

Melatonin as a Central Hub of Abiotic Stress Resilience in Tomato

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Climate change increasingly threatens tomato productivity by intensifying abiotic stresses. Recent studies recognize melatonin as a multifunctional regulator that integrates redox homeostasis, protected photosynthetic apparatus, root system architecture, ion homeostasis, and hormonal signaling networks. This Spotlight summarizes emerging evidence demonstrating that melatonin enhances tomato tolerance to abiotic stresses, highlighting key unresolved mechanistic questions as well as challenges related to translational applications.

Melatonin as an Integrative Regulator of Abiotic Stress Response

Tomato (*Solanum lycopersicum* L.) is a globally important horticultural crop but is highly susceptible to a range of abiotic stresses, including salinity, drought, heat, cold, and metal toxicity. These abiotic stresses rapidly impair photosynthesis, disrupt cellular membrane integrity and nutrient homeostasis, and ultimately reduce yield and fruit quality (Litskas et al. 2019). Traditionally, abiotic stress responses in tomato have been studied largely as autonomous processes, each associated with a specific signaling pathway and physiological outcome.

Increasing evidence suggests that multiple stress-response pathways are coordinated by central regulatory nodes that collectively determine abiotic stress tolerance in plants. Melatonin (N-acetyl-5-methoxytryptamine), a low-molecular-weight antioxidant molecule considered a novel plant growth regulator (Arnao and Hernández-Ruiz, 2014). In tomato, melatonin modulates diverse stress-responsive processes, including reactive oxygen species (ROS) homeostasis, photosynthetic efficiency, root system architecture, ion fluxes, and phytohormonal signaling networks (Siddiqui et al., 2019). Together, these findings indicate that melatonin functions upstream of individual stress responses, enabling coordinated physiological and molecular reprogramming during exposure to environmental stress.

Coordination of Redox Signaling and Antioxidant Defense

The Overproduction of ROS is a universal hallmark of abiotic stress in plants. Under stress conditions, excessive accumulation of hydrogen peroxide and superoxide radicals leads to lipid peroxidation, protein oxidation, membrane leakage, and ultimately cellular dysfunction (Shaffique et al. 2024). At the same time, ROS function as important secondary messengers that convey stress signals and initiate adaptive responses. Therefore, abiotic stress tolerance relies on maintaining redox homeostasis through tight regulation of ROS production and scavenging, rather than complete suppression of ROS generation (Siddiqui et al., 2019).

Melatonin effectively integrates redox signaling with antioxidant defense under stressful conditions. In tomato, melatonin consistently reduces ROS accumulation, lipid peroxidation, and electrolyte leakage in tissues exposed to salinity, drought, heat, cold, and metal stresses (Altaf et al. 2023). These protective effects arise from both the direct free-radical-scavenging capacity of melatonin and its ability to enhance the activities of antioxidant enzymes. Notably, melatonin also regulates the expression of genes encoding antioxidant enzymes, thereby providing sustained redox homeostasis under stress conditions. In addition, melatonin interacts with NADPH oxidases, nitric oxide, and polyamine metabolism, indicating a

broader role in modulating ROS production (Gong et al. 2014). This capacity to balance oxidative damage control with redox signaling likely underpins the broad protective effects of melatonin across diverse abiotic stress conditions.

Protecting Photosynthesis Under Adverse Environments

Photosynthesis is one of the primary biological processes in tomato and is particularly sensitive to abiotic stress. Salinity, drought, and heat stress disrupt the ultrastructure of chloroplasts, damage photosystem II, impair electron transport, and reduce carbon assimilation. Consequently, maintaining photosynthetic performance under stress is central to sustaining plant growth and productivity (Jahan et al. 2021).

Melatonin consistently alleviates stress-induced inhibition of photosynthesis in tomato. Melatonin-treated plants exhibit higher chlorophyll content, improved chlorophyll fluorescence parameters, and better ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) activity under adverse conditions (Ru et al. 2025). Moreover, melatonin enhances the repair of the D1 protein and stabilizes thylakoid membranes, thereby maintaining efficient electron transport during photosynthesis under stressed conditions (Zhou et al. 2016). In addition to protecting the photosynthetic apparatus, melatonin delays stress-induced leaf senescence. It prolongs the functional lifespan of photosynthetic tissues by suppressing the expression of chlorophyll catabolic genes and senescence-associated pathways during prolonged exposure to unfavorable environmental conditions (Dou et al. 2025).

Root System Architecture and Ion Homeostasis

Root system performance is critical for determining whole-plant tolerance to abiotic stress. Adverse environmental conditions often impair root growth and absorptive capacity, thereby limiting the uptake of water and mineral nutrients (Koevoets et al. 2016). Under stress conditions, melatonin markedly modifies tomato root system architecture by promoting primary root elongation, lateral root formation, root surface area, and root tips. These morphological adjustments enhance soil exploration capacity and improve the acquisition of water and essential nutrients under limiting conditions (Wen et al. 2016). In parallel, melatonin plays a crucial role in restoring ionic homeostasis.

Under salinity stress, melatonin restricts sodium (Na⁺) uptake while promoting potassium (K⁺) retention, thereby maintaining optimal Na⁺/K⁺ ratios that are essential for enzymatic activity and cellular metabolism (Ali et al. 2020). Under heavy metal toxicity, melatonin reduces the translocation of toxic metals from roots to shoots and enhances the uptake of macro- and micronutrients (Altaf et al. 2023). Collectively, these findings suggest that melatonin regulates whole-plant ion homeostasis, linking root architecture system with shoot performance and overall abiotic stress tolerance.

Melatonin as a Hormonal Signaling Hub

Melatonin interacts extensively with other phytohormone signaling pathways to modulate plant responses to abiotic stress. In tomato, melatonin influences abscisic acid (ABA), gibberellin, auxin, salicylic acid, and jasmonate

signaling, thereby regulating the balance between growth and defense under adverse environmental conditions (Khan et al. 2024). For example, melatonin suppresses excessive ABA accumulation during heat stress while promoting gibberellin biosynthesis, alleviating growth inhibition without compromising stress tolerance (Jahan et al. 2021). Interactions between melatonin and auxin signaling enhance lateral root development, whereas crosstalk with salicylic acid and jasmonate pathways strengthens stress protection and primes defensive responses. At the molecular level, stress-responsive transcription factors, including heat shock factors, directly

regulate the expression of genes involved in melatonin biosynthesis. These regulatory networks link melatonin production and signaling with hormonal, redox, and metabolic pathways that collectively orchestrate plant adaptation to environmental stress (Altaf et al. 2022). Through this integrative role, melatonin represents a promising translational target for crop improvement. In tomato, exogenous melatonin application enhances growth, yield, fruit quality, and antioxidant capacity under diverse abiotic stress conditions, while genetic manipulation of melatonin biosynthetic pathways further supports its central role in stress tolerance.

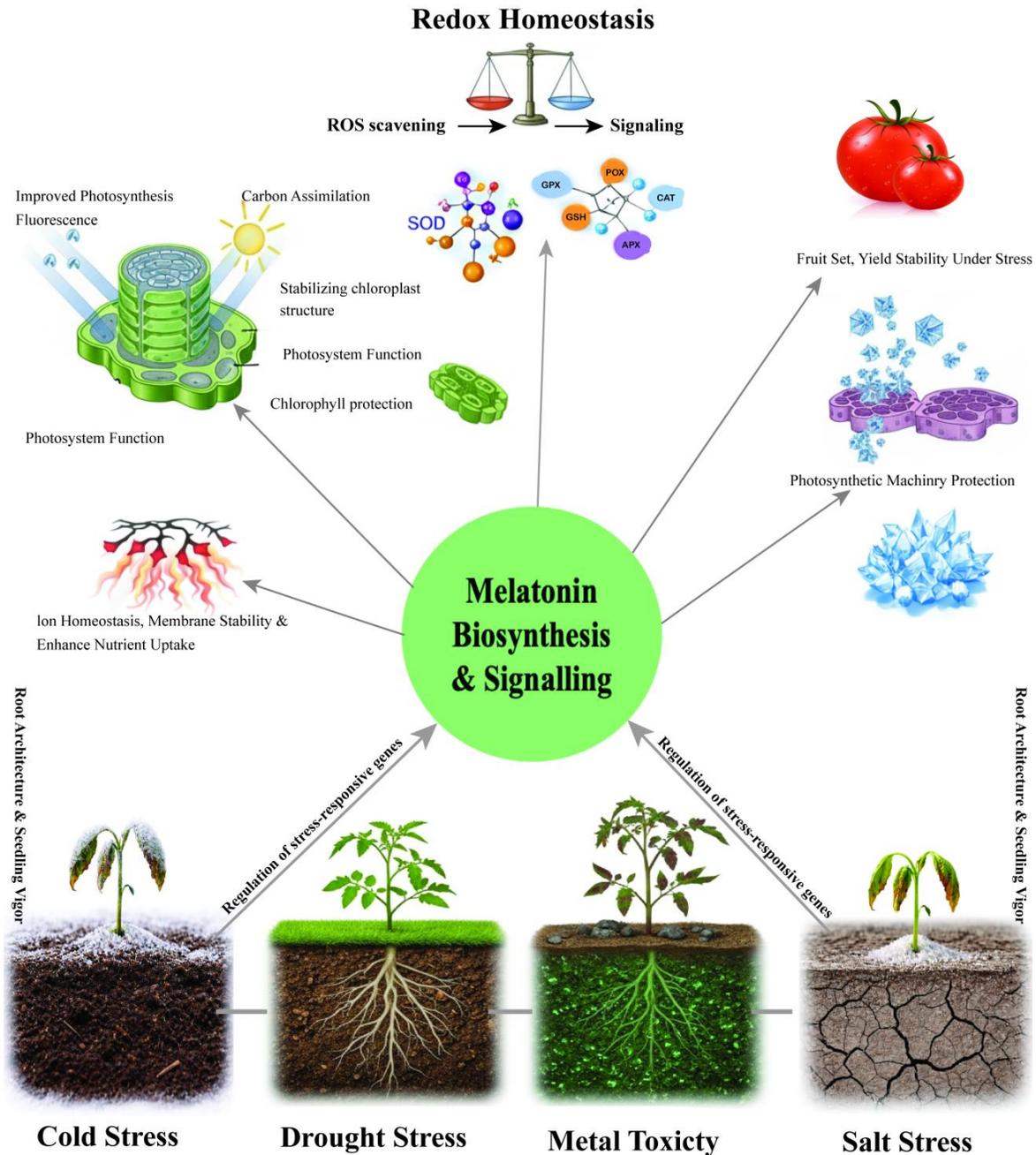


Fig. 1. Conceptual model illustrating melatonin as an integrative regulator of abiotic stress responses in tomato. Abiotic stresses (salinity, drought, heat, cold, and metal toxicity) induce melatonin biosynthesis. Melatonin acts as a central hub that (i) fine-tunes redox homeostasis by balancing ROS scavenging and signaling, (ii) protects photosynthetic machinery by stabilizing chloroplast structure and photosystem function, (iii) modifies root system architecture to enhance water and nutrient acquisition, (iv) restores ion homeostasis by regulating Na^+/K^+ balance and limiting toxic metal translocation, and (v) interacts with phytohormonal networks (ABA, gibberellins, auxin, salicylic acid). Together, these processes confer enhanced whole-plant stress resilience.

Concluding Remarks

Accumulating evidence indicates that melatonin functions as a central regulator of abiotic stress tolerance in tomato through its coordinated effects on redox balance, photosynthetic performance, root system architecture, ion homeostasis, and phytohormone signaling. To fully realize the potential of melatonin-based strategies for enhancing tomato stress tolerance, it will be essential to dissect the underlying molecular pathways governing melatonin-mediated stress responses and to evaluate their effectiveness under field conditions.

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