Hydrogen Peroxide

Signaling Mechanisms and Crosstalk in Plant Development and Stress Responses

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INTRODUCTION

Seed germination is a fundamental process in the life cycle of plants. It marks the transition from a dormant seed to an actively growing seedling, laying the foundation for a plant's life. However, the successful germination of seeds is not guaranteed, as many seeds exhibit dormancy—a state of arrested development and reduced metabolic activity. Seed dormancy allows seeds to survive adverse environmental conditions and synchronize germination with favorable circumstances. Understanding the mechanisms of seed dormancy and its regulation is of paramount importance in agriculture, ecology, and conservation. Seed dormancy is a complex and highly regulated process involving multiple genetic, physiological, and environmental factors. It serves as a survival mechanism for seeds, allowing them to delay germination until conditions are favorable for the seedling's survival. Two primary types of seed dormancy exist: exogenous dormancy and endogenous dormancy. Exogenous dormancy is primarily driven by external factors that prevent the germination of seeds (Geneve, 2003). These factors include hard seed coats and the presence of chemical inhibitors. These inhibitors may include allelopathic chemicals produced by other plants in the vicinity or compounds naturally occurring in the seed itself. Breaking exogenous dormancy typically involves the techniques of scarification and stratification (Górnik et al., 2023). Scarification involves mechanical treatments such as abrasion, sandpaper rubbing, or acid treatment that can be used to break down hard seed coats, allowing water penetration and germination to occur. Cold stratification involves exposing seeds to cold, moist conditions for a specific period. This treatment is particularly effective for seeds with morphological dormancy (MD) and can simulate the natural winter chilling that some seeds require for germination (Schütz and Rave,1999).

Endogenous dormancy, on the other hand, is governed by internal factors within the seed, including hormonal regulation and genetic predisposition (Nautiyal et al., 2023). It is further categorized into three main types: physiological dormancy (PD), MD, and combined dormancy (CD). PD is the most common form of endogenous dormancy and is primarily controlled by hormonal interactions, particularly the balance between abscisic acid (ABA) and gibberellic acid (GA). ABA acts as an inhibitory hormone, while GAs promote germination (Baskin and Baskin, 2021). MD primarily involves the development of a dormant embryo within a seed that requires a specific period of cold stratification to mature fully. This type of dormancy is often observed in temperate plant species. CD is a more complex form of dormancy that combines elements of both PD and MD. Seeds exhibiting CD have hormonal regulation mechanisms, as in PD, but also require specific environmental cues or treatments, as in MD, to initiate germination (Baskin and Baskin, 2021).

The transition from dormancy to germination begins when the dry seed comes into contact with water and ends when the radicle has emerged through all the coats of the developing embryo (Wang et al., 2020). This encounter activates the internal metabolic process, involving the careful equilibrium of phytohormones (Oracz and Karpiński, 2016) in the presence of optimum light and temperature to overcome the seed's dormancy (Shu et al., 2016). ABA and GA play a key role in several physiological processes during seed germination, and increased biosynthesis of GA and ABA degradation, resulting in a low ABA:GA ratio that favors the release of dormancy and triggers germination (Sano and Marion-Poll, 2021). Light, temperature, and soil conditions are major signals

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that can be perceived by seeds to regulate the timing of germination. The regulatory effect of light on seed germination depends on its spectrum (Springthorpe and Penfield, 2015). Blue light activates ABA and delays seed germination, whereas red or far-red light plays a key role in the activation of seed germination via the activation of GA biosynthesis and restricting the production of ABA (Jiang et al., 2021). Seed germination is dependent on the surrounding temperature, which can delay or expedite the germination process after sowing. Most species germinate in the presence of temperatures between 15°C and 30°C (Yang et al., 2020). Weakening of the endosperm is a prerequisite for the initiation of seed germination and is driven by various internal and external factors. The decay of the endosperm is directly linked to the production of ROS in response to the availability of external environmental signals (Zhang et al., 2019).

H_2O_2: DUAL ROLE AS SIGNALING MOLECULE AND STRESSOR

Hydrogen peroxide (H_2O_2) is a versatile signaling molecule in plants, participating in various physiological processes, including growth, development, and stress responses. While H_2O_2 primarily serves as a signaling molecule in stress adaptation, excessive accumulation can lead to oxidative damage and stress amplification (Hossain et al., 2015). Plants are constantly exposed to a wide array of environmental stresses, including drought, salinity, extreme temperatures, pathogens, and pollutants. To survive and thrive under these adverse conditions, plants have developed intricate defense mechanisms. Among the key players in plant stress responses is H_2O_2, a reactive oxygen species (ROS) that serves a dual role in stress adaptation (Møller et al., 2007).

H_2O_2 is not only a toxic byproduct of metabolic processes but also a pivotal signaling molecule involved in the regulation of various physiological and stress-related processes (Reczek and Chandel, 2015).

In plant cells, H_2O_2 is primarily generated through the activity of several enzymes, including nicotinamide adenine dinucleotide phosphate (NADPH) oxidase, xanthine oxidase, and peroxidases (PODs) (Sutherland, 1991; Corpas et al., 2001; Bhattacharjee, 2005). H_2O_2 can also be produced non-enzymatically through reactions involving superoxide radicals or by the breakdown of other ROS (Kärkönen et al., 2017). Plants tightly regulate H_2O_2 levels through a balance of production and scavenging mechanisms. Antioxidant enzymes such as catalase (CAT), PODs, and superoxide dismutase (SOD) help neutralize excess H_2O_2, maintaining cellular homeostasis (Sharma et al., 2019).

ROLE OF H_2O_2 IN ABIOTIC STRESS RESPONSES

Drought Stress: H_2O_2 acts as a secondary messenger in the response to drought stress. It activates various stress-responsive genes and pathways, helping plants adapt to limited water availability (Zou et al., 2015).

Salinity Stress: H_2O_2 plays a crucial role in mitigating salt stress by regulating ion transport, enhancing antioxidant defense mechanisms, and promoting osmotic adjustment (Li et al., 2011).

Temperature Stress: During temperature stress, H_2O_2 mediates the activation of heat shock proteins (HSPs) and antioxidant enzymes, aiding in thermal tolerance (Cavusoglu and Kabar, 2010).

Heavy Metal Stress: Plants exposed to heavy metal stress accumulate H_2O_2, which triggers the expression of metal detoxification genes and antioxidants (Nazir et al., 2020).

ROLE IN BIOTIC STRESS RESPONSES

Pathogen Defense: H_2O_2 is involved in plant defense against pathogens. It activates hypersensitive response (HR) and systemic acquired resistance (SAR), leading to the synthesis of pathogenesis-related (PR) proteins (Orozco-Cárdenas et al., 2001).