Agric Res J **61** (2): 155-166, *April* 2024
DOI: 10.5958/2395-146X.2024.00022.8

Review Article

IMPACT OF ABIOTIC STRESSES ON WHEAT YIELD AND STRATEGIES FOR MITIGATION: A COMPREHENSIVE REVIEW

Harkanwaljot Singh [1], P K Kingra[1 *], R K Pal[2] and Sompal Singh[1]

[1]Department of Climate Change and Agricultural Meteorology,
Punjab Agricultural University, Ludhiana – 141 004, India
[2]PAU Regional Research Station, Bathinda-151 001, India

ABSTRACT

Climate change is causing various stresses on field crops, potentially threatening global crop production. Wheat, a cool-season crop, is particularly vulnerable to rising temperatures. Several abiotic stresses, including heat, moisture, and nutrient deficiencies, significantly impact wheat yields. Heat stress during the grain-filling period can drastically reduce wheat yields by shortening the growing period due to earlier flowering and maturity. Water stress, especially under rainfed conditions in arid and semi-arid regions, is a major environmental challenge. Reduced irrigation can negatively affect leaf water potential, transpiration rates, stomatal conductance, and photosynthesis, leading to a notable decline in yield attributes, particularly the number of grains per spike. Nutrient stress also contributes to significant reductions in wheat yield. Adequate nitrogen supply can increase the number of grains per spike and plant height, but excessive use of nitrogenous fertilizers can result in excessive vegetative growth, lodging of plants, and increased greenhouse gas emissions. Given the increasing variability in climate and limited water availability, it is crucial to optimize nutrient and water application and improve their efficiency to sustain productivity and ensure food security.

Keywords: Climate change, Stress, Wheat, Yield

Wheat (*Triticum aestivum* L.) is a crucial cereal crop in North India, particularly across the Indo-Gangetic plains and especially in Punjab. It provides more than 50 percent of the calories for the population that depends on it, thereby playing a significant role in the Nation's food security (Barkha *et al.* 2017). Wheat is a major source of carbohydrates for humans, and its straw is an important component of livestock feed. In the 2021-22 growing season, wheat was cultivated on 30.05 million hectares in India, yielding 106.8 million tonnes (Anonymous 2023a). In Punjab alone, wheat was grown on 3.52 million hectares, with a production of 1.48 million tonnes and a productivity of 42.16 quintals per hectare (Anonymous 2023b). The introduction of short-statured wheat varieties, coupled with advanced production techniques and protective technologies, has significantly enhanced overall wheat output.

To ensure food security for a growing population, it is crucial to increase the yield of food grains per unit area. Several factors contribute to annual variations in wheat yield, including sowing time, irrigation practices, and others. However, these factors are significantly influenced by prevailing weather conditions, such as rainfall during different growth phases, temperature, and humidity (Malik *et al.* 2009). Consequently, climate variability leads to substantial annual fluctuations in wheat productivity (Kaur and Behl 2010). Climate change has further exacerbated this issue by increasing the intensity and frequency of extreme weather events. For instance, extremely high temperatures during the grain-filling stage can cause severe losses in crop production, as observed under extreme terminal heat stress in March 2022 (Balla *et al.* 2009).

Wheat is a long-day plant that requires a photoperiod of 14 to 18 hours for optimal growth (Pandey and Sinha 2006). It also needs cold weather conditions during its initial growth stages. The temperature during various growth phases of wheat significantly impacts both the quantity and quality of the grain yield. The global average temperature has already risen by more than 1°C. Flooding, which damages land and crops, further exacerbates food shortages (Singh 2015). Temperature increases are expected to be more pronounced during the winter (*rabi*) season compared to the rainy season (*kharif*) (IPCC 2013). By the end of this century, the mean annual temperature and rainfall in India are projected to rise by 3-5°C and 10-12 percent, respectively. The warming trend is particularly noticeable over terrestrial areas, with the most significant increases occurring in northern India.

The state of Punjab is currently facing significant climatic variability and water scarcity, which are causing thermal, nutrient, and water stress in agriculture. The recent heat stress in March 2022 led to a severe reduction in grain yield. Additionally, the excessive use

*Corresponding author: pkkingra@pau.edu
Date of receipt: 26.02.2024, Date of acceptance: 20.04.2024

of fertilizers in the state contributes to high greenhouse gas emissions from agriculture and increases production costs. Therefore, it is essential to assess wheat productivity under various stress conditions and agro-climatic scenarios in the region. This will help identify viable mitigation and adaptation strategies to sustain wheat productivity amidst changing climatic conditions.

WHEAT YIELD AND ABIOTIC STRESSES

Temperature, moisture, and nutrients are major abiotic factors influencing crop growth, development, and yield. Higher rates of nitrogen application have been associated with increased hectoliter weight and grain protein but reduced nutrient use efficiency (Campillo *et al.* 2010). While reducing nitrogen decreases grain yield, agronomic nitrogen use efficiency, grain protein content, and bread volume, it does lead to an increase in kernel weight (Khalilzadeh *et al.* 2011). The rise in greenhouse gas concentrations and warming is expected to enhance evaporation, create uncertainty in rainfall, and increase the frequency of extreme weather events such as floods, droughts, and heat waves. These changes are likely to significantly impact crop productivity by exacerbating abiotic stresses in the future (Reddy and Hodges 2000; IPCC 2013). However, the negative effects of temperature stress on crop growth and yield can be mitigated by adjusting the sowing time of the crop (Kajla *et al.* 2015).

Bala and Kaur (2013) found that optimal wheat yields are achieved when temperatures are between 18-22°C (maximum) and 5-10°C (minimum) during the vegetative phase, 17-20°C (maximum) and 4-9°C (minimum) during the reproductive phase, and 20-25°C (maximum) and 5-9°C (minimum) during the grain-filling phase. Tyagi (2013) reported that high relative humidity and elevated minimum temperatures during the reproductive stage are detrimental to achieving high wheat yields. Different growth phases of wheat are highly sensitive to temperature variations, which can significantly impact both the quantity and quality of grain yield. During the initial stages, high temperatures can reduce tillering, impair vegetative growth, and hasten maturity (Reddy 2006). Consequently, warming scenarios may severely affect future wheat productivity. Both excessively high or low temperatures and inappropriate nutrient applications can adversely impact crop growth and yield. Terminal heat stress, particularly under late-sown conditions, has been observed to reduce the duration of the reproductive growth phase and ultimately result in poorer grain yields (Mavi and Tupper 2005; Farooq *et al.* 2011). Global warming, with its increased frequency and intensity of extreme weather events, is proving to be increasingly detrimental to crop production.

Effect of heat stress on wheat yield

Temperature is a crucial factor influencing crop growth through its effects on phenological and morphological development. Perry and Swaminathan (1992) predicted that a 0.5°C increase in temperature could decrease wheat yields in North India by 0.5 tonnes per hectare (Rahman *et al.* 2009). Warmer temperatures accelerate crop development, thereby shortening the growing duration (Zacharias *et al.* 2010; Hossain *et al.* 2012). Heat stress experienced during early growth stages tends to result in higher grain yields compared to heat stress during anthesis (Zhang *et al.* 2013). An increase of 1°C in temperature has been associated with an 8 percent decrease in wheat grain and biomass yield (Mohanty *et al.* 2015). Refay (2011) observed that delaying sowing can lead to a substantial grain yield loss of up to 7.98 percent. However, late-sown genotypes often exhibit higher protein content, which may be attributed to reduced grain weight under late sowing conditions (Sial *et al.* 2005).

Reynolds *et al.* (2005) concluded that sink capacity is a critical limiting factor for crop productivity, and any physiological stress that reduces this capacity will ultimately affect yields. Lobell *et al.* (2005) found that each 1°C increase in temperature results in a 10% decrease in wheat yield. Shah and Paulson (2003) observed that while high temperatures during the early grain-filling period improved the grain-filling rate, it decreased significantly after reaching a maximum around twenty-one days post-anthesis. Pathak *et al.* (2003) identified the rise in minimum temperatures in the Indo-Gangetic plains as a major factor contributing to the decline in wheat yields. Slafer and Rawson (1994) noted that shoot growth between the terminal spikelet and flowering stages was severely reduced when temperatures exceeded 19°C. Hundal and Kaur (1995) reported that a 10% decrease in solar radiation led to a 7.6% reduction in the maximum leaf area index of wheat, whereas a 10% increase in solar radiation raised the leaf area index by 7.1%.

Abbate *et al.* (1997) determined that intercepted radiation is a critical factor influencing both crop and spike growth during the spike development period, as well as the number of grains per square meter. They found that the number of grains per square meter was linearly related to the accumulated intercepted photosynthetically active radiation during this period. Sial *et al.* (2005) observed that late sowing adversely affected wheat due to reduced plant height, fewer internodes, shorter periods to heading and maturity, and a diminished grain-filling period, ultimately leading to decreased yields. Singh *et al.* (2006) reported that increases in maximum and minimum temperatures during the grain-filling period led to reductions in all yield components such as the number of tillers per square meter, ear length, number of grains per ear, and 1000-grain weight ranging from 4.77% to 10.05%. Schapendoek *et al.* (2007) found that leaf photosynthesis decreased significantly (50-60%) when heat shock occurred at the end of the tillering stage. Wahid *et al.* (2007) noted that high temperatures during the reproductive stage had a more pronounced impact on fertilization and post-fertilization processes, potentially leading to reduced crop yields.

Prasad *et al.* (2008) reported a decrease in spikelet fertility of 18% and 26% when wheat plants were exposed to nighttime temperatures of 20°C and 23°C, respectively. Singh *et al.* (2008) found that wheat sown on November 5th and 20th achieved higher yields and accumulated more growing degree days (AGDD), helio-thermal units (HTU), photo-thermal units (PTU), and phenothermal index (PTI) throughout all phenophases compared to wheat sown on December 5th. Kaur and Hundal (2010) conducted a simulation study assessing the impact of rising temperatures from February to March on wheat yields and found a yield decrease ranging from 0.69% to 3.30%. Kingra *et al.* (2010) developed regression models using canopy temperature-based indices such as canopy temperature (Tc), the difference between canopy and air temperature (Tc-Ta), and stress degree days (SDD) which showed a significantly negative relationship with wheat yield, explaining 71-87% of the variation. Asseng *et al.* (2011) conducted a simulation study in Australia and reported up to a 50% decline in grain production and leaf senescence when temperatures exceeded 34°C, due to a variation of ±2°C in the average growing season temperature. Mishra *et al.* (2015) studied the sensitivity of three *Triticum aestivum* and one *Triticum durum* wheat cultivars to changes in sunshine hours, maximum and minimum temperatures using the WOFOST model. Their results indicated that increases in sunshine hours led to higher yields across all cultivars, while decreases in sunshine hours had the opposite effect.

Rahman *et al.* (2009) reported that high temperatures adversely affect the growing period, crop growth, grain yield, and yield components of wheat genotypes. Tripathi *et al.* (2009) found that seeds from normal sowing conditions had significantly higher root and shoot dry weights and shoot lengths compared to those from late-sown crops. Lobell (2012) noted that wheat yields in India are highly susceptible to short-term weather extremes, with heat stress being a major factor contributing to reduced yields, particularly when the crop is exposed to high temperatures during anthesis and grain-filling stages. Pal *et al.* (2012) observed that grain yield, biological yield, and straw yield decreased when sowing was delayed by 3-4 weeks. Ram *et al.* (2012) suggested that lower grain yields from delayed sowing might be due to fewer days required to complete various phenological stages, reduced radiation use efficiency, and diminished yield-attributing characteristics. Amrawat *et al.* (2013) found that grain yields from sowing on November 5th were statistically comparable to those from sowing on November 20th, but significant decreases in yield occurred when sowing was delayed beyond November 20th. Kaur *et al.* (2015) conducted a simulation study and reported that a 5% decrease in solar radiation led to a 3.8% decline in wheat yield.

Data from the years 2009-10 to 2012-13, collected under the All India Coordinated Research Project on Agrometeorology (AICRPAM-Ludhiana 2014), revealed that maximum and minimum temperatures, as well as morning relative humidity, were positively correlated with wheat growth from emergence to the vegetative stage. In contrast, sunshine hours, rainfall, and evening relative humidity showed negative correlations during these stages. Nizamuddin *et al.* (2014) conducted a field experiment and found that crops sown on November 1st and 15th produced the highest grain yields (kg/ha), plant heights (cm), spike lengths (cm), number of grains per spike, and straw yields (kg/ha). Sanghera and Thind (2014) reported that delays in sowing time significantly reduced the dry matter accumulation of wheat genotypes at maturity. Kaur and Dhaliwal (2015) also conducted a field experiment and noted that the grain yield was highest in the crop sown on November 1st (5132.83 kg/ha) compared to crops sown on November 15th and 30th.

Mohanty *et al.* (2015) reported a negative correlation between temperature and wheat grain yield, although atmospheric CO_2 concentration had a positive relationship with grain yield in the Bhopal region of Madhya Pradesh. Rao *et al.* (2015) found that minimum temperature during the post-anthesis period was a major factor affecting wheat yield. They observed a 7% decline in yield (204 kg/ha) for each 1°C increase in minimum temperature. Maximum temperatures exceeding 34°C for 7 days and minimum temperatures above 12°C for 6 days during the post-anthesis period caused terminal heat stress in wheat crops. Tack *et al.* (2015) identified a threshold temperature of 34°C in spring, noting that each additional degree day above this threshold could reduce yields by up to 7.6%. Tomar *et al.* (2015) found that early sowing on November 14th resulted in a 12.80% higher grain yield compared to sowing on November 21st. Delayed sowing on December 8th reduced the grain yield to 38.19 q/ha, which was 19.30% lower than the yield from November 14th sowing.

Kaur *et al.* (2016) observed that heat use efficiency (HUE) increased from the vegetative stage to physiological maturity of wheat. Among different sowing dates, HUE was highest for early-sown crops and decreased with later sowing dates. Prasad *et al.* (2016) reported significant temperature increases during the 2011-12 growing season compared to 2010-11. At emergence, temperatures were 4.3°C higher for rain-fed wheat and 2.3°C higher for irrigated wheat. During tillering, temperatures were 5.6°C higher for rain-fed and 4.2°C higher for irrigated wheat, resulting in reductions in tiller numbers by 24.4% and 11.5%, respectively. Higher temperatures during heading led to yield reductions of 84.3% in rain-fed wheat and 45.2% in irrigated wheat. Sourour *et al.* (2016) emphasized the importance of optimal sowing times and the selection of improved cultivars to maximize wheat yield potential under specific agro-climatic conditions. Villegas *et al.* (2016) used regression models to study the relationship between weather variables and agronomic traits, finding that the number of days from sowing to anthesis was negatively correlated with day length and mean daily minimum temperature. Singh *et al.* (2017) conducted a field experiment at IARI, New Delhi, to assess the response of wheat varieties to heat stress. They concluded that the varieties HD 2967 and WR 544 were more suitable for the changing climatic conditions in North-West India.

Heat stress leads to a significant reduction in wheat yield, particularly during the grain-filling period. High temperatures during this phase shorten the crop's growing period by accelerating plant growth, flowering, and maturity. This results in a marked decrease in the number of days to booting, heading, anthesis, and maturity, thereby adversely affecting overall wheat productivity. These findings indicate the severe threat that global warming poses to future wheat yields.

Effect of water stress on wheat yield

Water stress occurs when the demand for water exceeds its availability or when the water quality is inadequate, restricting its use. This term describes both a reduction in water quantity and a decline in water quality due to various factors. Research has shown that excessive precipitation can inhibit wheat cultivation. For example, Bunting *et al.* (1982) found that wheat is typically not grown in areas where the mean annual precipitation exceeds 1000 mm. Similarly, Russell and Wilson (1994) highlighted that in regions with excessive rainfall, the likelihood of successfully establishing and harvesting winter wheat is so low that the risks of crop failure outweigh the potential benefits. The efficiency with which wheat uses water is strongly influenced by weather conditions. Tanner and Sinclair (1983) demonstrated that these conditions affect how plants transpire and assimilate nutrients. Breckner and Frohberg (1987) observed a direct correlation between wheat yields and precipitation levels in rain-fed conditions. Furthermore, Ritchie (1991) showed that under limited water availability, moderately complex models can effectively predict plant growth stages, water balance, biomass accumulation rates, and the distribution of biomass to yield.

Singh *et al.* (1990) observed significant variations in water potential among different wheat genotypes under water-stressed conditions. They noted that improving water productivity could be achieved by increasing the amount of water transpired by crops relative to the water evaporated from the soil surface. Since the effectiveness of transpiration is influenced by atmospheric vapor saturation deficit (i.e., the relative dryness of the air), optimizing biomass production during periods of lowest atmospheric demand could be beneficial (Gupta 1995). Aggarwal and Sinha (1993) investigated the impact of increased CO_2 levels (up to 425 ppm) on wheat crops sown on November 15th from 1973 to 1990. Their results revealed that in irrigated environments, the mean grain yield declined by 6.2%, whereas in rain-fed environments, the mean grain yield increased by 31% under modified environmental conditions. Oweis (1997) assessed water use efficiency for wheat cultivated under both irrigated and rain-fed conditions in Syria. He found that the average water use efficiency for rain-fed wheat in Syria was 0.5 kg/m³.

Hassan *et al.* (2000) found that the highest wheat yields were achieved with a two-stage deficit irrigation strategy, applied at the yield formation and ripening stages. Tubiello *et al.* (2000) reported that variations in total water use or evapotranspiration (ET) by crops can occur due to limited soil water storage or insufficient rainfall (Fig. 1). Additionally, management practices such as nutrient application, sowing time, and the selection of different species or cultivars can influence crop transpiration (Asseng *et al.* 2001). Wang *et al.* (2001) highlighted that water shortages restrict crop productivity, emphasizing that the primary goal of irrigation should be to reduce crop water stress and achieve maximum yield. Hobbs and Gupta (2003) noted that increasing competition for water resources from domestic and industrial uses, coupled with decreasing water use efficiency (WUE) in the Indo-Gangetic Plains, is making water an increasingly critical constraint in agriculture.

Zhang *et al.* (2004) observed that severe soil water deficits led to a decrease in the grain yield of winter wheat, while slight water shortages did not significantly affect grain yield or water use efficiency (WUE) during the growth stages from spring green-up to grain filling. Zhang *et al.* (2005) also found that in the arid environment of Northwest China, high grain yield and WUE in spring wheat could be achieved through welltimed, synchronized deficit irrigation at key stages, including jointing, booting, heading, and the end of filling and maturity. Li (2006) emphasized that improving water use efficiency (WUE) is crucial for increasing crop production, conserving water, and protecting the environment, especially if the area of cropped land remains unchanged. Sun *et al.* (2006) concluded from their experiments on winter wheat irrigation at various growth stages that full irrigation to field capacity did not necessarily produce higher yields compared to treatments with some water stress at specific stages. Li *et al.* (2007) reported that enhancing water use efficiency and grain yield in deficit irrigation regimes could be significantly influenced by the soil moisture content before sowing.

Kattge and Knorr (2007) found that increased air temperatures and changes in precipitation patterns significantly impact crop phenological processes and stomatal conductance. These changes can alter both yield and water use efficiency. Sharma and Pannu (2008) observed that limited irrigation led to substantial reductions in canopy temperature depression, leaf water potential, stomatal conductance, transpiration rate, and photosynthesis compared to fully irrigated controls. Ali (2009) noted that stages of growth more susceptible to water stress, such as the early and booting to heading phases, had higher lambda values, making water supply crucial during these periods. Mirbahar *et al.* (2009) reported that water stress significantly reduced plant height, spikelet number per spike, spike length, thousand-grain weight, and grains per spike across all twenty-five wheat varieties studied. Guo *et al.* (2010) concluded that wheat yield could increase by 38% and water use efficiency by 40% if atmospheric CO_2 concentrations rose to approximately 600 ppm, compared to levels without CO_2 fertilization.

Quanqi *et al.* (2010) found that soil water availability decreased when irrigation was applied later in the winter wheat growing season or when irrigation frequency was increased. Akram (2011) performed a sensitivity analysis on wheat under water stress at different growth stages, revealing that higher relative water content was linked to better yield and yield components. Kingra and Mahey (2013) highlighted the necessity of evaluating crop growth stage sensitivity to evapotranspiration for the effective and efficient use of irrigation water, particularly under water-limited conditions. Yan and Wu (2014) investigated crop water productivity in winter wheat in North-Eastern China and identified a strong linear relationship between evapotranspiration and yield (R^2 = 0.86). Tari (2016) reported that the effects of water deficits on wheat yield, quality, and water-use efficiency varied depending on the growth stages during which the deficits occurred.

Under rainfed conditions, yield decreases due to water stress. A reduction in irrigation adversely affects leaf water potential, transpiration rate, stomatal conductance, and photosynthesis, leading to a significant decline in yield attributes, with the greatest loss seen in the number of grains per spike. On the other hand, maintaining adequate relative water content can lead to increased yield and improved yield components. Given the anticipated limitations in water availability, it is crucial to optimize water application and utilization efficiency to sustain both productivity and water resources.

Effect of nutrient stress on wheat yield

Nutrient stress is commonly viewed in terms of how cells detect and respond to insufficient nutrient supplies needed for their bioenergetic functions. However, cells can also experience stress due to nutrient excess, which leads to the production of reactive oxygen species beyond the levels required for normal physiological responses. Asseng *et al.* (2004) observed that elevated CO_2 positively affected yield, provided that nitrogen was not a limiting factor, under conditions of varying water supply and nitrogen applications. Ali *et al.* (2003) found that the highest plant height was achieved with a nitrogen application rate of 200 kg ha^{-1}, while the highest number of grains per spike was obtained with 175 kg ha^{-1} of nitrogen. Bundy and Andraski (2004) reported that the maximum number of spikes per square meter was observed with 2% potassium nitrate, followed by sodium nitroprusside (SNP) at 400 µg/ml and thiourea at 20 mM, compared to the untreated control, showing increases of 11.9%, 10.9%, and 9.4%, respectively (Fig. 1). Hongbo *et al.* (2005) found that the application of potassium orthophosphate resulted in higher K^+ content, increased soluble sugar, and proline levels in leaves, which may contribute to improved heat tolerance.

Sahu *et al.* (2006) observed that treating seeds with external thiols, such as thiourea, could regulate the antioxidant defense system, leading to improved plant growth and development under various stresses in wheat. Tian and Lei (2006) highlighted the essential role of potassium (K) in enzyme activation, protein synthesis, and photosynthesis, noting that it may act as an osmo-regulator during stress by enhancing K^+ uptake in guard cells and regulating stomatal function. Meshah (2009) reported that potassium plays a crucial role in carbohydrate formation, maintaining leaf water balance, and regulating stomatal closure, which directly affects stress resistance and water use efficiency (WUE), ultimately leading to increased yield attributes and higher grain yield. Tripathi *et al.* (2013) found that early sowing resulted in a 10.06% higher grain yield compared to normal sowing, due to 15 days earlier flowering that provided a more favorable environment for wheat growth and development. Additionally, applying 50 kg more N ha^{-1} than the recommended dose significantly increased grain yield.

Schierhorn *et al.* (2014) emphasized that enhancing water and nutrient supply, along with using crop varieties adapted to recurrent drought conditions, is crucial for reducing yield gaps in European Russia. Shirazi *et al.* (2014) assessed the impact of nitrogen levels and irrigation regimes on wheat growth and yield, finding that the combination of 120 kg N ha^{-1} and 200 mm irrigation was particularly effective. Mandic *et al.* (2015) discovered that nitrogen levels of 75 and 150 kg ha^{-1} significantly influenced grain yield (4396 and 4494 kg ha^{-1}), radiation use efficiency (8.24 and 8.45 kg ha^{-1} mm^{-1}), nitrogen agronomic efficiency (3.11 and 2.21 kg kg^{-1} N), and nitrogen use efficiency (58.62 and 29.96 kg kg^{-1} N), with both NAE and NUE declining at higher N rates (Fig. 1). Shabbir (2015) investigated the effects of supplemental foliar applications of N, P, and K, alone or in combination, on nutrient uptake and physiological processes in wheat under water scarcity. The study found that insufficient water supply severely reduced growth, germination, and the uptake of N, P, and K.

Zain *et al.* (2015) found that foliar application of micronutrients significantly enhanced several wheat attributes, including plant height, spike length, spikelets per spike, grains per spike, test weight, tillers per square meter, grain yield, biological yield, and harvest index. Kameai *et al.* (2016) reported that terminal heat stress due to late planting (5th January) reduced wheat yield and yield components; however, seed inoculation with phosphate bio-fertilizer improved these metrics. Singh *et al.* (2016) also noted that foliar spraying of potassium nitrate (KNO_3) at 0.5% during the 50% flowering stage and 1.0% during anthesis, along with 2.5 millimoles of arginine, zinc spray, extra irrigation during the grain-filling stage, and the use of potassic fertilizers with municipal wastewater, all contributed to increased wheat productivity under high temperature conditions.

The highest number of grains per spike and maximum plant height are achieved with increased nitrogen supply. However, excessive use of nitrogenous fertilizers can result in excessive vegetative growth, which increases the risk of plant lodging and contributes to greenhouse gas emissions. Therefore, it is crucial to apply nitrogenous fertilizers at optimal rates to balance crop productivity with environmental health. Additionally, inadequate water supply can lead to reduced germination and growth while limiting the uptake of primary nutrients such as nitrogen (N), phosphorus (P), and potassium (K) by plants.

MANAGEMENT/ADAPTATION STRATEGIES

Adjustment of sowing time

Pal *et al.* (2017) reported that the timing of sowing is a crucial factor influencing crop yield. Delays in sowing wheat beyond the optimal window can negatively impact crop yield. Similarly, Sarkar *et al.* (2019) found that each location has an optimal sowing date, and deviations from this date either earlier or later result in reduced yields. Chen *et al.* (2013) highlighted that agro-meteorological factors, such as air temperature, solar radiation, and the seasonal distribution of rainfall, also significantly affect yield (Fig. 2). Additionally, Sarkar *et al.* (2020) observed that delays in sowing are associated with significant declines in yield attributes.

Nutrient management

Seleiman (2019) studied that effective nutrient management strategies, including the balanced use of organic and inorganic fertilizers, are essential for enhancing abiotic stress tolerance in wheat crops (Fig. 2). Various macro and micronutrients play distinct roles in regulating stress responses in wheat plants. According to Abedin *et al.* (1999), the source, timing, methods, and quantities of nutrient application are critical factors determining the effectiveness of plant nutrients in alleviating abiotic stress in wheat.

Irrigation management

Rana *et al.* (2017) found that effective irrigation management is crucial for alleviating both osmotic and heat stress in wheat production systems. Panda *et al.* (2003) highlighted that judicious application of irrigation water not only boosts yield but also helps mitigate various abiotic stresses. Wheat is known to be highly sensitive to water stress, and sometimes limited irrigation cannot meet the crop's full water requirements (Fig. 2). Ahmed *et al.* (2019) identified the reproductive and grain formation stages as the most critical for moisture stress, reporting that wheat yield can be reduced by up to 30% and 92% depending on the severity of moisture stress during the post-anthesis and grain formation stages, respectively.

Climate Smart Technology

Sun *et al.* (2018) reported that the climate-smart (CS) technological approach emphasizes adopting optimal agronomic practices, such as timely sowing, efficient nutrient and water management, adaptive crop planning, and protective measures during critical growth periods. Cormier *et al.* (2013) noted that conservation agriculture (CA) has emerged as a CS technology to address several challenges in the rice-wheat cropping

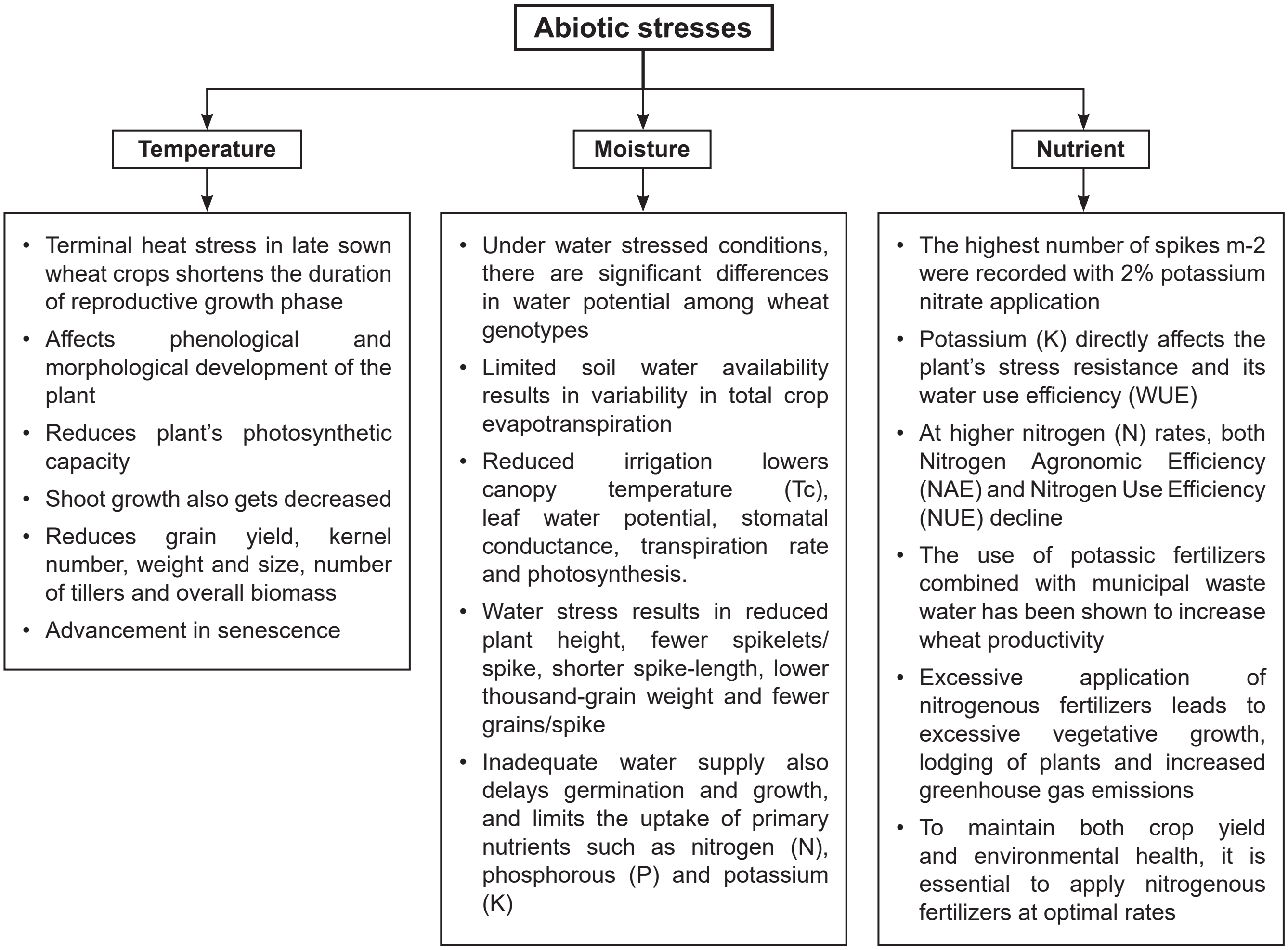

Fig. 1. Impact of abiotic stresses on wheat yield and yield contributing characters

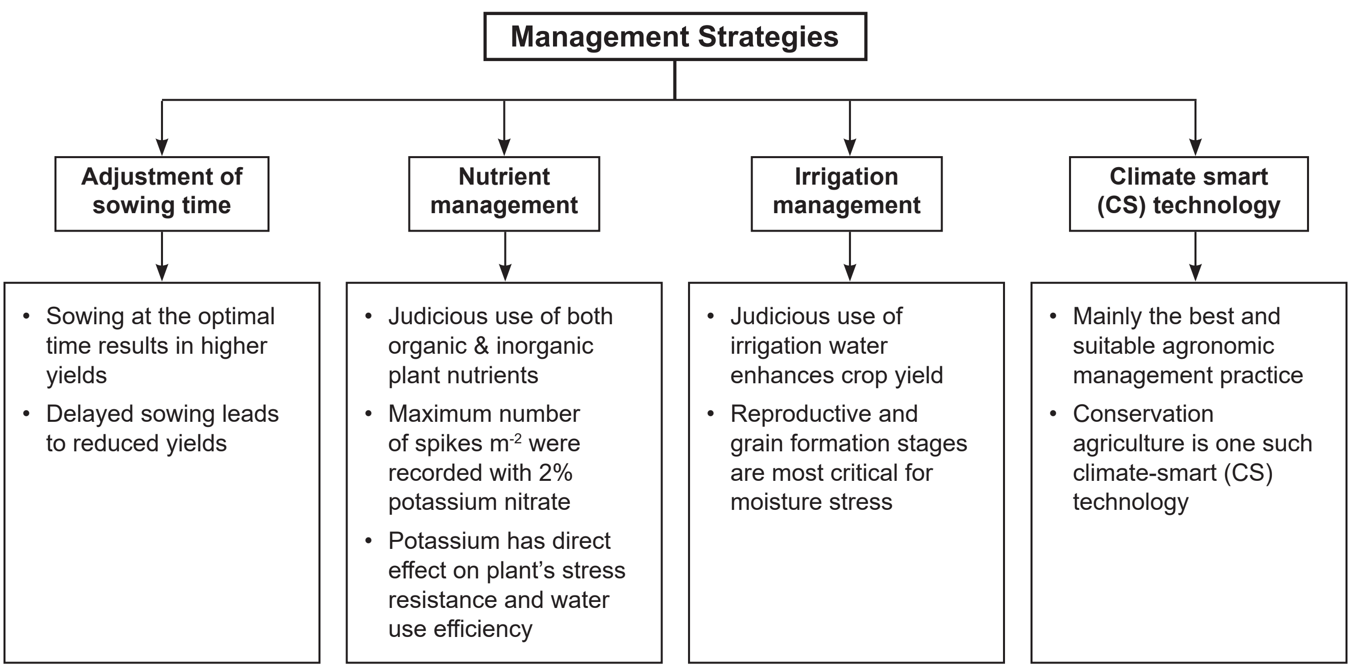

Fig. 2. Strategies for mitigating and adapting to abiotic stresses in wheat

system (RWCS). In South Asia, the practice of cultivating wheat with reduced or zero tillage and retaining surface residue has become a widely accepted CS tool for combating various abiotic stresses (Fig. 2). Bell *et al.* (2017) found that CA is particularly successful in non-rice aerobic crops, such as wheat, maize, and pulses. Zhang *et al.* (2017) demonstrated that CA is an effective CS technology for mitigating drought stress by facilitating early planting of winter wheat in the rice-wheat cropping system, utilizing residual soil moisture after the monsoon harvest.

CONCLUSION

In conclusion, the intricate interplay of abiotic stresses-heat, moisture, and nutrient deficiencies-poses significant challenges to wheat production, impacting yield and overall crop health. Heat stress accelerates crop development stages, shortening the growing period and compromising yield potential. Water stress, driven by inadequate irrigation, impairs essential physiological processes such as transpiration and photosynthesis, leading to notable reductions in yield attributes, with severe impacts on grain numbers per spike. Nutrient stress, while also detrimental, is exacerbated by excessive nitrogen application, which fosters excessive vegetative growth, increases lodging risks, and contributes to greenhouse gas emissions.

To address these challenges, a multifaceted approach is essential. Effective management practices, including precise sowing times and the selection of stress-tolerant varieties, are critical for mitigating heat and water stress. Additionally, optimizing nitrogen application rates is necessary to enhance productivity while minimizing environmental impacts. As climate variability and water scarcity become more pronounced, it is imperative to adopt climate-smart technologies such as conservation agriculture and zero tillage with residue retention. These practices not only help sustain productivity but also protect natural resources.

Overall, integrating optimal nutrient and water management strategies with innovative agricultural practices will be key to ensuring food security and maintaining crop resilience in the face of changing climatic conditions.

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