informative variables for cultivar discrimination. Controlled screening studies similarly showed that tolerant genotypes maintain higher chlorophyll content, relative water content, membrane stability, gas exchange, and antioxidant activity than sensitive lines, confirming that drought tolerance in wheat is a composite physiological syndrome rather than a single trait (Ahmad et al., 2022). This supports selection frameworks that combine carbon-assimilation traits with oxidative-stress markers.

Precision agriculture tools now make this integrated screening scalable at breeding and field levels. Canopy temperature is already a low-cost, large-scale indicator with a negative linear relationship to grain yield during grain filling under drought. Spectral approaches further improve throughput: NDWI and the red-edge chlorophyll index closely tracked drought-tolerance indices in field trials and can serve as inexpensive alternatives for identifying tolerant genotypes, while multi-environment phenotyping showed that NDVI and MTSI are effective tools for identifying stable drought-tolerant germplasm across locations. UAV-based crop-health indices also correlated with yield in sodic rain-fed environments and successfully separated tolerant from sensitive genotypes, and sensor-based irrigation-gradient platforms validated NDVI, PRI, and fluorescence-related indices as non-destructive selection tools for breeding programs (Soares et al., 2025). Overall, agricultural regulation of wheat drought resistance is most effective when mild, stage-specific water deficit, targeted nutritional or exogenous support, and integrated phenotyping-based cultivar selection are used together. In the context of wheat leaves, these approaches converge on the same physiological objective: preserving photosynthetic capacity while strengthening antioxidant protection under limited water supply.

9 Conclusions and Future Perspectives

Drought stress imposes a coordinated physiological challenge on wheat leaves, simultaneously disrupting carbon assimilation and accelerating reactive oxygen species (ROS) accumulation. The initial response is predominantly stomatal: as leaf water potential declines, stomata close to conserve water, which restricts CO_2 influx and immediately reduces net photosynthetic rate. This stomatal limitation is the earliest diffusive barrier to photosynthesis, but it rapidly triggers downstream metabolic constraints. With restricted CO_2 fixation, the Calvin cycle slows, NADP+ regeneration fails to keep pace, and the photosynthetic electron transport chain becomes over-reduced. This excess excitation energy drives electron leakage to molecular oxygen, generating superoxide and hydrogen peroxide primarily in the chloroplasts, peroxisomes, and mitochondria. The resulting oxidative stress damages membranes through lipid peroxidation, impairs PSII repair cycles, and degrades photosynthetic pigments, creating a destructive feedback loop where impaired photosynthesis generates more ROS, and ROS further inhibit photosynthesis. Tolerant wheat genotypes break this cycle through the coordinated activation of photoprotective and antioxidant mechanisms. Non-photochemical quenching dissipates excess light energy as heat, while enzymatic antioxidants-superoxide dismutase, catalase, ascorbate peroxidase, and glutathione reductase-detoxify ROS in a compartment-specific manner. The ascorbate-glutathione cycle plays a central role in maintaining redox homeostasis by continuously regenerating reduced antioxidant pools. Non-enzymatic antioxidants, including ascorbate, glutathione, carotenoids, and proline, provide additional buffering capacity. Crucially, ROS at controlled concentrations also function as signaling molecules, activating ABA-dependent and ABA-independent pathways that upregulate stress-responsive genes. This dual role of ROS-as toxic byproducts and essential signals-means that drought tolerance is not achieved by maximizing ROS elimination but by maintaining redox balance within a signaling-compatible range. The integration of photosynthetic protection, antioxidant defense, and hormone-mediated signaling networks ultimately determines whether a wheat leaf survives, acclimates, or suffers irreversible damage under drought.

Despite extensive documentation of drought-induced physiological changes in wheat, several critical gaps remain in understanding the temporal and spatial coordination of photosynthetic and antioxidant responses. Most studies measure antioxidant enzyme activities and photosynthetic parameters at discrete time points, providing only a snapshot of dynamic processes that unfold over hours to weeks. The real-time kinetics of ROS generation, antioxidant activation, and photosynthetic decline within specific subcellular compartments remain poorly resolved. Furthermore, the threshold at which ROS shift from signaling molecules to destructive agents is not clearly defined for wheat leaves under field-relevant drought conditions. This knowledge gap limits the ability to