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Review

Drought and Terminal Heat Stress Effects and Its Management on Wheat Genotypes: A Review

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Abstract: Wheat (*Triticum aestivum*) is a vital cereal crop that plays a crucial role in global food security, supplying essential calories and protein to over 80% of the world's population. In recent decades, the effects of climate change, particularly rising temperatures, have raised concerns about Wheat production worldwide. The optimal daytime temperature for Wheat growth during its reproductive stage is around 15°C. However, the sustainable production of Wheat is increasingly challenged by the adverse effects of climate change, notably through drought and terminal heat stress. This comprehensive review examines the complex interactions between these abiotic stresses and various Wheat genotypes, highlighting their significant impacts on plant physiology, biochemistry, growth dynamics, and grain yield. The review also evaluates a range of genetic, biotechnological, and agronomic strategies designed to enhance the resilience of Wheat genotypes to heat stress. By integrating the latest research findings with practical applications, this review offers a detailed roadmap for enhancing the adaptive capacity of Wheat plants to cope with the growing threats of drought and terminal heat stress, thereby promoting sustainable Wheat production in an evolving climate. Drought stress leads to significant biochemical changes within plants, notably an increase in Abscisic Acid (ABA) levels in xylem sap due to soil moisture deficiency. Similarly, heat stress can damage thylakoid membranes, resulting in the formation of reactive oxygen species that deactivate chloroplast enzymes. Addressing these stresses through genetic, biotechnological, and agronomic management practices is essential for maintaining Wheat productivity.

Keywords: Climate Change, Drought, Heat Stress, Heat Shock Protein, Temperature

Introduction

Wheat (*Triticum aestivum*) is a globally essential cereal, producing approximately 785 million metric tons annually. In Nepal, this crop is crucial for food security, with around 750 thousand hectares under cultivation, yielding 1,841 thousand tons at an average productivity of 2.5 tons per hectare (Marahatta *et al*., 2018). To assess a country's reliance on cereal imports, the Food and Agriculture Organization (FAO) employs the cereal import dependency ratio. For Nepal, this ratio has increased over the years, standing at 1.2% in 1990, 1.7% in 2000, 3.9% in 2014 and 7.6% in 2016. During the 2016/17 fiscal year, the country imported 0.19 million metric tons of Wheat at a cost of NPR 5.2 billion (approximately 48 million USD) (Pokhrel *et al*., 2013).

Wheat is a mesophytic species that thrives within specific temperature ranges 10-15°C for sowing and 21-26°C for ripening, although certain varieties can tolerate temperatures as high as 35°C. However, climate change is altering these ideal conditions by causing shifts in rainfall patterns, increasing greenhouse gas concentrations, and reducing annual precipitation levels (Poudel *et al*., 2020a). Biotic factors, such as parasitic and non-parasitic diseases (Singh *et al*., 2013), along with abiotic stressors like drought, salinity, and heat, lead to significant reductions in Wheat production (Abhinandan *et al*., 2018). Given these challenges, it is essential to explore the effects of these stressors on future Wheat breeding and crop improvement programs.

In countries such as Nepal, where agricultural practices heavily depend on monsoon rainfall and climate patterns, wheat production is particularly vulnerable to climate variability (Thapa-Parajuli and Devkota, 2016). Heat stress occurs when temperatures exceed critical limits, while drought stress is triggered by high temperatures coupled with low soil and atmospheric moisture (Regmi *et al.*, 2021). An increase of just 1°C in temperature could result in a 6% decrease in global Wheat yields (Poudel *et al.*, 2021). Even during the reproductive stage, a 1°C rise can cause substantial grain yield losses. Wheat plants undergo several physiological, biological, and biochemical changes due to heat stress, including impacts on osmotic regulation, seed germination, seedling emergence, and photosynthesis (Akter and Rafiqul Islam, 2017). Additionally, heat stress post-an thesis lowers grain filling rates, while pre-an thesis stress can reduce yields as well (Poudel *et al.*, 2020b).

Furthermore, climate change exacerbates drought, negatively affecting wheat's growth, development, and overall physiology. Drought decreases the number of spikes per square meter, and grains per spike, and shortens the wheat life cycle (Poudel *et al*., 2020a). Globally, drought affects about 50% of the wheat crop annually and impacts 44% of Nepal’s wheat-growing regions, resulting in yield losses between 15 and 20%. Water scarcity also reduces plant height, stunts growth, and disrupts assimilation and gas exchange processes (Regmi *et al.*, 2021). To counter these stresses, wheat plants have evolved various mechanisms to cope with both biotic and abiotic challenges (Hakeem, 2015). In addition to high yield potential, wheat varieties should also be bred for resilience against drought and high temperatures (Poudel *et al*., 2020b). Despite several food security initiatives, increasing wheat productivity under these challenging environmental conditions remains a difficult task (Abhinandan *et al*., 2018).

Materials and Methods

This content is drawn from multiple secondary sources, such as peer-reviewed research and review articles published in credible journals. It combines insights and data from a variety of references obtained through different platforms and resources we've examined.

Results and Discussion

Drought Condition in Nepal

The threat of drought has intensified due to climate change, presenting a significant challenge (Adhikari, 2018). Nepal, being particularly vulnerable to the effects of climate change, has experienced temperature increases that surpass the global average in recent years. Simultaneously, rainfall patterns have become more unpredictable, with an average monthly rainfall decline of 3.7 mm (or 3.2%) per decade. These changes have contributed to persistent drought conditions, particularly in hill farming areas where communities rely on both summer and winter rains for agriculture. Notably, dry spells and droughts were recorded in 2012, 2013, and 2015 (Dahal *et al*., 2016).

Drought is a subtle yet pervasive issue caused by insufficient water supply, which can have devastating impacts on agriculture, water resources, and the environment (Dhakal, 2021). Unlike other natural disasters, droughts evolve slowly and often without immediate warning signs. Research has linked declining cereal crop yields to the increased water stress brought on by rising temperatures and reduced rainfall. Drought also impairs various plant metabolic processes, decreasing chlorophyll content and limiting photosynthesis in the leaves. It remains one of the most critical factors threatening global food security (Poudel *et al*., 2020b).

In Nepal, droughts tend to occur most frequently from late March to early June, just before the monsoon season and during the winter months when rainfall is at its lowest, leaving the soil dry and unproductive. This has significantly impacted the hill farming system, disrupting crop production and undermining farmers' livelihoods. However, these challenging conditions also present an opportunity to explore new strategies for adapting to changing environmental circumstances (Rijal *et al*., 2020).

Effect of Drought Stress

Drought plays a critical role in global food security and has a harmful impact on the overall morphology and physiology of crops worldwide (Poudel *et al*., 2020a). It affects plants at multiple levels, from visible structural changes to subtle molecular disruptions, interfering with nearly all physiological functions. Here are some of the key effects of drought stress and their severity (Rijal *et al*., 2020). Drought stress can harm the thylakoid membranes and trigger the production of reactive oxygen species, which inactivate essential enzymes in chloroplasts. This leads to reduced photosynthesis in Wheat, causing slower plant growth and ultimately lower yields (Poudel *et al*., 2020b).

Morphological Alteration

I. Small plant size: Drought-induced water stress is strongly associated with poor germination and weak crop establishment. Cell growth, which depends on turgor pressure, is particularly sensitive to water scarcity (Rijal *et al*., 2020). Under drought conditions, Wheat plant height was found to decrease by 35% during the stem elongation stage, 23% at the booting stage, and 7% during the grain filling stage. This highlights the significant role drought plays in stunting Wheat plant growth (Rijal *et al*., 2020)

II. Leaf senescence: Drought occurring during the reproductive stage accelerates the aging of leaves (senescence), which leads to a noticeable decline in grain yield. One of the most visible signs of senescence is chlorosis, which reduces photosynthetic activity, further impacting crop yields (Rijal *et al*., 2020)
III. Root system changes: Roots are vital for absorbing nutrients and water, particularly during droughts. When water becomes scarce, the roots of Wheat plants grow deeper into the soil to tap into moisture, aiding in their survival under such conditions (Rijal *et al*., 2020)

Wheat Biochemistry Under Drought Stress

Drought causes considerable biochemical changes in plants. For instance, reduced soil moisture increases Abscisic Acid (ABA) levels in xylem sap, leading to higher concentrations of ABA in various leaf compartments. In Wheat and other plants, the activity of PM-ATPase declines as the soil dries, increasing cell wall pH and further stimulating ABA production (Dhakal, 2021).

Managing Drought Stress in Wheat

Effective drought management in Wheat requires monitoring and assessing drought impacts using scientific techniques. This includes selecting drought-resistant genotypes and modifying agronomic practices, such as adjusting plant density, sowing times, and soil management practices. These measures help ensure that Wheat plants reach critical growth stages when drought risks are minimized (Dahal *et al*., 2016). Reductions in Relative Water Content (RWC) and closed stomata reduce photosynthesis during drought (Singh *et al*., 2020). Increasing leaf trichome density and minimizing water loss can enhance drought tolerance (Sallam *et al*., 2019). The severity of drought's effects on Wheat varies depending on the timing, intensity, and frequency of drought events (Gyanwali and Khanal, 2021).

Drought-Tolerant Cultivars

Over the past decade, numerous breeding programs have aimed to develop drought-tolerant Wheat varieties. International research institutes, such as the International Centre for Agricultural Research in Dry Areas (ICARDA), have advanced drought-tolerant germplasm through crossbreeding wild Wheat species. Additionally, genetic engineering has played a crucial role in improving Wheat's drought resilience (Dhakal, 2021).

Agricultural Practices

Adjusting agronomic practices, such as efficient irrigation, modified sowing times, and seed priming, can mitigate the effects of drought (Hussain *et al*., 2019). Successful drought management strategies should focus on optimizing soil moisture use, establishing crops efficiently, and maintaining stable biomass and grain yields. Seed priming, particularly when combined with osmoprotectants, improves seedling vigor and germination (Dhakal, 2021).

Molecular Mechanisms

Drought tolerance in Wheat involves activating specific genes. Research into Wheat gene expression typically focuses on the seedling stage, even though the junction stage between vegetative growth and flowering is more vulnerable to drought stress. Wheat varieties with deeper, denser, and longer root systems, as well as greater radial hydraulic conductivity, tend to show higher yields and improved drought tolerance (Savyata, 2021).

Heat Stress

Terminal heat stress is a significant abiotic factor that adversely affects wheat productivity (Poudel *et al*., 2021). Wheat is particularly sensitive to heat stress; studies show that even a 1°C rise in temperature can result in a 6% decline in global Wheat yield (Pawan *et al*., 2022). In various regions of the Asian subcontinent, Wheat is typically cultivated after rice, which often leads to delayed planting and increased vulnerability to heat stress. As temperatures escalate during the grain-filling phase, late-planted Wheat is at a heightened risk of terminal heat stress.

Effect of heat stress: Heat stress during anthesis and grain filling accelerates maturity and significantly decreases both grain size and weight (Puri *et al*., 2021). The following outlines the impacts of heat stress on wheat:

Morphological Changes

Extreme heat (up to 45°C) can damage embryonic cells, resulting in poor crop establishment and irregular germination (Pawan *et al*., 2022). Wheat experiences varying levels of heat stress throughout different growth stages; however, stress during the reproductive phase is more detrimental than during the vegetative phase, as it directly influences grain count and weight (Singh *et al*., 2013). While heat stress can negatively affect yield at any growth stage, the seed-filling stage is especially crucial for determining average seed weight and composition, which ultimately impacts both the quantitative and qualitative aspects of the final yield (Sehgal *et al*., 2018).

Physiological Changes

Temperature fluctuations can disrupt a plant's water balance. Increased heat can cause plant tissues to dehydrate, hindering growth and development. The maximum temperature at which crops can maintain water content during flowering is around 31°C (Regmi *et al*., 2021). Heat stress typically reduces photosynthesis due to the inactivation of chloroplast enzymes, primarily resulting from oxidative stress. A decrease in the net photosynthesis rate is often associated with increased non-photo respiratory activity (Akter and Rafiqul Islam, 2017). Heat and water stress can lower internal CO_2 levels in plants, affecting enzyme activity (including Rubisco) and ATP production, both critical for chemical energy and metabolic regulation. Heat stress exposure can lead to elevated levels of Reactive Oxygen Species (ROS), which can damage lipids, proteins, and DNA, disrupting cellular functions. The oxidative damage caused by heat stress can reduce membrane stability by 54% Pawan *et al*., (2022). Additionally, heat stress can deactivate ribulose-1,5-bisphosphate carboxylase, an enzyme essential for carbon fixation in photosynthesis (Paudel *et al*., 2021).

Biochemical Changes

Heat stress alters the expression of genes that are vital for protection against high-temperature conditions at the molecular level. These genes regulate the synthesis of osmoprotectants, detoxifying enzymes, transport proteins, and regulatory proteins. When subjected to heat stress, changes in gene expression can result in shifts in physiological and metabolic processes, gradually enhancing heat tolerance through acclimatization or, ideally, adaptation (Gupta *et al*., 2022). Furthermore, the protein content of Wheat grains is affected by heat stress; researchers (Lizana and Calderini, 2013) observed that protein concentrations tend to remain relatively stable, showing minimal changes (Pawan *et al*., 2022).

Relative Water Content (RWC)

Genotypes capable of maintaining turgid leaves during stressful conditions gain physiological advantages (Singh *et al*., 2020). To measure this, fresh leaf samples from field-grown crops are weighed, soaked in water, chilled, and then reweighed the next day. Finally, the samples are oven-dried and weighed again (Singh *et al*., 2020).

Management of Heat Stress in Wheat

Heat tolerance refers to a plant's ability to survive, grow, and produce viable yields under high-temperature conditions (Pawan *et al*., 2022). Wheat cultivation is particularly vulnerable to high temperatures, drought, and heat stress. In Nepal, the primary constraints on Wheat farming are water scarcity and genetic traits (Poudel *et al*., 2020a). Various stress tolerance indices have been developed to identify cultivars that can withstand stress, although only a few are routinely used to evaluate heat-tolerant genotypes in Wheat. Examples of these indices include the tolerance index (TOL), Stress Susceptibility Index (SSI), Yield Stability Index (YSI), Mean Productivity (MP), Geometric Mean Productivity (GMP), and Stress Tolerance Index (STI) (Poudel *et al*., 2021). High temperatures pose a significant challenge to plant growth, affecting both the quality of grains and overall productivity in Wheat cultivation. Efforts to enhance wheat's thermal tolerance are ongoing, with the development of heat-tolerant cultivars being a key focus to improve yields (Pawan *et al*., 2022).

Crops adapt to heat stress through three primary strategies: Heat avoidance, heat tolerance, and heat escape. In Wheat, terminal heat tolerance encompasses mechanisms such as leaf rolling and cuticle waxiness for heat avoidance, the activation of stress response genes for heat tolerance, and altered plant phenology for heat escape. The heat tolerance and sensitivity of Wheat genotypes can be evaluated by planting them in warmer environments or delaying sowing to expose them to higher temperatures (Poudel *et al*., 2021).

Management strategies for heat stress tolerance can be categorized into three approaches: Avoidance, escape, and maintaining a green state. Avoidance strategies involve minimizing direct sunlight exposure and conserving water, while escape strategies focus on early maturation and accelerated grain filling. The "stay green" approach promotes an active photosynthetic state during prolonged grain filling.

Genetic Management

Crop breeding is a crucial component of a plant's adaptation to changing environmental conditions. In recent years, researchers have focused on identifying Wheat genotypes that can tolerate heat stress (Poudel *et al*., 2021). Despite advancements in developing several high-yielding and stress-resistant varieties, challenges remain in enhancing productivity and profitability in Wheat farming. Thus, enhancing heat tolerance and creating new heat-tolerant genotypes through breeding is essential (Bishwas *et al*., 2021).

Figure (1) mechanism of wheat against heat stress management of heat stress tolerance are (1) Avoidance (2) Escaping and (3) Stay green in wheat. avoidance can be done by avoiding direct sunlight and Conservation of water, escaping by early maturation and accelerated grain filling and stay green by active photosynthesis state and long grain filling period.

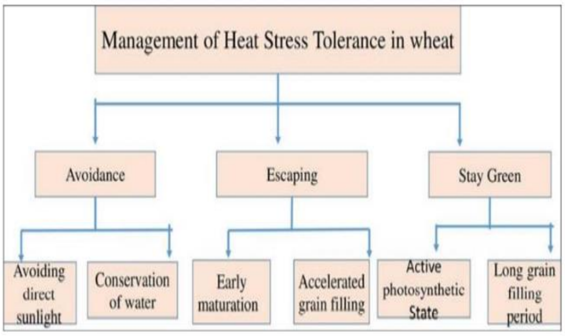

Fig. 1: Mechanism of Wheat against heat stress

Screening and Breeding for Heat Tolerance

Breeding programs have identified several physiological indicators that are beneficial in their research. A key strategy is screening genetic resources to discover sources of heat tolerance in crops. By integrating these traits through physiological crossing, breeders can develop new varieties capable of withstanding the future climate challenges posed by rising temperatures (Bhandari *et al*., 2021).

Agronomic Management

Modifying specific agronomic practices can effectively facilitate Wheat growth in warmer climates. Techniques such as water conservation, optimizing planting methods and timing, applying appropriate fertilizer dosages, mulching, and utilizing protective agents can all mitigate the effects of elevated temperatures on Wheat. Consequently, climate change profoundly impacts Wheat production, particularly in regions like Nepal, where agriculture heavily relies on the monsoon season and associated climatic conditions (Devkota and Phuyal 2016). The most straightforward and widely applied method to alleviate heat stress is by selecting genotypes and creating new cultivars that can sustain consistent yields even under challenging conditions (Bishwas *et al*., 2021).

Biotechnological Approach for Improving Heat Tolerance

Plants can adapt to environmental challenges through a range of molecular mechanisms, including signal transduction, stress sensing, metabolite formation, and the expression of stress-related genes (Pandey *et al*., 2019). Innovative biotechnological methods have enhanced our understanding of how plants respond to stress at both the molecular and whole-plant levels (Nguyen *et al*., 2018).

Bacterial Seed Treatment

Biological control agents, such as certain bacteria and fungi, provide a faster and more cost-effective solution for addressing heat stress than traditional breeding approaches. Some rhizobacteria, known for promoting plant growth, have also been found to enhance Wheat's resilience to high temperatures (Akter and Rafiqul Islam 2017).

Heat Tolerant Mechanism in Wheat

Plants utilize various adaptive strategies to cope with heat stress. The three primary strategies that enable them to survive and flourish in high-temperature environments are heat avoidance, heat escape, and heat tolerance. Heat tolerance refers to a plant's ability to withstand elevated temperatures while still growing and producing a viable yield. Key mechanisms for heat tolerance in Wheat include antioxidant defenses, the production of Heat Shock Proteins (HSPs), and maintaining a green state (Pandey *et al*., 2019).

Heat Shock Protein

Under conditions of heat stress, the processes of protein folding and synthesis can become disrupted, leading to the accumulation of stress-inducing factors within the cell. These factors can interfere with crucial metabolic functions, such as DNA replication, transcription, mRNA transport, and translation until the cell recovers (Pandey *et al*., 2019). In response to these disruptions, plants increase the production of heat stress-induced proteins known as Heat Shock Proteins (HSPs), which provide a protective mechanism against heat stress.

Conclusion

Wheat is vital for enhancing cereal production in Nepal, a country deeply rooted in agriculture. In light of this, we have explored the effects of abiotic stress on Wheat crops. Despite the implementation of several policies aimed at promoting food security, achieving higher crop yields under challenging environmental conditions continues to be a major obstacle. Our study primarily focuses on drought and heat stress, examining their impacts on Wheat and the strategies that can be employed to mitigate these challenges. We have addressed both the adverse effects of these stresses and the potential resistance mechanisms within Wheat. Recently developed drought- and heat-tolerant varieties, such as NL1202, NL1253, Bhrikuti, RR21, and Gautam, are recommended for cultivation across various regions due to their stability and resilience. We believe that the strategies discussed in our article will provide valuable insights for addressing the challenges posed by these environmental stresses.

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Author’s Contribution

Prabin Kumar Mahato, Sharada Phullel, Pratikshya Pokhrel and Rohit Kumar Sah: Wrote the manuscript.
Naresh Upadhyaya: Wrote the introduction and manuscript.

Ethics

This article is unique and contains unpublished content. The corresponding author confirms that all authors read and approved the manuscript, and there are no ethical issues.

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