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Review Article

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POTENTIAL ROLE OF MELATONIN IN ALLEVIATING HEAVY METALS PHYTOTOXICITY IN PLANTS

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ABSTRACT

Heavy metal contamination is a major environmental concern because of their potential to severely damage plant growth and yield. Plants are unable to complete their morpho-physiological growth when subjected to heavy metal stress because heavy metals are toxic and can accumulate in plant tissues, disrupting normal physiological processes. Melatonin, a hormone produced by plants has been shown to play an important role in protecting plants against heavy metal toxicity by mitigating the damage caused by oxidative stress and improving antioxidative defense mechanism. This review provides an overview of the existing literature on the potential use of melatonin in plant sciences with the purpose of determining its effectiveness in alleviating heavy metal toxicity in plants. The increase in antioxidative enzymes superoxide dismutase and catalase and the levels of reactive oxygen species (ROS) and malondialdehyde are lowered after exogenous melatonin treatment indicating that heavy metal-induced oxidative stress in plants can be mitigated. Under heavy metal stress, melatonin provision increases plant growth and yield in a several ways, including by enhancing photosynthetic activity, nitrogen absorption, and root characteristics. It is concluded in this review that research on melatonin in plant sciences is providing a new avenue for reducing plant heavy metal stress. Melatonin mediated heavy metal resistance can have a great potential in mitigating the adverse effects of transgenic metals which open new avenues of research in plant stress physiology.

Keywords: Melatonin, Heavy metals, Plant stress, Environmental toxicology, Plant stress, stress tolerance

Introduction

Plant development and yield are reported to be affected by heavy metal contamination which is a serious environmental issue. Reduced plant growth, production and quality are the consequences of the physiological disturbances caused by heavy metal accumulation in plants, such as oxidative stress and ion toxicity (Kumar *et al*., 2022). Several strategies for mitigating heavy metal stress in plants have been investigated over the years, including the use of exogenous antioxidants and plant growth regulators (Nawaz *et al*., 2018). Melatonin, a crucial biological hormone that regulates the plant's circadian cycle (Gu *et al*., 2022) has recently attracted attention as a potential solution to the issue of heavy metal stress in plants. This review summarizes how melatonin alleviate heavy metal stress in plants.

Melatonin Biosynthesis and Functions: Plants like all other forms of life naturally produce the hormone melatonin. Through a sequence of enzymatic processes involving tryptamine, serotonin and N-acetylserotonin, melatonin is produced from tryptophan in plants (Ali *et al*., 2022). The rate of melatonin production is controlled by environmental and developmental factors and this pathway is substantially conserved across plant species (Wang *et al*., 2022). Seed germination, root development, leaf senescence and plant responses to stress are only some of the physiological processes that may be altered by melatonin (Ali *et al*., 2021). Plants circadian rhythms, regulated by melatonin are essential for coordinating plant growth with daily variations in environmental conditions. Melatonin also play a significant role in protecting plant from oxidative damage under stress environment as it acts as a powerful antioxidant and free radical scavenger (Arnao *et al*., 2021).

Heavy Metals effects on Plants: Soil conditions become unfavorable for plants to mature and reproduce when the concentration of certain heavy metals is above the threshold limit that might induce phyto-

toxicity increases (Huang *et al*., 2021). Soil heavy metals have been linked to oxidative stress, ion toxicity and other physiological disorders in plants, all of which reduce growth and productivity (Zhou *et al*., 2020). Heavy metal stress impairs a plant's capacity to take up and transport water, causing root cell death and nutritional shortfalls (Goyal *et al*., 2020). Plant cells are also susceptible to heavy metal accumulation, which is dangerous since these elements can disrupt cell membrane function and halt cell division (Zand *et al*., 2020).

The role of melatonin in mitigating heavy metal stress in plants: Recent studies have shown that melatonin plays a crucial role in preventing heavy metal toxicity in plants. Exogenous melatonin treatment improves plant development and productivity under heavy metal stress environment. By maintaining ion homeostasis, osmotic pressure regulation and activation of antioxidant defense systems, melatonin strengthens plant ability to withstand heavy metal stress (Asif *et al*., 2019).

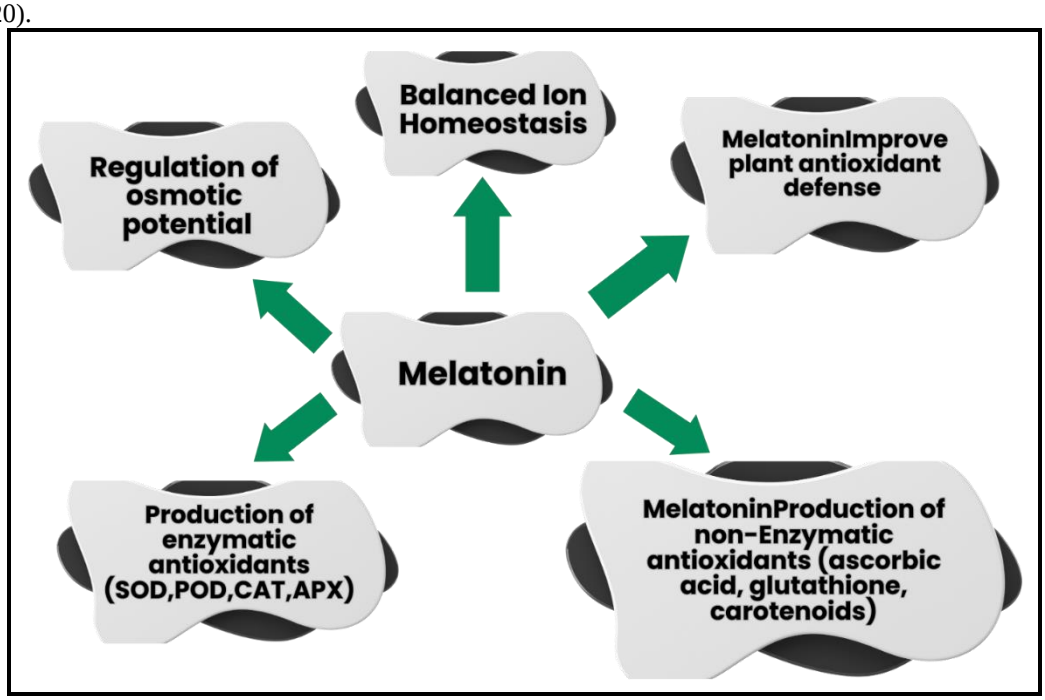

Figure 1. Role of melatonin in regulating physio-biochemical mechanisms in plants to mitigate heavy metals stress

Melatonin and Ions Homeostasis: Ionic imbalance in plant cells caused by excessive concentration of heavy metals in the growth medium causes the buildup of toxic ions including cadmium, lead and mercury (Sun *et al*., 2021). Accumulation of these toxic ions results in cell death and other physiological problems in plants. Ion homeostasis is aided by melatonin's involvement in regulating intracellular ion transport and distribution (Kul *et al*., 2019). Ion transporters like H^+-ATPases and Ca^{2+}-ATPases are responsible for maintaining the cellular ionic balance, and their activity is positively correlated with the exogenous application of melatonin (Rehaman *et al*., 2021)

Regulation of Osmotic Potential by Melatonin: Heavy metal stress causes plant cells to lose water, which in turn disrupts the osmotic potential and results in less nutrients uptake in plants (Xiang *et al*., 2019). Melatonin aid in keeping the plant osmotic equilibrium by stimulating the production of suitable solutes such proline and glycine betaine. Compatible solutes aid in maintaining the osmotic equilibrium in plant cells by stabilizing proteins and membranes (Fan *et al*., 2018).

Melatonin improve plant antioxidant defense: Oxidative stress and consequent damage to proteins, lipids and DNA result from the accumulation of reactive oxygen species in plant cells in response to heavy metal interaction (Khan *et al*., 2022). To protect from the potentially negative consequences of oxidative stress, plants have developed a specific antioxidative defense system that makes use of both enzymatic and non-enzymatic antioxidants. Melatonin, a significant antioxidant has been shown to significantly contribute to plants antioxidative defense system, contributing mitigating heavy metal stress (Xie *et al*., 2022). Protecting plasma membrane and proteins from oxidative stress, melatonin actively scavenge reactive oxygen species. In addition to lowering ROS levels, melatonin can help in synthesis of antioxidative enzymes and other biologically important compounds (Imran *et al*., 2022).

Enzymatic Antioxidants: Plants have developed a wide range of enzymatic antioxidants to combat with oxidative stress under heavy metal phyto-toxicity. These enzymes include superoxide dismutase, ascorbate peroxidase, catalase and peroxidase (Farooq *et al*., 2022). The primary defensive mechanism against reactive oxygen species in the plant body is the enzyme SOD, which catalyzes the dismutation of superoxide radicals into hydrogen peroxide and oxygen (Ali *et al*., 2021). Melatonin has been shown to enhance the

activity of SOD which reduces the generation of superoxide radicals and oxidative damage in plants when exposed to heavy metals (Hoque *et al*., 2021). Catalase (CAT) decomposes hydrogen peroxide into innocuous byproducts like water and oxygen. Melatonin prevents oxidative damage in plants by increasing CAT activity when they are exposed to heavy metals (Jahan *et al*., 2020). The peroxide oxidation of several different substrates is catalyzed by POD. Melatonin increase the activity of POD in plants that are exposed to heavy metals, protecting them from oxidative damage and the generation of hydrogen peroxide (Altaf *et al*., 2021). Ascorbate peroxide oxidase (APX) is an enzyme that catalyzes the dehydration of hydrogen peroxide. Protecting plants from oxidative stress and hydrogen peroxide accumulation following heavy metal exposure, melatonin has been found in enhancing the APX activity (Seleiman *et al*., 2020).

Non-enzymatic Antioxidants: Many plants also produce non-enzymatic antioxidants that help them deal with the oxidative damage brought as a consequence of heavy metal stress. Ascorbic acid, glutathione, tocopherol, and carotenes are all examples of antioxidants. Vitamin C (ascorbic acid) is a powerful antioxidant that may neutralize reactive oxygen species (ROS) in a significant amount (Xie *et al*., 2022). Melatonin has been found to protect plants from oxidative stress by increasing their ascorbic acid production when exposed to heavy metals (Chen *et al*., 2018). As a tripeptide, glutathione is essential for cellular redox equilibrium. Xia *et al*. (2020) found that when plants were exposed to heavy metals, melatonin increased glutathione production, which in turn decreased ROS generation and protected plants against oxidative damage. In the lipid phase of membranes, the antioxidant tocopherol (vitamin E) may directly scavenge ROS. Melatonin has been found to protect plants from oxidative stress by increasing tocopherol production (Xia *et al*., 2020) when they are exposed to heavy metals. Carotenoids are pigments that prevent oxidative stress and overexposure to light in plants. Ni *et al*. (2018) found that when plants were exposed to heavy metals, melatonin increased the synthesis of carotenoids, which in turn decreased the buildup of reactive oxygen species (ROS) and protected the plants from oxidative damage.

Importance of melatonin in reclaiming heavy metal stress in plants and its potential for use in agriculture: Plants are particularly vulnerable to the oxidative stress and cellular component destruction caused when plants are subjected to abiotic environmental stress. Plants' antioxidative defenses can be improve by the powerful antioxidant melatonin which has been found to play a significant role in reducing heavy metal stress. Melatonin has the potential to be adopt as a strategy to improve plant development and agricultural output due to its properties in alleviating heavy metal stress (Ke *et al*., 2018). Reduced oxidative stress on membranes and proteins is one of the significant role of melatonin by scavenge reactive oxygen species (ROS). In addition to regulating ROS levels, melatonin has been shown to increase production of antioxidant enzymes and molecules (Ni *et al*., 2018; Shi *et al*., 2017). In order to avoid oxidative damage, melatonin has been proved to increase the production of antioxidant enzymes such as superoxide dismutase, catalase, peroxidase and ascorbate peroxidase. Furthermore, melatonin prevents oxidative damage by increasing the production of non-enzymatic antioxidants as ascorbic acid, glutathione, tocopherol and carotenoids (Gong *et al*., 2017).

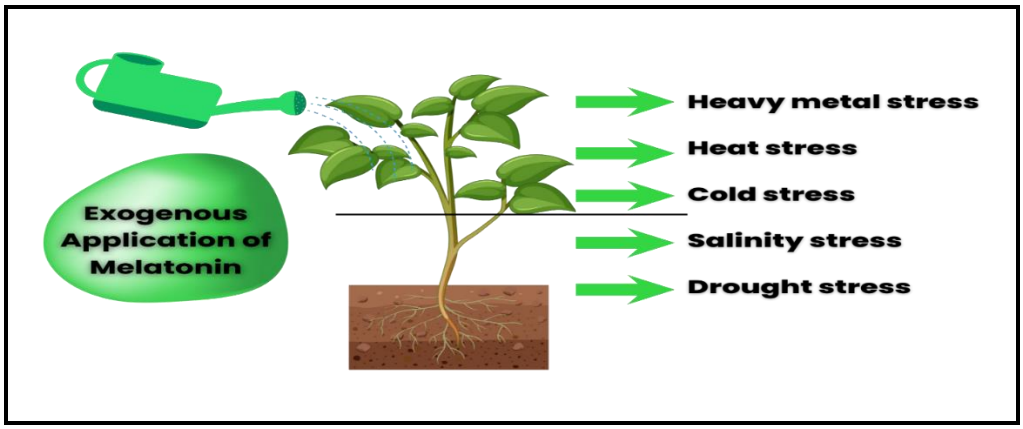

Figure 2. Potential uses of melatonin in alleviating abiotic environmental stress in plants

Several studies on different plants species including rice (Samanta *et al*., 2020), wheat (Talaat, 2021), tomato (Jahan *et al*., 2020), and cucumber (Madebo *et al*., 2021) have concluded that melatonin can reduce heavy metal stress. Melatonin, for instance, has been shown to increase the activity of antioxidative enzymes and decrease oxidative damage to cellular components in cadmium-exposed rice plants (Huangfu *et al*., 2022). Melatonin was reported to increase seed germination and root development while decreasing oxidative damage in wheat plants exposed to lead (Zafar *et al*., 2019). Melatonin has the potential to be used as a anti stress hormone in agriculture to improve plant growth and production with the exception of its reaction in reducing heavy metal stress. There is evidence that melatonin can enhance photosynthesis, agricultural

productivity and crop quality. Provision of melatonin was found to improve strawberry plants' yield and quality by boosting both fruit size and sugar content (El-Mogy *et al*., 2019). The stress tolerance of plants to salinity, temperature and drought has also been found to be improved by melatonin. This data indicates that melatonin may be useful for increasing agricultural yields in high-stress conditions (Colombage *et al*., 2023).

Future prospects : Melatonin is being studied as a potential bio-hormone for reducing plant toxicity to heavy metal stress. Future applications of melatonin might include: (i) While numerous studies have focused at melatonin's role in reducing plant heavy metal stress under controlled conditions (laboratory and green house experiments), further studies are needed in the field for final recommendations and evaluate melatonin's efficacy in natural plant growing fields. (ii) The use of melatonin-based products such as bio-fertilizers or foliar sprays to increase plant tolerance of heavy metal stress has promising future applications. This may be a practical and long-term solution for reducing plant heavy metal stress. Further mechanism-based research is required to completely understand the molecular pathways involved in melatonin protective effects against heavy metal stress in plants, (iii) it was found that some plant species responded eminently to melatonin application as compared to the other plants, therefore it is important to test several plant species to determine which ones respond best to melatonin application that can further be recommended to grow on metal contaminated soils (iv) The time and application rate of melatonin must be considered to get its maximum effectiveness. This may enhance melatonin's beneficial role in mitigating potential negative effects of heavy metals on plant growth.

Conclusion

Melatonin play a crucial role in alleviating heavy metal stress because due to its potential role in stimulating the plant antioxidative defense mechanism. Melatonin's ability to increase photosynthesis, crop productivity and crop quality suggests it might be used to aid plant recovery from severe abiotic environmental stresses. Melatonin significantly scavenges a variety of ROS that protects cells and tissues of plants from the deteriorated effects of oxidative stress under heavy metals exposure. In future, sustainable crop yield and food security are both positively affected by the usage of melatonin in agriculture and new research should be encouraged to better underlying the positive role of melatonin for sustainable crop production from metal contaminated soil

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