to high temperatures, and a temperature rise may disrupt the source-sink connection, resulting in a loss of yield. High-temperature stress during wheat reproductive development is a substantial yield constraint. Terminal heat stress (temperatures above 40° Celsius) can cause leaf and branch scorching, sunburns on leaves, leaf senescence, abscission, shoot and root growth inhibition, and fruit discoloration, all of which lead to lower production (Vollenweider and Gunthardt Goerg, 2005). During the wheat growing season, a wide area of India faces excessive heat, including the northeastern plain zone, the central zone, and the peninsular zone (Bamboriya *et al*., 2017). Mishra *et al*. (2015) found that heat stress reduced yield by 33.6 % in most wheat cultivars under late-sown situations. Terminal or late heat stress during the later stages of wheat growth, particularly during the flowering, heading, anthesis, and grain filling stages of spring wheat cultivars, is one of the most significant environmental restrictions to wheat productivity. Besides. It considerably disturbs grain number/spike and grain weight, leading to an extensive reduction in wheat grain production in most bread wheat-growing regions. Furthermore, each 1°C rise in temperature is expected to reduce wheat grain filling length by 2.8 days, resulting in a 6% reduction in wheat grain production .The global temperature will have risen by 1.1–6.4 degrees Celsius by the end of the 21st century (IPCC, 2007) which may reduce wheat production considerably.

Terminal heat stress:

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The wheat crop is vulnerable to two different forms of heat stress: continuous heat stress and terminal heat stress. It is called "continual heat stress" if heat stress occurs throughout the complete growing season of wheat (sowing- maturity); however, it is termed "terminal heat stress" if it occurs during reproductive phases, mainly from heading to the maturity phase. Temperature stress develops throughout the reproductive development phases, notably during the period from heading to maturity, and is denoted as "terminal heat stress" (Horvath*et al* (2007).Increased temperature above the ideal temperature will decrease the period of wheat maturity (days), accelerate growth, and reduce the duration of wheat growth, consequently reducing yield. The optimal temperature for grain setting and grain filling in wheat is between 19 °C and 22 °C (Porter and Gawith 1999). According to Hurkman *et al*. (2009), heat stress (37/28°C day/night) for a period of 10 to 20 days after anthesis till maturity lowers grain filling length and maturity; fresh and dry weight, proteins, and carbohydrate contents in grain drastically reduce grain size and yield.Wheat plants in Figure 1. are displaying indications of terminal heat and water stress due to a lack of water. Due to heat stress, the awns and higher heads are going white/chaff colored, while the lower stems are turning yellow straw-colored due to water stress.

Figure1. Symptoms of terminal heat stress on wheat

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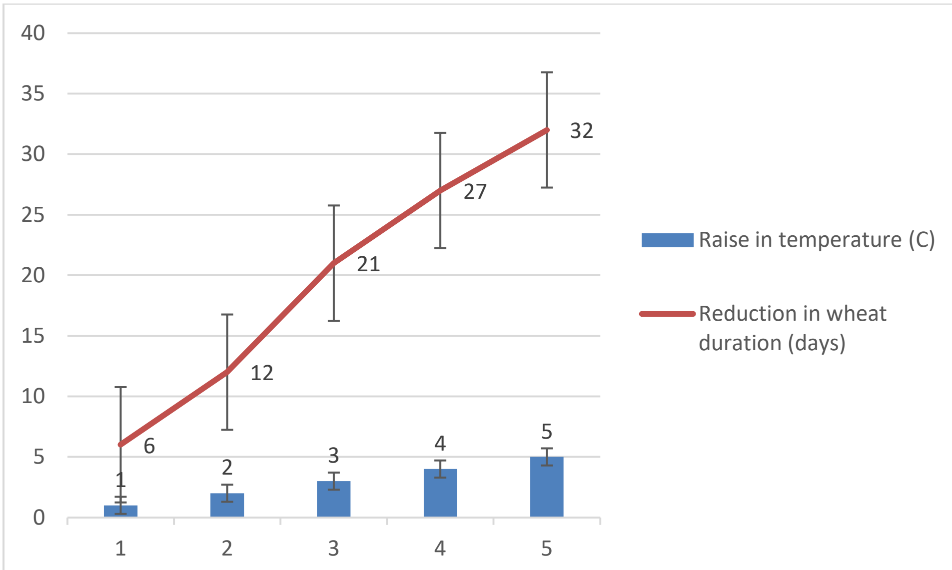
Figure2. The consequence of increasing temperature and reduction of the wheat growing duration



Source: Tripathy (2008)

Table 1:Base (T_{min}), optimum (T_{opt}) and maximum (T_{max}) temperatures for various reproductive phases in wheat

Stage	Temperature	Mean temperature
Spikelet phase	Tem_{min}	1.8±0.25
	Tem_{opt}	11.7±1.61
	Tem_{max}	> 21.4±2.33
Anthesis phase	Tem_{min}	9.7± 0.43
	Tem_{opt}	23.0± 1.15
	Tem_{max}	32.0±1.74
Grain filling phase	Tem_{min}	9.6± 0.75
	Tem_{opt}	21.3± 1.27
	Tem_{max}	34.3±2.66

Source: Farooq *et al.*, 2011

Table 2: Decrease (%) in severalwheat characters under heat stress conditions

Wheat Trait	Reduction in %
Height of plant	6.5
fertile tillers	-31
No. of days taken to heading	10
No. of days taken to anthesis	10
No. of days taken to maturity	11
Periodof grain filling	11
No. of grains per spike	3
grain weight/ spike	17
Test weight	14
Grain	26

Source: Sareen *et al*., 2012

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Effect of terminal heat stress on the physiological parameter of wheat

Wheat suffers from terminal heat stress, which changes various physiological pathways, resulting in diminished growth and development. When the ambient temperature changes, the state of plant water becomes the most unstable. High temperatures cause plant tissue to dehydrate, inhibiting plant growth and development. Heat stress has adverse impact on photosynthetic efficiency, stomatal conductance, leaf area, and water-use efficiency in cereal crops such as wheat and maize.Heat stress decreased the chlorophyll A concentration by 55.5 percent. Wheat crops have been found to be temperature sensitive throughout the reproductive stage, disrupting the source-sink connection and resulting in lower yields.Heat stress during the reproductive phase has a negative impact on wheat anthesis, flowering, and grain filling (Wardlaw *et al*,. 1994, stone *et al*., 2001).During the floweringtime, a temperature of 31 degrees Celsius is regarded as the top limit, and any additional increase in temperature results in a decline in water potential, relative water content in leaves, and, as a result, condensed photosynthetic efficiency of wheat.Furthermore, photosynthesis is the most important physiological function that is very susceptible to high temperatures, resulting in poor growth and development .Heat stress reduced photosynthesis due to diminished leaf area growth, inefficient photosynthetic apparatus, and early leaf senescence, resulting in poorer wheat productivity (Mathur *et al*., 2014; Ashraf and Harris, 2013). The drought and heat stress increased the activities of catalase, peroxidase, superoxide dismutase, and ascorbate peroxidase, both individually and together (Rivero *et al.,* 2014; Thalmann *et al*; 2017; Caverzan *et al*., 2016). Increased enzyme activity is assumed to be caused by the generation of damaging reactive oxygen species such as superoxide radical (O_2), singlet oxygen (OH), and hydrogen peroxide (H_2O_2) (Dat *et al*., 2000; Marutani *et al*., 2012).

Effect of terminal heat stress on wheat yield attributing characters and yield

Climate change has become a major concern for wheat growers, researchers, and policymakers due to its early onset near the end of the *Rabi* season, which coincides with the crop's grain filling stage, resulting in pollen viability loss, reduced grain number and size, and, ultimately, a reduction in crop yield (Tamta *et al*., 2021).Wheat yield is expected to fall by 400 kg/ha for every degree Celsius (°C) increase in mean temperature between March and April. further, Crop duration is predicted to decline by approximately 7 days for every degree Celsius (°C) rise in mean temperature between March and April (Singh *et al*., 2011). Moreover, when temperatures rise during grain filling, development speeds up, resulting in a shorter grain-filling period. Consequently, heat stress affects grain size and weight by limiting starch synthesis, increasing starch breakdown, and causing senescence to occur early and rapidly. However, because of heat stress, grain (46.7%), test weight (20.6%), and grain filling time (20.4%), kernel/spike (23.6%), and spikelet/spike (11.7%) decreased (Modarresi *et al*., 2010).Likewise, as the temperature rises, the test weight decreases because of a decrease in grain filling time and grain growth rate (Garg *et al*., 2013). Similarly, post-anthesis heat stress increased wheat grain protein content while decreasing the glutenin/gliadin ratio, which has a negative influence on flour quality (Ashraf, 2014).

Table 3. Yield loss due to terminal heat stress in wheat crop

No	Yield loss %	Reference
1	46.7%)	Modarresi *et al*., 2010
2	26 - 54.2%	Asthir *et al*., 2011
3	30%	Malik *et al*., 2014)
4	33.6%	Mishra *et al*. 2015
5	56.47%,	Qaseem *et al*., 2019
6	57.3%	Schittenhelm *et al*., 2020

7	11.1 – 18.1	Dubey *et al*., 2020
8	11.8- 22.1	Kaur *et al*., 2020
9	59.5%	Narendra *et al*., 2021

Agronomic intervention to address terminal heat stress

As a result of climate change, the global temperature has risen, imposing structural barriers on wheat producers and resulting in a loss of growth and development.In most regions, the wheat flowering stage coincides with a rise in temperature, resulting in a shortened reproductive time that has a detrimental influence on pollination, grain filling, and grain weight.There are several approaches for reducing the negative effects of terminal heat stress and increasing wheat production in order to feed the world's rising population. Among the various options, introducing heat tolerant and resistant varieties, as well as short growing period types, using breeding tools is conceivable, but it is a time-consuming and expensive procedure that requires more time and effort. Agronomic interventions such as the use of heat-tolerant varieties, altering sowing dates, adapting conservation agriculture practices (zero tillage and mulching), managing proper irrigation scheduling during anthesis and post-anthesis anthesis, and applying osmoprotectants are also regarded as the most applicable and cost-effective methods of mitigating the negative effects of terminal heat stress. Different agronomic approaches for minimizing adverse effects of terminal heat stress are as follows:

I. Selection of varieties

To cope with terminal heat stress, choosing a good and early maturing variety is critical. Because early maturing varieties may complete their reproductive growth before the temperature rises, they can avoid terminal heat stress. According to Bamboriya*et al*. (2017), bread wheat genotypes GW 190, HI 1418, HUA 543, Raj 4014, Raj 4000, Raj 4027, HD 2285, and PBW 497 appear promising under heat stress. Whereas, PBW-343 and DBW-17, according to Jena *et al*. (2017), are suitable for varied sowing periods.Because of its increased flexibility in terms of temperature and water stress tolerance, the variety PBW-343 was introduced to Northern India.

II. Sowing time

Sowing timing is a non-monitory element that helps to mitigate the negative effects of heat stress in order to get the best possibleyield under severe weather conditions. Early sowing avoid

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the hot, desiccating wind that occurs during flowering and grain filling and ultimately determines crop performance (Jena *et al*., 2017). Wheat planting is delayed, exposing the crop to terminal heat stress during grain filling. Wheat productivity is reduced by around 50 kg/ha per day if planted after mid-November. As a result, one of the most promising and low-cost strategies for farmers to avoid terminal heat stress is to advance the wheat planting date (before November 15). (McDonald, 2015; Aryal *et al*., 2016).Delaying wheat sowing reduced the grain yield by 17.4 %. The fall in yield was due to a reduction in gearnhead density and grain weight.According to Buttar *et al*. (2018), early planted crops generate considerably greater tiller count, plant height, leaf area index, and dry matter production, resulting in increased yield and yield attributing attributes.Gupta *et al*. (2010) similarly observed that normally sown wheat crop produced a higher 1000 grain weight, and late sowing caused a decreasein grain weight. Likewise, Tamta *et al*. (2020) observed that manipulating the sowing date reduced the effects of heat stress on grain production by 33.5% and 12.9%, respectively, for crops sown on November 8 and November 23, as opposed to those sown on December 8.

III. Zero tillage and mulching

Under high-temperature stress, conservation agricultural (CA) methods based on sustaining soil moisture look like viable alternatives. CA is a climate-smart technique that enables early planting of winter wheat under the rice-wheat cropping system (Mengel *et al*., 2001). Wheat cultivation with reduced and zero tillage and surface residue retention is one of the most common C Astrategies employed by farmers in South Asia (SA) to combat abiotic stress (Cormier*et al*., 2013).No-tillage (NT) showed consistently lower soil temperatures at 5 and 10 cm than CT, and NT reduced heat shock (>32°C up to 5 cm soil depth) during the grain filling period . Similarly, Singh *et al.* (2011) discovered that using rice debris as a surface mulch which helpedimprovement of soil water status and regulate soil temperature, resulting in improved root growth, plant canopy, and dry matter. In comparison to the neighboring field, however, minimum tillage with residue retention resulted in a lower wheat crop canopy temperature.In a prolonged investigation in an IGP rice-wheat system, Jat *et al*. (2009) observed that keeping rice residue in an IGP rice-wheat system lowered canopy temperature in wheat by 1–4°C relative to ambient temperature between 138–153 days after planting (DAS) According to Alwin *et al*. (2020), ZT techniques resulted in considerably greater grain production during terminal heat stress. Furthermore, as compared to no mulching, paddy straw mulching conserved more water during the post-anthesis period, which may have resulted in enhanced grain production (Dhyani *et al*., 2016). When compared to conventional tillage, zero tillage improved growth and yield factors such as plant height, effective tillers/m, and grains per ear (Mishra *et al*., 2011).

IV. Irrigation management

High temperatures primarily promote plant transpiration. As a result, as long as the plants meet the greater transpiration requirement, they are not vulnerable to heat stress. Heat stress is commonly associated with water stress. Water-stressed plants conserve water by closing their stomata, which results in less evaporative cooling and a pause in photosynthesis, which results in a reduction in other metabolic activity. As a result, water management is crucial during heat stress because appropriate moisture availability in the field can mitigate the harmful effects of high temperatures. Jena *et al*. (2017). It has been stated that crops can withstand temperatures of up to 40°C if enough water is provided to meet the demand for transpiration during heat stress. In the case of a restricted water supply, however, 40°C will destroy the leaves (Kajla *et al*. ., 2015). Grain yield and WUE responses to irrigation differ depending on soil water content and irrigation schedules (Kang *et al.*, 2002). Sprinkler watering under heat stress situations when the plant has achieved critical temperature benefits in the reduction of high soil temperatures, and nighttime irrigation aids in the crop's recovery from day heat stress. To reduce the influence of high temperatures on crop growth at other phases, the crop should not be water-stressed at such times.Numerous studies have shown that a lack of water at any developmental period results in significant losses in wheat production and yield components. However, if there is a water deficit throughout the tillering and heading stages, the yield loss will be greater .Similarly, it has been said that grains/spike are the yield component most vulnerable to heat and drought stress because to intense competition for nutrients during stem elongation (Mirza, 2001; Calderini*et al*., 1999). There is a considerable boost in plant height, leaf area index, dry matter accumulation, root development parameters, and grain yield when comparing drip irrigation to both check basin and spray irrigation (Suryavanshi, 2016).However, it was reported by Kharrou*et al*., 2011the grain yield obtained with drip irrigation was 24% higher than full irrigation treatment and 59% higher than the existing rule treatment.

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V. Spray of osmoprotectants

Potassium is vital in carbohydrate synthesis, maintaining water balance in leaves, and regulating stomataclosing, all of which have a direct influence on the plant's stress tolerance and water usage efficiency, resulting in optimal yield characteristics and, eventually, maximum grain yield (Meshah *et al*., 2009).Foliar treatments of sodium nitroprusside (Bavita *et al*. 2012), thiourea (Sahu and Singh 1995), and potassium nitrate (Bardhan *et al.* 2007) have been shown to improve wheat productivity in unfavorable environmental circumstances. According to a number of research, spraying 0.5 percent KNO3 at the 50% blooming stage of the crop resulted in higher grain and straw yields of wheat (Sarkar *et al*.,1991 and Sarkar *et al*.,1990).).Spraying potassic fertilizers enhances photosynthates synthesis in plants and dry matter transfer to grain.Foliar spray applications of either SNP 400 g/ml or 2 percent KNO3 after anthesis were shown to be more suited for producing greater wheat growth and production (Suryavanshi *et al*., 2016).

Table 4. Increased in wheat grain yield by application of osmoprotactants

No	Osmoprotectants rate	Increased in grain yield	Reference
1	sodium nitroprusside 400 µg/ml (two spray after anthesis)	18.8%	Suryavanshi *et al*., 2016
2	2% KNO3 (Two spray after anthesis)	17.9%	Suryavanshi *et al*., 2016
3	Thiourea 20 mM (Two spray after anthesis)	14.9%	Suryavanshi *et al*., 2016

Conclusion

Based on Several studies we can conclude that terminal heat stress affects wheat phenology and all yield-related parameters in all major wheat-growing regions. To achieve a stable wheat yield in this changing climate, agronomic manipulations such as heat-resistant wheat cultivars, conservation agriculture approaches (zero tillage, mulching), altering sowing dates, and irrigation schedule management, on the other hand, can help to alleviate the detrimental effects of terminal heat stress.

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