Chapter 2
Melatonin in Plants: Biosynthesis, Occurrence and Role in plants

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Abstract Melatonin (N-acetyl-5-methoxytryptamine) is a pineal gland hormone, relatively little research has been done on it in this area up until 1995. It can be found in several plant species in different concentrations. Melatonin has even been proposed as nature's most adaptable biological signal molecule due to its widespread distribution throughout all kingdoms. Since Hattori first discovered melatonin in plants, Numerous studies have been released, expanding the field of phytomelatonin i.e. melatonin generated from plants. Plants biosynthesize phytomelatonin from the precursor tryptophan. Because of their powerful antioxidant properties, the majority of herbs with high melatonin content have been utilised for centuries to treat neurological problems linked to the production of free radicals. This brief summary aims to give a general understanding of phytomelatonin, including information on its distribution, biosynthesis, potential roles in the regulation and growth, and abiotic stress management of plants.

Keywords Phytomelatonin · Tryptophan · Medicinal plants · Abiotic stress · Antioxidant

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2.1 Introduction

Melatonin has a long history and is a well-known companion in animal and human physiology, but it is new to plant physiology (Reiter et al. 2011). In 1958, Lerner and colleagues isolated melatonin for the first time from the pineal gland of cattle (Lerner et al. 1958) Melatonin was given that name because it can make the skin of several fish amphibians, and reptiles (Chava and Sirisha 2012). Melatonin is essential for controlling the circadian rhythm in mammals (Sahna et al. 2005). This powerful antioxidant boosts the gene expression of antioxidant enzymes while also protecting mitochondrial homeostasis. (Nitulescu et al. 2009; Carrillo et al. 2013; Fatma et al. 2013; Bhavini et al. 2009). Consequently, it is very helpful in treating neurological diseases like Alzheimer's, etc. whose pathophysiology is linked to the cytotoxic effects of reactive oxygen species (Russel et al. 2010; Ayushi and Maheep 2007; Hardeland 2005; Jian and Ze 2006; Venkatramanujam 2011). For the first time, melatonin was independently discovered in plants by Dubbels et al. 1995; Hattori et al. 1995 (Dubbels et al. 1995; Hattori et al. 1995). Since then, research into phytomelatonin generated from plants has become one of the fastest-growing fields in plant physiology. Numerous scientific studies support the presence of melatonin is present in many plant species (Rudiger and Burkhard 2003). Melatonin is regarded as one of nature's most adaptable biological signals due to its widespread dispersion and multidirectional activity. According to the current study, plants both produce and absorb this conventional indole derivative (Marino and Josefa 2006). The results of the experiments provide the clearest evidence for phytomelatonin's functions as an antioxidant, free radical scavenger, and growth promoter (Russel et al. 2014). According to studies, excessive UV radiation increases the formation of indole compounds, which is strong evidence for phytomelatonin's activity as an antioxidant that protects plants from strain related to oxidation and lessens macromolecule damage in a way that is comparable to that of animals (Katerova et al. 2012). It is essential for controlling plant reproductive physiology and protecting plant cells from apoptosis brought on by unfavorable environmental factors. Phytomelatonin has been identified to have a variety of physiological roles, including a probable role in blooming, regulating circadian rhythms and photoperiodicity, and serving as a growth regulator. Melatonin content varies by plant organ or tissue, with leaves and fragrant plants having higher levels than seeds (Dun 2015). It has auxin-like activity and regulates root, shoot, and explant growth. It also promotes seed germination and rhizogenesis, slows the start of induced leaf senescence, and regulates explant growth (Krystyna and Małgorzata 2013). Recently, a potential function in lupin rhizogenesis has also been suggested (Katarzyna et al. 2014).

Melatonin production in plants is well established and relatively little is known about its existence in organisms other than angiosperms. This is mostly owing to insufficient detection techniques and a lack of experimental protocols to look into phytomelatonin's molecular and biochemical properties. To get quick, accurate results on phytomelatonin content, however, certain methodological protocols had been designed successfully. Tryptophan was discovered to be a common precursor for serotonin, melatonin, and indole-3-acetic acid (IAA) in investigations using radioisotope tracer techniques (Hernandez et al. 2004; Marino 2014; Russel et al. 2007). The whole biosynthetic pathways of phytomelatonin synthesis are yet to be explored vividly. According to certain accounts, plants may be able to absorb melatonin from the soil in which they are grown. According to the research, melatonin is also involved in the maintenance of chlorophyll and the promotion of photosynthesis (Van Tassel et al. 1995; Kolar and Machackova 2005). High-melatonin transgenic plants may significantly contribute to raising food yields and enhancing human health in general (Amit and Vinod 2014). This article's goals include deepening our comprehension of the various physiological functions of phytomelatonin as well as discussing intriguing data about the substance.

2.2 Biosynthesis of phytomelatonin

The precursor tryptophan has a phylogenetic widespread distribution and is the source of melatonin. It was long believed that only vertebrates' pineal glands could produce this neuro-hormone (Ebels and Tommel 1972). Later, a new area of study on this substance was created when melatonin was discovered in photosynthesizing organisms. Animals cannot synthesis the necessary amino acid tryptophan, hence they must get it from other natural sources since it cannot be produced by them (Marino and Hernandez 2007). In addition to the hormone auxin, phytoalexins, glucosinolates, alkaloids, and indoleamines, tryptophan also serves as a precursor for phytomelatonin (Bandurski et al. 1995). In angiosperms, the rate of melatonin production varies rhythmically, peaking at night and seasonally during the flowering period (Katri et al. 2012). Chorismate and anthranilate are used in the shikimic acid pathway to biosynthesize tryptophan. The conversion of tryptophan to 5-hydroxytryptophan to serotonin is regulated by tryptophan hydroxylase. Arylalkylamine N-acetyl Transferase (AANAT) converts serotonin into N-acetyl serotonin, from which hydroxyindole-O-methyltransferase (HIOMT) produces melatonin. It should be emphasized that AANAT is yet to be identified, although plants can still produce melatonin on their own. As a result, the genetic features of the serotonin N-acetylating enzyme in plants may differ from those of animal AANAT. Tryptophan decarboxylase is the only enzyme in plants that makes indole-3-acetic acid (IAA) from tryptophan (Yeo et al. 2007; Bruno et al. 2005; Marcello et al. 2006) (Fig. 2.1).

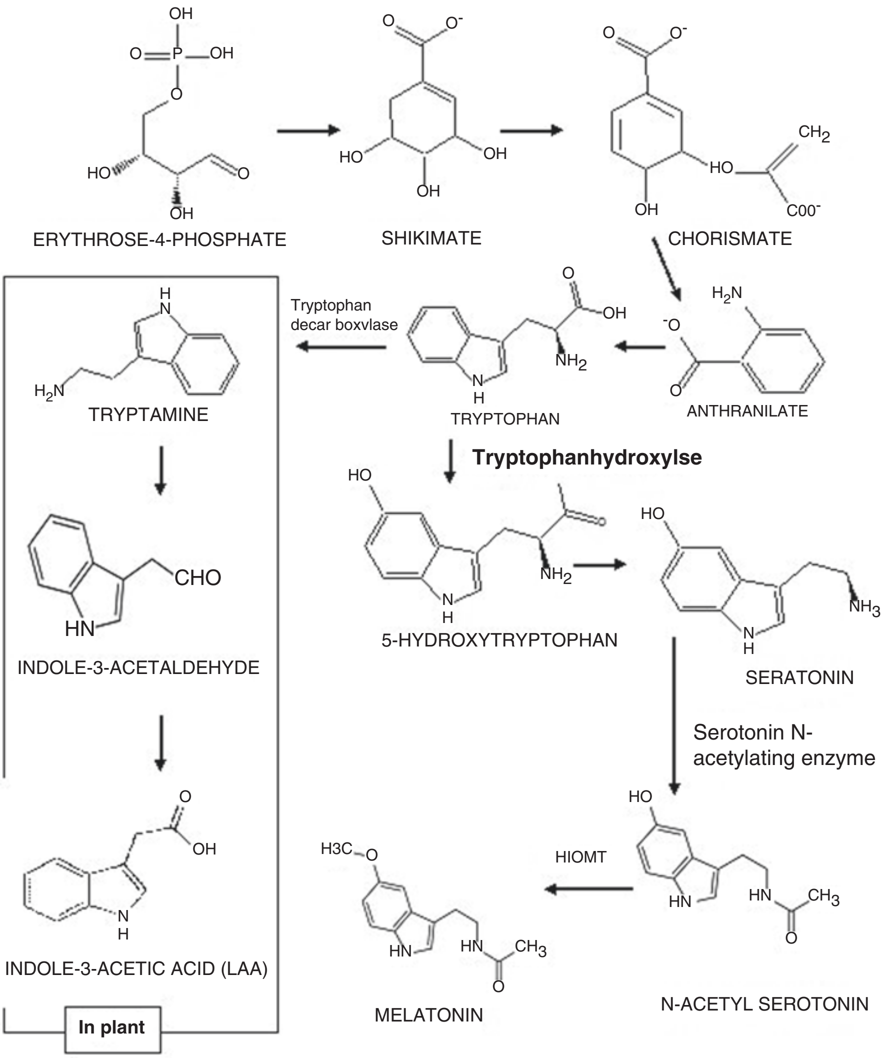

Fig. 2.1 The biosynthetic pathway of melatonin

2.3 Melatonin in Edible Plants

Humans have discovered the presence of melatonin in more than 140 distinct fragrant, medicinal, and food plants (Jan and Ivana 2005). To find melatonin in plant tissues, several advanced analytical methods were created. The most trustworthy sources among these include radioimmuno assays (RIA), enzyme-linked immunoadsorbent assays (ELISA), high-performance liquid chromatography (HPLC), and gas chromatography-mass spectrophotometry (GC-MS) (John et al. 2011; Kolar

2003; Marcello et al. 2012). According to reports, cereals from the family of Graminae, such as rice, barley, sweet corn, and oats, contain significant amounts of melatonin (Dun et al. 2007). Melatonin was found in bananas in a concentration of 0.655 ng/g, according to GC-MS analysis, but HPLC-MS suggested higher melatonin content (1 ng/g of plant tissue) (Badria 2002). In many fruits like berries, kiwis, etc., melatonin contents were reported. Both white and black mustard seeds contained melatonin (189 ng/g of plant tissue and 123 ng/g of plant tissue, respectively through RIA analysis) (Burkhardt et al. 2001; Manchester et al. 2000). Both green and roasted beans contained melatonin, with concentrations of 5.8 g/g dry weight and 8.0 g/g dry weight, respectively (Akula et al. 2012) (Table 2.1).

Table 2.1 Phytomelatonin occurrence

Common name	Taxonomy	Detection method	Amount (pg/g)	Reference
Kiwi fruit	*Actinidia deliciosa* Liang-Ferg (Actinidiaceae)	ELISA	24.4	Hattori et al. (1995)
Beet root	*Beta vulgaris* L. (Amaranthaceae)	ELISA	2	Dubbels et al. (1995)
Taro	*Colocasia esculenta* L. (Araceae)	ELISA	54.6	Hattori et al. (1995)
Asparagus	*Asparagus officinalis* L. (Asparagaceae)	ELISA	9.5	Hattori et al. (1995)
Feverfew	*Tanacetum parthenium L.* (Asteraceae)	HPLC-UV	1300–7000 ng/g	Pandi et al. (2006)
Barren wort	Epimedium brevicornum M. (Berberidaceae)	ELISA	1105 ng/g	Hardeland et al. (2011)
Indian spinach	*Basella alba* L. (Basellaceae)	ELISA	38.7	Hattori et al. (1995)
white radish	*Raphanus sativus* L. (Brassicaceae)	ELISA	657.2	Hattori et al. (1995)
Pineapple	*Ananas comosus* L. (Bromeliaceae)	ELISA	36.2	Hattori et al. (1995)
Cucumber fruit	*Cucumis sativus* L. (Cucurbitaceae)	HPLC	24.6	Hattori et al. (1995)
Alfalfa seed	*Medicago sativa* L. (Fabaceae)	HPLC-UV	16,000	Manchester et al. (2000)
Saint John’s wort	Hypericum perforatum L. (Hypericaceae)	Leaf Flower	1750 ng/g 2400–4000 ng/g	Tan et al. (2007)
Walnut	*Juglans regia L.* (Juglandaceae)	ELISA	3500	Kolar (2003)
Poppy seed	*Papaver somniferum* L. (Papaveraceae)	RIA	6000	Manchester et al. (2000)
Burmese grape	Baccaurea ramiflora (Phyllanthaceae)	ELISA HPLC-UV	76.7 43.2	Hardeland (1997)

(continued)

Table 2.1 (continued)

Common name	Taxonomy	Detection method	Amount (pg/g)	Reference
Rice seed	*Oryza sativa* L. (Poaceae)	ELISA	1006	Hattori et al. (1995)
Welsh onion	*Allium fistulosum* L. (Liliaceae)	RIA	85.7	Hattori et al. (1995)
Pomegranate	*Punica granatum* L. (Lythraceae)	HPLC-MS	540–5500	Hardeland et al. (2011)
White mulberry	Morus alba M. (Moraceae)		1510 ng/g	Sergio et al. (2009)
Banana	*Musa acuminata* Colla (Musacea)	GC-MS	0.46	Marino (2014)
Olive oil	*Olea europaea* L. (Oleracea)	ELISA	50–119 pg/mL	Xiaoyuan et al. (2014)
Chinese rhubarb	*Rheum palmatum* L. (Polygonaceae)	ELISA	1078 ng/g	Marino (2014)
Chinese goldthread	*Coptis chinensis* F. (Ranunculaceae)	ELISA	1008 ng/g	Marino (2014)
Almond seed	*Prunus amygdalus Batsch.* (Rosaceae)	ELISA	1400–11,260	Marino (2014)
Gambir Vine	*Uncaria rhynchophylla* (Rubiaceae)	ELISA	2460 ng/g	Marino (2014)
Amur cork tree	*Phellodendron amurense* (Rutaceae)	ELISA	1235 ng/g	Marino (2014)
Silver leaf nightshade fruit	*Solanum elaeagnifolium Cav.* (Solanaceae)	HPLC	7895	Hattori et al. (1995)
Devil's trumpet flower	*Datura metel L.* (Solanaceae)	HPLC	1500	Pandi et al. (2006)
Anise seed	*Pimpinella anisum* L. (Umbelliferae)	ELISA	7000	Pandi et al. (2006)
Coriander seed	*Coriandrum sativum* L. (Umbelliferae)	ELISA	7000	Pandi et al. (2006)
Fennel seed	*Foeniculum vulgare* L. (Umbelliferae)	ELISA	28,000	Pandi et al. (2006)
Sunflower seed	*Helianthus annuus* L. (Umbelliferae)	ELISA	29,000	Manchester et al. (2000)
Grapevine	*Vitis vinifera* L. (Vitaceae)	ELISA	5965	Manchester et al. (2000)
Cardamom seed	*Elettaria cardamomum* L. (Zingiberaceae)	HPLC-MS	15,000	Marino (2014)
Curcuma	*Curcuma aeruginosa Roxb.* (Zingiberaceae)	GC-MS	120,000	Marino (2014)

2.4 Role of phytomelatonin

2.4.1 Circadian Rhythm

Melatonin regulates the circadian rhythm in animals, peaking during the scotophase and remaining constant during the photoperiod (Kazutaka et al. 2013). Consequently, phytomelatonin was assumed to serve a similar purpose in plants. It produces a diurnal oscillation that increases at night and decreases during the day (Shiddamallayya et al. 2010). This showed how the photoperiod affects melatonin's involvement in regulating circadian rhythm. Circadian alterations in melatonin levels have been seen in algae and dinoflagellates in addition to higher plants (Amod et al. 2005; Parvin et al. 2011; Atanu et al. 2014). Researchers looked at how exogenous melatonin treatment affected Chenopodium rubrum flowering. In comparison to the control plants, the data did not indicate any harmful effects or changes in the form, colour, or quantity of leaves. Thus, the role of melatonin in flowering remains unclear (Ackermann et al. 2006; Pasquale et al. 2003). Figure 2.2 elaborates on the multi-directional role of melatonin in plants.

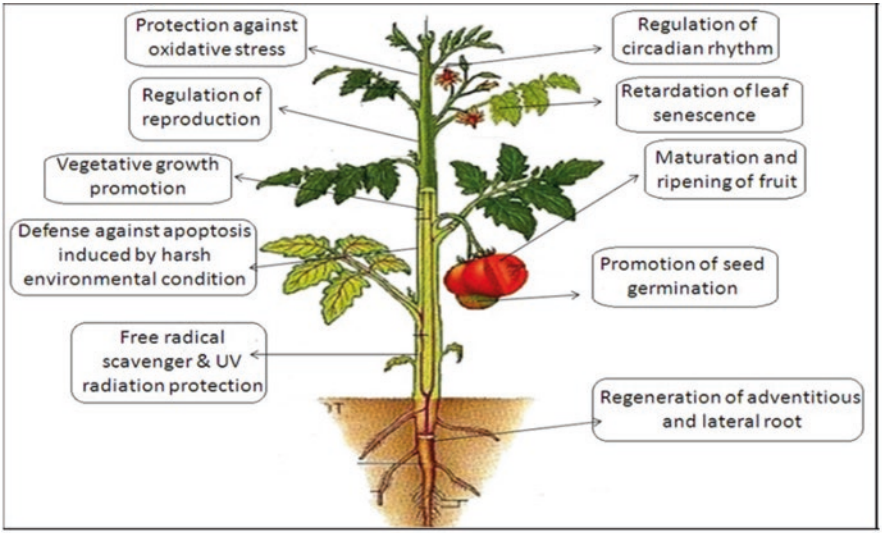

Fig. 2.2 The summary of multi directional actions of melatonin in plant growth, metabolism and redox balance (Bhattacharjee and Kumar 2018)

2.4.2 Antioxidant and Free Radical Scavenger

Melatonin is a well-known antioxidant in mammals (Russel 2001). This prompted the scientists to speculate that the indole molecule would behave similarly in plants. According to reports, Lycopersicon esculentum Mill. (cultivated tomato) melatonin concentration is five times higher than that of *Lycopersicon pimpinellifolium* Mill. (wild tomato), making the first one more tolerant in higher ozone levels. Melatonin protects against photography (Fuhrberg et al. 1996). Large amounts of free radicals, reactive nitrogen species (RNS), are evolved during photosynthesis. Additionally, as photophase exposure to light increases, the violaxanthin cycle becomes hindered, resulting in reduced plastidial photo-protection. *Eichhornia crassipes* had a perfect diurnal rhythm, with melatonin metabolites peaking in the late-night section of the light-dark cycle. This suggested melatonin metabolites may protect against harmful ROS and RNS damages (Balzer and Hardeland 1991). Additionally, it has been suggested higher plants and algae can benefit from melatonin's photoprotective actions against UV radiation (Wolf et al. 2001). Alpine and Mediterranean plants subjected to high UV levels in their native habitat contain more melatonin than the same species exposed to lower UV levels, lending support to this notion. (Tettamanti et al. 2000).

2.4.3 Growth Promoter

Melatonin and IAA, a powerful plant growth stimulant, are structurally similar. Melatonin is thus recommended to imitate auxin and promote vegetative development in a wide range of plant species (Kolar et al. 2003). Changes in endogenous melatonin levels, according to research, impeded auxin and cytokinin-induced root and shoot organogenesis respectively. This demonstrates the role of melatonin as a plant growth regulator (Russel and Manchester 2005). Later, Hernandez-Ruiz et al., incubated etiolated hypocotyls from Lupinus albus L. to further explore the function of melatonin with various melatonin and IAA concentrations (Hernandez and Arnao 2008). Both chemicals were scattered in plant tissues along a concentration gradient, with lower concentrations stimulating growth and higher concentrations inhibiting growth in both intact and de-rooted plant tissues. Melatonin produced the most roots and hypocotyls in this study, with values for root length that were nearly identical to those of the IAA concentrations studied (Hernandez et al. 2005).

Further, the growth-promoting effects of melatonin were demonstrated in various monocots, including oat, wheat, canary grass, and barley. Studies showed that melatonin, as opposed to IAA, stimulated development in coleoptiles by about 10, 20, 31, and 55%, respectively (Dubbels et al. 1995).

2.4.4 Defense Against Herbivores

Melatonin possesses a bitter and unpleasant palate, and offers defense against herbivores (Kolar and Machackova 2001). Additionally, because melatonin tends to accumulate in animal bodies, ingestion of plants like walnut (3.5–1.0 ng/g) that contain high levels of the hormone can disrupt the physiology of herbivores. According to studies, feeding rats a diet high in melatonin elevated their blood levels from 11.51.9 pg/ml to 38.04.3 pg/ml (Rudiger 2015). This finding might be relevant to how plants defend themselves from herbivores. White fly reproduction in tobacco is reduced by tryptophan decarboxylase overexpression, an enzyme that converts 5-hydroxytryptophan to 5-hydroxytryptamine (Thomas et al. 1995). Melatonin inhibits white fly reproduction, but the exact mechanism by which it does so is still unknown.

2.4.5 Abiotic Stress Tolerance

The use of melatonin can help to mitigate the detrimental consequences of abiotic stressors. The manufacture of phytomelatonin, which generally occurs within chloroplasts, and the accompanying metabolic processes have been widely researched. Melatonin controls stress responses by reducing ROS and RNS species buildup and modulating stress response pathways. Phytomelatonin role in abiotic stress is mentioned below.

2.4.5.1 Drought Stress

Drought inhibits plant growth and development. Drought aggravates ROS and RNS species via activation of stress signalling pathways. Drought stress activates transcription factors such as NACs, MYBs, AP2/EREBPs, bZIPs, HDs, and bHLHs (Zhang et al. 2014). Melatonin production is often stimulated by a lack of water (Shi et al. 2015). Endogenous melatonin levels alter when melatonin biosynthesis genes (e.g., TDC, ASMT, COMT, and SNAT) are activated during a water shortage. Drought also stimulates melatonin generation in Graminae species. (Moustafa et al. 2020).

Increased melatonin levels improve the stability of drought-stressed plants (Meng et al. 2014; Ding et al. 2018). Melatonin treatment can promote seed germination and lateral root formation, process (Hosseini et al. 2021; Sun et al. 2021). Melatonin also suppresses ROS-induced oxidative damage and increases antioxidative enzyme levels during drought in plants (Li et al. 2015; Antoniou et al. 2017; Alharby and Fahad 2020; Sadak and Bakry 2020).

2.4.5.2 Waterlogging Stress

Crop survival, growth, and productivity can all be harmed by waterlogging. This checks gas diffusion, resulting in hypoxic stress in the roots, and promotes ROS accumulation (Zhang et al. 2019; Gu et al. 2020; Wu et al. 2021). Waterlogging causes a rise in endogenous melatonin levels (Moustafa et al. 2020). Exogenous melatonin treatment significantly improves the seedling vitality of many plants (Zheng et al. 2017; Zhang et al. 2019; Gu et al. 2020). It reduces stomatal closure, chlorophyll and photosynthesis reduction, and leaf senescence (Zhang et al. 2019; Gu et al. 2020; Zheng et al. 2017). Melatonin treatment also reduces the oxidative damage caused by waterlogging. To maintain redox homeostasis under waterlogging stress, melatonin activates antioxidant enzymes and minimized H_2O_2 levels in both leaves and roots of peach seedlings (Gu et al. 2020).

2.4.5.3 Salt Stress

Melatonin improves salt tolerance in many plants such as maize, wheat, etc. (Liang et al. 2015; Zhou et al. 2016; Chen et al. 2018; Ke et al. 2018; Zhang et al. 2021). Salt stress alters the expression of essential biosynthetic enzyme patterns resulting increase in endogenous melatonin levels (Arnao and Hernández 2009). Furthermore, overexpression of SNAT can improve plant salt tolerance considerably (Wu et al. 2021). SNAT inhibition, on the other hand, lowers endogenous melatonin levels, making rice more sensitive to salt stress (Byeon and Back 2016). Exogenous melatonin protects plants from salt stress by regulating antioxidant enzyme expression (Zhan et al. 2019) resulting in suppression of ROS and H_2O_2 caused level by salinity. Furthermore, melatonin-NO crosstalk regulates redox equilibrium via differential expression of copper/zinc-SOD and manganese-SOD under salt stress (Arora and Bhatla 2017; Kaya et al. 2020).

2.4.5.4 Cold Stress

Melatonin protects plants from cold-induced stress. Plant cold tolerance can be improved by increasing endogenous melatonin levels. SNAT transgenic rice showed better stability than wild-variety (Kang et al. 2010). Melatonin improves cold tolerance in grafted watermelons (Tan et al. 2007; Li et al. 2021a).

2.4.5.5 Heat Stress

Heat stress has physiological, transcriptional, post-transcriptional, and epigenetic effects on plants (Zhao et al. 2020). Melatonin improves thermal tolerance in plants. COMT1 and TDC silencing in tomatoes resulted in a decline in melatonin biosynthesis causing temperature-induced stress (Ahammed et al. 2019).

Tolerance to potassium deficiency is a critical issue in crop production. Melatonin increases potassium levels in Malus and wheat (Li et al. 2016, Li 2021a). TaNAC71-regulated TaHAK1 is a vital factor to cope with MT-mediated potassium deficiency in wheat (Li et al. 2021b). Furthermore, melatonin reduces nano-plastic uptake by roots and translocation to shoots by regulating the expression of aquaporin-related genes (TIP2-9, PIP2, PIP3, PIP1-5, and PIP1.2) (Li et al. 2021c).

2.5 Conclusion & Future Aspects

Melatonin regulates various physiological functions in plants, including the circadian rhythm, cytoprotection and growth promotion, antioxidant defence, and free radical scavenging (Xiaoyuan et al. 2014). Additionally, it encourages rhizogenesis, cellular growth, and protects from environmental stress conditions (Chandana et al. 2014). Uses of phytomelatonin in agriculture; and humans have gained momentum at present. The first, exogenous melatonin administration to plants promotes improved growth and development as well as greater response to a variety of environmental stressors, including radiation, heat, cold, and drought.

Additionally, melatonin speeds up plant germination, development, and productivity. It slows the senescence of leaves brought on by stress. These cumulative findings suggest that treating farmed plants with exogenous melatonin or overproducing plants with greater melatonin levels may aid crops in more readily resisting various harmful environmental situations that they typically experience throughout their growth (Pandi et al. 2006). The latter parts deal with the potential introduction of melatonin-rich plant foods or dietary supplements because of the enormous health benefits it offers, especially in the fight against neurodegenerative diseases like Alzheimer's. According to studies, persons who take up to 1 gram of melatonin orally each day experience no negative side effects. Melatonin is additionally quickly absorbed through the digestive system. As a result, the use of melatonin as a nutraceutical appears to have a bright future in promoting a better lifestyle (Charanjit et al. 2008; Jemima et al. 2011).

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