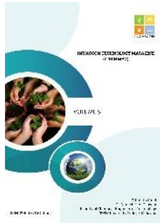
INWASCON

***i* TECH MAG**

DOI: http://doi.org/10.26480/itechmag.05.2023.22.25

ISSN: 2710-5873 (Online)
CODEN: ITMNBH



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S&T REVIEW

EFFECTS AND MANAGEMENT PRACTICES OF HEAT STRESS IN MAIZE (*ZEA MAYS L.*): A REVIEW

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ARTICLE DETAILS

Article History:

Received 11 August 2023
Revised 23 September 2023
Accepted 05 October 2023
Available online 09 October 2023

ABSTRACT

A vital crop in various agro-ecological regions, Maize (Zea mays L.) ranks second only to rice in terms of cultivation in Nepal. Although Maize is considered heat resistant, exposing it to the temperature exceeding 37-degree Celsius results in the heat stress reducing its productivity. Threat of global warming is real with the changing climate, studies indicate future heat waves will likely be more severe and persistent, negatively impacting the productivity. Reduced plant height, decreased leaf area, and delayed flowering are some of the consequences of heat stress in maize plants. It disrupts photosynthetic efficiency, damaging photosynthetic machinery, reducing enzyme activity, and impairing chloroplast functioning. Furthermore, heat stress induces ROS causing cell membrane damage, disruption of enzymatic activities, ultimately resulting in stunted plant growth and productivity. During the flowering stage, heat stress reduces the number of florets, impairs silk and grain development, and promotes premature senescence, leading to a shorter plant lifespan and decreased grain yield. Early sowing of maize, effective irrigation and nutrient management can help reduce soil temperature, enhance water use efficiency and minimize heat stress. The adoption of heat-resistant maize varieties and improved breeding techniques is also essential for mitigating the adverse effects of heat stress in maize cultivation. This paper addresses the consequences of heat stress on maize, including effects on growth, photosynthetic characteristics, reactive oxygen species (ROS), reproductive development, premature senescence, and overall grain yield while also exploring strategies for mitigating the impacts of heat stress on maize through agronomic practices and breeding.

KEYWORDS

Maize, Heat Stress, Yield, Breeding

1. Introduction

A substantial crop on a worldwide scale, maize (*Zea mays L.*) also has significant importance in Nepal. With a global production of more than 1.2 billion metric tons in 2020, it is one of the most widely grown cereal crops globally, according to (FAO, 2022). Maize is a significant staple crop and a vital source of food and income for farmers in Nepal. It is the second most extensively cultivated crop in Nepal, behind rice, with a total cultivated area of 957,650 hectares in 2020. Production of maize equaled 2,835,674 metric tons in that year, with a productivity of 2.96 metric tons per hectare (Ministry of Agriculture Development, 2020). Maize is cultivated in diverse agro-ecological regions, including the Terai plains, mid-hills, and high mountains (Shrestha et al., 2022). Maize, a C4 crop species, is thought to be heat tolerant, but a prolonged exposure to temperature >35^{0}C is unfavorable (El-Sappah et al., 2022). Maize is cultivated under various seasons in Nepal, among which spring season maize is likely to suffer high temperature stress during its reproductive stage, which is among the most sensitive to temperature (Waqas et al., 2021).

Climate change is showing its impacts worldwide and agriculture is very susceptible to climate change like rise in temperature, and the changing precipitation pattern (Mahato, 2014; Walsh et al., 2020), maize is no exception to this (Chandio et al., 2023). The average global a temperature has risen by 1.10°C over the previous ten years (2011–2020) and also predicted to rise by 1.30°C–5.70 °C by the year 2100 according to (Intergovernmental Panel on Climate Change, 2021). This global warming will have higher risk of affecting agricultural sectors along with water resources, biodiversity, energy and land use in South Asia (FAO, 2019). According to the Country Climate and development Report for Nepal by (World Bank Group, 2022), it is expected to increase Nepal's temperature by about 0.9^{0}C between 2016 and 2045. With agriculture being Nepal's largest industry, accounting for more than 23% of national GDP (MoAD, 2020) and maize being the second most extensively farmed crop after rice, climate change is anticipated to have huge influence in Nepalese agriculture and the economy as heat stress causes yield loss as much as 75% in maize (Koirala et al., 2017).

High temperature induced heat stress during the flowering stage and grain filling periods has a significant consequence on crop output. Pollination and Fertilizations are the major critical phase, which are affected mostly by drought and heat stress and major yield reduction is seen during this phase (Waqas et al., 2021). Temperature exceeding 38°C diminish viability of pollen and receptivity of silk, leading to insufficient seed set and production. Spring season maize grown in a maize-rice system accounts for roughly 15.5% of Nepal's total maize cultivated area, with production losses of up to 75% (Koirala et al., 2017). High temperature is primarily associated with anthesis and silking of maize, which promote leaf burning and tassel blast, leading to ineffective pollination. Various researches have projected that heat waves in future through the latter half of the twenty-first century will be more severe, persistent, and will last for longer period of time (Meehl & Tebaldi, 2004) resulting even bigger decline in production (Lobell et al., 2011; Zhu et al., 2019).

Heat stress being adverse condition for the maize, several approaches in agronomic and breeding technique of maize to adapt to the harmful effects of high temperature are inevitable (Jha et al., 2020; Sabagh et al., 2020; Waqas et al., 2021). Moreover, while doing so, it is essential to recognize the heat stress and its consequences in maize. In this context, this review covers the overview of various effects shown by maize in response to the prolonged period of exposure to high temperature situation and some of its management practices.

2. Effects of Heat Stress

2.1 Growth

Heat stress has significant negative effect in number of maize growth indices in numerous studies. A study by (N. Wang et al., 2022) discovered that heat stress caused decreased plant height, reduced leaf area, and delayed flowering in maize plants. Similar to this, (LI et al., 2022) described that heat stress significantly reduced aboveground biomass and grain yield in maize. Heat stress condition significantly reduced the growth, grain yield and yield attributing characters like in Maize (H. A. Hussain et al., 2019). Heat stress detrimentally influences the growth of maize by disrupting photosynthesis and inducing oxidative stress. Additionally, heat stress can lead to reduced nutrient uptake and nutrient imbalances in maize, further affecting its growth (Hussain et al., 2006).

2.2 Photosynthetic Characteristics

Several studies on the impact of heat stress on the photosynthetic characteristics of maize have shown significant effects in maize plants. These studies demonstrated that heat stress lowers photosynthetic efficiency and its associated parameters. (Hussain et al., 2019) concluded that the heat stress has notable effect on reduction in the rate of net photosynthesis, stomatal conductance, and chlorophyll content in maize. High temperature condition reduces the chlorophyll concentrations, including Chl a, Chl b, and total chlorophyll, compared to non-stress conditions (Hussain et al., 2019). Damaged photosynthetic machinery, reduced enzyme activity, and impaired chloroplast functioning are the main cause of this photosynthetic loss. Similarly, (El-Sappah et al., 2022) found that heat stress causes maize to decline in photosynthetic pigments and its gas exchange parameters.

2.3 Reactive Oxygen Species (ROS)

Reactive oxygen species (ROS) accumulate because of heat stress in various compartments resulting to the oxidative stress in plants (Hussain et al., 2019; Yang et al., 2018). ROS, like superoxide (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl group(-OH), are highly reactive molecules which damage the cellular components like protein, lipid, and DNA. Several researches shown to have significant effect of high temperature on increasing the production of reactive oxygen species (Castro et al., 2021; Sharma et al., 2012) by mitochondrial electron transport chain, photosystem II in chloroplasts, and peroxisomes (Doğru, 2021; Suzuki et al., 2012). Higher concentration of ROS can affect cell membrane; disrupt enzymatic activities, and interfere cellular processes, finally causing dwarfed growth, cell death and productivity (Hasanuzzaman et al., 2013). To reduce the harmful effects of ROS, plant activates antioxidant defense systems. Study of interplay between ROS production and antioxidant defense mechanisms is crucial for developing strategies to boost the heat endurance of maize plants and minimize the adverse effects of heat stress on the crop productivity.

2.4 Reproductive Development

Temperature above 35^0C during before and after flowering stage of maize reduces the CO2 exchange rate by 17%, crop growth rate up to 29%, number of grains up to 45% and grain yield up to 45% (Neiff et al., 2016). Heat stress during blooming adversely influences the number of florets, production of silk, and grain formation (Edreira et al., 2011). This abovementioned temperature suppresses pollen numbers, ovary fertilization and the grain filling, associating with the overall yield (Lizaso et al., 2018; Siebers et al., 2017). In addition, Conversion of photosynthates into starch could not happen in maize under heat stress environment. All these effects together have the direct effect of distorted fertilization on maize (Wang et al., 2019).

2.5 Premature Senescence

High temperature stress condition in maize plant causes premature senescence, characterized by accelerated yellowing and leaf deterioration (Y. Wang et al., 2019). Series of physiological and molecular damages triggered by heat stress promote senescence causing a smaller lifespan of the plants. (Ma et al., 2020; Xu et al., 2019) highlighted the early senescence and the role of oxidative stress in heat stress condition. It leads to an imbalance between the production of reactive oxygen species (ROS) and the antioxidant defense mechanism, causing oxidative damage and the damage of cellular components. High temperature disturbs the regulation of hormones with reduction of growth promoting hormones like auxin and cytokinin in maize, plus rise in senescence-related hormones such as ethylene and abscisic acid further contributing to early senescence (Zhang, 2019). The heat induced premature senescence in maize leads to significant impact on shortened grain filling period, grain filling and yield.

2.6 Yield

In maize, reproductive stage is the most susceptible stage to the prolonged period of high temperature. Heat stress during the reproductive stage results in dried-out silks, sterile pollen, and poor seed formation, all of which lower the grain yield (Lesk et al., 2016; Sánchez et al., 2014). It is the widely known view that high temperature facilitates faster grain filling rate but also shortens its duration in Maize (LI et al., 2022). There are several studies conducted to study the mechanism of this change in rate and duration of grain filling. (Zhang, 2019) found that the heat stress increases the area of vascular bundle explaining the faster transportation of the photo-assimilates, which is responsible for faster grain filling rate. Despite the enhanced sucrose transportation, heat stress also decreases the enzymatic activity responsible for the carbon metabolism in maize kernel (Yang et al., 2018). These results in an assemblance of sucrose in the kernels, limiting the movement of assimilate and significantly lowers the grain filling rate during the latter part of the grain-filling stage (Zhang, 2019). At the end, the loss of duration for grain filling outweighs the increase in grain filling rate resulting in less grain yield (Farooq et al., 2011).

3. Management of Heat Stress in Maize

3.1 Agronomic Practices

To avoid heat stress, farmers have to adjust their cropping practices. Early sowing of maize can be beneficial to avoid heat stress in maize during reproductive stage keeping in mind that this can expose plants to the lower soil temperature during early seedling stage, which influences development of the leaf (Waqas et al., 2021). According to (Tian et al., 2019), Adjusting planting time to escape heat stress during silking and grain filling stage significantly minimize the yield loss. Similarly, drip irrigation during night minimizes the soil temperature, increase the water use efficiency and hence reduce the effect of heat stress resulting in better yield (Dong et al., 2016). Irrigation also helps to reduce plant temperature through transpiration and can play important role in heat stress tolerance (Zhu & Burney, 2022).

Adequate amount of nutrient is essential for structural and physiological functions. Nutrient management can compensate the heat stress, for example, appropriate application of potassium fertilizer improves the stability of cell membrane (Tao & Zhang, 2010). PGRs applied during seed priming improve the performance of maize under heat stress condition (Hussain et al., 2019). Hormones such as BR helps to scavenge ROS (Arif et al., 2020), increase membrane stability, and improves the nutrient absorption along with formation of secondary metabolite (Waqas et al., 2019). The foliar application of AsA, H_2O_2 and SA improves growth, facilitate membrane stabilization and by induction of antioxidant activities and hence ameliorate the effects of high temperature in late grown spring maize (Ahmad et al., 2017).

3.2 Breeding

An essential first step to increasing maize yield in heat stress conditions is the development of high temperature-tolerant maize cultivars (Koirala et al., 2017). Availability of genetic variation and the knowledge of genetic parameters is also important (El-Sappah et al., 2022). Identification of ideal high temperature tolerant parents is key for breeding program. Utilizing of distant and wild relatives in intra-specific crosses could be highly beneficial tool for maize cultivar improvement (Waqas et al., 2019). A good strategy to increase heat tolerance is to breed heat tolerant cultivars. Various maize genotypes have been suggested for better performance in photosynthesis, plant canopy and yield under stressed condition (Sah et al., 2020). According to (Nguyen et al., 2019) the use of genetic markers in conjunction with next-generation sequencing (NGS) has also sped up a number of breeding technique developments. In addition, Marker based breeding along with genetic and metabolic engineering are encouraging breeding options for developing the heat stress tolerance in maize plant (El-Sappah et al., 2022).

4. Conclusion

With the climate change and rising global temperature, heat stress is the major concern for Maize production as it causes detrimental effects on various aspects of plants such as plant growth, photosynthetic activity, and reproductive development reducing the overall grain yield. Elevated temperatures lead to reduced plant height, leaf area, biomass, and ultimately, lower crop productivity. In addition, high temperature affects the photosynthetic efficiency, disturbing the assimilation of carbon by plants. The accumulation of reactive oxygen species (ROS) further intensifies the problem, resulting oxidative stress and damaging cellular components. Furthermore, along with these physiological effects, heat stress also disrupts crucial processes such as pollen development, pollination, and fertilization, resulting in reduced seed set and malformed grains. To alleviate the negative impacts of heat stress on maize, several strategies can be helpful, such as adjusting planting time, utilizing early maturing varieties, implementing effective irrigation techniques, managing nutrient levels, and breeding heat-tolerant maize varieties. Adopting these practices is of utmost importance, especially in the face of climate change, to ensure sustainable food production and enhance global food security.

Authors' Contributions

Mithun Poudel, as the first author, made significant contributions to the conception of the research topic, guided by the expertise of Dr. Mukti Ram Poudel. Mithun Poudel conducted an extensive literature review, critically analyzed the gathered information, and synthesized the relevant findings. Additionally, Mithun Poudel and Binu Dhungana were actively involved in the writing and structuring of the manuscript, ensuring clarity and coherence throughout the document. The invaluable guidance and mentorship provided by Dr. Mukti Ram Poudel played a crucial role in shaping the direction of the study and providing valuable insights during the entire research process.

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