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Melatonin and it's Effects on Abiotic Stress Management in Crop Plants- A Critical Review

D. Behera[1*], S. Das[2], N. Ranasingh[3] and S. Behera[4]
[1]*Associate Professor (Horticulture), College of Agriculture, OUAT, Bhawanipatna (Odisha), India.*
[2]*Assistant Professor, Department of Nematology, CA, OUAT, Bhawanipatna (Odisha), India.*
[3]*Associate Professor (Plant Pathology), College of Agriculture, OUAT, Bhawanipatna (Odisha), India.*
[4]*Programme Assistant (Plant Physiology), KVK, Kalahandi, OUAT (Odisha), India.*

(Corresponding author: D. Behera)*
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ABSTRACT: Numerous biotic and abiotic stressors are constantly present in the environment for plants. Reducing these losses is a key priority to ensuring food security in the face of climate change, as food productivity is declining as a result of the negative effects of numerous biotic and abiotic pressures. Plant growth and productivity are severely hampered globally by environmental abiotic stresses as drought, harsh temperatures, cold, heavy metals, and excessive salinity.

Keywords: Melatonin, Abiotic stress, Stress Physiology, antioxidants, Stress Tolerance.

INTRODUCTION

Stress is any environmental factor that keeps a plant from reaching its full genetic potential. Because they are sessile, plants cannot escape abiotic stress by merely relocating to an environment that is more conducive. Increasing the food supply for a constantly expanding human population in the face of deteriorating environmental circumstances in many parts of the world is the challenge facing agriculture today and in the future. Plant cell homeostasis is impacted by the many abiotic stresses that the environment imposes, which are typically interrelated and frequently have an osmotic component (Gull *et al.*, 2019).

Because plants respond to various environmental stress situations with distinct changes in their physiology, metabolism, and gene expression, research on crop abiotic stress responses is varied (Zhu, 2016). Abiotic stress has risen to a staggering 71% of the declining amount of agricultural product, while other pressures are at 29%. Only about 10% of the world's arable land is thought to be free of stressors. According to reports, abiotic stressors are the primary global crop production limiting factors, resulting in yield reductions of over 50%. The impact of major stress factors has been lessened by increasing the use of appropriate fertilisers, soil improvement, and various irrigation techniques.

As an alternative strategy, the application of certain externally applied healers during plant growth has been attempted recently, and it has been noted that the use of MEL may increase the plant's capacity to withstand stress. Plant tolerance to several abiotic or environmental stressors, including heat, salinity, and drought, is enhanced by melatonin. Plant growth, morphogenesis, and response to biotic and abiotic stressors are all regulated by the low molecular weight indoleamine chemical melatonin (N-acetyl-5-methoxytryptamine).

Melatonin was named for its ability to lighten the skin of some fish, reptiles, and amphibians. Melatonin is a neurotransmitter that is widely involved in a variety of biological processes and is recognised as an important plant metabolite. Melatonin is an indolic compound derived from tryptophan and was discovered in plants in 1995. It is present in nearly all plant species (more than 20 dicotyledonous and monocotyledonous plant families), with the amount of the plant tissues varying depending on the light.

However, fragrant plants and leaves have a higher melatonin content than seeds. Melatonin's primary roles include rooting, growth promotion, antioxidant molecule, and first line of defence against oxidative damage. It is well recognised that melatonin helps to improve abiotic stress (salt, drought, cold, heat, oxidative stress, and heavy metals), osmoregulation, root development, leaf senescence, and seed membrane integrity.

Melatonin's main roles are as an antioxidant due to its solubility in lipids and water and its ability to flow freely throughout the body to any watery area. However, melatonin has been shown to enhance plants' overall development. It increases wheat, barley, and canary grass's coleoptile length. Better seed vigour and quality as well as improved seed storage proteins were the outcomes of the melatonin-treated maize seeds. Melatonin has been shown to play a similar effect in etiolated *Lupinus albus* L., where it has been linked to the stimulation of vegetative growth as well as the regeneration of adventitious and lateral roots.

Furthermore, in barley, wheat, sweet cherry, and rice, melatonin therapy was found to boost photosynthetic activity, improve redox homeostasis, control root growth and development, and elongate seminal roots. In *Mimosa pudica* L., it has a favourable effect on root organogenesis.

THE IMPACT OF MELATONIN ON DROUGHT STRESS

According to Anjum *et al.* (2011), drought is a multifaceted stress that impacts plants at several levels of their organisation, ranging from the molecular to the phenological and morphological. Due to social and economic advancements as well as population expansion, water shortage has been a significant issue globally. More than 100 nations are experiencing water scarcity, and by 2025, around two-thirds of the world's population will be at risk of moderate to severe water stress. Water used in agriculture is under danger due to rising water contamination and domestic and industrial water demands. Drought is therefore one of the world's most significant agricultural issues. In arid regions, two-fifths of global agriculture is practiced .

Relative water content (RWC), leaf water potential, stomatal conductance, rate of transpiration, leaf temperature, and canopy temperature are important characteristics that influence plant water relations. A decrease in the RWC in response to drought stress is commonly observed in a variety of plant species. Arid conditions have a negative effect on photosynthetic activity, cause changes in chlorophyll content and components in the cell, and damage photosynthetic parts. It also inhibits photochemical activity and lowers the activity of enzymes in the Calvin circle. Cell elongation is inhibited by interruption of water flow to elongating cells under severe water deficit.

Additionally, it impairs cell elongation, expansion, and mitosis, which results in decreased growth. Due to stomata closure, phloem loading, assimilate translocation, and dry matter partitioning, which affect leaf gas exchange, crop plants with water deficits exhibit a sharp drop in yield traits. Drought inhibits plant development and growth, which hinders flower formation and grain filling. Consequently, fewer and smaller grains ultimately lead to significant yield losses. Additionally, oxidative damage was brought on by drought stress through the increased production of reactive oxygen species (ROS), which decreases photosynthesis, stomatal closure, and changes enzyme activity. Because it results in electron leakage, lipid peroxidation, and consequent membrane damage, as well as damage to proteins and nucleic acids, ROS generation is seen as a hazard to cells. Plants have developed various strategies to reduce these damages, such as increasing antioxidant compounds, either enzymatic (like guaiacol peroxidase (GPX), ascorbate peroxidase (APX), catalase (CAT), superoxide dismutase (SOD), or nonenzymatic (like glutathione, ascorbic acid carotenoids, and α-tocopherols).

The various phenolic compounds are another antioxidant that enhances plant tolerance in plant tissue. Numerous phenolic chemicals found in plant tissues, including flavonoids, tannins, and lignin precursors, have the potential to function as antioxidants and may scavenge reactive oxygen species (ROS). These antioxidants use a sequence of redox processes to function as a cooperative network. Furthermore, it has been demonstrated that phenolic compounds may play a role in the plant cells' ROS scavenging cascade. Exogenous natural plant growth compounds have been shown to be a successful method for increasing drought tolerance in plants. Because exogenous MEL treatments boost zeatin and indole acetic acid (IAA) while decreasing the synthesis of H_2O_2 and aminocyclopropane-1 carboxylic acid (ACC), they have improved photosynthetic capacity and water use efficiency (Li *et al.*, 2017). By boosting antioxidant activity and reducing ROS and membrane damage, MEL treatments mitigated the negative effects of drought stress in wheat. They also revealed that MEL generated a thicker epidermal cell, intact grana lamella of chloroplast and leaf structure, and better photosynthetic activity. They attributed these favourable reactions to MEL treatments in wheat to increased gene expression and enzyme activity. By raising antioxidant activity, MEL was shown to have a positive impact on drought stress. Similarly, by increasing antioxidant enzyme activity and photosynthetic efficiency, it may be able to mitigate the negative impacts of drought stress by ROS scavenging. In Agrostis stolonifera, exogenous MEL treatments reduced water deficit-induced leaf senescence by increasing the expression of the melatonin biosynthesis genes (TDC1, SNAT1, and COMT). Another study found that MEL treatments during drought enhanced photosynthetic activity, lowered chlorophyll degradation, and decreased electrical leakage in two distinct drought-resistant apple cultivars. MEL treatments lower the amount of ABA under dry conditions by increasing the expression of catabolic genes (MdCYP707A1 and MdCYP707A2) and decreasing the expression of the ABA synthetic gene (MdNCED3).

Under dry conditions, the impact of MEL treatment on Brassica napus L. plant development and certain biochemical characteristics was ascertained. The study found that the negative effects of water scarcity on plant growth were lessened by exogenous MEL treatments (0.05 mmol/L). Additionally, MEL treatments raised osmotic solutes and antioxidant enzyme activity while decreasing H_2O_2. MEL treatments improved photosystem II, which produced a conserving factor in maize under drought stress, as demonstrated.

IMPACT OF MELATONIN ON SUBMERGENCE STRESS

Aside from drought, flooding is one of the most harmful abiotic stresses in the world, affecting 17 million km2 of land surface each year. Recent studies show that more extreme weather events, including flooding or soil waterlogging, are occurring as a result of climate change, which has a detrimental impact on crop productivity. Understanding the effects of flooding stress on crops and creating better production techniques that increase agricultural systems' resilience and capacity to withstand extreme weather events are therefore crucial. Aside from drought, flooding is one of the most harmful abiotic stresses, affecting 17 million km^2 of land surface each year. Globally, waterlogging or severe soil drainage restrictions are thought to damage 10–12% of the agricultural area (Shabala, 2011).

This map shows the 3,713 flood incidents that were documented in the public global database between 1985 and 2010. Abiotic stressors such as soil water loading and submergence, which are commonly referred to as flooding, affect the species diversity and productivity of many plant communities worldwide. Flooding is a complicated stressor that interferes with a plant's ability to operate normally in a number of ways. The main effect is oxygen and carbon dioxide starvation, which is caused by the floodwater's incredibly sluggish diffusion rates in comparison to the air. A lack of external carbon dioxide and shade significantly limit photosynthesis when flooding reaches the point where the shoot is submerged. Depending on the depth of the water table, soil flooding causes plants to experience composite and complicated stress that is referred to as either submergence stress or waterlogging stress. There are two types of flooding events: (1) waterlogging, which solely affects the soil's root system, and (2) submergence, which includes sections or the entire shoot submerged in water. Flooding is a complicated stressor that interferes with a plant's ability to operate normally in a number of ways. The main effect is oxygen and carbon dioxide starvation, which is caused by the floodwater's incredibly sluggish diffusion rates in comparison to the air. Grain yields are negatively impacted by excess water, which is a significant productivity barrier in many areas and circumstances. Without continuous photosynthesis, the oxygen content rapidly drops in flooded plant sections, resulting in hypoxic conditions (e.g.). Numerous plant species have evolved defences against flooding stress that allow them to grow and procreate in damp soil or underwater. Soil flooding and, in particular, total submersion hinder the growth and development of the great majority of vascular plant species, both of which can be fatal. However, in regions that are prone to flooding, many wetland species are extremely prolific. Anoxia tolerance avoiding oxygen deficiency through efficient internal aeration, physical "escape" from a submerged environment and the ability to prevent or repair oxidative damage during re-aeration are some of the key physiological adaptations and acclimations that help achieve this. Additionally, water logging decreases soil N mineralisation rates and encourages soil nitrogen (N) loss through processes as denitrification, nitrate leaching, and runoff.

By effectively suppressing the ROS burst and the ensuing mitochondrial breakdown, suggested the first mechanism of melatonin-mediated waterlogging tolerance in apple seedlings to maintain aerobic respiration and retain photosynthesis. An alternative model for lucerne by directly controlling or engaging with the ethylene and polyamine (PA) metabolic processes. In comparison to plants that were not under stress, waterlogging stress caused endogenous melatonin levels to rise by a factor of two to five. Melatonin first reduces ethylene production by downregulating genes linked to ethylene synthesis and easing growth inhibition, chlorosis, and premature senescence brought on by waterlogging. Then, by encouraging the expression of genes involved in PA metabolism and enzymatic activity, melatonin raises the levels of Pas.

By controlling polyamine and ethylene production through ethylene suppression and PAs promotion, the authors hypothesised that melatonin improved waterlogging tolerance at least in part. This resulted in a more stable cell membrane, improved photosynthesis, and reduced ethyleneresponsive senescence. Together, waterlogging produces ROS, polyamines (PAs), ethylene, and melatonin (2–5 times). In addition, exogenous melatonin and ROS formation trigger the production of melatonin. In contrast to ethylene biosynthesis, growth decrease, leaf senescence, ROS, and oxidative damage, melatonin promotes photosynthesis, membrane stability, and PAs biosynthesis. The antioxidant enzymes scavenge the oxidative damage caused by excessive ROS, which results in anaerobic respiration. Additionally, PAs inhibit growth reduction and leaf senescence, whereas ethylene increases both.

MELATONIN ON MITIGATING SALINITY STRESS

One of the main abiotic variables reducing agricultural output and endangering global food security. When plants are exposed to salt stress, the oxidative reaction of free radicals in membrane lipids results in the buildup of more reactive oxygen radicals and hydrogen peroxide. This damage to the membrane system and subsequent cross-linking polymerisation of proteins, nucleic acids, and other biomolecules raises the levels of malondialdehyde (MDA), electrolyte leakage (EL), and lipid peroxidation. One of the first areas that is harmed by stressors, such as high salinity, is the plant membrane system.

Osmotic control, ion transport, and changes in hormone levels are among the physiological processes that plants primarily use to fend off the harm caused by salt stress. Plant osmotic regulators primarily consist of inorganic osmotic regulators (Na^+, K^+, Cl^-) and organic osmotic regulators (proline, soluble sugar, soluble protein). These two types of regulators can work together to lower osmotic potential, raise cell fluid concentration, preserve intracellular homeostasis, and improve plant resistance to salt stress. Elevated salt levels can have a negative impact on photosynthetic activity, blooming and fruit behaviour, vegetative growth, seed germination, seedling growth, and ultimately poorer economic production and quality (Yu *et al.*, 2018).

In cucumbers cultivated under salinity stress, exogenous MEL treatments enhanced growth, photosynthetic capability, antioxidant activity, and chlorophyll content while lowering ROS levels and oxidative damage (Wang *et al*., 2016). MEL treatments on roots improved watermelon's antioxidant enzyme activity and decreased oxidative stress, which lessened the negative impacts of salinity on photosynthetic capability. This impact was ascribed to improved light energy absorption and electron transport in photosystem II, as well as the suppression of stomatal closure [Li *et al*., 2017]. In a potato cultivated under salinity stress, exogenous MEL treatments demonstrated a significant impact of MEL linked to lipid metabolism with K+/Na+ balance (Yu *et al.*, 2018). According to the findings of (Jiang *et al.*, 2016), exogenous MEL treatments significantly enhanced the growth, photosynthetic capacity, antioxidant enzyme activity, and homeostasis of salt-stressed maize plants. It was demonstrated that stress situations caused the MEL concentration in roots to rise, reaching six times the control level. According to Arnao et al. (2009), this rise may be crucial in reducing stressful situations. Increases in seedling development, food intake, and nitrogen metabolism were noted in Cucumis sativus, particularly following treatment with MEL under salinity conditions (Zhang *et al.*, 2017). By controlling polyamine metabolism in wheat, MEL pretreatments mitigated the adverse effects of salt stress, as demonstrated by Ke *et al.* (2018). Additionally, they proposed that MEL might stimulate enzyme activity, which would boost antioxidant defences that scavenge ROS in response to salinity. In a different investigation, it was found that in salinity-induced rice, 10–500 μM MEL solutions improved germination and seedling growth. According to Li *et al.* (2017), this improvement was caused by a decrease in the amounts of Na^+ and Cl^- in the roots and leaves. According to a different study, MEL treatments increased K+ and decreased NaCl content in potatoes, improving their tolerance to salt stress and K+/Na+ balance (Yu *et al.*, 2018). Similarly, MEL treatments on watermelon roots improved redox homeostasis and antioxidant enzyme activity while reducing oxidative stress and salt-stress damage to photosynthetic ability.

MELATONIN ON MITIGATING HEAVY METAL STRESS

Any metallic element that is poisonous even at low concentrations and has a relatively high density is referred to as a heavy metal. A class of metals and metalloids having an atomic density of more than 4 $g \cdot cm^{-3}$ is generally referred to as heavy metals. Of the elements found in nature, 53 are classified as heavy metals. Most of the heavy metals, which include chromium (Cr), silver (Ag), iron (Fe), zinc (Zn), cobalt (Co), arsenic (As), cadmium (Cd), nickel (Ni), lead (Pb), and platinum (Pt), are not necessary for plant life. Despite being naturally occurring in the soil, geology and human activity raise the concentration of certain heavy metals, which has a poisonous and detrimental effect on both plants and animals.

These days, heavy metal accumulation from broad industrialisation has a negative impact on crop yield and soil quality (Shahid *et al*., 2015). Damage to soil texture, such as changes in the pH, the presence of various elements, and the buildup of heavy metals, can directly or indirectly reduce plant growth by negatively influencing a variety of plant physiological and molecular processes (Panuccio *et al*., 2009; Hassan *et al.,* 2017). Important biological functions and developmental pathways depend on heavy metals like Zn, Cu, Mo, Mn, Co, and Ni (Salla *et al*., 2011; Shahid *et al.*, 2015).

However, if their concentrations reach to supraoptimal levels, these metals and four other extremely toxic heavy metals—arsenic (As), lead (Pb), cadmium (Cd), mercury (Hg), Cr, Al, and Be—can significantly lower crop productivity (Xiong *et al*., 2014; Pierart *et al*., 2015). These harmful substances result in metabolic problems and morphological defects that lower plant production (Amari *et al.*, 2017). Reactive oxygen species (ROS), such as superoxide anion radical (O^{2-}), H_2O_2, and hydroxyl radical (OH^-), are also produced as a result of these abnormalities, disrupting the redox homeostasis of cells (Gill and Tuteja 2010; Pourrut *et al*., 2011; Ibrahim *et al*., 2015; Shahid *et al.*, 2015).

On the other hand, a relatively high MT concentration of 100 µM was the most effective way to control the growth of tomato plants that were impacted by 100 µM Cd (Hasan *et al*., 2015). MT supplementation restored the bright yellow cell effect caused by lead-induced cell death and morphological distortion in cultivated tobacco (Nicotiana tabacum) (Kobylinska *et al*., 2016; Kobylinska *et al.*, 2017). But in tomato plants treated with 100 µM Cd, Se, given as selenocysteine (3µM), increased MT levels, resulting in stabilised growth, decreased photoinhibition, and decreased membrane leakage (Li *et al.*, 2016). Melatonin offers plants a variety of defences against heavy metal stress. There have been prior reports of ROS scavenging by MT in various plant species under HM stress (Hasan *et al.*, 2015; Zuo *et al.*, 2017). For instance, by raising Rubisco and ATPase activities, which are essential for photosynthesis, exogenous MT improved the tolerance of wheat (Triticum aestivum) plants to ZnO nanoparticles (Zuo *et al.*, 2017). By modifying the activities of ROS scavenging enzymes, Alstressed soybean plants treated with a modest dose of MT improved plant tolerance in another study (Zhang *et al*., 2017). Higher doses, however, had the opposite effect. This implied that the dose and type of plant determine how MT affects the activity of antioxidant enzymes in HM-stressed plants.

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