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Advancing Crop Resilience: Altering Physiological Traits To Address Climate Change Challenges

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Abstract

Climate change is a major driver of food insecurity, demanding urgent action and effective measures to prevent millions from falling into hunger and poverty. Subsistence farming communities and vulnerable populations are particularly at risk from climate-related hazards. Changes in future weather patterns including fluctuations in precipitation, increased frequency of floods, droughts, heat waves, and windstorms are expected as the climate continues to shift. These unpredictable and extreme weather events, coupled with shifting growing seasons, are causing inconsistent crop yields, threatening both food security and livelihoods around the world. In this context, promoting climate-resilient agriculture is essential for ensuring sustainable food systems and providing stable income for rural communities. This approach involves adopting farming practices and technologies that can endure and adapt to changing environmental conditions. A key strategy under review is the development of 'smart crops' through the enhancement of plant physiological traits, enabling them to thrive in the face of climate variability.

Keywords: Food insecurity, climate-resilient agriculture, Crop yield, smart crops physiological traits.

Introduction

The constant increase in the accumulation of greenhouse gases, in particular CO₂, has driven a dangerous rise in global land surface and ocean temperatures, termed global warming. This process is causing an increase in the frequency and intensity of drought episodes, heat waves, cold snaps, and flooding, termed climate change (Anderegg et al., 2020). In addition, many pathogen and pest outbreaks have been linked to changes in climate trends, such as increases in the frequency and intensity of drought episodes, heat waves, or flooding events (Salih et al., 2020). Meanwhile, different abiotic or biotic stresses described above emerge serious threat to agricultural production of major crops (Zandalinas et al., 2021). It is important to understand how different stresses emerge due to changing climate interact and affect plant growth, yield, and survival. Consequently, predicting the effects of climate change on plant growth and development, plant reproduction, and the interactions of plants with other organisms (including the soil microbiome)(Zhang and Sonnewald, 2017; Zandalinas et al., 202). Stress causes a disruption in plant homeostasis affecting key metabolic and physiological processes such as photosynthesis, stomatal regulation, Water- and nutrient-use efficiency and, hike CO₂ limiting energy production, and endangering cellular integrity.

Heat stress, salinity and drought caused water deficit stress in plants which leads to intense stomata closure consequently modulates the gas exchange and hindered the electron flow during light reaction in photosynthesis process (Jahan et al, 2023). The main problem plants face during stress combination is that the two different stresses simultaneously affecting the plant could require different and sometimes opposing physiological and metabolic responses. Using the example of drought and heat stresses, when combined, these two different stresses require opposing stomatal responses. Because different stresses may affect plants differently, the acclimation or adaptation responses of plants to each different stress condition might require a different strategy (Hsu et al., 2021).

In recent years, much attention has been given to developing strategies to alleviate plants from several kind of stress caused by changing climate

Impact of changing climate on plant physiology

Photosynthetic Efficiency in Crops

Photosynthesis is particularly vulnerable to the combined effects of environmental stresses. Numerous studies have shown that photosynthetic efficiency and transpiration rates decline under conditions such as drought, salinity, and heat stress (Perdomo et al., 2017). This decline is primarily attributed to two key factors: (i) **Reduced carbon assimilation** caused by stomatal closure, which limits the uptake of carbon dioxide and (ii) **Damage to the photosynthetic machinery**, especially the integrity of photosystem II, which is sensitive to high temperatures (Li et al., 2020; Jahan et al., 2023b). Additionally, research

suggests that the simultaneous occurrence of drought and heat stress leads to a significant reduction in both the steady-state levels and the functional performance of chloroplast nucleoids complexes of DNA and proteins essential for chloroplast gene expression and function (Shaar-Moshe et al., 2017).

Stomatal regulation

To avoid damage from drought and heat stress, plants adjust both the number and function of their stomata (Chávez-Arias et al., 2021). Stomatal pores open to allow the intake of CO₂ for photosynthesis and close to limit water loss through transpiration (Blatt et al., 2017). It is well established that drought stress triggers stomatal closure, thereby reducing water loss (Taiz and Zeiger, 2006). However, as rising temperatures and shifting precipitation patterns pose new challenges for crop production, the regulation of stomatal behavior becomes increasingly important. Although drought-induced stomatal closure limits transpiration and enhances water use efficiency, it also restricts photosynthesis. This trade-off highlights the complex role of stomatal regulation in maintaining both plant productivity and soil moisture under climate stress conditions (Webber et al., 2018).

Water- and Nutrient-Use Efficiency

Stomatal closure under stress conditions is closely associated with reduced water-use efficiency (WUE), a critical factor in how crops respond to osmotic stress. WUE is defined as the amount of carbon assimilated into biomass or grain yield per unit of water consumed by the crop (Hatfield and Dold, 2019). For over a century, WUE has been a major focus of crop improvement efforts, as water availability remains one of the primary environmental constraints on agricultural productivity. An initial rise in atmospheric CO₂ levels can enhance WUE, since higher CO₂ concentrations typically promote photosynthesis (Rivero et al., 2022). However, if additional stresses occur that disrupt stomatal regulation, this potential gain in WUE may be offset. As a complex, multi-faceted trait, WUE is influenced by several physiological and structural plant factors, including photosynthetic rates, stomatal and mesophyll conductance, and the overall architecture of the crop canopy (Leakey et al., 2019).

Physiological Trait	Impact of Climate Stress	Enhancement Strategies	References
Photosynthetic Efficiency	Decreased under drought, heat, combined stresses	Optimize Rubisco activity, improve chloroplast integrity	Perdomo et al. (2017); Li et al. (2020)
Stomatal Regulation	Stomatal closure reduces CO ₂ uptake, affecting photosynthesis but enhances WUE	Genetic manipulation for optimal stomatal density, ABA signaling	Hsu et al. (2021); Chávez-Arias et al. (2021)

Physiological Trait	Impact of Climate Stress	Enhancement Strategies	References
Water- and Nutrient-use Efficiency	Reduced under stress; critical for yield stability	Engineering root and vascular systems, microbiome interactions	Leakey et al. (2019); Govindasamy et al. (2023)

Physiological Modulation for Developing Climate-Resilient Crops

High CO₂ tolerance plants

Enhancing tolerance to stress combinations with special attention to different climate scenarios that include the simultaneous exposure of crops to heat combined with drought, salinity, flooding, high CO₂ levels, and/or pathogen attack. This task will require better understanding of the specific physiological, metabolic, and signaling mechanisms involved in crop responses to changing climate (Guo et al., 2012; Zhang et al., 2018).

Enhancement water and nutrient use efficiency crop

Increasing WUE and NUE, through root, stomata, vascular tissue, and biochemical and regulatory engineering, as well as through enhancing plant–microbiome interactions at the rhizosphere, endosphere, and phyllosphere. In this respect, genome-wide studies of crops and microbiomes, coupled with a deep metabolomic analysis and imaging, would be essential (Quemada, & Gabriel, 2016; Govindasamy et al., 2023).

Improve photosynthesis to lead high yielding crop

Optimizing photosynthetic efficiency by altering the abundance of photosynthetic proteins and minimizing photorespiration, contributing to the enhancement of photosynthetic light efficiency and CO₂ assimilation. Additional targets for this goal include, manipulating stomatal density and stomatal aperture control mechanisms, and optimizing light capture by a wider proportion of the plant canopy (Evans, 2013; Araus et al., 2021; Matthews, & Burgess, 2024). Any modification in photosynthesis also influenced final crop yield production as well as quality. Improving plant reproduction and seed filling processes under conditions of stress combination. This goal could be achieved by improving the heat and desiccation tolerance of flowers and by improving allocation of photoassimilates from leaves to flowers. Special emphasis should be given to scenarios of stress combinations that include heat stress, as heat was found to have a severe effect on flowering and reproduction.

Conclusion and future perspective

Utilizing biotechnological tools to develop climate-resilient crops is a key strategy for improving agricultural adaptability. Breeding programs aimed at addressing abiotic stress caused by climate change have proven highly effective in enhancing food production and resilience. To tackle the challenges of climate change, it is essential to thoroughly explore the physiological, genetic, and molecular foundations of these crops. Identifying and focusing on traits that provide resilience to climatic stress is crucial for advancing next-generation breeding (NGB) strategies. The knowledge of the upcoming climate changes together with the prediction of the developmental and physiological responses of crop will allow not only to anticipate crop yield in the next years, but also to contribute to the correct decision-making in the management of this important crop

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