identify precise intervention points for enhancing drought tolerance through targeted genetic or chemical strategies. A second major gap concerns the translation of controlled-environment findings to field conditions where drought interacts with heat, high vapor pressure deficit, and variable soil nutrient availability. Most mechanistic studies are conducted in growth chambers or greenhouses with uniform stress application, yet field drought is inherently heterogeneous in timing, severity, and duration. The interactive effects of drought with other abiotic stresses on photosynthetic electron transport and antioxidant redox signaling are insufficiently characterized in wheat. Additionally, the genetic architecture underlying the coordination of photosynthetic efficiency and antioxidant capacity is not fully resolved. While individual transcription factors and signaling modules have been identified, the regulatory networks that integrate chloroplast-to-nucleus retrograde signaling, ABA pathways, and antioxidant gene expression under recurrent drought cycles remain largely uncharacterized. These gaps raise key questions about how priming and acclimation memory are molecularly encoded and whether they can be reliably induced in diverse wheat genetic backgrounds.

Future research should prioritize dynamic, non-destructive monitoring of photosynthetic and antioxidant responses in wheat leaves under realistic field drought scenarios. Advances in chlorophyll fluorescence imaging, thermography, and hyperspectral reflectance offer the potential to track spatial and temporal heterogeneity in photosynthetic performance and canopy temperature at high resolution. Coupling these phenotyping tools with real-time ROS detection probes and redox-sensitive reporters would enable researchers to map the kinetics of oxidative stress and antioxidant activation at the tissue and subcellular levels. Such approaches could reveal the critical thresholds at which protective mechanisms fail and identify the earliest markers of irreversible photosynthetic damage. Integrating these physiological measurements with unmanned aerial vehicle-based multispectral imaging would further bridge the gap between leaf-level mechanisms and canopy-level drought responses in breeding nurseries and production fields. A second priority is the dissection of regulatory networks that coordinate photosynthetic protection with antioxidant defense through multi-omics integration. Combining transcriptomics, proteomics, metabolomics, and redox proteomics across time-series drought and rewatering cycles could identify the key nodes where ABA, ROS, and retrograde signaling converge to regulate both systems. Genome-wide association studies and CRISPR-based functional validation should target genes controlling the balance between ROS signaling and oxidative damage, particularly those governing the AsA-GSH cycle and PSII repair. Finally, research should explore how exogenous substances-such as strigolactones, melatonin, and glycine betaine-can be deployed under field conditions to prime antioxidant capacity and sustain photosynthesis during critical reproductive stages. Translating these findings into precision agriculture frameworks, where irrigation timing, nutrient management, and cultivar selection are optimized together, will be essential for maintaining wheat productivity under increasingly unpredictable drought regimes.

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Conflict of Interest Disclosure

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