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Melatonin: The Master Molecule for Climate-Smart Crops-From Field to Shelf

Siddhanta Sahu[1]
Zuby Gohar Ansari[2]
Champa Lal Regar[3]
Om Prakash Regar[4]
Manohar Lal Meghwal[5]

[1]M.Sc. Research Scholar
[2]Assistant professor
(Plant Physiology)
[3,4] Assistant Professor
(Vegetable Science-Horticulture)
[5]Assistant Professor
(Fruit Science-Horticulture)
Department of Agriculture and Veterinary Sciences
Mewar University, Chittorgarh
Rajasthan, India

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*Corresponding Author
Zuby Gohar Ansari*

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INTRODUCTION

Melatonin is a naturally synthesized key indoleamine compound, chemically referred to as N-acetyl−5-methoxytryptamine, that is ubiquitously found in animals, microorganisms and plants, and is present in different parts of more than 20 dicot and monocot plant families. Melatonin plays an important role, endogenously and exogenously, as a plant growth regulator that is highly beneficial for mitigating adverse stress and increasing resilience in plants. It is associated with seed germination, fruit ripening, biomass production, photosynthesis, the circadian rhythm, membrane integrity, the redox network, root development, osmoregulation and leaf senescence, as well as responses to abiotic stresses such as drought, high salinity, heat, cold, oxidative damage and heavy-metal toxicity. It also helps prevent leaf aging and improves and maintains the quality and shelf life of postharvest fruits and vegetables.

Melatonin has promising potential to help crops cope with increasingly adverse climatic and weather conditions. Recently some official media reports indicate that, as of August 2026, nearly 64% of India's agricultural area was under drought stress. According to the India Meteorological Department (IMD), June 2026 was among the driest Junes on record, with rainfall running well below the long-term average and several rainfed regions facing increased water stress. Globally, a study on plantain production in Central Africa reported a 43% decline in yield between 1991 and 2011, linked to rising temperatures, highlighting the growing impact of unpredictable weather on crop production and farmers. In this context, further advancement of melatonin-based strategies could play a crucial role in improving crop resilience and helping agriculture cope with emerging climate-related challenges while maintaining consistent production of fruits and vegetables supporting farmer like a backbone during uncertain climatic stress to prevent losses and continuum of quality production.

Role of Melatonin

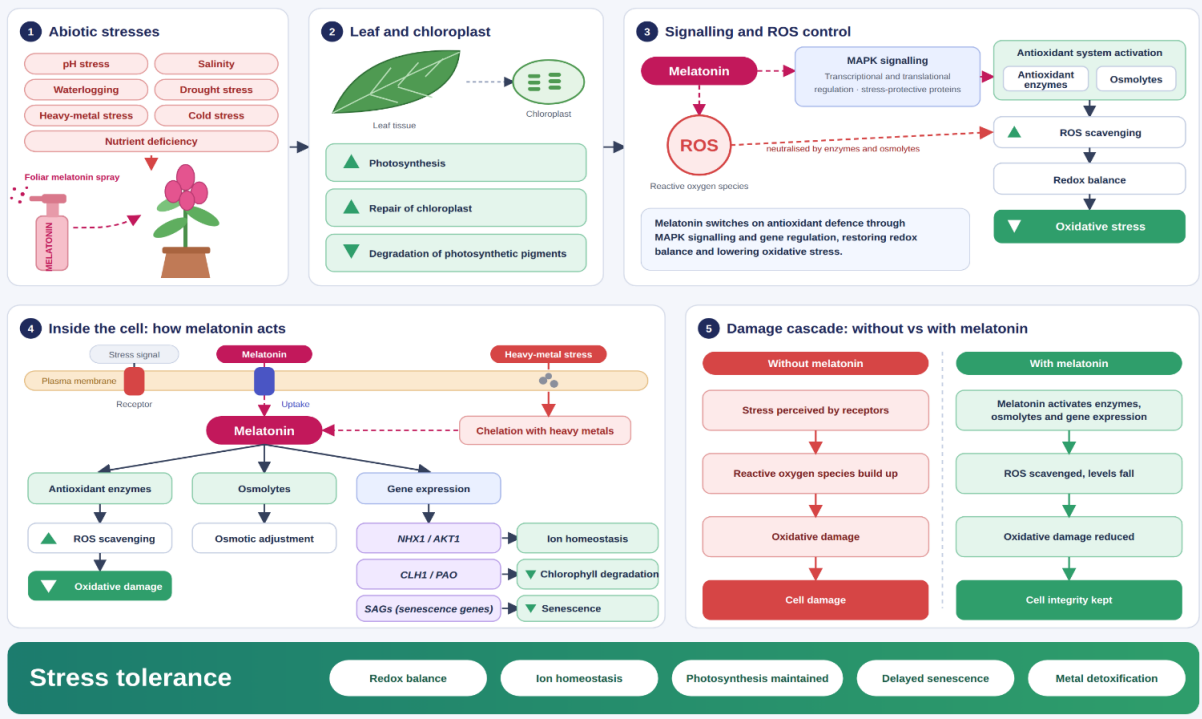


Fig. 1: Effect of Melatonin on plant during stress

1. Seed germination

- Melatonin possesses both hydrophilic and lipophilic properties, enabling it to readily penetrate seeds.
- Melatonin regulates seed germination primarily by influencing carbohydrate metabolism and coordinating cellular biosynthesis, metabolic activity and repair.

Example-

a) In *Brassica oleracea* seeds, treatment with low concentrations of melatonin particularly 1 and 10 µM has been shown to significantly promote seed germination.

2. Stimulating plant growth

- Melatonin regulates plant growth and development through its antioxidant activity and modulation of the MAPK signalling pathway.
- Melatonin enhances photosynthetic efficiency and influences flowering through temperature, vernalization, photoperiod, gibberellin (GA) and age-related (AGE) pathways.

Example:

a) Application of melatonin in wheat increased grain yield by 33.50%along with grain weight, root length, shoot length, leaf area, plant height, shoot weight and root weight.

3. Promoting plant rooting

- Low concentrations of melatonin stimulate auxin which promotes primary root elongation and growth.
- Melatonin also contributes to lateral root formation and development.

Example-

a) Transcriptome and hormone Analyses reveal that melatonin promotes adventitious rooting in shaded cucumber hypocotyls.

b) On applying of 20 µM of melatonin regulates root architecture by modulating auxin response in rice.

4. Regulating fruit development

- Melatonin enhances crop yield by increasing individual fruit weight and improving nutritional quality.
- Melatonin activates genes responsible for increasing primary metabolites like sucrase synthase, sucrose phosphate synthase, acid invertase and secondary metabolites like phenolic acids, flavonoids aroma-related volatile compounds (alcohols, aldehydes, ketones), improving flavour and nutritional quality.

Example-

a) Application of 100 µmol/L exogenous melatonin during tomato fruit development increased the activities of sucrose synthase, sucrose phosphate synthase, and acid invertase, and also increased accumulation of six phenolic acids, three flavonoids, and various volatile aroma compounds improving both flavour and nutritional quality.

5. Delaying leaf aging

- Melatonin delays leaf senescence by protecting chlorophyll from degradation, maintaining leaf vitality for longer.
- Provide protection of photosystem II, antioxidant homeostasis and work antagonistically against ABA.

Example:

a) In barley, melatonin treatment of leaves kept in darkness significantly slowed the onset of senescence.

b) Melatonin delays leaf senescence of postharvest Chinese flowering cabbage through ROS homeostasis.

6. Antioxidant effect of melatonin in plants

- Antioxidant activity is one of the major functions of melatonin, protecting plants against environmental stresses.
- Both endogenous and exogenous melatonin reduce oxidative stress under heat, cold, drought and salinity by scavenging ROS.
- Melatonin enhances antioxidant enzymes such as CAT, SOD, POD and PPO, limiting excessive ROS accumulation.

Example-

a) Foliar spray of 100 µM melatonin under 100 mM NaCl salt stress stabilizes photosynthesis and scavenges ROS to enhance salt tolerance in cucumber.

b) Exogenous melatonin enhances growth and physiological activities in cabbage under drought stress.

7. Role of melatonin in drought stress

- Activation of antioxidant defense system , ABA regulation ,aquaporin gene regulation.
- Melatonin also provides lipid membrane stability, protect photosystem, improve root architecture module.

Example-

a) Melatonin Improves Drought Stress Tolerance of Tomato by Modulating Plant Growth, Root Architecture, Photosynthesis, and Antioxidant Defense System.

b) Exogenous melatonin confers drought stress by promoting plant growth, photosynthetic efficiency and antioxidant defense system of pea.

8. Role of melatonin in salt stress

- Melatonin enhances osmotic adjustment in plants under salinity by improving water uptake and cellular water balance.

- Endogenous melatonin increases leaf osmotic potential, helping plants sustain water absorption and photosynthetic activity under salt stress.

  Example-

  a) Melatonin treatment in sugar beet seedlings enhanced photosynthesis, water status, ion homeostasis and antioxidant defense, alleviating salt stress and promoting growth, root yield and sugar accumulation.

9. Role of melatonin for high-temperature stress

- Melatonin enhances heat tolerance by upregulating HSP genes, promoting repair and protection of proteins damaged by high temperatures.
- Melatonin also activates HSFA1s, which induces heat-responsive genes such as HSFA2, HSA32, HSP90 and HSP101, strengthening tolerance to heat stress.
- Melatonin maintains osmotic and hormonal balance ,protect reproductive system and photosystem during heat stress.

  Example-

  a) A 100 µM melatonin foliar spray reduced heat-induced damage in the heat-sensitive strawberry cultivar 'Ventana'.

  b) Exogenous melatonin enhanced tomato heat resistance by regulating photosynthetic electron flux and maintaining ROS homeostasis

10. Role of melatonin for low-temperature stress

- Melatonin is transported from roots to shoots, where it enhances plant tolerance to cold stress.
- Melatonin treatment improves the cold-storage resilience and quality of fruits, vegetables and cut flowers.

  Example:

  a) Melatonin treatment enhances cold-stress tolerance in tomato plants.

  b) Exogenous melatonin improves the chilling tolerance and preharvest fruit shelf life in eggplant.

11. Role of melatonin for heavy-metal stress

- Melatonin enhances heavy metal tolerance by promoting secondary metabolites involved in metal chelation and reducing ROS accumulation, limiting metal-induced growth inhibition.

  Example:

  a) Melatonin attenuates cadmium induced oxidative stress in potato by remodelling redox homeostasis and activating multi pathway antioxidant networks.

  b) In Chinese cabbage, foliar melatonin application reduces ROS accumulation and Cd uptake while enhancing antioxidant activity, alleviating oxidative stress.

12. Inhibiting plant pathogenic microorganisms

- Melatonin functions as a broad-spectrum antifungal by targeting a conserved pathogen protein kinase.

  Example:

  a) Leaf application of 100 µM melatonin in cucumber alleviated downy mildew infection,

  b) In tea plants, exogenous melatonin treatment reduces fungal biomass on infected leaves, limiting disease development.

13. Postharvest preservation of fruits and vegetables

- Fruit and vegetable senescence is a natural, irreversible process involving

physiological, biochemical and metabolic changes that reduce colour, flavour, nutritional value and shelf life.

- Melatonin delays postharvest deterioration by slowing quality and nutrient losses, extending shelf life and maintaining fruit and vegetable quality.

In Fruits:

a) During post harvesting apples, 100–200 µM melatonin treatment effectively suppresses gray mold and helping to extend shelf life.
b) Exogenous melatonin reduces browning and enhances antimicrobial activity in apple juice, prolonging its shelf life.
c) In peach fruit, melatonin treatment delays senescence and reduces chilling induced flesh browning by alleviating oxidative damage.
d) Exogenous melatonin prolongs raspberry postharvest life quality by increasing some antioxidant and enzyme activity and phytochemical contents.
e) Melatonin reduces pesticide residue, delays senescence, and improves antioxidant nutrient accumulation in postharvest jujube fruit.

In Vegetables:

a) Melatonin extends shelf life in postharvest okra by delaying fruit softening and reducing weight loss.
b) Soaking cucumber in melatonin maintains quality, reduces oxidative damage, delays senescence and extends shelf life.
c) Exogenous melatonin lowers H_2O_2 levels in cassava roots, delaying postharvest physiological deterioration.
d) Melatonin alleviates chilling injury and maintains postharvest quality by enhancing antioxidant capacity and inhibiting cell wall degradation in cold-stored eggplant fruit.
e) Application of 50 µM melatonin increases lycopene content in postharvest tomato fruits by up to 5.8-fold.
f) Melatonin treatment extends broccoli shelf life.
g) Melatonin pretreatment reduces lesion development in potato tuber slices infected with *Phytophthora infestans*.

CONCLUSION

With agriculture increasingly challenged by drought, salinity, heat waves, unpredictable rainfall and rising temperatures, melatonin is emerging as a promising multifunctional plant growth regulator. It can support seed germination, root development, photosynthesis, fruit growth, antioxidant defense and tolerance to drought, salinity, heat, cold, heavy metals and pathogens. Melatonin could therefore become an important tool for connecting climate-stress protection in the field with quality preservation after harvest helping agriculture remain productive, resilient and sustainable in an increasingly uncertain climate.

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