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Phytomelatonin: A Molecular Shield Enhancing Plant Resilience to Abiotic Stress

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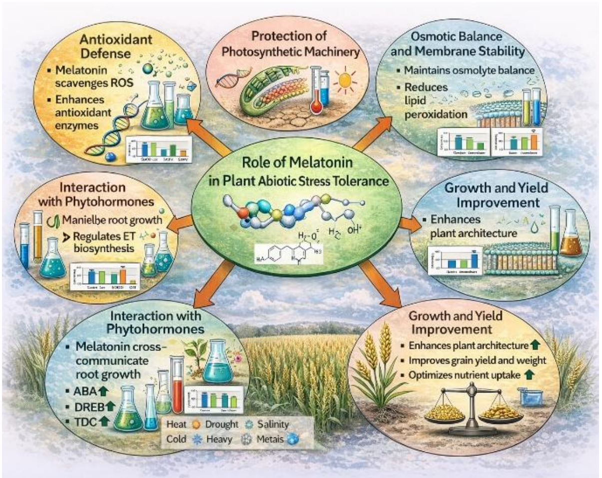
Abstract

Abiotic stresses such as heat, drought, salinity, cold, and heavy metal toxicity represent major constraints to plant growth and agricultural productivity worldwide. These environmental stresses disrupt metabolic processes, impair photosynthesis, and promote excessive accumulation of reactive oxygen species (ROS), ultimately leading to cellular damage and yield loss. In recent years, melatonin (N-acetyl-5-methoxytryptamine) has gained recognition as a crucial regulator of plant stress tolerance. Initially identified as an animal hormone, melatonin is now known to be ubiquitously synthesized in plants, where it performs diverse physiological and protective functions. Under abiotic stress conditions, melatonin accumulation is markedly enhanced and contributes to stress mitigation through its strong antioxidant capacity, modulation of gene expression, regulation of phytohormone signaling, and maintenance of cellular redox balance. Both endogenous production and exogenous application of melatonin have been reported to improve photosynthetic efficiency, stabilize membranes, activate antioxidant enzymes, and regulate stress-responsive genes. This review highlights the multifaceted role of melatonin in plant adaptation to abiotic stresses and discusses its potential significance for improving crop resilience under changing climatic conditions.

Key words: Melatonin, High temperature, Abiotic stress, Crop resilience

Introduction



Plants are continuously exposed to a wide range of abiotic stresses, including high temperature, drought, salinity, cold, flooding, and heavy metal toxicity, which significantly limit crop growth and productivity worldwide. These environmental stresses disrupt physiological processes, impair photosynthesis, alter metabolic activities, and ultimately reduce yield stability. With the increasing frequency of extreme climatic events, abiotic stress has become one of the most serious threats to global food security (Reiter et al., 2025).

A primary consequence of abiotic stress exposure is the excessive accumulation of reactive oxygen species (ROS), such as hydrogen peroxide (H_2O_2), superoxide radicals (O_2^-), and hydroxyl radicals (•OH). Although ROS act as signaling molecules at low concentrations, their overproduction under stress conditions causes oxidative damage to lipids, proteins, nucleic acids, and cellular membranes, leading to growth inhibition and premature senescence (Zhang et al., 2020). To counteract oxidative stress, plants have evolved sophisticated defense mechanisms involving enzymatic and non-enzymatic antioxidant systems, stress-responsive transcription factors, and phytohormonal signaling networks (Hasan et al., 2022).

Unlike classical phytohormones, melatonin exhibits both hormone-like regulatory functions and strong antioxidant capacity. It acts directly as a free radical scavenger and indirectly as a regulator of antioxidant enzymes, thereby playing a crucial role in maintaining cellular redox homeostasis (Wang et al., 2021). Numerous studies have reported a rapid increase in endogenous melatonin levels in plants subjected to drought, salinity, heat, cold, and heavy metal stress, indicating its involvement in stress perception and signaling (Zhang et al., 2020; Imran et al., 2023). Exogenous application of melatonin has been shown to enhance stress tolerance in a wide range of plant species, including wheat, rice, maize, soybean, tomato, and Arabidopsis. These protective effects are associated with improved antioxidant activity, stabilization of photosynthetic machinery, maintenance of membrane integrity, and regulation of osmolyte accumulation (Li et al., 2021; Zhao et al., 2022). Furthermore, melatonin modulates the expression of stress-responsive genes such as heat shock proteins (HSPs), dehydration-responsive element-binding proteins (DREBs), and antioxidant-related genes, strengthening plant adaptive capacity under adverse environments (Chen et al., 2024). In addition to its direct protective roles, melatonin interacts extensively with phytohormonal signaling pathways, including abscisic acid, auxin, gibberellins, and ethylene. This hormonal crosstalk enables plants to balance growth and defense responses under stress conditions (Hasan et al., 2022; Imran et al., 2023). Collectively, these findings highlight melatonin as a key regulator of plant stress tolerance with significant implications for crop improvement.

Understanding the physiological, biochemical, and molecular mechanisms underlying melatonin-mediated stress adaptation is therefore critical for developing climate-resilient crops. With increasing interest in sustainable agriculture, melatonin-based approaches—either through exogenous application or genetic manipulation of melatonin biosynthetic pathways—represent promising strategies to enhance plant performance under abiotic stress conditions (Reiter et al., 2025).

Conclusion

Melatonin plays a vital role in enhancing plant tolerance to abiotic stresses through its multifunctional antioxidant and signaling properties. By regulating ROS detoxification, preserving photosynthetic machinery, stabilizing cellular membranes, modulating gene expression, and interacting with phytohormonal networks, melatonin significantly improves plant stress resilience. Given the increasing severity of climate-related stresses, melatonin-based strategies including exogenous application and genetic manipulation of melatonin biosynthetic pathways represent promising approaches for sustainable crop improvement. Further research focusing on signaling mechanisms, field-level validation, and integration with breeding programs will accelerate the practical utilization of melatonin in modern agriculture.

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