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Terminal Heat Stress in Wheat: Impacts and Solutions

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ABSTRACT

Wheat (Triticum aestivum L.) is recognized as one of the most significant cereal crops worldwide. A major challenge to wheat production is heat stress, an abiotic factor that significantly diminishes grain yield, particularly in semi-arid and subtropical regions. Heat stress poses severe threats to wheat growth, with yield losses estimated at approximately 6% for each 1°C increase in temperature. Terminal heat stress, which becomes critical when the average temperature during the grain-filling phase surpasses 31°C, is a primary factor contributing to reduced productivity. The elevated temperatures experienced during this crucial developmental stage are the primary drivers of low wheat yields. During the 2020-21 and 2021-22 growing seasons, the average temperatures in March and April were 2-3°C higher than usual, exacerbating the impact of terminal heat stress. Consequently, wheat yields were reduced by 2-3 quintals per acre. The sudden increase in both maximum and minimum temperatures across North-West India contributed to an 8-10% reduction in final crop yields during these years. This review summarized the general effect and management to this problem. Findings indicated that elevated temperatures accelerated wheat maturation, leading to earlier-than-normal harvests. On March 15 of both consecutive years, maximum temperatures reached 40°C and remained at or above this threshold throughout the harvesting period. To mitigate the effects of heat stress, several strategies were employed, including the development of heat-resistant crop varieties, the adoption of climate-adaptive cropping practices, the implementation of conservation agriculture, and adjustments to planting windows. Researchers can use this review to better understand the landscape of terminal heat stress research and shortcomings.

Keywords: *Terminal heat stress, Temperature, Wheat, Yield loss, Climate Change, Mitigation and Adaptation*

1. Introduction

Wheat is the most widely grown rabi crop in India, positioning the country as one of the leading global producers of wheat. However, rising temperatures in the foreseeable future are expected to adversely impact agricultural output, with pronounced effects from periods of extreme heat, commonly referred to as 'heat stress'. The characteristics of wheat plants are known to be affected by the genetic makeup of the cultivar alone as well as in combination with the weather conditions in which it is grown. The optimal temperature range for wheat plants during the flowering and grain-filling stages is typically 12°C to 22°C [68]. This trend has been evident in India's wheat crops over the past decade, but this year, the impact has been significantly more intense. India is witnessing a trend of reduction in the duration of winter and the onset of significantly higher temperatures much earlier than normal.

Extremely high temperatures during the grain-filling stage, particularly in the Indo-Gangetic plains, lead to poor temperature regulation and yield losses. Due to India's proximity to the equator and delayed wheat sowing, the crop often experiences elevated temperatures during this stage, restricting production and productivity in these regions.

These findings underscore the importance of adopting climate-resilient farming practices and understanding the impact of rising temperatures on wheat growth and yield. Consequently, it is crucial to develop adaptation strategies, as the direct impact is most significant for the country's small and medium-scale farmers, who represent around 70-80% of the farming community and manage 2-3 hectares of land. If we talk about production, then in the year 2021-22 the production of wheat has been 106.41 million tonnes, which is less than the previous year's 109.59 million tonnes, one of the main reasons for this is terminal heat stress, and therefore, arises the need for terminal heat management.

2. Terminal heat stress in wheat

Effective terminal heat management in wheat is essential when high temperatures negatively impact the crop, limiting both growth and yield. During the flowering stage, heat stress causes pollen and other sterility, as well as underdeveloped embryos, leading to fewer grains. In the grain-filling phase, heightened heat stress slows grain filling, ultimately reducing grain weight and overall yield.

This type of weather is seen the months of March and April in the form of an increase in temperature. At this time the wheat crop is either in the milking stage or from the milking stage it is moving towards the stage of hardening of the grains. Wheat crop requires a temperature of 20 to 25 degrees Celsius at the time of grain filling. If the temperature remains higher than this, the process of grain formation is interrupted and the grain becomes thin in the head and ultimately the yield decreases. Simulated results indicate that terminal heat stress is expected to decrease wheat yield by 16.1% in 2020 and 11.1% in 2050 [21].

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In Northwest India, March 2022 recorded the highest average maximum temperature at 30.73 ºC, the second highest average minimum temperature at 15.26 ºC, and the second highest mean temperature at 22.99 ºC since 1901. Similarly, during April, the average maximum and mean temperatures were ever highest with 36.32 ºC and 28.18 ºC respectively and the minimum temperature was second highest with 20.04ºC since 1901. This was coupled with a rainfall departure of -89 and -82 % in March and April respectively. Due to this the wheat crop ripened before time.

In the 2021-22 period, the average temperature in March and April was 2-3 degrees higher, intensifying the impact of internal heat. Due to this, a reduction of 2-3 quintals per acre was recorded in the yield. Due to this India has also had to stop the export of wheat. Laymen terms, then 4 to 6quintals of wheat grain per acre have been lost. The results of different researchers have shown that in the year 2022 and 2050 scenarios, in the absence of heat management wheat yield will decrease by 16.10% and 11.10% respectively.

Table 1 Optimal temperature requirements of wheat at different growth stages [70]

Stage	Minimum temperature (°C)	Optimum temperature (°C	Maximum temperature (°C)
Terminal spikelet	2.50 ± 0.49	16.0 ± 2.30	20.0 ± 1.60
Anthesis	10.0 ± 1.12	23.0 ± 1.75	26.0 ± 1.01
Grain filling duration	13.0 ± 1.45	26.0 ± 1.53	30.0 ± 2.13

3. Effect of terminal heat stress on wheat crop

3.1 Effect of terminal heat stress on the physiology of wheat crop

Heat stress, particularly during the later stages of crop growth (terminal heat stress), significantly harms wheat crops. [78] highlighted various yield-reducing effects of terminal heat stress, such as its impact on physiological processes, including assimilate partitioning, heat dissipation, electrolyte conductance, photosynthesis, plant water status, and senescence. Similar findings were reported by [32]. Heat stress at any growth stage is known to reduce cell size and overall growth due to loss of cell water content [64]. High evaporative demand during heat stress lowers relative water content (RWC) [31], accelerating senescence-related metabolic changes. This results in poor assimilate partitioning, leading to significant reductions in harvest index [78] and thousand-grain weight (TGW) [2]. To maintain plant water status during anthesis, an upper-temperature limit of 31°C is generally recommended [5].

Heat stress-induced dehydration leads to a reduction in osmotic potential [3] and an increase in the water conductivity of the plasma membrane due to heightened aquaporin activity [45]. Relative water content is an indicator of membrane stability, and under heat stress, reduced membrane stability impedes the transport of assimilates from source to sink [73, 78, 24]. Membrane dysfunction caused by heat stress results in an increase in electrical conductivity (EC) [35]. Furthermore, heat stress induces oxidative stress, reduces membrane thermostability by 54%, increases electrolyte leakage, and reduces cell viability in wheat [65]. Leaf relative water content (RWC), stomatal conductance, and transpiration rate are influenced by canopy temperature (CT) [25]. Heat stress raises CT, decreases plant water status [54], and reduces the plant's ability to remain green [55, 44].

Photosynthesis is a physiological process highly impacted by heat stress, with the chloroplast stroma and thylakoid lamellae being the primary sites affected in wheat [63, 46]. The deactivation of stromal enzymes disrupts the photorespiratory electron transport chain, leading to reduced Rubisco activity, which contributes to a decrease in the leaf photosynthesis rate [4, 32]. Exposure of wheat leaves to high temperatures (around 40°C) causes irreversible changes in Rubisco, Rubisco activase, and photosystem II [47]. [60] highlighted that under heat stress, Rubisco activase dissociates, resulting in a significant decline in photosynthetic efficiency in wheat.

Heat stress increases the respiration rate and mitochondrial activities. Initially, respiration rises with temperature, reaching a critical point before declining due to photorespiratory damage [58]. The elevated carbon loss from photorespiration reduces ATP production and increases the generation of reactive oxygen species (ROS) in the rhizosphere [37]. During the flag leaf stage of wheat, heat stress significantly heightens photorespiration, driven by changes in the solubility of O2 and CO2, as well as modifications in Rubisco's affinity for these gases [8, 17]. Heat-induced damage accelerates leaf senescence, with chloroplast destruction, vacuolar collapse, and the eventual rupture of plasma membrane integrity and cellular homeostasis being key factors [5]. Under intense heat stress, plants can quickly suffer protein denaturation or aggregation, while prolonged or moderate heat stress leads to gradual senescence. Both conditions can cause reduced growth or even plant death [64, 32].

3.2 Effect of terminal heat stress on yield components of Wheat Crop

Morphologically, terminal heat stress leads to a significant reduction in relative growth and dry weight, smaller internode sizes, unproductive tillers, accelerated senescence, and reduced biomass. It can also cause a decrease in cell size, limiting water loss through stomatal closure. In wheat, the survival of productive tillers (PT) under higher temperatures is greatly compromised, which is a major factor contributing to yield loss. Research suggests that the ability to produce and sustain PT in wheat depends on genotype, agronomic practices, and temperature [43]. [32] also observed that heat stress inhibits the initiation and survival of PT in wheat. Late-sown Spring wheat crops in subtropical regions face low soil temperatures that reduce germination, PT production, and early stand establishment [30, 36]. Elevated day and night temperatures increase the respiration rate of wheat, shorten the crop's growth duration, and lead to empty grains in spikelets, ultimately causing a significant decrease in yield.

Grain size and number are highly susceptible to heat stress, with the severity depending on the developmental stage [26]. Heat stress impacts spikelet initiation, as well as male and female pollination and fertilization. [57] observed that heat stress accelerates spikelet initiation and sporogenesis, leading to sterile spikelets. [66] reported that heat stress (>20°C) during heading and anthesis accelerates spike enlargement but reduces the number of spikelets. Heat stress during floral initiation negatively affects microspores and pollen cell development, resulting in complete sterility [10, 39]. In wheat, 3-day heat stress during flowering results in structurally abnormal or nonfunctional florets [34]. Additionally, heat stress at 31/20°C (day/night) reduces grain size by altering the structures of endosperm cells and the aleurone layer [19].

Reduced photosynthesis during floret development under heat stress limits grain number due to insufficient assimilate availability [18]. Abnormal anther development and reduced pollen viability under heat stress led to poor fertilization and grain formation [26].

Post-fertilization grain filling (GF) is the final growth phase in cereals, with its duration and rate playing critical roles in determining the final grain weight, which is the most significant factor influencing overall yield [13, 48]. About 40% of the grain dry matter is synthesized from photo-assimilates accumulated in the stems and sheaths during GF, which occurs simultaneously with whole-plant senescence [82]. Heat stress during GF can negatively impact grain yield (GY) by accelerating maturity, triggering premature senescence, shortening grain filling duration (GFD), and reducing grain weight [56, 32, 49, 12]. Heat stress during the early stages of GF results in a reduced number of endosperm cells, while in later stages, starch synthesis is halted due to insufficient photo-assimilates or the inactivation of starch biosynthetic enzymes in the grain [84].

Under heat stress, wheat completes its life cycle more rapidly than under normal temperature conditions, leading to a shortened duration [50, 6, 7]. Prolonged suboptimal temperatures during grain filling (GF) significantly reduce the duration of grain fill, with only a marginal increase in the filling rate [79, 22]. A temperature regime of 37/28 °C reduces the grain filling duration (GFD) by 3 weeks [38]. Temperatures above the optimal (>20 °C) shorten GFD while accelerating the grain filling rate [19]. Heat stress during GF leads to premature halting of grain growth and accelerates physiological maturity. For every 1 °C above the optimal growing temperature of 15–20 °C, GFD is estimated to decrease by 2.8 days [71]. [84] found that a 5 °C increase above the optimum reduces GFD by 12 days in wheat. [12] observed that each 1 °C increase in mean temperature from the optimum reduces GFD by 0.4 days. A reduction of 3–12 days in GFD due to heat stress can decrease average grain weight (GW) by up to 36% [77]. While heat stress promotes a high rate of GF, the reduced GFD cannot be fully compensated by the increased growth rate [85]. [80] studied GF rate and duration in heat-tolerant and heat-sensitive wheat cultivars, finding that tolerant cultivars exhibit a very high GF rate under heat stress, suggesting that the increased rate compensates for the reduced GFD. Accelerated GF with reduced GFD appears to be a favorable trait for enhancing tolerance to severe heat stress.

The recorded decline in grain weight can reach 85% when temperatures rise from 20/16 °C (day/night) to 36/31 °C from 7 days post-anthesis (DPA) until maturity [74]. In winter wheat, heat stress during grain filling (GF) has been shown to reduce grain yield (GY), grain number (GN), and grain weight (GW) by 78%, 63%, and 29%, respectively. Heat stress imposed 20 days after anthesis results in an 18% decrease in GW [27]. Delayed planting shortens the overall growth period, leading to a reduction in yield and yield components (Din and Singh, 2005). [1] found a progressive decline in GW with delayed sowing, showing a 33% reduction due to heat stress. [19] reported grain shrinkage due to terminal heat stress. Similarly, post-anthesis heat stress increases wheat grain protein content while decreasing the glutenin/gliadin ratio, which negatively affects flour quality [70]. Overall, late sowing reduced yield traits such as spike length, number of grains per spike, thousand-grain weight, and biological yield compared to timely sown crops, although the response varied under different sowing conditions [62].

4. Plant mechanisms to cope with heat stress

Heat tolerance in plants, often referred to as their ability to survive and maintain normal growth under high temperatures, is a critical adaptive trait [78]. Wheat has evolved several mechanisms to cope with heat stress, including escape, avoidance, and/or the ability to maintain greenness [78; 24]. One of the ways plants can escape high temperatures is by shortening the growth and filling periods, utilizing stem reserves to boost growth rates and sustain yield.

A significant association between catalase and peroxidase enzyme activity and grain yield has been identified in conditions of heat stress. The peroxidase activity exhibited an increase under heat stress, indicating an improved level of thermo-tolerance [52]. Zinc concentration was observed to be higher under heat stress compared to optimal temperatures [52]. The increased zinc concentration under heat stress may be associated with a reduction in grain size, leading to a change in the aleurone-to-endosperm ratio. However, the iron content in the grain remains relatively stable under heat stress compared to optimal conditions [76]. Plants mitigate heat stress by maintaining an optimal water status, minimizing water loss through various mechanisms such as stomatal closure, the presence of trichomes, leaf wax, leaf rolling, changes in leaf angle, and senescence of older leaves. Additionally, plants efficiently utilize available water by enhancing root architecture and growth. Plants can tolerate some amount of water stress by maintaining low water potential, maintaining cooler canopies, sustaining an active photosynthetic state to support the current assimilate supply, improving radiation use efficiency, and prolonging the growth and filling duration to sustain growth in elevated temperatures. This is also known as the "stay green" behavior of plants.

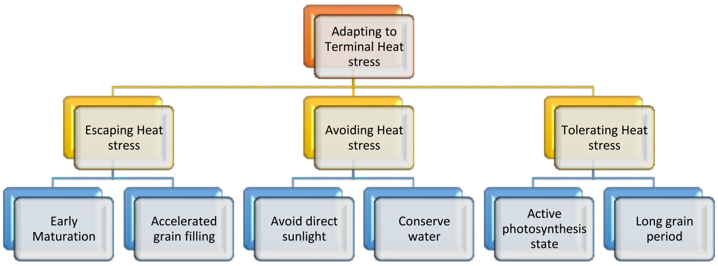

Figure 1. Adaptive mechanisms of wheat crop to terminal heat stress

In their 2023 study, [41] found that heat-tolerant genotypes were able to maintain their phenological, physiological, and biochemical balance, while heat-sensitive genotypes experienced significant declines under stress conditions. Among the phenological traits, days to maturity (R^2 = 0.52) and biological yield (R^2 = 0.44) positively influenced seed yield, indicating that biomass and crop duration contributed to the yield advantage under heat stress. During the grain-filling stage, heat-tolerant genotypes exhibited enhanced photosynthesis, delayed senescence, and improved assimilation remobilization under terminal heat stress. Additionally, the biochemical activities of superoxide dismutase (SOD), peroxidase (POX), and ascorbate peroxidase (APX) were induced in these tolerant genotypes under heat stress conditions.

5. Management of terminal heat stress in wheat crop

The impact of heat stress, particularly terminal heat stress, on the growth and development of wheat crops is substantial and continues to intensify annually due to climate change [21]. Various efforts have been made to develop heat-tolerant genotypes by applying the knowledge gained from understanding wheat's response to heat stress. To ensure sustainable wheat production in heat-affected regions, in addition to introducing new heat-tolerant and resistant varieties through breeding programs, it is crucial to implement a range of agronomic management strategies that address heat stress in field conditions [11,15] This review focuses on these agronomic approaches in detail. Some of the strategies to mitigate the impact of terminal heat stress on wheat include adopting climate-resilient cropping practices, promoting climate-resilient policies, practicing conservation agriculture, enhancing water use efficiency, and adjusting sowing dates.

5.1 Agronomic measures to mitigate the impact of terminal heat stress on wheat plant

To mitigate terminal heat stress in the field, several measures can be taken, including adjusting the planting date, providing additional life-saving irrigation, and applying an extra dose of nitrogen fertilizer. Notably, advancing the sowing date by 10 or 15 days has been shown to increase yield, as crops sown earlier have more time to complete their grain-filling period before high temperatures occur [21]. [42] have also noted that crops planted earlier avoid heat stress, whereas in the case of late sowing, a temperature rise for just 5–6 days results in a 20% greater yield loss compared to the early sown crops. Therefore, terminal heat stress in wheat can be alleviated by sowing the crop between October 25th and November 15th [70].

Studies have demonstrated that under suboptimal environmental conditions, such as high temperatures or water stress, the application of nitrogen fertilizer can improve plant performance [53]. However, [23] discovered contrasting results under a diurnal temperature variation of 37/28 °C. The application of nitrogen fertilizer after anthesis did not enhance the rate or duration of protein accumulation, as seen under the 24/17 °C temperature regime. This failure to enhance protein levels under high-temperature conditions led to earlier leaf senescence, ultimately resulting in reduced grain yield. Another approach to reducing yield loss from terminal heat stress is the application of life-saving irrigation during the grain-filling stage [21]. It is important to avoid irrigating the crop on windy days to prevent lodging [70]. In the event of a sudden temperature rise, light irrigation should be applied to the wheat crop, ensuring that no standing water accumulates in the field. If possible, sprinkle water in the fields by sprinkler method. In the areas where the sprinkler method of irrigation is adopted, run the sprinkler in your fields for some time in the evening. If possible then apply drip irrigation in the field for better management of wheat crops against heat stress.

By combining early sowing, additional irrigation, and an extra nitrogen dose of 30 kg ha−1 during the grain-filling stage, the increase in yield exceeds the effects of any individual strategy. Early sowing allows the wheat crop to complete its grain-filling phase before high temperatures stress the plant, reducing spikelet sterility. Additionally, the timely application of irrigation and nitrogen during this crucial stage facilitates the conversion of assimilated starch into filled grains, thus increasing the 1000-grain weight. This approach minimizes canopy temperature depression, reducing leaf senescence, and ultimately results in a higher yield [29]. In regions like the Indo-Gangetic plains, where a rice-wheat cropping system is practiced, early sowing may require adjustments to the overall crop management throughout the year. If clearing the field on time is not possible, the introduction of additional nitrogen fertilizer and supplementary irrigation can help mitigate yield loss and ensure better performance under terminal heat stress conditions [81]. This combination of strategies ensures that wheat crops can better adapt to environmental stress and maintain productivity. The use of straw mulch is effective in preserving soil moisture by minimizing soil evaporation, as demonstrated by [16]. Retaining rice residue within an Indo-Gangetic Plains (IGP) rice-wheat system resulted in a reduction of wheat canopy temperature by 1–4°C compared to the ambient temperature from 138 to 153 days after sowing (DAS) [70]. Nevertheless, mulching is recommended to prevent yield reduction in wheat when practicing reduced tillage, as highlighted by [28]. Reports from other studies, such as [14], indicate that employing mulch can enhance wheat productivity in the presence of heat stress and water deficits. The application of organic mulches is particularly beneficial, as it not only conserves soil moisture effectively but also enhances plant growth and development. This, in turn, leads to increased water and nitrogen use efficiency, potentially resulting in a reduction, as indicated by [69]. Cultivation of wheat with resource conservation techniques saves time, labor, money, and other resources and these fields do not get waterlogged during heavy rains. Therefore, after harvesting paddy, sow wheat with machines like Happy Seeder, Super Seeder, and Smart Seeder and save your crop from the side effects of weather.

Utilizing biological control agents, such as fungi and bacteria, is increasingly recognized as an effective alternative approach to enhancing heat tolerance in plants [59]. Plant growth-promoting rhizobacteria (PGPR) have been identified as beneficial for wheat growth during heat stress [51]. The application of rhizobacteria, either through seed treatment or foliar sprays with various organic and inorganic agents, has been shown to improve heat tolerance in wheat [82]. Moreover, inoculating seeds with rhizobacteria has significantly boosted wheat's heat tolerance, as evidenced by [9]. This approach offers a sustainable, eco-friendly solution for mitigating heat stress effects on wheat crops.

5.2 Mitigation of terminal heat stress in wheat crop by chemical application

One more mitigation for terminal heat stress is the application of chemical spray. The application of potassium nitrate, salicylic acid, thiourea, and sodium nitroprusside through foliar treatments has however, demonstrated the ability to enhance wheat productivity in unfavorable environmental conditions [72].

The application of two sprays containing 2% Potassium nitrate (13:0:45) during the boot leaf and anthesis stages, achieved by dissolving 4 kg of potassium nitrate in 200 liters of water, has been shown to effectively combat terminal heat stress and improve grain yield. Additionally, salicylic acid, when applied as two sprays (15 g dissolved in 450 ml of ethyl alcohol and mixed with 200 liters of water per acre at the boot leaf and early milk stages), helps mitigate high temperatures during grain filling, leading to increased wheat yield. Calcium, in the form of CaCl2, has been found to play a crucial role in enhancing heat tolerance. It increases Malondialdehyde (MDA) content, a marker of lipid peroxidation, while also stimulating the activities of key enzymes such as superoxide dismutase (SOD) and catalase. These biochemical changes contribute to improved heat tolerance and, ultimately, higher wheat yield [70]. If the continuous increase in temperature is being seen in the month of March, then to avoid such a situation, sprinkling of potassium chloride can be beneficial.

For this, make a solution by adding 200 grams of potassium chloride in 100 liters of water and spray it per acre. If the condition is serious then repeat this process again after 15 days. If potassium chloride is not available, then dissolving 200 grams of Muriate of Potash or Red medicine in 100 liters of water and spraying it twice at an interval of 15 days will be equally beneficial and effective.

Zinc (Zn) is known to play a crucial role in modulating free radicals and mitigating their damaging effects during stress conditions by enhancing the plant's antioxidant systems, as noted by [19]. Additionally, under heat or drought stress, silicon helps maintain the plant's water balance, photosynthetic efficiency, leaf erectness, and the structure of xylem vessels during high transpiration rates. This leads to improved shoot and root biomass, contributing to increased grain production in wheat under water-stressed conditions [70]. However, a study by [40] found no significant effect on wheat when sprayed with water, salicylic acid, and calcium chloride during heat stress imposed between 108 and 114 days after sowing. This suggests that the response to these treatments may vary depending on the timing, intensity, and duration of heat stress. The external application of various growth-promoting protective substances, such as osmoprotectants, phytohormones, signaling molecules, and trace elements, has shown considerable potential in mitigating the harmful effects of heat stress on plants. Studies by [67] and [75] highlight how these substances can enhance plant thermotolerance by reducing reactive oxygen species (ROS) levels and boosting antioxidant capacity, which helps protect plants from oxidative damage under heat stress conditions. [24] and [35] emphasize the role of these substances in increasing the plant's antioxidant defense mechanisms, which are essential for managing the oxidative stress induced by heat. The widespread use of plant bio-regulators in horticultural crops, as mentioned by [61], holds promise for their application in field crops like wheat, suggesting that these bio-regulators could emerge as valuable tools for improving heat stress tolerance in agricultural environments.

6. Future Scope

Terminal heat stress in wheat, particularly in Northwest India, is an increasing concern due to rising temperatures during the grain-filling stage, leading to reduced yields and poor grain quality. Future research can focus on advanced climate modeling, using regional climate models (RCMs) and ensemble approaches to predict heat stress patterns and their impact on wheat production. In genetic and breeding innovations, developing heat-resilient wheat varieties using genomics, transcriptomics, and gene-editing tools like CRISPR can enhance adaptation. For example, HD 2967 and DBW 187, known for their heat tolerance, could be further improved using marker-assisted selection. Remote sensing and precision agriculture offer promising solutions, such as hyperspectral and multispectral imagery to monitor stress conditions, and AI-driven predictive models using satellite-derived indices like NDVI, EVI, and LST to estimate yield losses under high temperatures. Additionally, agronomic and management strategies such as crop diversification, intercropping, and climate-smart irrigation techniques like deficit irrigation and alternate wetting and drying (AWD) could mitigate stress effects. The use of bio-stimulants, nano-fertilizers, and plant growth regulators (PGRs) like salicylic acid and brassinosteroids may enhance heat resilience in wheat crops. The socio-economic and policy perspectives also need attention, as assessing the economic losses due to terminal heat stress can help formulate better crop insurance schemes and heat-resilient seed distribution programs. Furthermore, barriers to adopting climate-resilient technologies must be identified to ensure their successful implementation. The integration of AI and IoT in agriculture could revolutionize heat stress management, with IoT-based soil sensors providing real-time temperature monitoring and AI-powered decision-support systems guiding irrigation scheduling. AI models trained on past heatwave data can help forecast stress conditions and recommend adaptive measures. Additionally, long-term sustainability strategies such as conservation agriculture, agroforestry, and carbon sequestration can help improve soil resilience to heat stress. The role of soil microbiomes and root-associated fungi like mycorrhizae in improving water uptake and heat tolerance is another emerging area for research. Sustainable adaptation strategies, including integrated nutrient management and organic amendments, could further enhance wheat's resilience to terminal heat stress. Given the severity of climate change impacts, a multi-disciplinary approach integrating genetic improvements, precision agriculture, climate adaptation strategies, and policy reforms is essential to mitigate terminal heat stress and sustain wheat production in Northwest India. Future studies should emphasize farmer-centric solutions and develop climate-resilient wheat production systems that can withstand increasing heat stress conditions.

7. Conclusion

The variability of weather and its unpredictable changes have a significant impact on crop yields, particularly in wheat, which is highly sensitive to heat stress. During the flowering and grain-filling stages, high temperatures can adversely affect wheat yield and quality, primarily through the phenomenon known as 'terminal heat stress.' This stress disrupts pollination, reduces grain number, and lowers grain size and protein content by shortening the grain filling period. As climate change progresses, particularly with the early onset of summers in the northwest parts of India, the incidence of terminal heat stress in wheat crops is expected to increase. To mitigate these effects, it is crucial for farmers to adapt their agricultural practices based on accurate weather forecasts, enabling timely and effective management of crops. Additionally, the strategic use of certain chemicals, such as growth regulators and antioxidants, can help alleviate the negative impact of elevated temperatures on the wheat crop during critical growth stages. Incorporating agronomic practices like altering sowing dates, providing irrigation, and applying fertilizers can further enhance wheat resilience to terminal heat stress, ensuring more stable and sustainable yields despite changing climate conditions.

Conflict of Interest

The authors declare no relevant financial or non-financial conflict of interest to disclose

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