Hydrogen Peroxide

Signaling Mechanisms and Crosstalk in Plant Development and Stress Responses

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Contents

6 Physiological and Molecular Inferences of Plant Hydrogen Peroxide Metabolism During Stress Conditions

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INTRODUCTION

Hydrogen peroxide (H_2O_2) stands as a pivotal player in the intricate tapestry of plant biology, contributing to diverse physiological processes essential for growth, development, and responses to environmental challenges. This small, reactive oxygen species (ROS) molecule serves as both a signaling messenger and a double-edged sword, participating in fundamental cellular events and orchestrating defense strategies against various stressors. Arising primarily as a byproduct of aerobic metabolism within cellular organelles such as chloroplasts, peroxisomes, and mitochondria, H_2O_2 levels are tightly regulated to maintain redox homeostasis in plants. Its production, however, is not limited to routine metabolic activities. Environmental stimuli, ranging from biotic factors like pathogen attacks to abiotic stresses such as drought and high light intensity, can stimulate a surge in H_2O_2 levels. This surge often acts as a molecular herald, prompting plants to activate intricate defense mechanisms. H_2O_2 operates as a versatile secondary messenger in cellular signaling pathways. It plays a crucial role in modulating gene expression, influencing the activation of stress-responsive genes, and orchestrating adaptive responses. Under pathogenic assaults, H_2O_2 induces programmed cell death and hypersensitive responses, limiting the spread of pathogens within plant tissues. Moreover, H_2O_2 contributes to abiotic stress tolerance, facilitating the activation of genes that enhance resilience against environmental challenges. Its involvement in redox signaling extends to the modification of proteins, particularly redox-sensitive enzymes, and transcription factors (TFs), further shaping the molecular landscape in response to changing conditions. The delicate balance between H_2O_2 production and scavenging through antioxidant systems is paramount. Plants deploy a sophisticated arsenal of enzymes, including catalase, peroxidase (POX), and superoxide dismutase (SOD), to detoxify excess hydrogen peroxide and mitigate potential cellular damage. As research advances, unraveling the nuances of H_2O_2 involvement in plant processes becomes imperative. The knowledge gleaned holds significant promise for deciphering stress response mechanisms, enabling the development of strategies for crop improvement and fostering agricultural sustainability in the face of a changing climate (Figure 6.1).

OVERVIEW OF ABIOTIC STRESS AND ITS IMPACT ON PLANT GROWTH AND DEVELOPMENT

In contrast to animals, plants exhibit a sessile nature and continually face disruptions from unfavorable abiotic factors such as salinity, cold, heat, drought, and heavy metal stresses. These stressors

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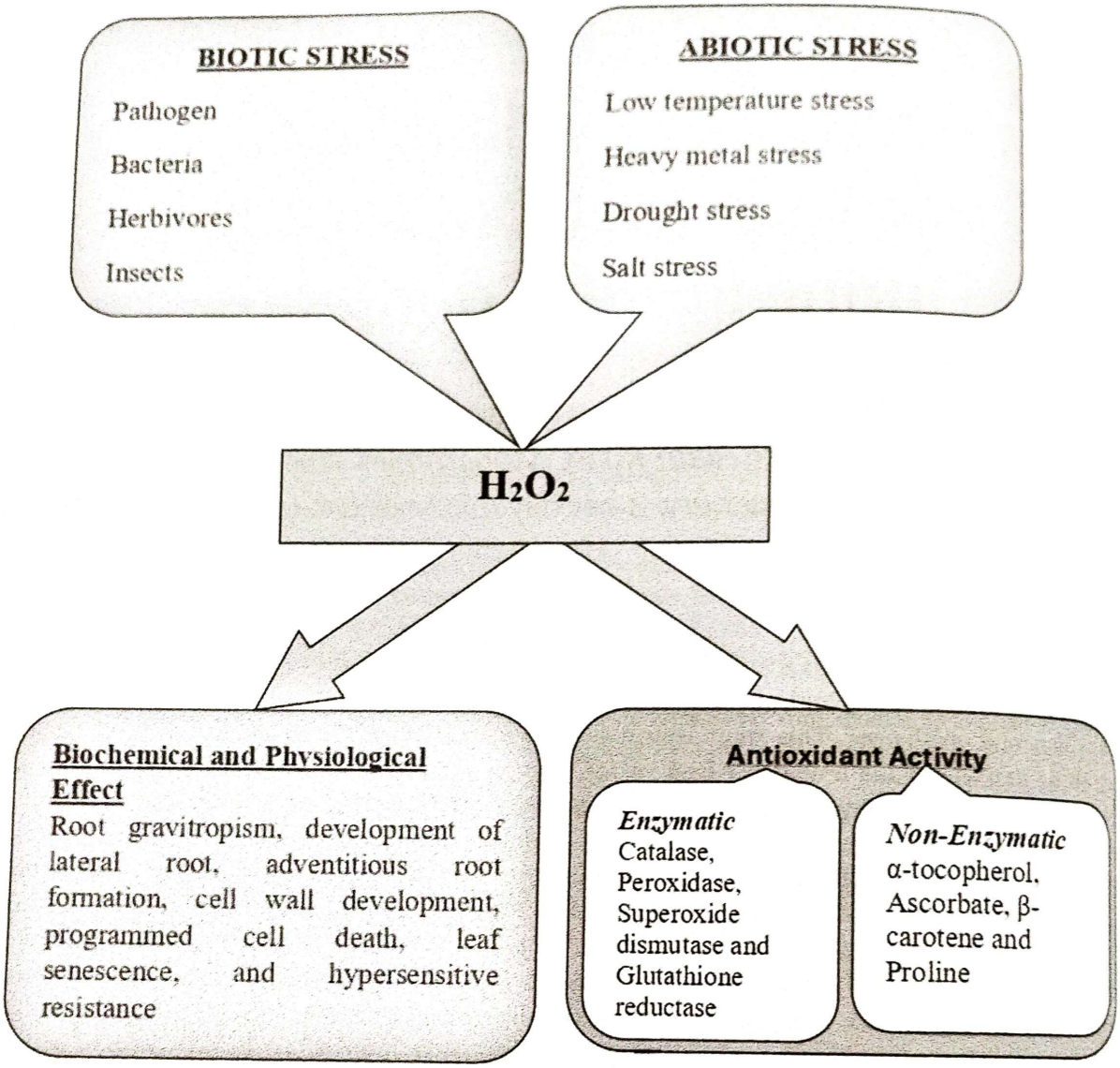

FIGURE 6.1 Central role of hydrogen peroxide in plants under biotic and abiotic stress conditions.

have profound effects on basic physiological functions, impairing photosynthesis and the absorption of nutrients and water. They also hinder general metabolic processes. Furthermore, these stresses negatively impact crucial phases of plant growth, such as germination, flowering, and seed production; all these result in reduced crop yields, compromised quality, and increased susceptibility to diseases (Radha et al., 2023; Zhang et al., 2022). Abiotic stress can induce the generation of ROS, including singlet oxygen ($^1O_2$), hydroxyl radicals ($OH^·$), H_2O_2, and superoxide radicals ($O_2^{·-}$), each with a characteristic oxidizing potential and half-life. Both positive and negative consequences can be seen when ROS generation occurs in plant cells (Noctor and Foyer, 2016; Sachdev et al., 2021). Even in standard conditions, higher plants naturally generate ROS as part of their metabolic processes. Nevertheless, excessive levels of ROS can cause apoptotic cell death due to lipid peroxidation, protein denaturation, DNA mutations, disturbance of cellular homeostasis, and various forms of oxidative harm to cells (Jira-anunkul and Pattanagul, 2021; Pandey and Shukla, 2015). To avoid the potentially harmful effects of ROS, cells constantly remove ROS through cellular antioxidant