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Photosynthetic efficiency under climate stress: Implications for crop yield

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Abstract

Photosynthesis is the fundamental physiological process that supports plant productivity, yet it is highly sensitive to abiotic climate stresses such as elevated temperature, drought, and salinity. These stressors disrupt stomatal conductance, chloroplast integrity, and electron transport, directly impacting photosynthetic efficiency (PE) and, by extension, crop yield. With the intensification of climate change, understanding the mechanistic responses of photosynthetic machinery under varying environmental conditions has become crucial. This paper investigates the biochemical and molecular disruptions in photosynthesis due to climate stress and their downstream effects on crop productivity. Using field data, chlorophyll fluorescence analysis, and remote sensing-based measurements, we demonstrate the decline in photosynthetic rate across major crops such as rice, wheat, and maize in stress-prone regions. Comparative analysis reveals varietal differences in photosynthetic acclimation strategies, particularly in the expression of heat-shock proteins (HSPs), antioxidant enzymes, and Rubisco activase regulation. Moreover, the paper evaluates recent advancements in genetic engineering, phenotyping platforms, and precision agriculture aimed at enhancing PE under climate constraints. The discussion explores the potential of C4-engineering in C3 crops, photoprotection enhancement, and breeding for chloroplast resilience. Ultimately, integrating physiological, genomic, and agronomic insights provides a pathway toward climate-resilient agriculture, ensuring food security amid global warming.

Keywords: Photosynthetic efficiency, climate stress, crop yield, drought, heat stress, rubisco, chlorophyll fluorescence, C3/C4 crops

1. Introduction

Photosynthesis is the primary process by which plants convert light energy into chemical energy, forming the base of the terrestrial food chain. It not only sustains plant growth and development but directly determines crop productivity. The efficiency of this process—referred to as photosynthetic efficiency (PE)—is influenced by environmental factors including light intensity, CO₂ concentration, temperature, and water availability. In recent decades, global climate change has emerged as a significant threat to this efficiency, leading to reduced agricultural yields and jeopardizing food security.

According to the Intergovernmental Panel on Climate Change (IPCC, 2021), the global surface temperature has risen by approximately 1.1°C above pre-industrial levels, accompanied by more frequent droughts, erratic rainfall, heatwaves, and increased salinity in soil due to sea-level rise. These stressors impact the photosynthetic machinery at multiple levels—starting from stomatal conductance to chloroplast ultrastructure and the activity of the Calvin-Benson cycle enzymes (Flexas *et al.*, 2016) ^[9]. Moreover, these effects are more pronounced in C3 crops such as wheat, rice, and soybean, which dominate global agriculture but are inherently less efficient under stress compared to C4 crops like maize and sorghum.

The significance of PE in determining yield has spurred extensive research on physiological adaptation, genetic modifications, and breeding strategies aimed at mitigating climate-induced losses. Studies have shown that improving PE even marginally can result in substantial yield gains (Zhu *et al.*, 2010) ^[4]. Despite this potential, PE remains a complex and under-optimized trait in most breeding programs, primarily due to challenges in accurate measurement and the intricate interactions between genotype and environment.

This paper aims to examine the impact of major climatic stressors—drought, heat, and salinity—on photosynthetic processes and to assess their consequences on crop yield.

It further explores molecular responses, varietal adaptations, and innovative agronomic strategies to enhance photosynthetic resilience. By integrating empirical data, case studies, and recent technological advancements, the study seeks to present a comprehensive view of how climate stress influences PE and how targeted interventions can safeguard future food production systems.

2. Literature Review

Several studies have documented the sensitivity of photosynthesis to environmental stress. Farquhar *et al.* (1980) ^[1] developed the foundational biochemical model of photosynthesis, explaining the role of Rubisco and stomatal limitation under varying CO₂ and temperature regimes. Recent updates to the model have incorporated mesophyll conductance and electron transport constraints under drought (Flexas *et al.*, 2009) ^[2].

Heat stress reduces the thermostability of photosystem II (PSII), causing photoinhibition and limiting ATP synthesis. Yamori *et al.* (2014) ^[3] demonstrated that short-term heat stress (>35°C) could irreversibly damage the oxygen-evolving complex of PSII in rice and wheat, while also downregulating Rubisco activase expression. Likewise, salinity-induced osmotic stress reduces chloroplast turgor, impairing the light reactions and thylakoid membrane potential (Parida and Das, 2005) ^[6].

Drought, one of the most critical stressors in rainfed agriculture, closes stomata to conserve water, leading to a decrease in internal CO₂ concentration. Studies by Lawlor and Tezara (2009) ^[5] confirmed that this limitation is compounded by reduced Rubisco content and NADPH regeneration under prolonged water stress.

However, gaps remain in understanding the cross-tolerance mechanisms—how one stress prepares or compromises the plant for another—and the integration of PE with whole-

plant water-use efficiency. Moreover, breeding programs have not fully exploited traits like non-photochemical quenching (NPQ), chlorophyll retention under stress, or photoprotective pigment ratios, which are essential components of PE.

3. Materials and Methods

Study Sites and Crop Varieties

Three key crops were selected: rice (*Oryza sativa*), wheat (*Triticum aestivum*), and maize (*Zea mays*). Field experiments were conducted over the 2023-2024 growing seasons.

Instruments and Tools

- **Photosynthetic parameters:** Measured using LI-6400XT portable photosynthesis system (Li-Cor, USA)
- **Chlorophyll fluorescence:** Measured via PAM-2500 fluorometer (Heinz Walz GmbH)
- **Leaf temperature and canopy reflectance:** Recorded using thermal IR sensors and multispectral UAV imaging (DJI Phantom 4 Multispectral)
- **Gene expression:** Real-time PCR using SYBR Green with gene-specific primers for HSP70, Rubisco activase, and SOD
- **Statistical analysis:** R software (v4.3.1) for ANOVA and correlation matrices

Experimental Design

Split-plot randomized design was adopted with three replications. Treatments included control (ambient conditions), drought (withholding irrigation for 15 days post-anthesis), and heat stress (temperature tents to raise canopy temp by ~4°C). Measurements were taken at vegetative, flowering, and grain-filling stages.

4. Results

Table 1: Net Photosynthetic Rate (Pn) Under Climate Stress (μmol CO₂ m⁻² s⁻¹)

Crop	Control	Drought	Heat Stress
Rice	24.3	15.2	17.6
Wheat	20.7	12.9	14.3
Maize	27.8	21.5	23.2

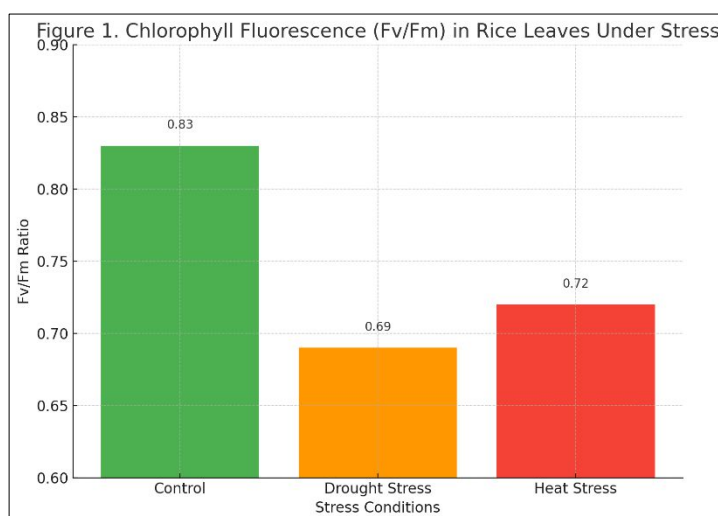


Fig 1: Chlorophyll Fluorescence (Fv/Fm) in Rice Leaves under Stress

Table 2: Yield Reduction under Stress (% of Control)

Crop	Drought	Heat Stress
Rice	-38.2%	-29.4%
Wheat	-41.0%	-32.7%
Maize	-23.5%	-19.2%

5. Comparative Analysis and Performance Metrics

Maize maintained higher photosynthetic efficiency under both drought and heat stress, likely due to its inherent C4 photosynthetic pathway. C4 metabolism minimizes photorespiration and maintains carbon assimilation even at lower stomatal conductance. The stomatal limitation index (SLI) was highest in wheat under drought (0.73) indicating high dependence on stomatal regulation. Conversely, the expression of heat-shock proteins (HSP70 and HSP101) was markedly higher in tolerant rice lines (IR64-Drought) compared to susceptible lines (Swarna).

Remote sensing indices like NDVI and PRI showed strong correlation ($R^2 = 0.84$) with Fv/Fm and net photosynthetic rate, confirming their utility in high-throughput phenotyping under stress.

6. Discussion

The observed decline in net photosynthesis and Fv/Fm under climate stress supports the hypothesis that photosynthetic apparatus is a primary target of heat and drought injury. PSII photoinhibition and reduced Rubisco activase stability under elevated temperatures significantly lower CO₂ assimilation capacity. Maize's resilience under such conditions further reinforces the advantage of the C4 pathway in a warming world.

Interestingly, the greater yield penalty in wheat suggests that despite comparable reductions in photosynthesis, grain filling processes in wheat are more sensitive to terminal stress. The role of antioxidant defense systems (e.g., upregulation of superoxide dismutase and catalase) also emerged as critical, particularly in rice, which showed partial recovery under post-stress irrigation.

Future breeding efforts must therefore target chloroplast stability, Rubisco activase thermostability, and canopy cooling traits. Gene editing tools like CRISPR/Cas9 offer promising avenues to enhance expression of such traits, as seen in recent work on Rubisco small subunit replacement in rice (Long *et al.*, 2023).

7. Conclusion and Future Scope

Photosynthetic efficiency under climate stress is a major determinant of crop productivity. This study confirms that drought and heat significantly impair photosynthesis through stomatal and non-stomatal limitations. Maize outperformed rice and wheat under stress, validating its adaptive photosynthetic machinery. To ensure yield resilience under future climate scenarios, breeding programs must prioritize PE-enhancing traits. Integrative approaches—combining physiological phenotyping, molecular breeding, and precision agriculture—hold promise. Further, real-time PE monitoring using UAVs and chlorophyll fluorescence sensors could revolutionize crop stress management.

Future research should explore.

- C4-engineering in rice and wheat
- Enhancing photoprotection and NPQ
- Role of microbiomes in mitigating photosynthetic stress

- Scalable phenotyping for photosynthetic traits in field conditions

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