Heliyon 7 (2021) e06150

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Phytomelatonin in stress management in agriculture

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ARTICLE INFO

Keywords:
Melatonin
Agriculture
Biotic stress
Abiotic stress
Tryptophan
Signaling molecule

ABSTRACT

Melatonin was discovered as a pineal gland hormone in animals and is now more significantly known as a signaling molecule in plants' biotic and abiotic stressors. Melatonin has been traced back to prokaryotic organisms during evolution and its primary function of antioxidant scavenging free radicals in photosynthetic prokaryotic bacteria is a lesser explored and exciting area for further research globally. The authors at IIT Delhi are trying to establish its potential role in stress management in agriculture. The present manuscript addresses the biosynthetic pathways hitherto suggested by scientists. In this manuscript, the potential scope of melatonin in agriculture as a growth promoter, post-harvest loss inhibitor, and signaling and quality improvement molecule is envisaged.

1. Introduction

Melatonin is one of the critical molecules among living organisms which functions as a secondary metabolite engaged with various natural, hormonal, and physiological mechanisms in the cell, tissue, and organ levels. Melatonin is the final product of the Tryptophan Metabolic Pathway (TMP). Its presence has been traced back to prokaryotes, and studies have shown that till date it is a part of an evolutionary journey (Manchester et al., 2015; Zhao et al., 2019).

Stages of the evolution of life on earth, corresponding with the presence of Melatonin was reported and discussed by several authors as described in Figure 1 (Zhao et al., 2019).

In agriculture, the role of melatonin becomes very crucial because of the investigation of its involvement in the increase of biomass, germination of seeds, improvement in the photosynthetic activities, fruit ripening, delayed flowering, and tolerance in the different types of biotic and biotic stresses (Asif et al., 2020). Due to the amphipathic, melatonin can move across the membranes, which makes them an essential molecule in agriculture, and cross-talk with different plant hormones is a crucial mechanism for various abiotic stress tolerance in agriculture crops (Mukherjee, 2018).

Lerner et al. (1958) first reported Melatonin's presence in the bovine pineal gland (Lynch et al., 1975) and established the existence of Melatonin in all living forms. Over a period of time, different scientists had reported it in different organisms. Subsequently, in 1995, it was discovered in some plant species, and later on, multiple studies were conducted to understand its presence, pathway, and functions in plants (Arnao and Hernández-Ruiz, 2006). Studies (Manchester et al., 2015; Pshenichnyuk et al., 2017)reflected that the presence of Melatonin in the prebiotic organisms primarily comprised of cyanobacteria and proteobacteria, indicating its existence through the evolution of all living beings, establishing its ubiquitous status. Interestingly, the presence of Melatonin in these organisms suggested that its chemical nature has barely changed during the journey of the evolution of life (Zhao et al., 2019).

Interestingly, the presence of isomers of melatonin was also reported in the plants. It is also found that the level of these isomers in the plants is higher than the original form of the melatonin (Hardeland, 2016; Tan et al., 2014). Melatonin has been detected in about 300 plants of different groups ranging from monocots to dicots (Arnao, 2014). The presence of Melatonin in higher plants has also been reported and designated as phytomelatonin and has the chemical structure of N-acetyl-5 methoxytryptamine, as shown in Figure 2.

The present review focus on the importance of melatonin in agriculture to determine the motive of applying exogenous melatonin in agriculture. Exogenous melatonin can be easily absorbed by plant roots. So total amount of the melatonin in plants was observed tobe higher due to the increase of melatonin in leaves, but their endogenous synthesis under different stress is still under investigation. The higher concentration of melatonin can protect plants from excess water (water stress) and soil pollutants, other environmental stresses like UV-radiation, etc (Janas and Posmyk, 2013).

Although there were some preliminary indications about the presence of melatonin in plants (Kolar et al., 1995; Kolár et al., 2002; Van Tassel et al., 2001), the first publication by Van Tassel & O Neil in a Congress communication proved the presence of phytomelotanin in higher plants

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https://doi.org/10.1016/j.heliyon.2021.e06150
Received 23 July 2020; Received in revised form 17 September 2020; Accepted 27 January 2021

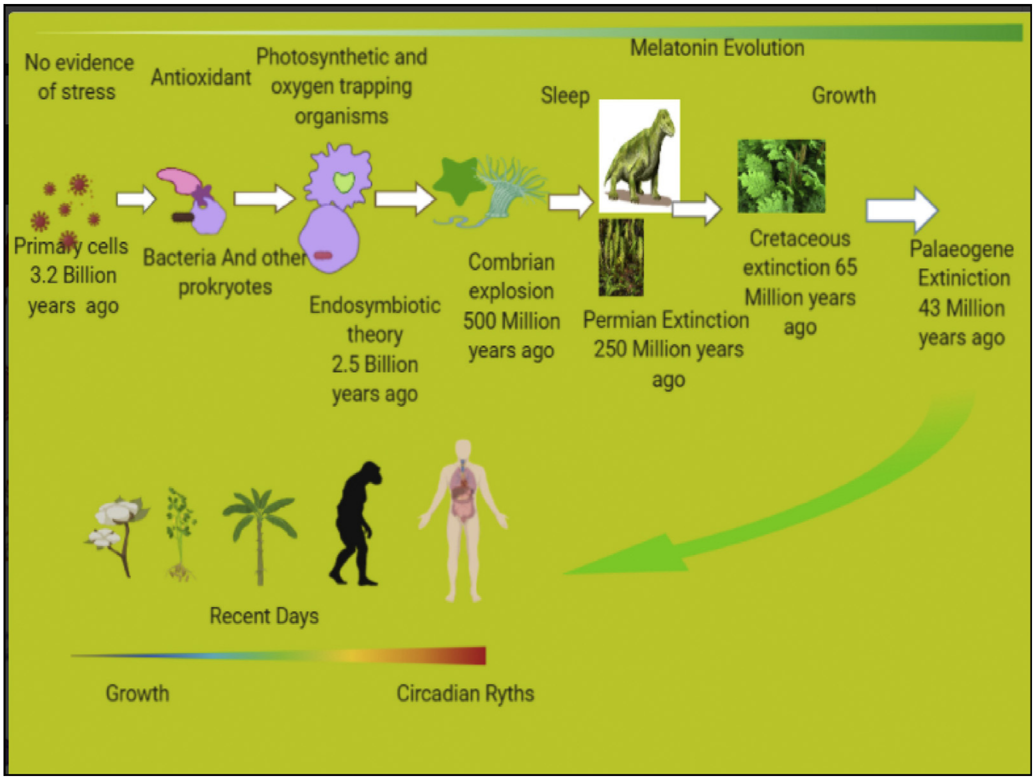

Figure 1. Stages of the evolution of life on earth, corresponding with the presence of Melatonin (Zhao et al., 2019) (Image credit- Biorender).

(Arnao,2014). The existence of phytomelatonin in all plants is now fully acknowledged, with concentrations varying from picogram to microgram. The research evidence confirming the *in-situ* synthesis of melatonin is mostly unexplored (Burkhardt et al., 2001). Melatonin's presence in two varieties of *Prunuscerasus* L. (tart cherry) mentioned that melatonin might be absorbed besides its potential synthesis in the cherry fruit exogenously through the roots, further transported to the nuts. Studies (Hardeland and Poeggeler, 2003; Manchester et al., 2015) proposed, as many microorganisms have melatonin in their cells, their decomposition in the soil may release melatonin into the surrounding material and is subsequently absorbed by the roots of the plants and recycle. Melatonin was absorbed exogenously from the plant growth medium. It was also observed that there were higher chances of survival of plants in melatonin enriched copper polluted water than the non-melatonin-enriched copper polluted water (Tan et al., 2007).

1.1. *Initial developments*

The development of melatonin from prokaryotes to higher mammals is highlighted in the sequence presented in Figure 1. Melatonin's journey from prokaryotic to evolved plant and animal species can be linked with tryptophan, the first molecule of Melatonin synthesis through a vital process of four-step reaction (Figure 3). Several research studies have confirmed that a significant portion of the phytomelatonin is synthesized by plants, even though the factors leading to the presence of a homolog of the classic arylalkylamine N-acetyltransferase (AANAT) in plants is yet to get more research attention. This indicates that the serotonin N-acetylation enzyme in plants may differ from the chemical and molecular composition of animal AANAT in sequence and structure. This supports that proteins with such catalytic properties are potential of multiple evolutionary origins. Melatonin's primary function in plants is established to serve as the primary defense against internal and environmental oxidative stressors. Six genes, namely, TDC, TPH, T5H, SNAT, ASMT, and COMT, have been found to potentially play a significant role in the biosynthesis of Melatonin, indicating the possibilities of the presence of multiple pathways. The two meaningful ways based on the enzyme kinetics have been proposed to be of production significance (Axelrod and Weissbach, 1960; Back et al., 2016; Weissbach et al., 1960).

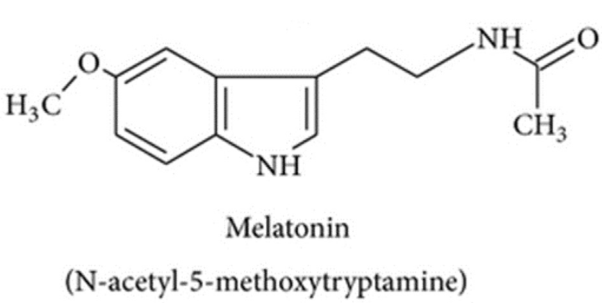

Figure 2. Chemical structure of phytomelatonin.

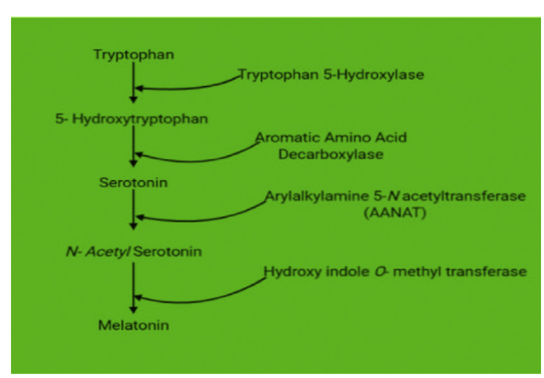

Figure 3. The Classical steps of biosynthesis of Melatonin from tryptophan as a four-step. reaction (Tan et al., 2016) (Image credit – Biorender).

Furthermore, serotonin plays a vital role in flowering, ion permeability, and a protective role as an antioxidant (Ramakrishna et al., 2011). Kang et al. (2009) suggested that tryptophan levels were considerably high during senescence, and the increased levels of tryptophan is converted into serotonin in the presence of Tryptophan decarboxylase (TDC). Though its efficacy against fungi and viruses was reported (Sharif et al., 2018), the role of Melatonin in plant protection against biotic stress is yet to be established with concrete research evidence. In a very recent paper published by Zhao & his coworkers (2021) in trends in plant sciences designating the melatonin as a regulator for biotic stress tolerance in plants. Authors have highlighted that phytomelatonin helps intolerance against biotic stresses. They also highlighted that melatonin contributes to the defense from pathogen attack. Interestingly the authors indicated that melatonin can modulate the biotic response when it interacts with the disease resistance signaling pathway (Zhao et al., 2021).

2. Synthesis of melatonin in plants

The pathway of melatonin in plants and microorganisms is unique in relation to that of the vertebrates. The utility of tryptophan for synthesis remains constant in these living beings (plants and microorganisms). The significant change in the plants' initial steps, i.e., decarboxylation of tryptophan into tryptamine, indicates the difference with vertebrates (Tan et al., 2014). Very recently, it is also discussed by Tan and Rieter (2020) that the final steps are also different in the vertebrates, which were earlier considered as the same in all the organisms. Some more studies are needed to find all the aspects related to the topic. Figure 4 indicates the suggested pathway for the production of melatonin. Tryptophan availability in the plants and microorganisms to initiate the pathway is assured by Shikimic acid pathways, which is followed in most of the plants and microorganisms except animals where tryptophan and other aromatic amino acids are supplied by food source The synthesis of the tryptophan in the plants, microalgae, and other prokaryotes also exhibit a complex process comes under Shikimic acid pathways where tryptophan can be integrated in the beginning with D-erythrose-4-phosphate and phosphoenolpyruvate, in phototrophs eventually with carbon dioxide (Bochkov et al., 2012).

The plant preference for either of the pathways requires more studies. The melatonin biosynthetic capacity associated with the conversion of tryptophan to serotonin is much higher than that related to the transformation of serotonin to melatonin, which results in low levels of melatonin. Depending on the pathway, melatonin synthesis final subcellular locations vary at either the cytoplasm or chloroplasts, which may differentially affect Melatonin's mode of action in plants (Back et al., 2016). Besides, Melatonin also play a critical role as a signaling molecule to mediate the plant defense response against pathogen attack via the mitogen-activated protein kinase (MAPK) pathway, as shown in Figure 5 (Lee et al., 2014, 2015).

2.1. Sites of melatonin synthesis in cells

The specific site of melatonin synthesis is still under investigation and a matter of debate. A very few literature are available, which provide a particular ground that the place of origin of melatonin in cells is mitochondria (Kanwar et al., 2018, Tan and Reiter, 2019). The main reason for the hypothesis is the occurrence of the SNAT gene in the mitochondria. It is also a predetermined fact that the generation of reactive oxygen species (ROS) in the mitochondria is very high. For ROS management, melatonin factors are produced and minimize the impact of ROS (Tan and Reiter, 2019). Along with mitochondria, the chloroplast is another organelle that is considered as a potential site for melatonin production. The evolutionary studies indicated that this may be possible due to the conversion of cyanobacteria into the chloroplast and the evolution of mitochondria from non-sulfur photosynthetic purple bacteria over time and distributed to other organisms (Kanwar et al., 2018).

3. Role of melatonin in plant stress management

It can be discerned that melatonin has a vital role in the plant kingdom due to its capacity to synthesize at a molecular level and activate plant growth level while enhancing its hydroxyl antioxidant capacity. The studies and reviews indicate enough scope for further research in ascertaining the role of phytomelatonin in the total gamut of plant physiology and plant protection. Melatonin could directly scavenge ROS under various abiotic and biotic stresses, generating these stresses as a powerful antioxidant, thus promoting plants' stress resistance (Reiter et al., 2018). Globally, scientists are making systematic and planned efforts to minutely probe the potential of phytomelatonin to make its

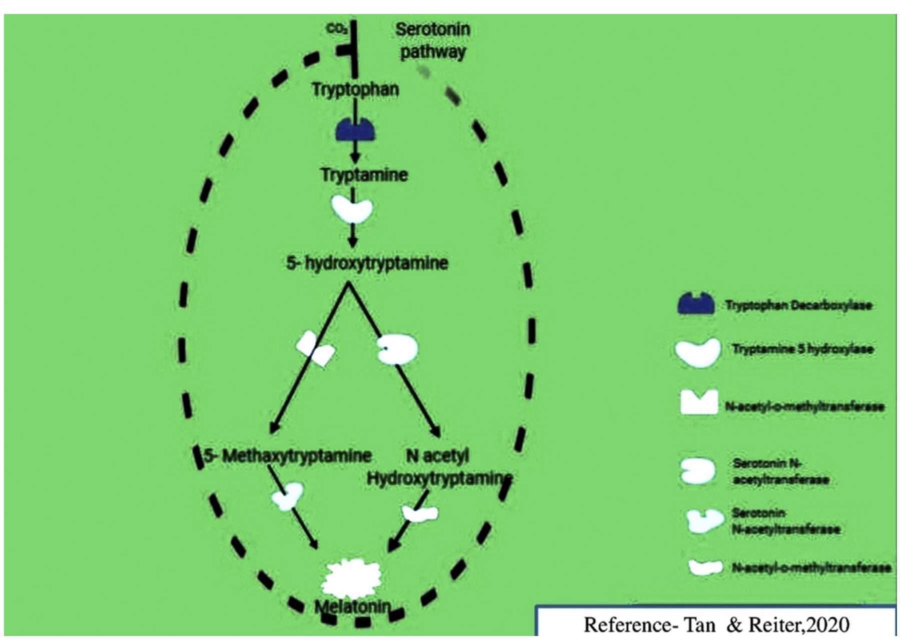

Figure 4. The pathways of biosynthesis of phytomelatonin in plant system. The steps have been divided in to two different ways for the synthesis of phytomelatonin (Diagram Credit- BioRender).

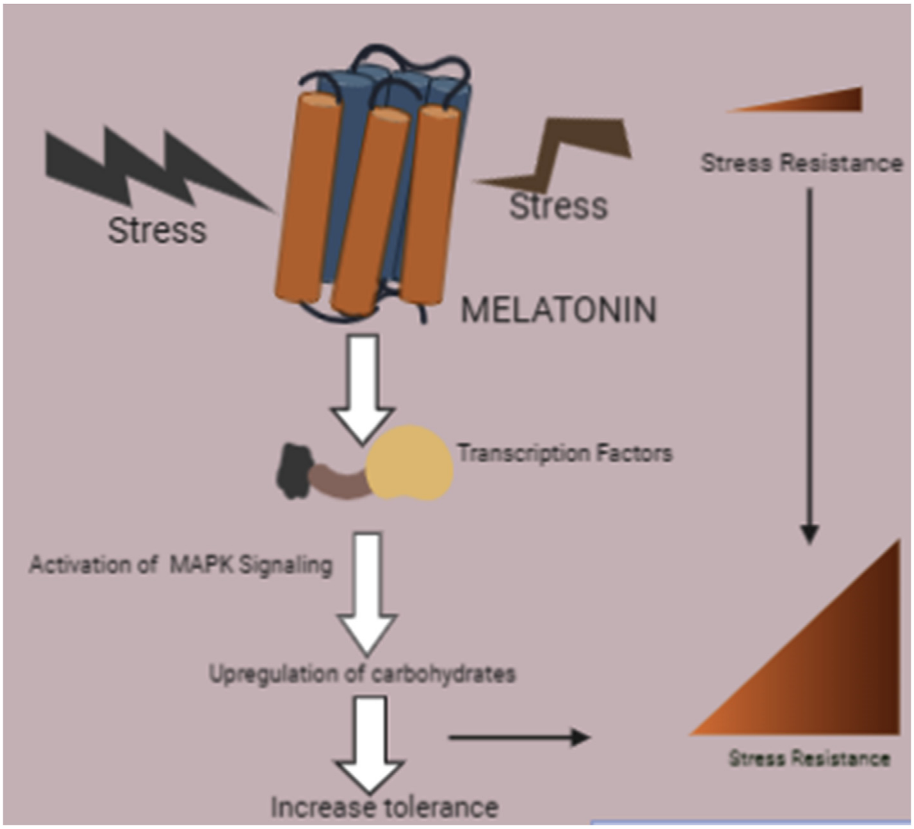

Figure 5. Mitogen-Activated Protein Kinase Pathways. The pathway describes an outline of the function of melatonin under stress (Lee et al., 2014, 2015) (Diagram Credit BioRender).

advantageous use synthetically. The efforts in this direction are focused on both biotic and abiotic stress management.

Though the role of phytomelatonin against selective abiotic stresses is widely reported, more research still needs to be done on the responses generated from specific plant parts and the conduction of signals. Effects of melatonin and its role in maize roots and leaves during drought conditions by comparing ROS accumulation and function of antioxidant enzymes (Huang et al., 2019). The study also concluded that melatonin was instrumental in addressing the increase in ROS, cell death, and deterioration of D1 protein. The outcome of leaf senescence in kiwifruit by giving a pretreatment of an exogenously applied melatonin indicated a significant reduction in membrane damage (Liang et al., 2018). Also, a reduced concentration of hydrogen peroxide was found with the increased activity of some antioxidant enzymes, resulting in Melatonin's potentially useful melatonin delaying the aging of kiwifruit leaves. Studies mentioned the potential of exogenous melatonin in protecting *Nicotianatabacum* L. suspension cells when exposed to lead. It was inferred that melatonin potentially functioned as a priming agent to support tobacco cells under lead-induced stress conditions (Kobylińska and Posmyk, 2016; Kobylińska et al., 2017). Apart from this, the relationship between exogenous melatonin in osmopriming of cucumber and antioxidant defense concluded the decisive role of melatonin in the growth of cucumber seeds and young seedlings oxidative stress (Marta et al., 2016).

ROS collection can actuate lipid peroxidation, loss in chlorophyll content, and damage of cell film respectability and photosynthetic action. To prevent these effects, plants have created a specific antioxidant mediated system (de Souza et al., 2014; Ye et al., 2016). Under unfavorable conditions, plants typically produce a lot of ROS, which actuate lipids membrane peroxidation and oxidative degradation. Melatonin is one of the critical molecules which detoxify the cells from the excess generation of ROS. It can not only reduce the ROS but also balance the group of reactions which are responsible for the development of ROS factors.

Melatonin has also been effective against various abiotic stresses, including heavy metals, drought, UV radiation, and toxic chemicals. Plant species having a lower concentration of melatonin showed their vulnerability to the presence of ozone in contrast to the relatively tolerant species for ozone (Dubbels et al., 1995). Similarly, the plant species grown in Alpine and Mediterranean regions are exposed to high UV radiations, and have a higher concentration of melatonin than the species grown away from these regions (Simopoulos et al., 2005). An increased level of melatonin was found, when the roots of *Glycyrrhizauralensis* plants exposed to UV-B radiations in contrast to the non-exposed plant's roots (Afreen et al., 2006). Subsequently, a similar effect of UV-B radiation on exposure of transgenic *Nicotianasylvestris* plants was observed (Zhang et al., 2017). It was reported that when the seeds of *Brassica oleracea* were pre-soaked in melatonin, copper ions did not exhibit any toxic effect on seed germination and inital growth phases (Posmyk and Janas, 2009).

Arnao and Hernández-Ruiz (2009) examined increased Melatonin concentration in *Hordeumvulgare* L roots when exposed to 1 mM zinc sulfate (ZnSO4), reconfirming the protective role of melatonin. Researchers suggested that increased melatonin concentration and reduced levels of malondialdehyde was observed in transgenic rice plants, along with elevated levels of activities of enzymes like catalase and superoxide dismutase as compared to control samples (Park et al., 2013; Nawaz et al., 2016).

There are several reports of involvement of melatonin in enhancing physiological processes such as improving germination and ripening process, photosynthetic activities, biomass production, root system development, and managing abiotic stresses (Kolár et al., 2002; Lee et al., 2014, 2015; Qian et al., 2015; Shi et al., 2015). However, recent researches and reviews reported that melatonin plays an instrumental role in managing biotic stresses and inducing gene expression in plants, which help to cope with different stressors. It is also said that inhibition of the in-vitro growth of filamentous fungi *Physalospora piricola*, *Botrytis cinerea*, or *Mycosphaerella arachidicola* was observed in the presence of a very high concentration (100 mM) of melatonin (Wang et al., 2012). The growth of *Alternaria* sp. had been reported to be inhibited at the concentration of melatonin at 4 mM. Alterations of the soil microbial community can significantly impact agricultural outcomes as microbes (both soil bacteria and fungi) are the critical drivers of soil health and agricultural crop productivity (Mau et al., 2019; Zhang et al., 2019).

During the last decade, on several occasions, it was reported that there is a difference in the concentration of melatonin between the different species depending on physical and edaphic parameters (Okazaki and Ezura, 2009; Wei et al., 2018). It was also reported that there is a the significant role of endogenous melatonin in regulating plant growth attributes in various species. To evaluate the concentration of melatonin in plants, many sensitive detection methods, and assays are available that include radioimmunoassay, ELISA, gas chromatography-mass spectrometry, and high-performance liquid chromatography, HPLC-electrochemical detection, HPLC fluorescence detection (HPLC-FD), and HPLC-mass spectrometry (HPLC-MS) which can detect even the slightest concentrations of the melatonin present in a sample (Zhang et al., 2017).

3.1. Plant immune system and melatonin

Melatonin is a significant messenger in plant for natural insusceptibility against the bacterial pathogen *Pseudomonas syringe* PV. Tomato (Pst) DC3000 in the salicylic acid (SA) and nitric oxide (NO) dependent pathway. Though the first study regarding the same has been done, the concrete research evidence still lacks in establishing the metabolic homeostasis in melatonin-mediated innate immunity.

Exogenous utilization of melatonin was found to restrict the potato late blight diseases caused by *Phytophthora infestans* by-a) suppressing mycelial development, b) changing cell ultrastructure, c) decreasing the virulence, and d) disabling pressure resilience of *P. investments* (Zhang et al., 2017). It was also observed that melatonin reduced the requirement of chemical fungicides significantly and improved the functions of fungicides for potato late blight fungus control because of the synergistic inhibitory effect produced by co-treating with melatonin and fungicide. The transcriptome studies suggested that melatonin can control the growth of *P. infestans*is most likely due to altering the homeostasis of amino acid metabolisms. Besides, melatonin also changed the role of significant components related to stress tolerance, fungal infestation, and the frequently used chemical fungicides which ordinarily show toxicity to most living forms. In contrast, Melatonin indicates less lethality even under high concentrations. Because of the above, there is a possibility to develop anovel transgenic potato crop that may deliver more melatonin as well as produce the sRNA focusing on the critical controllers of amino acid metabolism by manipulating the essential genes controlling the biogenesis of melatonin in potato and amino acid metabolism in *P. infestans*. Besides, as a potential synergist, melatonin can also possibly lessen the utilization of substance fungicides. It is reported to enhance substance fungicides effectiveness, limit the use of synthetic fungicides, and further diminish their requirements for crop protection (Madigan et al., 2019; Zhang et al., 2017).

In a recent study coined by Zhao and his coworkers(2021), reported that the production of endogenous production of melatonin, ROS and reactive nitrogen species (RNS) are interconnected and triggered by biotic stresses like pathogen attack or any other microbial infection to the plants. Also, under stress conditions, cellular responses may develop due to the interaction between extracellular signaling, which is ultimately received by plasma membrane receptors. This may alter the cellular homeostasis mechanism, resulting in the excessive production of ROS and RNS with some other ions. These are the possible reasons for oxidative stress and, finally, cell death (Zhao et al., 2021).

4. Interaction of melatonin with auxin, ABA and salicilic acid

Melatonin is somehow closely related to auxin in many ways. The structure of melatonin is almost similar to the IAA (Indole-3- Acetic Acid). Most importantly, tryptophan act as precursor molecule for both melatonin and IAA and exhibiting antioxidants properties. They promote plant growth promotion significantly. Melatonin exogenously enhances the development of roots and shoots directly or indirectly with the help of serotonin. It was found that both molecule co participate in plant growth activities. A dose-dependent activity relationship was also observed between melatonin and IAA in root formation. The lower concentration of melatonin in *Arabidopsis* and mustard roots augmented with the IAA level in the plant system (Kanwar et al., 2018). Similar to Auxin, melatonin can modulate the processes involved in plant morphogenesis like rhizogenesis in pericicle fromfrom *Lupinus albus* The process involved the development of letaral roots from adventitious stem roots.

A water deficiency can likewise trigger the creation of the phytohormone abscisic acid (ABA), which causes stomata to close (Li et al., 2015). Oxidative damage under drought stress is successfully managed by the application of melatonin. It is observed that the level of ABA production was significantly downregulated after the application of melatonin. It infers ABA production on a genetic level by suppressing the gene responsible for the ABA synthesis.

ABA plays an essential role in the stomatal closer with hydrogen peroxide as a signaling molecule. The influence of ion may generate with the increase of the ABA production, resulting in the loss of the turgor and ultimately closer of the stomatal pores. Melatonin may act via receptor-dependent and receptor-independent mechanisms. Antioxidant activities doubtless indication of its receptor-independent function. It was also observed that the capacity of phytomelatonin-intervened stomatal closer through controlling H_2O_2 creation was receptor-driven; also, this stomatal closer done with the application of melatonin different from the ABA, which means melatonin has a different receptor than the ABA. Thus, the attachment of phytomelatonin to the CAND2/PMTR1 receptor triggers the separation of Gγβ and Gα, which enacts the NADPH oxidase-dependent H2O2 synthesis, improves Ca2+ and K+ influxes (Wei et al., 2018; Hernández-Ruiz and Arnao, 2018).

Salicylic acid is importantly required in plants for protection against various pathogenic organisms (Mukherjee, 2018). The discovery of salicylic acid was earlier than melatonin, and both of these not only share a similar precursor, but they are having a significant role in the tolerance of biotic and abiotic stress tolerance. Somehow they are related in the biosynthetic pathways, but there are no comparative studies to demonstrate the relative effect. These molecules are considered as the stimulants of the photosynthetic pathways also. Melatonin and Salicylic acid are derived from the shikimic acid pathway in synthesis, but their mode of action is different (Hernández-Ruiz and Arnao, 2018).

Melatonin, auxin and salicylic acid are evolved from a common precursor called Chorsimate, which are involved in vital functions like signaling and regulation in plants. Melatonin has been found to have similar work as auxin (Arnao et al., 2015; Wen et al., 2016; Zuo et al., 2014). Researchers highlighted the role of melatonin against *Xanthomonas oryzae* pv.by regulating the responce generated by plant system against pathogens attack functions as a regulator of (Chen et al., 2018). Figure 5 explains the phytohormones obtained from Chorsimate derived pathway. The biochemical pathway(s) and enzymatic mechanism(s) of plant melatonin formation are yet to be explored. Studies using radioisotope tracer techniques indicated that tryptophan is the common precursor for serotonin and melatonin and indole-3-acetic acid (IAA) in higher plants. This fact also leads to the conclusion of a similar role of auxin and melatonin in plants (Murch et al., 2001). The collaboration between melatonin and other plant hormones has been examined widely. Melatonin prompts changes in endogenous ABA, IAA, gibberellins, cytokinins, and ethylene (Arnao and Hernández-Ruiz, 2015b; Wei et al., 2018).

5. Methods of the exogenous application of melatonin

Initially, melatonin was considered as an endogenous plant hormone and antioxidant, but later due to its remarkable properties against biotic and abiotic stress tolerance in plants, its exogenous application is also increasing day by day. Effective treatment of the phytomelatonin is essential for the function against the various types of stresses. However, several methods like root irrigation and leaf spraying are also used by researhers for the treatment of plants (Huang et al., 2019; Zhang et al., 2019). Some studies indicated that that root irrigation could be a better option.

On the other hand, foliar spraying could be effective under drought stress (Ye et al., 2016). In many cases, direct soaking treatment was done with the solution of an effective concentration (Bai et al., 2020). Soil drenching is also used for the treatment of the plants (Ahmad et al., 2019). On lab-scale research, saturated filter papers are used to study the impact of melatonin (Chen et al., 2009). During the study of seed germination Kołodziejczyk et al. (2016), applied exogenous melatonin with the help of the hydropriming techniques.

6. Conclusion and way forward

The attention and care of scientist for melatonin in the field of agriculture have given impetus to the importance of melatonin and establishing it as an important area of further research through systematic, well planned, location-specific, and crop-specific investigations to augment the production and productivity coupled with the improvement in the quality of produce. Hitherto, inspired by the results in the field of the animal kingdom, some random attempts have been made to study the role of melatonin in the plant kingdom. To date, we have only recognized melatonin as a potential molecule in plants' growth. The synergetic role of melatonin on physiology, biochemistry, yield potential, and quality of the product is significant in the larger gamut of plant studies. So far, scientists have indicated beneficial effects of melatonin and opined that it is an essential and useful molecule, but its antagonistic impact, if any, have yet not been envisaged and studied. The findings so far indicate that genes introduced from vertebrates to transgenic plants produced encouraging results. The possibility of an increased melatonin level, having similar promising results in non-transgenic plants is still a grey area where no suggestive opinion is available. There is a need to explore the biosynthesis mechanisms of melatonin inducing the resistance to both biotic and abiotic stresses for improved crop production. This may improve the nutritional value of crops and reduce the dependence of humans on synthetic dietary supplements. Melatonin enriched farm produce can potentially prevent the full range of post-harvest losses in different plants. There is a need to identify specific pathways for enhancing the defense mechanism in managing biotic stresses. This may lead us to use melatonin on a commercial scale. This will help reduce the cost of cultivation and promote organic farming and curb the use of chemicals in agriculture. It would be further interesting to examine whether melatonin improves the hyper accumulator plant species' phytoremediation capacity. If so, a detailed study on mechanisms about it can throw more light on the process.

It has been accounted for that melatonin advances root development. Nonetheless, the part of melatonin in supplement take-up still should hyperaccumulator association among melatonin and supplement take-up and transport has yet not been contemplated. Similarly, the reaction of foliar use of melatonin to its retention and change of plant development advancement actually should be explored. Even though melatonin is universally dispersed in plants, it is obscure whether all the plant organs produce melatonin.

Melatonin's relationship with auxin is still an area that needs exhaustive research, while the biochemical and physiological function of Melatonin in plants are little explained. The action inhibitors of melatonin receptors are unexplored. The information available so far about melatonin establishes it as an indispensable signaling molecule. Melatonin is produced endogenously and is essential in maintaining plant growth and development. Moreover, the mitigation of biotic and abiotic stresses makes it a more versatile molecule.

Additionally, the regulation of gene expression and interaction with other phytohormones is another crucial factor of melatonin's contributing to too many plant biological processes under normal and stressful conditions. Above all, melatonin is considered a non-toxic, biodegradable molecule that promotes organic farming. Interalia, the role of melatonin against actinomycetes, nematodes, or insects, along with non-target pests, require attention and scientific investigation. Lastly, melatonin in soil and plant roots uptake is also an important area where more specific research is still needed.

Declarations

Author contribution statement

All authors listed have significantly contributed to the investigation, development and writing of this article.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

No data was used for the research described in the article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors are thankful to the Indian Institute of Technology Delhi (New Delhi, India) for support and facilities.

References

Afreen, F., Zobayed, S.M., Kozai, T., 2006. Melatonin in Glycyrrhiza uralensis: response of plant roots to spectral quality of light and UV-B radiation. J. Pineal Res. 41 (2), 108–115.

Ahmad, S., Kamran, M., Ding, R., Meng, X., Wang, H., Ahmad, I., Han, Q., 2019. Exogenous melatonin confers drought stress by promoting plant growth, photosynthetic capacity and antioxidant defense system of maize seedlings. PeerJ 7, e7793.

Arnao, M.B., Hernández-Ruiz, J., DeMello, J., 2015. Melatonin: synthesis from tryptophan and its role in higher plants. In: Amino Acids in Higher Plants. CAB EBooks, pp. 390–435.

Arnao, Marino B., 2014. Phytomelatonin: discovery, content, and role in plants. Adv. Bot. 2014.

Arnao, Marino B., Hernández-Ruiz, J., 2006. The physiological function of melatonin in plants. Plant Signal. Behav. 1 (3), 89–95.

Arnao, M.B., Hernández-Ruiz, J., 2009. Protective effect of melatonin against chlorophyll degradation during the senescence of barley leaves. J. Pineal Res. 46 (1), 58–63.

Arnao, Marino B., Hernández-Ruiz, J., 2015. Functions of melatonin in plants: a review. J. Pineal Res. 59 (2), 133–150.

Asif, Mehanoor, Pervez, Arshid, Irshad, Usman, Mehmood, Qaisar, Ahmad, Rafiq, 2020. Melatonin and plant growth-promoting rhizobacteria alleviate the cadmium and arsenic stresses and increase the growth of Spinacia oleracea L. Plant Soil Environ. 66, 234–241.

Axelrod, J., Weissbach, H., 1960. Enzymatic O-methylation of N-acetylserotonin to melatonin. Science 131 (3409), 1312, 1312.

Back, K., Tan, D.-X., Reiter, R.J., 2016. Melatonin biosynthesis in plants: multiple pathways catalyze tryptophan to melatonin in the cytoplasm or chloroplasts. J. Pineal Res. 61 (4), 426–437.

Bai, Y, Xiao, S., Zhang, Z., Zhang, Y., Sun, H., Zhang, K., Liu, L., 2020. Melatonin improves the germination rate of cotton seeds under drought stress by opening pores in the seed coat. PeerJ 8, e9450.

Bochkov, D.V., Sysolyatin, S.V., Kalashnikov, A.I., Surmacheva, I.A., 2012. Shikimic acid: review of its analytical, isolation, and purification techniques from plant and microbial sources. J. Chem. Biol. 5 (1), 5–17. PubMed.

Burkhardt, S., Tan, D.X., Manchester, L.C., Hardeland, R., Reiter, R.J., 2001. Detection and quantification of the antioxidant melatonin in Montmorency and Balaton tart cherries (Prunus cerasus). J. Agric. Food Chem. 49 (10), 4898–4902.

Chen, Q., Qi, W.B., Reiter, R.J., Wei, W., Wang, B.M., 2009. Exogenously applied melatonin stimulates root growth and raises endogenous indoleacetic acid in roots of etiolated seedlings of Brassica juncea. J, Plant Physiol. 166 (3), 324–328.

Chen, X., Sun, C., Laborda, P., Zhao, Y., Palmer, I., Fu, Z.Q., Qiu, J., Liu, F., 2018. Melatonin treatment inhibits the growth of Xanthomonas oryzae pv. Oryzae. Front. Microbiol. 9, 2280.

de Souza, T.C., Magalhães, P.C., de Castro, E.M., Carneiro, N.P., Padilha, F.A., Júnior, C.C.G., 2014. ABA application to maize hybrids contrasting for drought tolerance: changes in water parameters and in antioxidant enzyme activity. Plant Growth Regul. 73 (3), 205–217.

Dubbels, R., Reiter, R.J., Klenke, E., Goebel, A., Schnakenberg, E., Ehlers, C., Schiwara, H.W., Schloot, W., 1995. Melatonin in edible plants identified by radioimmunoassay and by high performance liquid chromatography-mass spectrometry. J. Pineal Res. 18 (1), 28–31.

Hardeland, R., 2016. Melatonin in plants—diversity of levels and multiplicity of functions. Front. Plant Sci. 7, 198, 198.

Hardeland, R., Poeggeler, B., 2003. Non-vertebrate melatonin. J. Pineal Res. 34 (4), 233–241.

Hernández-Ruiz, J., Arnao, M.B., 2018. Relationship of melatonin and salicylic acid in biotic/abiotic plant stress responses. Agronomy 8 (4), 33.

Huang, B., Chen, Y., Zhao, Y., Ding, C., Liao, J., Hu, C., Zhou, L., Zhang, Z., Yuan, S., Yuan, M., 2019. Exogenous melatonin alleviates oxidative damages and protects photosystem II in maize seedlings under drought stress. Front. Plant Sci. 10, 677.

Janas, K.M., Posmyk, M.M., 2013. Melatonin, an underestimated natural substance with great potential for agricultural application. Acta Physiol. Plant. 35 (12), 3285–3292.

Kang, K., Park, S., Kim, Y.S., Lee, S., Back, K., 2009. Biosynthesis and biotechnological production of serotonin derivatives. Appl. Microbiol. Biotechnol. 83 (1), 27–34.

Kanwar, Mukesh Kumar, Yu, Jingquan, Zhou, Jie, 2018. Phytomelatonin: recent advances and future prospects. J. Pineal Res. 65 (4).

Kobylińska, A., Posmyk, M.M., 2016. Melatonin restricts Pb-induced PCD by enhancing BI-1 expression in tobacco suspension cells. Biometals 29 (6), 1059–1074.

Kobylińska, Agnieszka, Reiter, R.J., Posmyk, M.M., 2017. Melatonin protects cultured tobacco cells against lead-induced cell death via inhibition of cytochrome c translocation. Front. Plant Sci. 8, 1560.

Kolár, J., Johnson, C.H., Macháckova, I., 2002. Presence and possible role of melatonin in a short-day flowering plant, Chenopodium rubrum. In: Melatonin after Four Decades. Springer, pp. 391–393.

Kolar, J., Machackova, I., Illnerova, H., Prinsen, E., Van Dongen, W., Van Onckelen, H.A., 1995. Melatonin in higher plant determined by radioimmunoassay and liquid chromatography-mass spectrometry. Biol. Rhythm. Res. 26, 406–409.

Kołodziejczyk, Izabela, Dzitko, Katarzyna, Szewczyk, Rafał, Posmyk, Małgorzata M., 2016. Exogenous melatonin expediently modifies proteome of maize (Zea mays L.) embryo during seed germination. Acta Physiol. Plant. 138.

Lee, H.Y., Byeon, Y., Back, K., 2014. Melatonin as a signal molecule triggering defense responses against pathogen attack in Arabidopsis and tobacco. J. Pineal Res. 57 (3), 262–268.

Lee, H.Y., Byeon, Y., Tan, D.-X., Reiter, R.J., Back, K., 2015. Arabidopsis serotonin N-acetyltransferase knockout mutant plants exhibit decreased melatonin and salicylic acid levels resulting in susceptibility to an avirulent pathogen. J. Pineal Res. 58 (3), 291–299.

Lerner, A.B., Case, J.D., Takahashi, Y., Lee, T.H., Mori, W., 1958. Isolation of melatonin, the pineal gland factor that lightens melanocyteS1. J. Am. Chem. Soc. 80 (10), 2587, 2587.

Li, C., Tan, D.X., Liang, D., Chang, C., Jia, D, Ma, F., 2015. Melatonin mediates the regulation of ABA metabolism, free-radical scavenging, and stomatal behaviour in two Malus species under drought stress. J. Exp. Bot. 66 (3), 669–680.

Liang, B., Ma, C., Zhang, Z., Wei, Z., Gao, T., Zhao, Q., Ma, F., Li, C., 2018. Long-term exogenous application of melatonin improves nutrient uptake fluxes in apple plants under moderate drought stress. Environ. Exp. Bot. 155, 650–661.

Lynch, H.J., Ozaki, Y., Shakal, D., Wurtman, R.J., 1975. Melatonin excretion of man and rats: effect of time of day, sleep, pinealectomy and food consumption. Int. J. Biometeorol. 19 (4), 267–279.

Madigan, A.P., Egidi, E., Bedon, F., Franks, A.E., Plummer, K.M., 2019. Bacterial and fungal communities are differentially modified by melatonin in agricultural soils under abiotic stress. Front. Microbiol. 10, 2616.

Manchester, L.C., Coto-Montes, A., Boga, J.A., Andersen, L.P.H., Zhou, Z., Galano, A., Vriend, J., Tan, D.-X., Reiter, R.J., 2015. Melatonin: an ancient molecule that makes oxygen metabolically tolerable. J. Pineal Res. 59 (4), 403–419.

Marta, B., Szafrańska, K., Posmyk, M.M., 2016. Exogenous melatonin improves antioxidant defense in cucumber seeds (Cucumis sativus L.) germinated under chilling stress. Front. Plant Sci. 7, 575.

Mau, R.L., Dijkstra, P., Schwartz, E., Koch, B.J., Hungate, B.A., 2019. Addressing strengths and weaknesses of a multi-ecosystem climate change experiment. Appl. Soil Ecol. 133, 191–192.

Mukherjee, S., 2018. Novel perspectives on the molecular crosstalk mechanisms of serotonin and melatonin in plants. Plant Physiol. Biochem. 132, 33–45.

Murch, S.J., Campbell, S.S., Saxena, P.K., 2001. The role of serotonin and melatonin in plant morphogenesis: regulation of auxin-induced root organogenesis in in vitro-cultured explants of St. John's wort (Hypericum perforatum L.). In: Vitro Cellular & Developmental Biology-Plant, 37, pp. 786–793 (6).

Nawaz, Muhammad A., Huang, Yuan, Bie, Zhilong, Ahmed, Waqar, Reiter, Russel J., Niu, Mengliang, Hameed, Saba, 2016. Melatonin: current status and future perspectives in plant science. Front. Plant Sci. 6, 1230.

Okazaki, M., Ezura, H., 2009. Profiling of melatonin in the model tomato (Solanum lycopersicum L.) cultivar Micro-Tom. J. Pineal Res. 46 (3), 338–343.

Park, S., Lee, D.-E., Jang, H., Byeon, Y., Kim, Y.-S., Back, K., 2013. Melatonin-rich transgenic rice plants exhibit resistance to herbicide-induced oxidative stress. J. Pineal Res. 54 (3), 258–263.

Posmyk, M.M., Janas, K.M., 2009. Melatonin in plants. Acta Physiol. Plant. 31 (1), 1.

Pshenichnyuk, S.A., Modelli, A., Jones, D., Lazneva, E.F., Komolov, A.S., 2017. Low-energy electron interaction with melatonin and related compounds. J. Phys. Chem. B 121 (16), 3965–3974.

Qian, Y., Tan, D.-X., Reiter, R.J., Shi, H., 2015. Comparative metabolomic analysis highlights the involvement of sugars and glycerol in melatonin-mediated innate immunity against bacterial pathogen in Arabidopsis. Sci. Rep. 5 (1), 1–11.

Ramakrishna, A., Giridhar, P., Ravishankar, G.A., 2011. Phytoserotonin. Plant Signal. Behav. 6 (6), 800–809.

Reiter, R.J., Tan, D.X., Rosales-Corral, S., Galano, A., Zhou, X.J., Xu, B., 2018. Mitochondria: central organelles for melatonin′ s antioxidant and anti-aging actions. Molecules 23 (2), 509.

Sharif, R., Xie, C., Zhang, H., Arnao, M.B., Ali, M., Ali, Q., Muhammad, I., Shalmani, A., Nawaz, M.A., Chen, P., 2018. Melatonin and its effects on plant systems. Molecules 23 (9), 2352.

Shi, H., Chen, Y., Tan, D.-X., Reiter, R.J., Chan, Z., He, C., 2015. Melatonin induces nitric oxide and the potential mechanisms relate to innate immunity against bacterial pathogen infection in Arabidopsis. J. Pineal Res. 59 (1), 102–108.

Simopoulos, A.P., Tan, D.-X., Manchester, L.C., Reiter, R.J., 2005. Purslane: a plant source of omega-3 fatty acids and melatonin. J. Pineal Res. 39 (3), 331–332.

Tan, D.-X., Manchester, L.C., Di Mascio, P., Martinez, G.R., Prado, F.M., Reiter, R.J., 2007. Novel rhythms of N1-acetyl-N2-formyl-5-methoxykynuramine and its precursor melatonin in water hyacinth: importance for phytoremediation. Faseb. J. 21 (8), 1724–1729.

Tan, Dun-Xian, Hardeland, Rüdiger, Back, Kyoungwhan, Manchester, Lucien C., Alatorre-Jimenez, Moises A., Reiter, Russel J., 2016. On the significance of an alternate pathway of melatonin synthesis via 5-methoxytryptamine: comparisons across species. J. Pineal Res. 61 (1), 27–40.

Tan, D.-X., Zheng, X., Kong, J., Manchester, L.C., Hardeland, R., Kim, S.J., Xu, X., Reiter, R.J., 2014. Fundamental issues related to the origin of melatonin and melatonin isomers during evolution: relation to their biological functions. Int. J. Mol. Sci. 15 (9).

Tan, Dun-Xian, Reiter, Russel J., 2019. Mitochondria: the birth place, battle ground and the site of melatonin metabolism in cells. Melatonin Res. 2 (1), 44–66.

Tan, Dun-Xian, Reiter, Russel J., 2020. An evolutionary view of melatonin synthesis and metabolism related to its biological functions in plants. J. Exp. Bot. 71 (16), 4677–4689.

Van Tassel, D.L., Roberts, N., Lewy, A., O'Neill, S.D., 2001. Melatonin in plant organs. J. Pineal Res. 31 (1), 8–15.

Wang, P., Yin, L., Liang, D., Li, C., Ma, F., Yue, Z., 2012. Delayed senescence of apple leaves by exogenous melatonin treatment: toward regulating the ascorbate–glutathione cycle. J. Pineal Res. 53 (1), 11–20.

Wei, Y., Chang, Y., Zeng, H., Liu, G., He, C., Shi, H., 2018. RAV transcription factors are essential for disease resistance against cassava bacterial blight via activation of melatonin biosynthesis genes. J. Pineal Res. 64 (1), e12454.

Weissbach, H., Redfield, B.G., Axelrod, J., 1960. Biosynthesis of melatonin: enzymic conversion of serotonin to N-acetylserotonin. Biochim. Biophys. Acta 43, 352–353.

Wen, D., Gong, B., Sun, S., Liu, S., Wang, X., Wei, M., Yang, F., Li, Y., Shi, Q., 2016. Promoting roles of melatonin in adventitious root development of Solanum lycopersicum L. by regulating auxin and nitric oxide signaling. Front. Plant Sci. 7, 718.

Ye, J., Wang, S., Deng, X., Yin, L., Xiong, B., Wang, X., 2016. Melatonin increased maize (Zea mays L.) seedling drought tolerance by alleviating drought-induced photosynthetic inhibition and oxidative damage. Acta Physiol. Plant. 38 (2), 48.

Zhang, Q., Jin, H., Zhou, H., Cai, M., Li, Y., Zhang, G., Di, H., 2019. Variation of soil anaerobic microorganisms connected with anammox processes by 13C-phospholipid fatty acid analysis among long-term fertilization regimes in a crop rotation system. Appl. Soil Ecol. 133, 34–43.

Zhang, S., Zheng, X., Reiter, R.J., Feng, S., Wang, Y., Liu, S., Jin, L., Li, Z., Datla, R., Ren, M., 2017. Melatonin attenuates potato late blight by disrupting cell growth, stress tolerance, fungicide susceptibility and homeostasis of gene expression in Phytophthora infestans. Front. Plant Sci. 8, 1993.

Zhao, D., Yu, Y., Shen, Y., Liu, Q., Zhao, Z., Sharma, R., Reiter, R.J., 2019. Melatonin synthesis and function: evolutionary history in animals and plants. Front. Endocrinol. 10.

Zuo, B., Zheng, X., He, P., Wang, L., Lei, Q., Feng, C., Zhou, J., Li, Q., Han, Z., Kong, J., 2014. Overexpression of MzASMT improves melatonin production and enhances drought tolerance in transgenic Arabidopsis thaliana plants. J. Pineal Res. 57 (4), 408–417.

Zhao, Duke, Wang, Houping, Chen, Suiyun, Yu, Diqiu, Reiter, Russel J., 2021. Phytomelatonin: an emerging regulator of plant biotic stress resistance. Trends Plant Sci. 26 (1), 70–82.