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PHYSIOLOGICAL, MORPHOLOGICAL AND PHYTOCHEMICAL RESPONSES OF MAIZE TO ABIOTIC RESPONSES

ASHRAF M*

Department of Plant Breeding and Genetics, Faculty of Agricultural Sciences, University of the Punjab
P.O.Box.54590, Lahore, Pakistan
**Correspondence author email address: muzammilashraf9095140@gmail.com*

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Abstract *This review paper thoroughly analyses maize's morphological, physiological, and phytochemical responses to different abiotic stressors. As a staple cereal crop of global importance, maize has several challenges that significantly impact its growth and yield, including salinity, drought, and extreme temperatures. Climate change will generally impact plants' abiotic stress tolerance mechanisms, and maize specifically, despite many unanswered questions. Despite this, it is still impossible to draw wide conclusions because plants react differently to various stresses at different times. The review synthesizes current knowledge on the morphological adaptations, encompassing changes in root architecture and leaf morphology, as strategies maize employs to navigate adverse environmental conditions. Additionally, the article examines the physiological responses of maize, shedding light on mechanisms that enhance stress tolerance, including adjustments in water use efficiency, pH and the activation of cellular protective pathways. Furthermore, the review delves into the dynamic alterations in phytochemical profiles, highlighting maize's capacity to synthesize secondary metabolites as part of its adaptive arsenal. This comprehensive exploration of maize's responses to abiotic stressors contributes valuable insights for researchers, breeders, and policymakers working towards developing resilient maize varieties and sustainable agricultural practices in an ever-changing environment.*

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Introduction

Crops provide 80% of humans' food, with cereals making up half of the world's food production. (Langridge and Fleury, 2011; Salika and Riffat, 2021). A major annual cereal crop in the world, Zea mays L., also called corn or maize, is a member of the family Poaceae(Rouf Shah et al., 2016). Maize (*Zea mays* L.) originated between 7,000 and 10,000 years ago from the teosinte (Zea mays L. spp Mexicana) in the Western Hemisphere (García-Lara and Serna-Saldivar, 2019). Native Americans grew maize on a large scale(For example, in North Dakota, it was the first crop) (Benson, 2011; Hallauer and Carena, 2009) in the United States between 1600 and 1700 (Hallauer and Carena, 2009). Maize (*Zea mays* L.) is grown worldwide in diverse environments(Du Plessis, 2003). After wheat and rice, maize is The world's most significant cereal crop (Panda, 2010). Corn is called the "Queen of Cereals" dueto its high productivity(Kiran et al., 2018; Lone et al., 2021; Sravani et al., 2021). The main purposes of maize cultivation are grain, fodder, industrial processes, and various other products(Abdelaziz, 2020; Dinesh et al., 2018; Panda, 2010). Maize is a renewable fossil fuel substitute due to bioethanol production (Mohapatra et al., 2019; Zabed et al., 2017). Comprehending the effects of climate change on this staple crop's development and growth is essential to understanding maize yield. Abiotic stressors, including salinity, nutrient shortage, temperature extremes, and drought, are considered fundamental components of the environment that reduce the overall production of maize. According to recent research, the two most significant climate variables are temperature and precipitation; radiation is another important factor influencing its yield (Salika and Riffat, 2021; Xu et al., 2016).

Recently, extremes in temperature, droughts and waterlogging have significantly decreased maize growth and yield (Ahuja et al., 2010; Prasanna, 2016; Ren et al., 2014). 25–30% of maize is lost because of drought or waterlogging (Kaur et al., 2021; Lone et al., 2018; Srivastava et al., 2010). Mostly used in poultry diets across the globe, including India, it is the source of energy because of its high energy content, palatability, pigment content, and essential fatty acid content. Eggs yolks, poultry fat, and skin are naturally colored yellow, so yellow-kerneled cultivars are the best choice for feeding chickens because they are abundant in β-carotenes and xanthophylls (Kaul et al., 2019). Effective global measures must be implemented to enhance the yield per hectare of highly demanded crops and develop crops that are tolerant of harsh environmental circumstances. Maize is the most sought-after crop because it can be cultivated into sophisticated and resilient varieties to address the issues with global food security (Vinocur and Altman, 2005). To meet the demands of the expanding human population and adapt to the current climatic conditions, maize varieties must have improved resistance to abiotic stresses, particularly those related to heat and drought(Salika and Riffat, 2021). This means that the main focus of the current study will be on how maize responds to various abiotic stresses and climate change in terms of morphology, physiology, and photochemistry. Maize contains fat 4.57g (Ujong et al., 2023), protein 8.84% (Mandal et al., 2023), fiber 2.15g (Alexandru et al.), carbohydrates 71.88g (Bariw et al., 2020; Ujong et al., 2023), moisture 10.23% (Bariw et al., 2020), ash 2.33% (Tankem et al., 2023), phosphorus 0.348g (Mandal et al., 2023) and minerals 1.5g (Abbas et al., 2021; Rouf Shah et al., 2016).

Zea mays and Abiotic stress

Annual crop grain yields are decreasing globally at an accelerated rate due to abiotic stressors like drought and nutrient shortages(Hossain et al., 2021; Mueller et al., 2012). When analyzing how climate change affects crops, maize is most adversely affected (Bassu et al., 2014; Kang et al., 2009; Khan et al., 2019). The main environmental disturbances that harm global maize production are salinity, nutrient shortages, droughts, and extremely high or low temperatures (Ahuja et al., 2010; Salika and Riffat, 2021). Furthermore, some studies suggest that as temperatures rise in the world's major corn-producing regions, the maturity period may shorten (Sánchez et al., 2014; Zhao et al., 2017), While rising temperatures may cause changes in metabolism that result in a decrease in the absorption of carbon, which in turn causes a decline in pollination and grain set (Moriondo et al., 2011). The severe climate change scenario is expected to reduce corn yields by 10–20% by the end of the 21st century, even when maize receives all the water it requires (Xu et al., 2016). Simultaneously, world's agricultural system needs to produce 70% of the food required to feed a world population expected to reach 9 billion by 2050 (Rahman, 2016; Searchinger et al., 2014). Therefore, plant breeders continue to develop crops with more yield security in recent production systems, such as corn, by using genetic concepts and biotechnology techniques (Habben et al., 2014) All possible responses that corn might have to different abiotic stressors are listed in Figure 1.

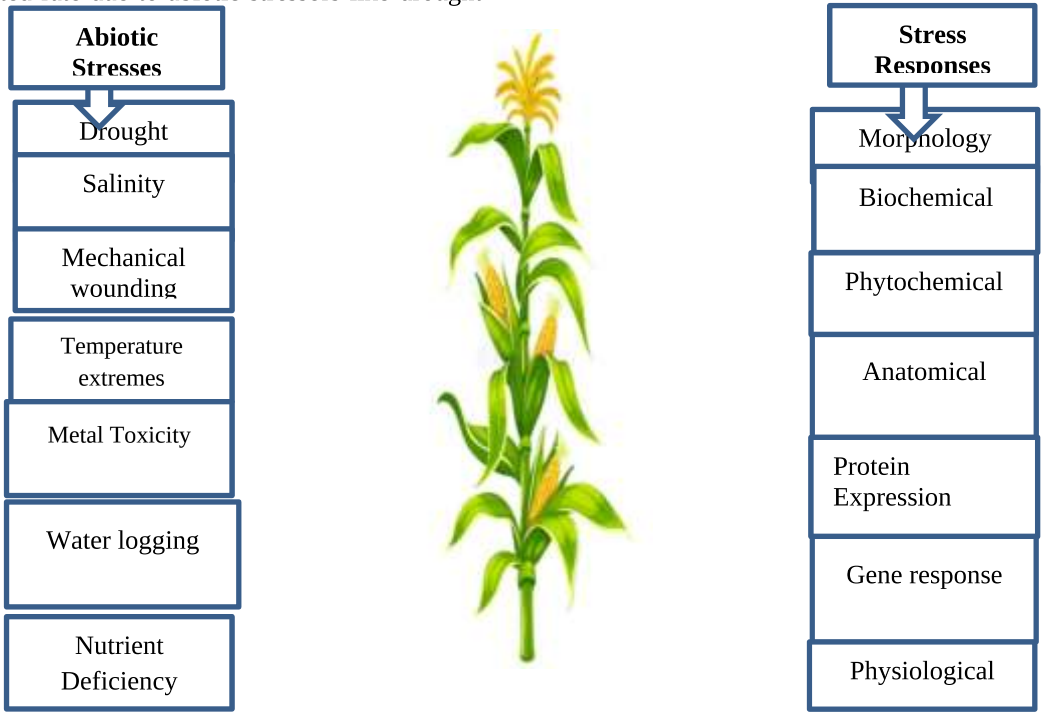


Figure: 1 Features of Abiotic Stressors in Maize and Their Reactions

Responses of the Maize Morphology to the Abiotic Stress

More diverse morphogenic responses are seen in plants in response to abiotic stressors (Potters et al., 2007). Because of its poorly developed root system and larger transpiration surface area, maize is generally thought to have poor drought tolerance (Camacho and Caraballo, 1994). The maize plant's aerial section exhibited most of its responses to the combined abiotic stress(Vescio et al., 2020) and its reproductive organs, most likely with the intention of breeding. To our knowledge, no data is accessible regarding how the combined heat stress and drought affect the maize root system (Hu et al., 2015). Considering that individual types of maize roots, including nodal and lateral postembryonic roots, and primary and seminal embryonic roots (Hochholdinger et al., 2018), have different reactions to external stimuli and may serve as a "source" for stress adaptation. Different responses of the different kinds of roots to drought stress(Hund et al., 2008; Zhan et al., 2015), allelochemicals(Abenavoli et al., 2004; Lupini et al., 2016), Phosphorus deficiency(Rubio et al., 2004), and to the combined drought stress and N deficiency reported (Lynch, 2013). While the plant's ability to control leaf growth is maintained in natural conditions by inadequate root development, which is highly correlated with soil temperature, the rate of leaf appearance under cold stress was found to be roughly three times slower than that of maize grown at normal temperature(Farooq et al., 2009).

It has been noted that there is no discernible decrease in root growth in maize under water stress (Cai et al., 2017), larger root lengths(Ali, 2016) and with smaller lateral roots in maize that is more resistant to drought (Ali et al., 2017; Cai et al., 2017). When a drought occurs, maize plants frequently adapt their root architecture to search for water in deeper soil layers (Hammer et al., 2009). Knowing better about the changes in the root dimensions that occur during droughts or any other type of stress is important. Hybrid maize seedlings under low-temperature stress exhibit markedly altered root morphology, with larger seminal roots, thicker axes, and swollen roots behind the tip(Farooq et al., 2009). decrease in growth parameters, including plant height, photosynthesis, and fresh and dry shoot weight (Ali et al., 2015; Aslam et al., 2013). Changes in maize leaf morphology due to high temperatures include a reduction in leaf size and shape (Ong and Baker, 1985). The weight of maize seedlings is decreased by osmotic stress(Moharramnejad et al., 2015). Crop yield losses are the direct or indirect result of all these detrimental effects on the morphology of the maize plant. Grain yield decreased when maize plants were subjected to water deficit conditions for longer than 12 days during grain filling and flowering (Li et al., 2018; Mangani et al., 2018). Additionally, during chilling, it has been discovered that significant alterations in tassel morphogenesis, as well as a reduction in the number of spikelet pairs and tassel branches, occur in maize, which results in losses in grain yield (Salika and Riffat, 2021; Thakur et al., 2010).

Responses of Maize Physiology to Abiotic Stress

There are wide differences in how low temperatures affect corn physiology (Wijewardana et al., 2016). Thermal thresholds for the ideal morphological development or physiological and biochemical activity in maize decrease metabolic and growth processes, damaging cells and tissues and reducing the genetically determined yield potential (Ali et al., 2013; Ali et al., 2016; Ali et al., 2010a; Cairns et al., 2012; Farooq et al., 2009). Within corn, A decrease in turgor pressure and cell elongation can result from dehydration of the cells(Kutschera and Niklas, 2013). Osmotic stress caused by salinity in maize can alter the plant's ability to move water (Farooq et al., 2015). Furthermore, changes in pH are caused by low temperatures across thylakoid membranes (Pasini et al., 2005). However, it was shown in a previous study that When an artificial electron acceptor was used to penetrate the leaves of maize, the light reaction of photosynthesis was unaffected by temperature (Fracheboud and Leipner, 2003; Salika and Riffat, 2021). In corn, Damage to cellular membranes can result from high temperatures (Ali et al., 2011; Ali et al., 2014; Ali and Malik, 2021; Tiwari and Yadav, 2019). Adding different kinds of suitable organic solvents is another important and widespread physiological stress response in plants (Bohnert and Shen, 1998). According to earlier research, a few solutes, including glycine betaine, sorbitol, mannitol, proline, and trehalose, function as osmoprotectants in water-stressed environments and support plant growth and development (Hadiarto and Tran, 2011; Slama et al., 2015). Maize may change metabolism to deal with stressful situations (Ali et al., 2010b; Iqra et al., 2020; Ramazan et al., 2022). Maize activates antioxidant systems to prevent cellular damage and scavenge reactive oxygen species (ROS) (Majid et al., 2017; Naveed et al., 2012; Prasad, 1996; Sarwar et al., 2021). For maize seedlings to adapt to oxidative stress brought on by chilling, they must be able to increase the synthesis and activity of various antioxidant enzymes, such as catalase (CAT), peroxidases (POD), and superoxide dismutase (SOD) (Hussain et al., 2020). In maize, osmoprotectants such as proline can accumulate to maintain cellular turgor and prevent dehydration (Zulfiqar et al., 2020). Additionally, abscisic acid (ABA), one of the plant growth regulators necessary for the plant's reaction to drought stress, is more abundant under osmotic stress (Muhammad Aslam et al., 2022; Rajasheker et al., 2019; Sarwar et al., 2022). However, Plant growth regulators are widely acknowledged to communicate and affect one another, and that interaction is necessary for plants to resist abiotic stress. Therefore, more research is required to understand the various plant growth regulators that completely enhance maize's resistance to abiotic stress.

Response of maize phytochemicals to abiotic stressors

Plants naturally contain bioactive chemicals called phytochemicals, which are good for human health and may reduce the chance of developing severe chronic illnesses(Xiao and Bai, 2019). Maize is an essential source of several significant phytochemicals, such as phytosterols, phenolic compounds, and carotenoids(MANN; Saeed and Saeed, 2020; Serna-

Saldivar et al., 2015; Zubair et al., 2016). Climate factors also influence the amount and make-up of protective phytochemicals, critical for resistance to biotic and abiotic stressors(Vaughan et al., 2018). Maize produces a range of resilience compounds in response to environmental stimuli, including flavonoids, cell wall components like lignin, and defense-related proteins(Vaughan et al., 2018). In addition to age and plant organ variation, benzoxazinoid concentration and composition amongst maize genotypes are also affected by weather patterns linked to climate change(Cambier et al., 2000; Salika and Riffat, 2021). It is well known that warmer temperatures promote maize growth and development(Sunoj et al., 2016), which might inadvertently alter the concentration of benzoxazinoid in maize tissues. Moreover, it is commonly recognized that the amount of nitrogen in the soil has a major influence on the potential for benzoxazinoid production (Brevik, 2013). It is believed that temperature, soil moisture, humidity, and light intensity are all factors in creating volatile organic compounds (VOCs) in maize. It's interesting to note that when soil moisture content varies, maize releases volatiles. Additionally, plants release more volatiles into dry soil than wet soil(Gouinguené and Turlings, 2002). A recent review provided detailed information on the possible impacts of climate change on the production of volatile organic compounds (VOCs) from various plant sources(Peñuelas and Staudt, 2010). An interaction between ethylene and jasmonic acid (JA) results in an elevated rate of terpenoid phytoalexin biosynthesis in maize stalks(Liu et al., 2023). Still, in maize roots, it is induced by applying ABA exclusively to the underground portions (Salika and Riffat, 2021), demonstrating the diverse regulatory mechanisms across the different plant organs. It has been demonstrated that the buildup of terpenoid phytoalexins in maize is impacted by both drought and elevated [CO2] (Vaughan et al., 2015; Vaughan et al., 2016) Moreover, the production of salicylic acid (SA) and JA is compromised when maize plants grow at high [CO2] levels(Tahjib-Ul-Arif et al., 2018; Wani et al., 2017). Furthermore, further study is required to fully understand the intricate processes by which crop plants produce volatile organic compounds (VOCs) in reaction to various stressors. This scenario occurs frequently in nature.

Abiotic stress coupled with climate change: A problem for maize

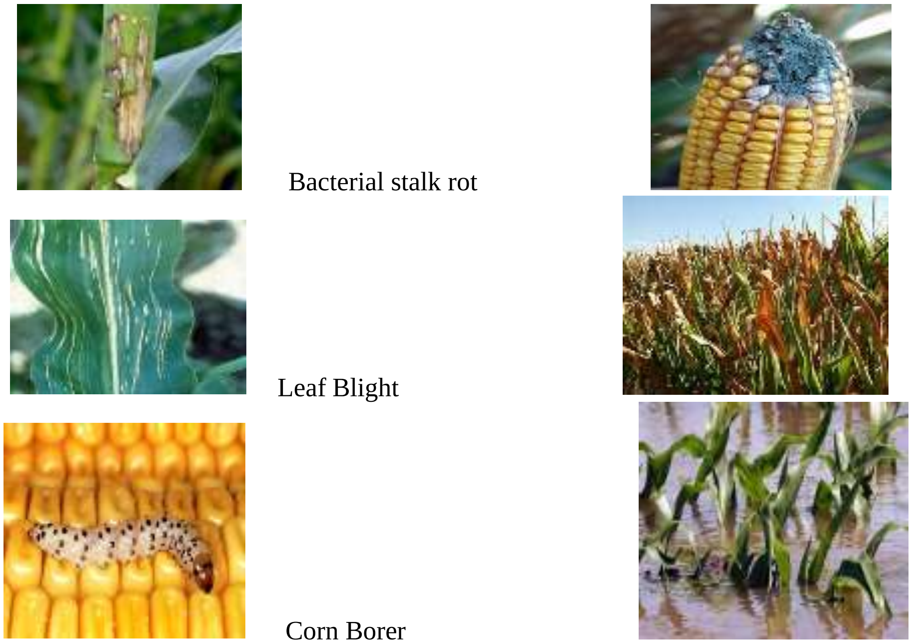
Plant growth, development, and productivity can be adversely influenced by non-living environmental elements known as abiotic stresses(Mosa et al., 2017). Increasing temperatures due to climate change can lead to heat stress, adversely affecting maize growth(Deryng et al., 2014); the overall yield of maize, the development of kernels, and the success of pollination during the reproductive stage can all be negatively impacted by high temperatures(Wang et al., 2021). Frost can harm immature plants and develop tassels in maize, which lowers yield(Miedema, 1982). Maize is sensitive to dehydration, and inadequate water availability during critical growth stages can reduce yields (Comas et al., 2019; Jain et al., 2019). Storms, hurricanes, and floods are more frequent and powerful climate events that can harm maize crops, resulting in lower yields and a higher vulnerability to disease (Elias et al., 2019). Abiotic stressors include high concentrations of ultraviolet B and ultraviolet A radiation, temperature extremes, Water as a drought-causing stressor, submergence and flooding, massive concentrations of Na+, sharp variations in the amount of essential nutrients, air pollutants (ozone, sulfur dioxide) that cause salt stress, mechanical stressors, heavy metal presence, and other less frequent variables, as well as chemical stressors like acidic pH (Suzuki et al., 2014). Abiotic stress has been shown to significantly affect crop productivity in the last few decades, both in terms of frequency and intensity, in addition to extreme weather (Venkateswarlu and Shanker, 2011). Climate change will, as expected, have the greatest effect on crop productivity and agricultural wealth; this impact will particularly noticeable in developing nations situated at lower latitudes(Wheeler and Von Braun, 2013). Therefore, It is necessary to develop pathogen-resistant and climate-resilient varieties of maize to meet the increasing demands of the world's expanding human population. Here are some types of biotic and abiotic stress that impact maize productivity.


Weevil


Sugarcane Mosaic


Aflatoxin maize


Drought



Bacterial stalk rot

Ear Rot

Leaf Blight

High temperature

Corn Borer

Flooding

Fig. 3 Stress factors, both biotic and abiotic, that affect maize productivity

Conclusion

Climate plays a significant impact on plant growth and agricultural productivity. A suitable climate is necessary to ensure proper soil moisture levels during these periods, as maize is especially sensitive to water stress. The morphological, physiological, and phytochemical reactions of maize to abiotic stressors highlight the morphological changes that have been noticed, such as adjustments to leaf morphology and root architecture in response to environmental stresses. Physiological responses demonstrate the plant's resistance to unfavorable circumstances. These responses include modifications to pH, water use efficiency, and stress tolerance mechanisms. Moreover, the modulation of phytochemical profiles in the crop reveals maize's ability to produce secondary metabolites as a defense mechanism against abiotic stressors. Therefore, to protect and improve maize productivity and the economy in the future, a thorough understanding of maize's various morphological, physiological, and biochemical responses to one or more abiotic stresses concerning climatic fluctuations is required. Furthermore, it is necessary to comprehend several other significant uncertainties, such as canopy and CO2 effects. This thorough review would give the scientific community a better perspective for upcoming research aimed at producing maize at the commercial and industrial scale in both quality and quantity efficiently and sustainably.

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Declarations

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All data generated or analyzed during the study are included in the manuscript.

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Regarding conflicts of interest, the authors state that their research was carried out independently without any affiliations or financial ties that could raise concerns about biases.