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Mechanism of Seed Aging and Molecular Approaches to Enhance Longivity

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Seed longevity is a vital attribute determining seed quality, crop establishment, and long-term conservation of plant genetic resources. Over time, seeds undergo physiological, biochemical, and molecular deterioration collectively referred to as seed aging, leading to reduced viability and vigor. Major mechanisms responsible for seed aging include oxidative stress caused by reactive oxygen species, membrane lipid peroxidation, protein degradation through Maillard reactions, genomic and epigenetic alterations, and a gradual decline in antioxidant defense systems. Environmental factors such as temperature, moisture content, oxygen availability, and genetic makeup significantly influence the rate of seed deterioration. Recent advances in molecular biology have provided new strategies to enhance seed longevity. Genetic engineering approaches focusing on antioxidant enzymes, Late Embryogenesis Abundant proteins, and heat shock proteins have shown promising results. Omics technologies have helped identify key genes, proteins, and metabolites involved in seed protection and repair mechanisms. Additionally, seed priming techniques, genome editing tools like CRISPR-Cas, and epigenetic regulation offer innovative avenues to improve seed storability and performance. Understanding the mechanisms of seed aging and integrating molecular approaches with conventional storage practices are essential for sustainable agriculture, food security, and effective conservation of plant genetic resources.

Keywords: Seed aging; Seed longevity; Oxidative stress; Reactive oxygen species (ROS); Antioxidant defense; Molecular approaches; Genome editing

Introduction

Seed longevity is a crucial factor in agriculture, biodiversity conservation, and food security. Seeds gradually lose their vigor and viability over time due to complex physiological, biochemical, and molecular processes collectively known as seed aging. Understanding the mechanisms of seed aging and adopting molecular strategies to enhance longevity are essential for improving crop productivity and maintaining genetic resources in seed banks.

Mechanism of Seed Aging

1.Oxidative Stress and Reactive Oxygen Species (ROS)

One of the primary causes of seed aging is the accumulation of reactive oxygen species (ROS). ROS such as superoxide anion, hydrogen peroxide, and hydroxyl radicals damage lipids, proteins, and nucleic acids. Oxidative stress leads to lipid peroxidation, protein carbonylation, and DNA strand breaks, ultimately impairing cellular function.

2. Membrane Deterioration

Seed membranes undergo structural and functional changes during storage. Lipid peroxidation reduces membrane fluidity and disrupts permeability, resulting in electrolyte leakage and reduced germination potential.

3.Maillard Reaction and Protein Modifications

Non-enzymatic Maillard reactions occur between reducing sugars and amino groups of proteins during storage. These reactions alter protein structure, decrease enzyme activity, and interfere with normal metabolism.

4.Genomic and Epigenetic Changes

Seed aging is associated with DNA damage such as base modifications, crosslinking, and strand breaks. Epigenetic modifications, including DNA methylation and histone modifications, also affect gene expression patterns related to stress tolerance and repair capacity.

5.Loss of Antioxidant Defense

The natural antioxidant defense system of seeds, including enzymes like catalase, peroxidase, and superoxide dismutase, declines over time. This reduction further aggravates oxidative damage and accelerates deterioration.

Factors Affecting Seed Longevity

Seed longevity is influenced by several factors, including moisture content, storage temperature, and oxygen availability. Orthodox seeds, which can be dried and stored at low temperatures, typically show longer longevity compared to recalcitrant seeds that are sensitive to desiccation and freezing. Genetic variation among species also plays a crucial role in determining natural longevity.

Molecular Approaches to Enhance Seed Longevity

1.Genetic Engineering Approaches

Genetic engineering offers strategies to improve seed longevity by overexpressing genes encoding antioxidants (such as SOD, CAT, and APX). Enhancing the expression of Late Embryogenesis Abundant (LEA) proteins and Heat Shock Proteins (HSPs) helps protect cellular structures during storage.

2.Omics-Based Insights

Omics technologies provide a comprehensive understanding of seed aging. Transcriptomics identifies genes involved in stress response, proteomics highlights protective proteins, and metabolomics reveals metabolites such as trehalose and proline that contribute to desiccation tolerance.

3.Seed Priming Techniques

Seed priming methods like hydro-priming, osmopriming, and hormopriming enhance germination and longevity. At the molecular level, priming induces stress memory, activates antioxidant systems, and promotes repair pathways.

4.CRISPR-Cas Based Genome Editing

Genome editing technologies like CRISPR-Cas enable precise modifications in genes associated with antioxidant defense, DNA repair, and storage protein stability. This approach offers great potential to develop crop varieties with enhanced seed longevity.

5.Epigenetic Approaches

Epigenetic regulation plays an important role in seed longevity. Manipulating DNA methylation patterns and histone modifications may help maintain gene activity linked to stress tolerance and viability during storage.

Case Studies and Advances

Research on Arabidopsis mutants has provided valuable insights into genetic factors controlling seed longevity. In crops like rice and wheat, transgenic lines overexpressing antioxidant and protective proteins have shown improved seed vigor. Gene banks are now integrating molecular markers to monitor seed quality during long-term storage.

Conclusion

Seed aging is a multifaceted process driven by oxidative stress, molecular damage, and epigenetic changes. Molecular approaches including genetic engineering, omics-based studies, genome editing, and epigenetic modulation offer promising solutions to enhance longevity. Integrating conventional storage practices with modern biotechnology will be vital for sustainable agriculture and conservation of plant genetic resources.

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