# Mechanism of Melatonin in Horticultural Plants

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It has been discovered that melatonin, a hormone that is known for its involvement in regulating sleep-wake cycles in mammals, has a range of different functions in horticultural plants. Research has shown that melatonin plays an important role in many physiological processes in plants. This includes the regulation of growth and development, stress tolerance and antioxidant defense. Melatonin has been found to be beneficial in supporting seed germination, roots, shoot growth and biomass accumulation in horticultural crops. It also has a key role in regulating vegetative and reproductive growth stages, floral transition and leaf senescence. Moreover, melatonin helps to improve stress tolerance in crops by regulating root architecture, nutrient uptake and ion transport. Additionally, melatonin acts as a broad-spectrum antioxidant by effectively scavenging reactive oxygen species and enhancing antioxidant activity. The mechanism of melatonin's action in horticultural plants involves gene expressions, hormone signaling pathways and antioxidant defense pathways. Melatonin interacts with other plant growth regulators, including auxins, cytokinins and abscisic acid, to coordinate different physiological processes in plants. Melatonin has become a versatile chemical entity with diverse functions in horticultural plants and its potential applications in crop production and stress management are being increasingly explored.

crops tomato plants melatonin

## 1. Introduction

There are several proposed mechanisms through which melatonin operates in horticultural crops. One of these involves melatonin functioning as an antioxidant in horticultural crops. Melatonin is found to scavenge reactive oxygen species (ROS) and protect from oxidative damage in plants. For instance, in apple plants, melatonin application enhanced the activity of antioxidant enzymes, like superoxide dismutase (SOD) and peroxidase (POD), and reduced the buildup of ROS during alkaline stress conditions [1]. Similarly, in litchi fruit, melatonin application has been found to enhance the activity of antioxidant enzymes and decrease the pile-up of ROS under post-harvest storage conditions [2] and in kiwifruits under chilling stress [3]. Another mechanism proposes that melatonin controls the expression of genes linked with various physiological processes in horticultural plants. For instance, in tomato plants, melatonin treatment has been shown to be involved in the upregulation of genes involved in abscisic acid (ABA) biosynthesis and signaling, such as NCED1, NCED2, and AAO3, and in enhancing heat tolerance [4]. In tomato plant, SlcAPX, SIGR 1, SIGBT, and SIPh-GPX genes get upregulated and SIDHAR1 gets downregulated for enhancing the melatonin action in the plants [5].

Melatonin's role in regulating ion uptake and transport is another suggested mechanism of action in horticultural crops. It appears to promote the uptake of essential nutrients, such as $K^+$, $Ca^{2+}$, and $Mg^{2+}$ while mitigating the pile-up of toxic ions, such as $Na^+$ and $Cl^-$ [6][7]. This has been illustrated in rice plants, in which melatonin treatment enhanced salt tolerance by regulating ion uptake and transport [8]. Melatonin also upregulates the expression of genes associated with ion transport, such as OsSOS1 in roots and of OsCLC1 and OsCLC2 in roots and leaves, and reduces the pile-up of $Na^+$ and $Cl^-$ in tomato plants under salt stress conditions. It has also been found to manage ion homeostasis in apples under salt stress conditions [1]. Melatonin has also been proposed to control root architecture in horticultural crops, which can enhance stress tolerance by augmenting the surface area of roots and improving nutrient and water absorption. In cucumber, melatonin application enhances the length and density of lateral roots and genes related to cell wall formation and carbohydrate metabolic processes and enhances salt tolerance [9].

Melatonin increases the expression of antioxidant genes (Cu-ZnSOD, Fe-ZnSOD, CAT, POD, etc.) and key genes involved in gibberellin (GA) biosynthesis (such as GA20ox and GA3ox) but decreases the expression of key genes involved in ABA biosynthesis (such as NECD2). Melatonin treatment after harvest increases lycopene levels, accelerates fruit softening, and improves ethylene release in tomatoes by up-regulating the expression of SlACS4, SlNR, SlETR4, SlEIL1, SlEIL3, and SlERF2 [10]. Melatonin is a multifunctional bio-stimulant that serves as a "defense molecule" to protect plants from the harmful effects of temperature stress. Plant growth and temperature tolerance are improved by melatonin treatment by increasing numerous defense mechanisms [11]. The HSFs MeHsf20, MeWRKY79, and MeRAV1/2 bind to the promoters of melatonin biosynthesis genes in cassava (*Manihot esculenta*) to stimulate melatonin production and confer disease resistance [12][13]. Melatonin affects many enzymes and other components involved in amino acid biosynthesis in Krebs cycles, nitrogen-related processes, an ascorbate-glutathione (ASC–GSH) cycle, and osmoregulatory compound biosynthesis [13].

Melatonin acts through various mechanisms to regulate physiological processes in horticultural plants, including antioxidant defense, gene expression, hormone signaling pathways, ion uptake and transport, and root architecture. However, the exact mechanisms of melatonin action in horticultural crops are yet to be fully elucidated and require further research.

# 2. The Physiological Functions of Endogenous Melatonin in Horticulture Crops

## 2.1. Function of Melatonin in Seed Germination

Melatonin performs a vital function in the seed germination of horticultural crops. Experiments have shown that the exogenous melatonin treatment can improve seed germination and seedling growth under normal and stressful conditions [14]. In some horticultural plants, like tomato, red cabbage, carrot, and cucumber, melatonin application has been found to improve the percentage of germinated seeds and the rate of seedling emergence and growth [15][16][17][18]. Besides this, melatonin has been found to improve seedling tolerance to various abiotic stress, such as drought and salt stress, by boosting antioxidant defense systems and regulating stress-responsive genes in watermelon and cucumber [6][19].

Melatonin has also been reported to improve seed germination and seedling growth under suboptimal temperature conditions. In cucumber, for instance, melatonin treatment increased germination rate and seedling vigour under low-temperature stress [15]. Similarly, melatonin treatment improved seedling growth under high-temperature stress by enhancing the activity of antioxidant enzymes and regulating the expression of stress-responsive genes in soybean and rice [7][20]. These shreds of evidence suggest that melatonin plays a vital role in the seed germination and seedling growth of horticultural plants, particularly under stress conditions.

## 2.2. Function of Melatonin in Root Organogenesis and Lateral Root Development

Melatonin is known to play a pivotal role in root organogenesis and lateral root development in horticultural plants. Studies have demonstrated that melatonin promotes root growth and improves the quality of the root system by regulating various physiological processes [21]. Melatonin has been found to promote root organogenesis in various horticultural crops. For example, in grapevines, exogenous application of melatonin has been found to increase the number of adventitious roots, improve root morphology, and enhance root growth under salt stress [22]. Likewise, in cucumber, melatonin treatment has been found to stimulate the formation of adventitious roots and improve root system architecture by enhancing the expression of genes involved in root development [9]. Sarropoulou et al. [23] reported that the application of 1 μM melatonin improved the adventitious root formation from shoot tip explants of cherry rootstock PHL-C (*Prunus avium* L. × *Prunus cerasus* L.). Melatonin has also been found to promote lateral root development in horticultural crops. In tomato, for instance, melatonin treatment has been observed to accelerate lateral root formation and increase the length of lateral roots and expressed auxin biosynthesis genes and cell cycle genes [24].

## 2.3. Function of Melatonin in Shoot Growth and Differentiation in Horticultural Plants

Melatonin has been proven to play an important function in shoot growth and differentiation in horticultural plants. Studies have demonstrated that melatonin can boost shoot growth and regulate shoot development by influencing numerous physiological processes [25]. Exogenous application of melatonin, for example, has been shown to improve shoot growth and amplify the expression of genes involved in shoot development in vitro in blueberry [26]. Increased production of shoots has been observed for exogenous melatonin application in mimosa, pomegranate, and blueberry [26][27][28]. Melatonin has also been associated with differential patterning of branching and leaf production [29][30]. Melatonin application has also been demonstrated to enhance shoot growth and improve shoot morphology. In in vitro cultured tissue of coffee (*Coffea canephora* P. ex Fr.) and mimosa, melatonin led to an increase in the generation of somatic embryos from callus tissue [27][31].

## 2.4. Function of Melatonin in the Regulation of Vegetative and Reproductive Growth Stages and Floral Transition in Horticultural Plants

Melatonin has been discovered to be crucial in regulating vegetative and reproductive growth stages in horticultural plants. Research has demonstrated that melatonin aids in the transition from vegetative to reproductive growth and improves reproductive organ development by influencing several physiological processes [32]. Melatonin has been found to promote the transition from vegetative to reproductive growth in various horticultural crops. Murch and Saxena [33] observed the appearance of melatonin peak in the intermediate stages of flower development while studying the floral development of the plant St. John's wort (*Hypericum perforatum*). They observed melatonin accumulation in specific tissues and stages that acted as a signal in the development of gametophytes, transforming them into viable microspores. Murch et al. [34] probed a narcotic plant used in natural medicine, devil's trumpet (*Datura metel*), and noted that melatonin concentration peaked at the time of flower bud maturation indicating a protective role in the plant's reproductive parts.

Zhao et al. [35] analyzed melatonin content during the different flower developmental stages of herbaceous peony (*Paeonia lactifora*). They observed that melatonin content gradually increased from the flower bud to the initial bloom stage, which later started declining until withering. Exposure to sunlight and blue light stimulated melatonin production, whereas lower values were recorded in shade, and under white and green lights [35].

## 2.5. Function of Melatonin in Biomass Accumulation and Differentiation in Horticultural Crops

Melatonin has been found to perform a crucial function in boosting biomass growth and differentiation in horticultural plants. Studies have shown that melatonin stimulates biomass accumulation and differentiation of various plant organs, such as leaves, stems, and roots [36]. Exogenous treatment of melatonin, for example, has been shown to boost biomass accumulation and promote plant development in tomatoes under a variety of abiotic conditions [37][38]. Similarly, melatonin application has been reported in kiwi seedlings to restore and enhance biomass accumulation and plant development under drought stress [39]. Melatonin has also been found to enhance the differentiation of various plant organs in horticultural crops. Sarropoulou et al. [23] reported that the application of 1μM melatonin improved biomass accumulation by increasing root regeneration, photosynthetic pigments, and total carbohydrate concentration in cherry rootstock PHL-C. In apples, melatonin has been found to enhance root differentiation and improve root morphology by regulating the expression of genes related to root development [40].

The effect of exogenous melatonin (foliar spray, 100 μmol $L^{-1}$) on the pear fruit tree [41]. They observed an increase in melatonin in pear fruit. It was found that melatonin enhanced the size of pear fruit by enhancing the net photosynthetic rate and maximal quantum efficiency of photosystem II photochemistry during the advanced stage of pear fruit development. This led to an increase in fruit weight by 47.85% over the untreated plants. They also evaluated the biochemical parameters affected due to the exogenous use of melatonin at the ripening stage and found an increase in the contents of soluble sugar, especially sucrose, and sorbitol, possibly due to improved deposition of starch and expansion of pear fruit. These factors collectively contributed to a higher yield. They recommended that the use of melatonin in pear trees can be utilized to produce bigger and sweeter fruit of higher economic value [41]. The application of 100 μmol $L^{-1}$ of melatonin solution through spray on the fruits of young grapes might help in promoting the build-up of endogenous melatonin contents in berries of grapes and have a substantial influence on enhancing the yield of the berries and their weight [42].

## 2.6. Function of Melatonin in Leaf Senescence in Horticultural Plants

Melatonin has been shown to play a significant role in leaf senescence in horticultural plants. Studies have demonstrated that melatonin delays leaf senescence by regulating various physiological processes, including antioxidant activity and gene expression [43]. Melatonin has been shown to postpone leaf senescence in a variety of horticulture crops. Exogenous melatonin, for example, has been shown to postpone leaf senescence in apples by enhancing antioxidant activity and decreasing oxidative stress [44]. In apple melatonin also decreased chlorophyll degradation and downregulation of senescence-associated gene 12 (SAG12) [44]. Melatonin application has also been found to postpone leaf senescence in rice and *Arabidopsis* by modulating the expression of genes involved in chlorophyll breakdown and protein degradation.

Melatonin has also been found to delay leaf senescence by regulating the expression of genes involved in stress responses. In Chinese flowering cabbage, for instance, melatonin treatment has been shown to delay leaf senescence by upregulating the expression of genes involved in the ABA signaling pathway and chlorophyll degradation [43]. Additionally, in tomato, exogenous melatonin has been found to delay leaf senescence by activation of endogenous melatonin and GA biosynthesis and inhibition of ABA biosynthesis pathways [4].

## 2.7. Function of Melatonin in Physiological Maturity and Harvest of Crops in Horticultural Plants

Melatonin has been demonstrated to play a significant role in the physiological maturity and harvest of crops in horticultural plants. Studies have demonstrated that melatonin promotes fruit ripening and enhances fruit quality by regulating various physiological processes, including sugar metabolism and gene expression in tomato [21]. Melatonin has been observed to promote fruit ripening in various horticultural crops. For example, in tomato, exogenous application of melatonin has been found to promote fruit ripening and improve fruit quality by increasing sugar metabolism and enhancing antioxidant activity [21]. Similarly, in pear, melatonin treatment promoted fruit ripening and improved fruit quality by enhancing the expression of genes involved in sugar metabolism [41].

Melatonin has been reported to enhance the shelf life of horticultural crops. In banana, for instance, melatonin treatment has been reported to delay fruit ripening and enhance fruit quality by reducing ethylene production and enhancing antioxidant activity [45]. Additionally, in strawberry, melatonin has been shown to prolong the shelf life of fruits by reducing postharvest decay and improving fruit quality [46]. In addition, melatonin has been found to promote seed maturity in several horticultural crops. In wine grapes (*Vitis vinifera* L.), melatonin accumulation signals the transition through veraison, making the onset of seed maturation [47].

## 2.8. Role of Melatonin in Stress Tolerance in Horticultural Plants

Melatonin plays a critical role in enhancing stress tolerance in horticultural plants. Melatonin works as a signaling molecule in response to numerous abiotic and biotic stressors, influencing many physiological functions and improving stress tolerance in horticulture crops. Melatonin has been shown to enhance stress tolerance in a variety of horticulture crops. Exogenous melatonin application has been found to improve salt stress tolerance in apple and cucumber by modulating the antioxidant enzyme activity and the expression of genes involved in osmotic adjustment and antioxidant activity [1][9][48]. Melatonin has also been reported to enhance stress tolerance by regulating the expression of stress-responsive genes and hormone signaling pathways. In *Arabidopsis* for instance melatonin treatment has been shown to enhance tolerance to heat stress by upregulating the expression of genes (HSP 90 and 101) involved in heat shock response [49]. Additionally, in cucumber, melatonin has been found to enhance tolerance to salt stress by regulating the expression of genes involved in the GA and ABA signaling pathways related to their biosynthesis and catabolism [50].

Melatonin has also been reported to enhance stress tolerance by regulating the accumulation of compatible solutes and detoxifying reactive oxygen species. This has been observed in cucumber and apple, where melatonin treatment was found to increase salt stress tolerance by facilitating the buildup of soluble sugars and boosting antioxidant enzyme activity [1][50]. Jahan et al. [4] and Altaf et al. [17] reported that exogenous melatonin helped to detoxify the over-accumulated ROS, thereby reducing the damage caused by heat stress in tomato plants. Similarly, in post-harvest peach fruits, melatonin has been found to enhance tolerance to cold and oxidative stresses by promoting the accumulation of compatible solutes and regulating the expression of genes involved in osmotic adjustment [51]. This beneficial effect of melatonin was also observed in watermelon and kiwifruits under cold and chilling stress, respectively [14][52].

Melatonin has been reported to regulate water stress tolerance through changes in both physiological and anatomical characteristics. In tomato, exogenous melatonin treatment increased drought tolerance by controlling leaf cuticle synthesis and non-stomatal water loss in leaves [53]. Furthermore, melatonin has been found to enhance stress tolerance by regulating physiological systems associated with photosynthesis. Melatonin has also been shown to improve drought tolerance in apple by modulating photosynthetic efficiency, transpiration, and stomatal conductance as well as minimizing chlorophyll degradation and oxidative damage [54].

Furthermore, melatonin has been reported to enhance stress tolerance by regulating root architecture and nutrient uptake. In tomato plants, melatonin has been found to enhance tolerance to salt stress by regulating root morphology and ion uptake [17] as well as ion homeostasis in apple [1]. Specifically, melatonin treatment has been reported to increase the root length, surface area, and volume of tomato seedlings under salt stress conditions [17]. Additionally, melatonin has been found to increase the accumulation of essential nutrients, such as $K^+$, $Ca^{2+}$, and $Mg^{2+}$ while reducing the accumulation of toxic ions, such as $Na^+$ and $Cl^-$ [7]. These results suggest that melatonin enhances salt stress tolerance in horticultural crops by regulating root morphology and ion uptake. Similarly, in tomato, melatonin has been found to enhance tolerance to salt stress by regulating the expression of genes involved in the ABA signaling pathway [55].

## 2.9. Role of Melatonin in the Regulation of Autophagy in Horticultural Plants

Melatonin has been linked to the regulation of autophagy in horticultural plants. Autophagy is a cellular mechanism that degrades and recycles cellular components in order to preserve cellular homeostasis under stress conditions. Autophagy is a critical stress-response process in plants that helps them to deal with a variety of stresses like food deprivation, oxidative damage, and pathogen attack. Melatonin has been proven in studies to modulate autophagy activity and improve stress tolerance in horticulture plants.

In tomato plants, melatonin treatment has been reported to enhance tolerance to heat stress by regulating the activity of autophagy [56]. Specifically, melatonin treatment has been found to increase the expression of genes involved in autophagy, such as TG5, ATG6, ATG8a, ATG8f, ATG12, and ATG18c, and to enhance the formation of autophagosomes. These results suggest that melatonin improves heat stress tolerance in tomato by promoting autophagy. Melatonin treatment has been shown to increase the expression of genes involved in autophagy, such as AtAPX1 and AtCATs, and enhance the formation of autophagosomes in *Arabidopsis* [57]. Additionally, melatonin treatment has been found to increase the accumulation of ROS and activate antioxidant enzymes, suggesting that melatonin enhances drought stress tolerance by promoting autophagy and regulating oxidative stress. The expression of several autophagy-related genes isolated from apple was significantly delayed in melatonin-induced leaf senescence. These pieces of evidence suggest that melatonin plays a vital role in regulating autophagy in horticultural plants, enhancing stress tolerance by fostering autophagy under stressful conditions [44].

## 2.10. Role of Melatonin in Post-Harvest Fruit Ripening

In kiwi and pear fruits melatonin treatment has been shown to delay post-harvest ripening by inhibiting respiration and the biosynthesis and signaling of ethylene [38][58]. Specifically, melatonin treatment has been found to decrease the expression of genes involved in ethylene biosynthesis, such as PcACO, PcACS, MaACS1, MaACO1, and MaETR1, and to reduce the production of ethylene [38][59]. Additionally, melatonin treatment has been shown to enhance the activity of antioxidant enzymes and related genes and reduce the accumulation of reactive oxygen species, suggesting that melatonin delays post-harvest ripening in litchi fruit by regulating oxidative stress [2][60].

Melatonin treatment has also been shown to delay post-harvest ripening in apples by regulating ethylene production and signaling [61]. It has been demonstrated that melatonin inhibits the expression of genes involved in ethylene biosynthesis, such as ACS1, ACS2, ACO1, and ERF1. Furthermore, melatonin treatment has been shown to increase antioxidant enzyme activity and decrease the buildup of reactive oxygen species, implying that melatonin delays post-harvest ripening in kiwifruit via controlling oxidative stress. However, contrasting results were found in tomatoes [21]. The research reported an increase in the lycopene and carotenoids contents and expression of ethylene signal transduction-related genes, such as NR, SlETR4, SlEIL1, SlEIL3, and SlERF2, along with aquaporin-related genes, like SlPIP12Q, SlPIPQ, SlPIP21Q, and SlPIP22, after applying 50 µM melatonin. These all factors simultaneously promoted ripening and improved the postharvest quality of tomatoes.

## 2.11. Role of Melatonin in Circadian Cycle Regulation in Horticultural Plants

Melatonin is important for the regulation of circadian rhythms in horticultural plants. Circadian rhythms regulate several physiological activities in plants, including photosynthesis, growth, and stress responses [62]. Melatonin has been proven in studies to control the production of clock genes and govern circadian rhythms in horticultural plants. Melatonin therapy, for example, has been demonstrated to modulate clock gene expression and increase the amplitude of circadian rhythms in *Arabidopsis* plants [63]. Melatonin has been shown to boost the expression of genes involved in the circadian clock, such as TOC1, GI, and PRR7, as well as to increase the amplitude of oscillations in clock gene expression. Furthermore, melatonin application has been demonstrated to increase the expression of photosynthesis genes and improve photosynthetic efficiency, implying that melatonin modulates circadian rhythms and photosynthesis in tomato plants.

Melatonin has also been reported to affect clock gene expression and increase the amplitude of circadian rhythms in grapevines [64]. Melatonin application has been demonstrated to boost the expression of circadian clock genes such as LHY, CCA1, and TOC1 as well as the amplitude of oscillations in clock gene expression. Furthermore, melatonin administration has been shown to increase anthocyanin accumulation and boost secondary metabolite synthesis, implying that melatonin affects circadian rhythms and secondary metabolism in the grapevine. Based on these findings, researchers may conclude that melatonin performs a vital function in the regulation of circadian rhythms in horticultural plants. It can influence clock gene expression and increase the amplitude of circadian rhythms.

## 2.12. Role of Melatonin as Antioxidant

Melatonin has been reported to behave as a broad-spectrum antioxidant in plants. It can scavenge a variety of reactive oxygen species (ROS), such as hydroxyl radicals, hydrogen peroxide, and superoxide anions [6]. Melatonin's antioxidant potential in plants is due to its ability to neutralize ROS and boost the activity of antioxidant enzymes [65]. Melatonin application has been found in studies to increase the activity of antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) as well as to minimize the formation of ROS in a plethora of horticultural crops. Melatonin administration, for example, has been shown to boost SOD and CAT activity while decreasing ROS accumulation under salt stress conditions in tomato [4] and apple plants [1]. Similarly, in strawberry, melatonin treatment has been found to enhance the activity of antioxidant enzymes and reduce the accumulation of ROS under post-harvest storage conditions [46]. In watermelon, melatonin treatment led to increased endogenous melatonin accumulation, which triggered antioxidant enzyme activity in distant untreated tissues, aiding in the mitigation of oxidative stress caused by cold stress [52].

In addition to its direct antioxidant activity, melatonin has been reported to regulate the expression of genes involved in antioxidant defense pathways in plants. For instance, in watermelon, melatonin application has been found to enhance the expression of genes involved in the ascorbate–glutathione cycle and to reduce oxidative damage under vanadium stress conditions [65]. Similarly, in tomato plants, melatonin treatment has been shown to enhance the expression of genes involved in the glutathione-ascorbate cycle and to reduce oxidative damage under salinity and heat stress conditions [5] as well as in post-harvest peaches under cold stress [51]. Melatonin improves the chilling tolerance of chloroplast by regulating photosynthetic electron flux and the ascorbate–

glutathione cycle in cucumber seedlings [66]. In apple, the application of melatonin helped to increase the expression of MdNHX1 and MdAKT1 genes in apple leaves and helped in improving ion homeostasis under salt stress. Therefore, melatonin acts as a broad-spectrum antioxidant in horticultural crops by directly scavenging ROS and regulating the expression of genes involved in antioxidant defense pathways.

## 2.13. Role of Melatonin in Enhancing Mycorrhization in Horticultural Crops

Mycorrhization is an important aspect of horticultural crop growth as it enhances nutrient uptake and can improve plant tolerance to various biotic and abiotic stresses. Melatonin has been found to play a role in promoting mycorrhization in horticultural crops. Several studies have reported that exogenous application of melatonin can promote the formation of arbuscular mycorrhizal (AM) symbiosis in plants. For example, in cucumber plants, melatonin application increased the colonization rate of AM fungi, resulting in enhanced plant growth and nutrient uptake in the fight against fusarium wilt [67]. Similarly, in sheep grass (*Leymus chinensis*) plants, melatonin application increased the number of AM spores and improved plant growth and yield under saline–alkaline conditions [68].

The mechanism by which melatonin promotes mycorrhization in horticultural crops is not fully understood, but it is believed to be associated with the regulation of plant defense responses and root morphology. Melatonin has been shown to activate the antioxidant defense system and reduce oxidative stress in plants, which can improve their ability to establish symbiotic relationships with AM fungi [67][69]. Additionally, melatonin can modulate root architecture and increase the density and length of root hairs, which can facilitate AM fungal colonization [69]. Therefore, the application of melatonin can enhance mycorrhization in horticultural crops, which can improve their growth, and yield, and impart stress tolerance.

## 2.14. Role of Melatonin in Defense in Horticultural Crops

Melatonin plays a crucial role in enhancing defense mechanisms in horticultural crops. One notable example is its involvement in plant–pathogen interactions. Studies have shown that exogenous application of melatonin can enhance the plant's resistance to various pathogens. For instance, in grape plants infected with fungal pathogens, such as *Botrytis cinerea*, melatonin treatment has been found to reduce disease severity and inhibit the pathogen growth cycle [70]. Instead of inhibiting *Botrytis cinerea* growth directly, exogenous melatonin treatment could induce disease resistance by priming defense mechanisms. Melatonin treatment inhibits grey mould and induces disease resistance in cherry tomatoes during postharvest [71]. In another study, melatonin application in tomatoes increased the expression of defense-related genes and the production of antimicrobial compounds, leading to enhanced resistance against fungal pathogens like *Botrytis cinerea* [72]. Melatonin helped to increase the expression of the *PR1*, *NPR1*, *PI II,* and *LoxD* genes, associated with disease resistance, and elevated the contents of vitamin C, titratable acid, soluble sugar, and soluble proteins in tomatoes [72]. These examples demonstrate the role of melatonin in triggering the plant's defense responses and improving its ability to combat pathogenic attacks. In apple trees, melatonin treatment reduced leaf lesions and increased the production of defensive metabolites and enzymes against *Botrytis cinerea* infection [73].

Melatonin has been found to have effective antibacterial properties against phytobacterial pathogens in plant–bacteria interaction studies [74]. In plant–virus interaction models, it has been observed that melatonin can eliminate apple stem grooving virus from apple shoots in vitro, thereby making it useful in producing virus-free plants. Additionally, it has been shown to reduce the concentration of tobacco mosaic virus, viral RNA, and virus levels in infected *Nicotiana glutinosa* and *Solanum lycopersicum* seedlings [35][74]. Melatonin has also been shown to enhance the plant's defense against herbivorous pests [25][75].

In this way Melatonin serves as a key player in enhancing defense mechanisms in horticultural crops. Its application has been shown to activate defense pathways, induce the production of antimicrobial compounds, and strengthen the plant's antioxidant defense system. Moreover, melatonin enhances the plant's resistance against pathogens and herbivorous pests, improving overall defense and resilience. Understanding the role of melatonin in enhancing defense in horticultural crops provides valuable insights for developing sustainable strategies to protect crops and enhance their productivity and quality.

## 3. Conclusions

Recent research has uncovered the diverse functions of melatonin in horticultural plants, including its role in growth and development, stress tolerance, and antioxidant defense. Melatonin's positive impact on seed germination, root and shoot growth, and biomass accumulation in horticultural crops highlight its potential as a valuable tool in crop production. Moreover, melatonin exerts crucial regulatory control over vegetative and reproductive growth stages, floral transition, and leaf senescence in plants. By modulating root architecture, nutrient uptake, and ion transport, melatonin enhances stress tolerance, allowing plants to thrive under adverse conditions. Melatonin acts as a broad-spectrum antioxidant, effectively scavenging reactive oxygen species and boosting antioxidant activity. Its intricate mechanisms of action involve gene expressions, hormone signaling pathways, and antioxidant defense pathways. Additionally, melatonin's interaction with other plant growth regulators, such as auxins, cytokinins, and abscisic acid, orchestrates various physiological processes in plants. The comprehensive insight provided by this research paves the way for further exploration and application of melatonin in horticulture. By bridging the gap between knowledge and practical implementation, researchers can uncover the full extent of melatonin's mechanisms of action and devise effective strategies for its utilization in horticultural practices.

Undoubtedly, melatonin has emerged as a versatile chemical molecule with immense potential for enhancing crop production and managing stress in horticultural plants. As the research progresses, continued investigation into melatonin's multifaceted functions will unlock new avenues for its utilization, benefiting both growers and the agricultural and horticultural industries. By unraveling the intricacies of melatonin's actions and harnessing its potential, researchers can shape a future in which melatonin becomes an invaluable asset in optimizing horticultural practices and fostering sustainable crop production. In addition to this research, additional research is needed to completely comprehend the activities of melatonin receptors in various plant species and how they interact with other signaling pathways to control plant physiology.

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