Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 05, Issue: 06 (NOV-DEC, 2025)
Available online at http://www.agriarticles.com

The Miracle Molecule Melatonin: A Natural Solution to Plant Stress Adaptation

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Horticulture is one of the most vibrant and dynamic sectors in Indian agriculture. It encompasses the cultivation of fruits, vegetables, spices, ornamentals, medicinal and aromatic plants, playing a vital role in ensuring food security and nutritional health. According to Agarwal et al. (2016), horticulture contributes over 30% to India's agricultural GDP. These crops not only provide essential nutrients, vitamins, and antioxidants but also supply valuable compounds for medicines and perfumes. However, the path to sustainable and safe horticulture is increasingly under threat. From climate change to unpredictable pests, from poor post-harvest management to an overreliance on chemical inputs—modern horticulture faces a wide range of challenges. Excessive use of fertilizers and pesticides, while temporarily boosting yield, often compromises food safety, depletes soil health, and harms the environment (Li et al., 2021). To overcome these challenges and usher in a greener era of cultivation, scientists are now turning their attention to a remarkable naturally occurring molecule: Melatonin.

The Journey of Melatonin: From Animal Hormone to Plant Protector

Melatonin, chemically known as N-acetyl-5-methoxytryptamine, was first discovered in 1958 by Lerner and colleagues in the pineal gland of cows. For decades, it was considered unique to animals, primarily recognized for regulating sleep and circadian rhythms. But in 1991, Blaer and Hardeland uncovered its presence in the unicellular marine alga *Gonyaulax polyedra*. This discovery rewrote the rulebook, proving melatonin exists in the plant world too. By 2004, the term **"phytomelatonin"** was coined to describe plant-based melatonin. Since then, its presence and roles in plants have become a focal point of scientific research. What emerged is the story of a versatile molecule with a wide array of physiological roles that could help revolutionize sustainable horticultural practices.

A Master Regulator in Plants

In plants, melatonin is nothing short of a multitasker. It plays crucial roles in seed germination, root development, floral transition, fruit setting, and ripening (Wang et al., 2020). It also enhances post-harvest quality and delays aging in produce thanks to its antioxidant and antisenescence properties (Gao et al., 2022).

Moreover, melatonin boosts photosynthesis, cell respiration, and osmoregulation—key processes that keep plants healthy and productive (Reiter et al., 2014; Sharma et al., 2020). What makes melatonin even more exciting is its ability to reduce the harmful accumulation of synthetic fertilizers and pesticides (Nawaz et al., 2018; Yan et al., 2019). When used in combination with fungicides, it enhances their efficacy and reduces the overall chemical load, promoting eco-friendly cultivation (Tiwari et al., 2020). This positions melatonin as a natural and powerful alternative in sustainable horticulture.

How Do Plants Make Melatonin?

Though once thought to be exclusive to animals, melatonin is now known to be synthesized in a wide range of plant species. In fact, in 1995, researchers like Dubbels and Hattori identified melatonin in edible plants using sophisticated techniques like radioimmunoassay and high-performance liquid chromatography. Interestingly, the grass family (Poaceae) showed the highest melatonin content among plants. Both animals and plants synthesize melatonin from the amino acid **tryptophan**. In plants, this process primarily occurs inside **chloroplasts** and **mitochondria**, the organelles responsible for photosynthesis and energy production. These sites are not coincidental—both have an evolutionary history dating back to ancient photosynthetic bacteria, and both are hotspots for stress-induced reactive oxygen species (ROS). Melatonin, with its antioxidant power, is naturally suited to protect these sensitive organelles (Hardeland et al., 2019).

The Biochemical Pathways

Melatonin biosynthesis in plants occurs through a multi-step process involving key enzymes and metabolic intermediates. The initial precursor, **tryptophan**, is derived from the shikimic acid pathway. This is then converted through several steps:

1. **Tryptophan** → **Tryptamine** via *tryptophan decarboxylase (TDC)*
2. **Tryptamine** → **Serotonin** via *tryptamine-5-hydroxylase (T5H)*
3. From serotonin, melatonin can be synthesized through two distinct pathways:

- **Pathway I (dominant, normal conditions)**: Serotonin → N-acetyl serotonin via *SNAT* → Melatonin via *ASMT* or *COMT*
- **Pathway II (activated under stress)**: Serotonin → 5-methoxytryptamine → Melatonin

Among these, **Serotonin N-acetyl transferase (SNAT)** is the rate-limiting enzyme and crucial for determining melatonin levels (Liao et al., 2021). When the chloroplast route is blocked, the plant can reroute melatonin synthesis through mitochondria (Tan and Reiter, 2020). Melatonin signaling in plants is just as fascinating. The molecule binds to a receptor called **PMTR1** in *Arabidopsis thaliana*, triggering downstream responses involving calcium ions and reactive molecules like hydrogen peroxide (Wei et al., 2018). This cascade not only helps regulate processes like stomatal closure but also boosts the plant's defense against stress.

Application of Melatonin in Mitigating Abiotic Stresses

Melatonin, a pleiotropic molecule synthesized endogenously in plants, has emerged as a potent natural biostimulant in alleviating various abiotic stresses. Due to its unique antioxidant, signaling, and gene-regulatory properties, melatonin plays a central role in enhancing plant resilience under stressful environments. Its applications span a wide spectrum of abiotic stress conditions (Figure1).

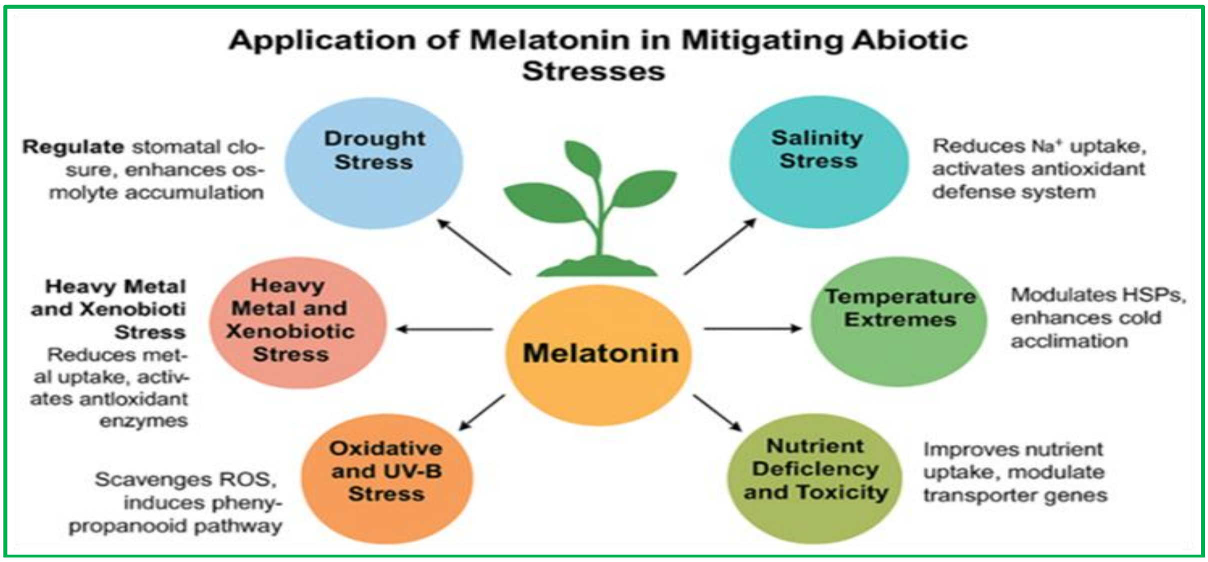

Figure 1: Role of Melatonin in mitigating abiotic stresses in plants

1. Drought Stress

Melatonin improves water-use efficiency by regulating stomatal closure and enhancing the accumulation of osmolytes such as proline and soluble sugars. It stabilizes cellular membranes and upregulates drought-responsive genes, including **RD29A**, **DREB2**, and **NCED3**, which contribute to stress tolerance. It also modulates abscisic acid (ABA) signaling to balance growth and stress responses.

2. Salinity Stress

High salinity disrupts ion homeostasis and causes oxidative stress in plants. Melatonin ameliorates salinity stress by:

- Reducing Na^+ accumulation and enhancing K^+/Na^+ selectivity
- Activating the antioxidant defense system (e.g., SOD, CAT, POD, APX)
- Enhancing photosynthetic efficiency and chlorophyll retention
- Upregulating ion transporter genes (e.g., **SOS1**, **HKT1**)

3. Temperature Extremes

- **Heat Stress**: Melatonin protects plants by stabilizing proteins and membranes, reducing ROS levels, and increasing the expression of **heat shock proteins (HSPs)** and **thermotolerance genes**. It also prevents premature senescence.
- **Cold Stress**: It enhances cold acclimation by inducing **CBF/DREB1** genes, increasing antioxidant enzyme activities, and promoting the synthesis of cryoprotectants like soluble sugars and polyamines.

4. Heavy Metal and Xenobiotic Stress

Melatonin plays a crucial role in detoxifying heavy metals like cadmium (Cd), lead (Pb), and arsenic (As) by:

- Enhancing phytochelatin and metallothionein synthesis
- Reducing metal uptake and translocation
- Activating antioxidant enzymes and glutathione pathways
- Modulating the expression of transporter genes involved in metal sequestration

5. Oxidative and UV-B Stress

Melatonin directly scavenges reactive oxygen species (ROS) and reactive nitrogen species (RNS), reducing oxidative damage. It also:

- Induces the **phenylpropanoid pathway** for secondary metabolite production
- Enhances UV-absorbing compound accumulation (e.g., flavonoids, anthocyanins)
- Stimulates DNA repair-related genes

6. Nutrient Deficiency and Toxicity

Melatonin mitigates nutrient imbalances by:

- Enhancing uptake and translocation of essential nutrients (N, P, Fe, Zn)
- Modulating nutrient transporter gene expression
- Improving root architecture and rhizosphere interactions under deficiency

Mechanisms of Action

Melatonin's role in abiotic stress mitigation involves:

- **Antioxidant activity**: Direct and enzymatic ROS scavenging
- **Signal transduction**: Via MAPK cascades and secondary messengers (Ca^{2+}, H_2O_2, NO)
- **Gene regulation**: Activation of transcription factors (WRKY, NAC, MYB)
- **Hormonal interplay**: Cross-talk with ABA, SA, auxin, ethylene, and JA

Conclusion

Melatonin serves as a master regulator in modulating stress-responsive pathways and maintaining cellular homeostasis. Its application, either through genetic engineering, seed priming, or foliar sprays, offers a sustainable and eco-friendly approach to combat the adverse effects of abiotic stressors and enhance crop productivity in changing climatic conditions.

References

1. Agarwal, A., et al. (2016). Horticulture Statistics at a Glance. Ministry of Agriculture and Farmers Welfare, Government of India.
2. Li, C., et al. (2021). Negative effects of agrochemicals in modern horticulture and the need for sustainable solutions. *Environmental Science and Pollution Research*, 28, 23012–23025.
3. Wang, P., Sun, X., Li, C., Wei, Z., Liang, D., Ma, F. (2020). Long-term exogenous application of melatonin delays drought-induced leaf senescence in apple. *Journal of Pineal Research*, 68(1), e12621.
4. Reiter, R. J., Tan, D. X., Zhou, Z., Cruz, M. H. C., Fuentes-Broto, L., Galano, A. (2014). Phytomelatonin: Assisting plants to survive and thrive. *Molecules*, 19(11), 17773–17790.
5. Sharma, A., et al. (2020). Melatonin as a master regulator in plant growth, development, and stress responses. *Plant Physiology and Biochemistry*, 150, 35–45.
6. Gao, S., et al. (2022). Exogenous melatonin improves postharvest quality and delays senescence of fruits and vegetables: Mechanisms and prospects. *Postharvest Biology and Technology*, 184, 111764.
7. Nawaz, M. A., et al. (2018). Melatonin and its potential role in plant growth and stress tolerance. *Frontiers in Plant Science*, 9, 1787.
8. Yan, Y., et al. (2019). Melatonin treatment enhances the efficacy of fungicides against *Botrytis cinerea* and reduces chemical residues in strawberry. *Food Chemistry*, 301, 125295.
9. Tiwari, R. K., Lal, M. K., Naga, K. C., et al. (2021). Melatonin: An emerging plant growth regulator for sustainable agriculture. *Acta Physiologiae Plantarum*, 43, 130.
10. Hardeland, R. (2019). Melatonin and chloroplasts: Arguments on their probable interaction. *Journal of Experimental Botany*, 70(20), 5507–5519.