Melatonin Function under Normal and Stressful Conditions

Subjects: Biology

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Plants are exposed to a variety of environmental stresses (biotic and abiotic) during the course of development. Stressful conditions alter the basic metabolism of the affected plants. Plants must cope with environmental constraints to effectively complete their life cycle. Plant produce and regulate various biomolecules to adapt to adverse environmental conditions. Melatonin (N-acetyl-5-methoxytryptamine) is a ubiquitous molecule that is present in plants, animals, and microorganisms. It has been revealed as an indolic chemical compound with structural similarities with other vital compounds such as tryptophan, serotonin, and indole-3-acetic acid (IAA). In plants, melatonin is a putative hormone involved in the regulation of plant growth and productivity, even under biotic and abiotic stress conditions.

melatonin phytohormone biotic stress abiotic stress plant growth

1. Introduction

The discovery of melatonin in plants paved the way for its understanding and revealed that melatonin is a common and multipurpose metabolite in the plant world. It is found in almost all parts of the plants, including the leaves, stems, roots, flowers, fruits, and seeds of numerous plants [1]. It is involved in the regulation of plant growth, leaf development, root organogenesis, fruit maturation, and senescence [2]. Furthermore, it significantly contributes to the responses of plants to environmental stresses including heat, salinity, drought, oxidative stress, and ultraviolet-B (UV-B) radiation [3].

In plants, melatonin production can be induced by a variety of conditions, including light, temperature extremes, and UV-B radiation [3]. Tryptophan serves as the precursor for the production of melatonin in a variety of plants. Tryptophan decarboxylase (TDC) catalyzes its conversion to tryptamine, which is then turned to serotonin by the enzyme tryptamine 5-hydroxylase (T5H) [4]. Serotonin N-acetyltransferase (SNAT)/arylalkyl amine N-acetyltransferase (AANAT) converts serotonin into N-acetyl serotonin. N-acetyl serotonin is converted into melatonin by the action of N-acetyl-serotonin methyltransferase (ASMT)/hydroxyindole-O-methyltransferase (HIOMT). In addition, SNAT can catalyze the conversion of tryptamine into N-acetyl-tryptamine (**Figure 1**). However, T5H cannot convert it into N-acetyl-serotonin. Whether there is a mechanism for turning N-acetyl-tryptamine into N-acetyl-serotonin is unclear. The second pathway involves the enzyme HIOMT, which changes serotonin into 5-methoxy-tryptamine, and the enzyme SNAT, which transfers 5-methoxy-tryptamine into melatonin [5]. Furthermore, in the reverse melatonin pathway, N-acetyl-serotonin deacetylase converts N-acetyl-serotonin into serotonin [6]. Additionally, tryptophan is a precursor for both melatonin and IAA, which indicates that melatonin has several functions in plants.

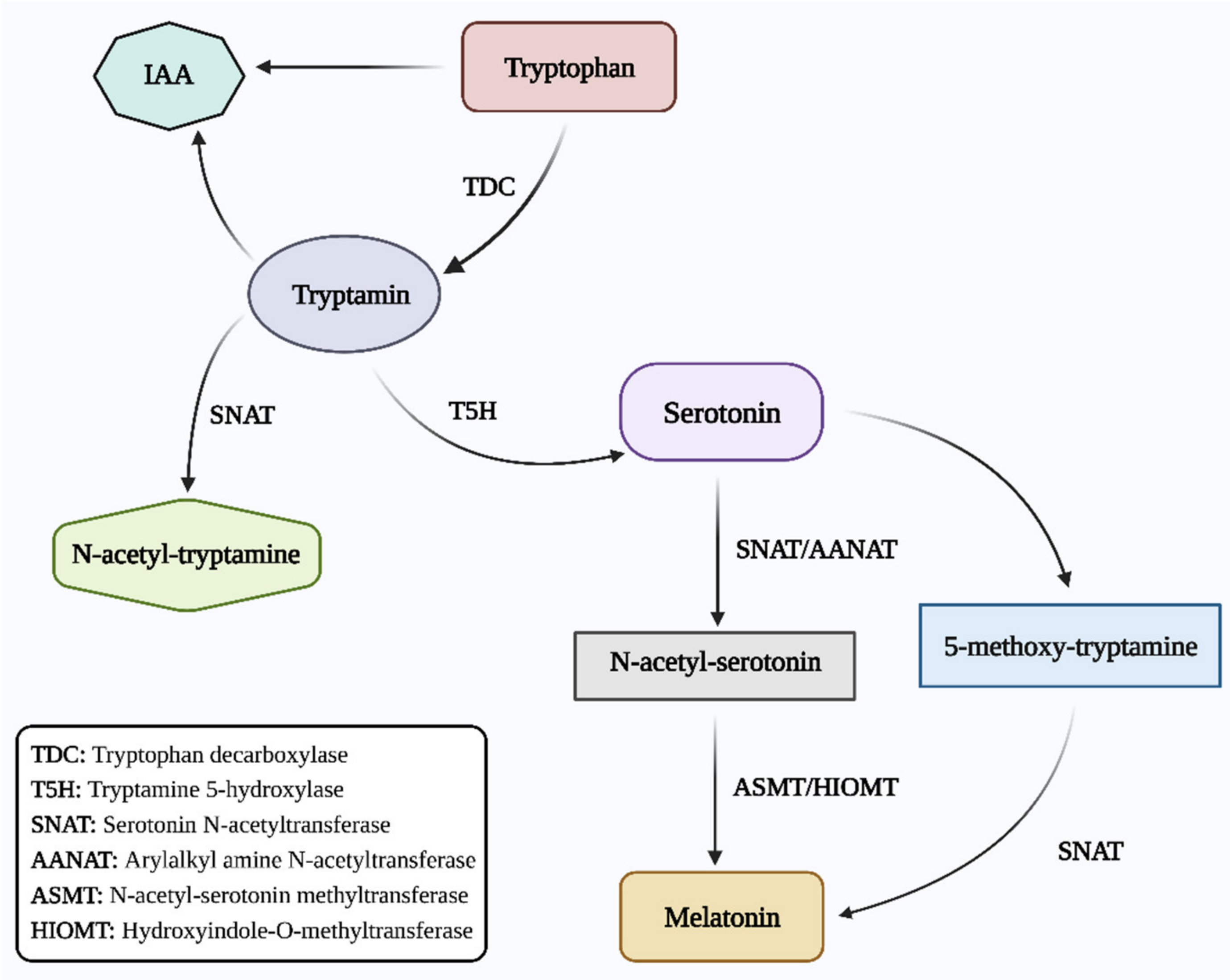

Figure 1. Schematic pathway of melatonin expression. This figure was created with BioRender.com (accessed on 15 September 2022).

2. Role of Melatonin in Plant Growth and Development

Several phytohormones, mainly auxin, play a crucial role in the growth and development of plants. Melatonin and indole acetic acid share the same precursor, tryptophan, making them both types of indoleamines. As such, melatonin should be involved in the control of plant growth and development (**Figure 2**). Previous results indicated that melatonin regulates the plant's circadian rhythms in the *Chenopodium rubrum* [7]. Furthermore, in *Chenopodium rubrum,* melatonin's application also affected the development of flowers in the early stage of the photoperiod [8]. After being treated with melatonin, the soybean plant's leaf size, plant height, pod size, and production of seeds all dramatically increased, indicating that the application of melatonin may enhance the soybean plant's growth and seed production [9]. Melatonin's shielding effect in the senescence process of plants was shown by the fact that it reduced the breakdown of chlorophyll in the leaves of barley plants [10]. Melatonin could encourage the growth of etiolated cotyledons in *Lupinus albus*, which is similar to how IAA works [11].

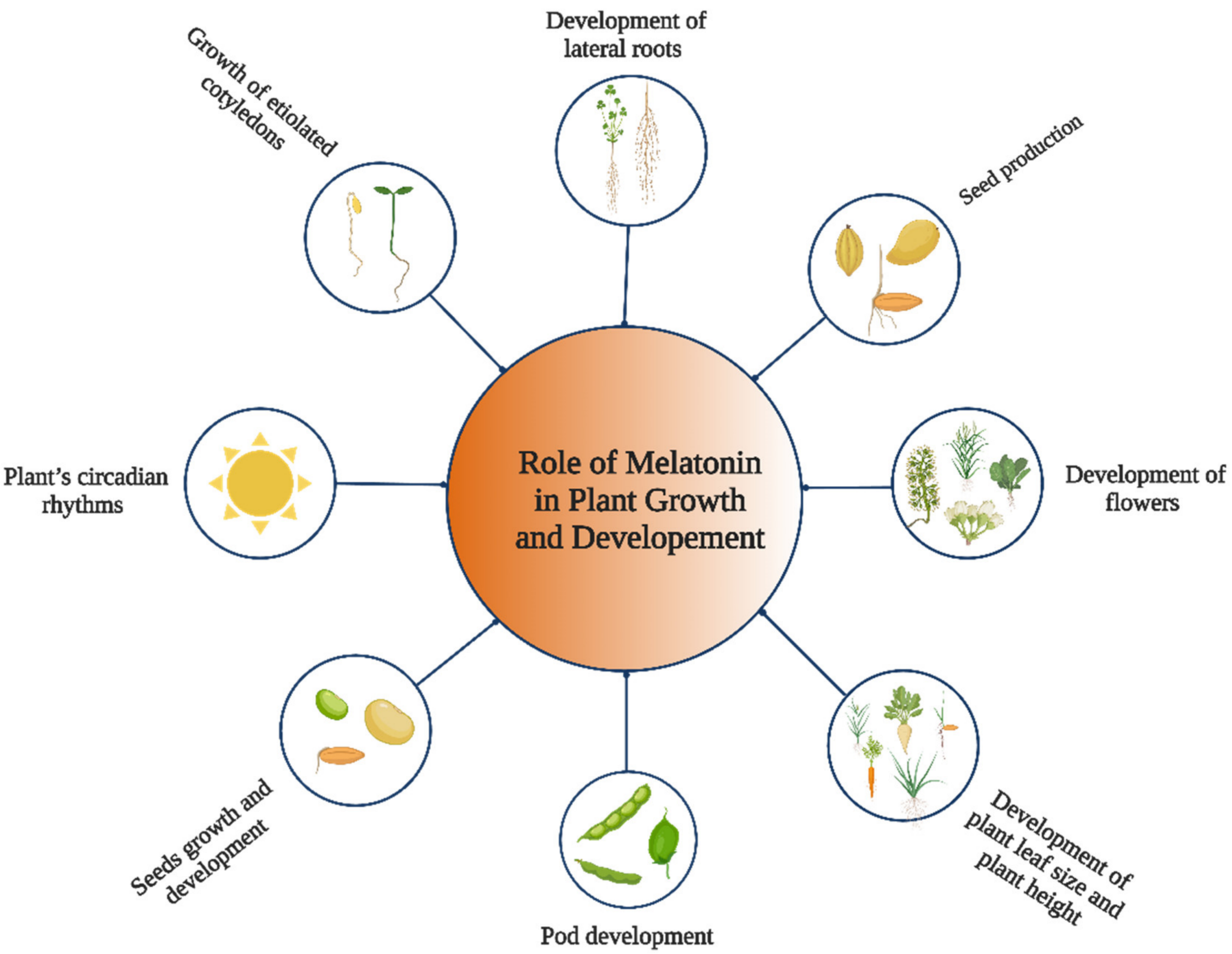

Figure 2. Role of melatonin in plant growth and development. This figure was created with BioRender.com (accessed on 7 September 2022).

Additionally, melatonin's effects on plants vary depending on its concentration. Low melatonin concentrations (10–20 µM) exhibited no discernible impact on root length in Arabidopsis seedlings. On the other hand, fresh weight at high melatonin content (200–400 µM) was greatly suppressed, and the ideal melatonin level for promoting plant growth and development was 40 µM [12].

3. Role of Melatonin under Abiotic Stress

Throughout their existence, plants are subject to a variety of environmental pressures. Plants, which are sessile organisms, have developed a variety of coping mechanisms to deal with challenging situations, maintaining their survival and ability to reproduce [13][14]. Melatonin is a universal abiotic stress regulator in plants [15]. Exogenously applied melatonin increases plant tolerance against abiotic stresses, including drought, waterlogging, extreme temperatures, salinity, and heavy metals toxicity, by modifying the production of endogenous melatonin and antioxidant systems [16] (**Figure 3**).

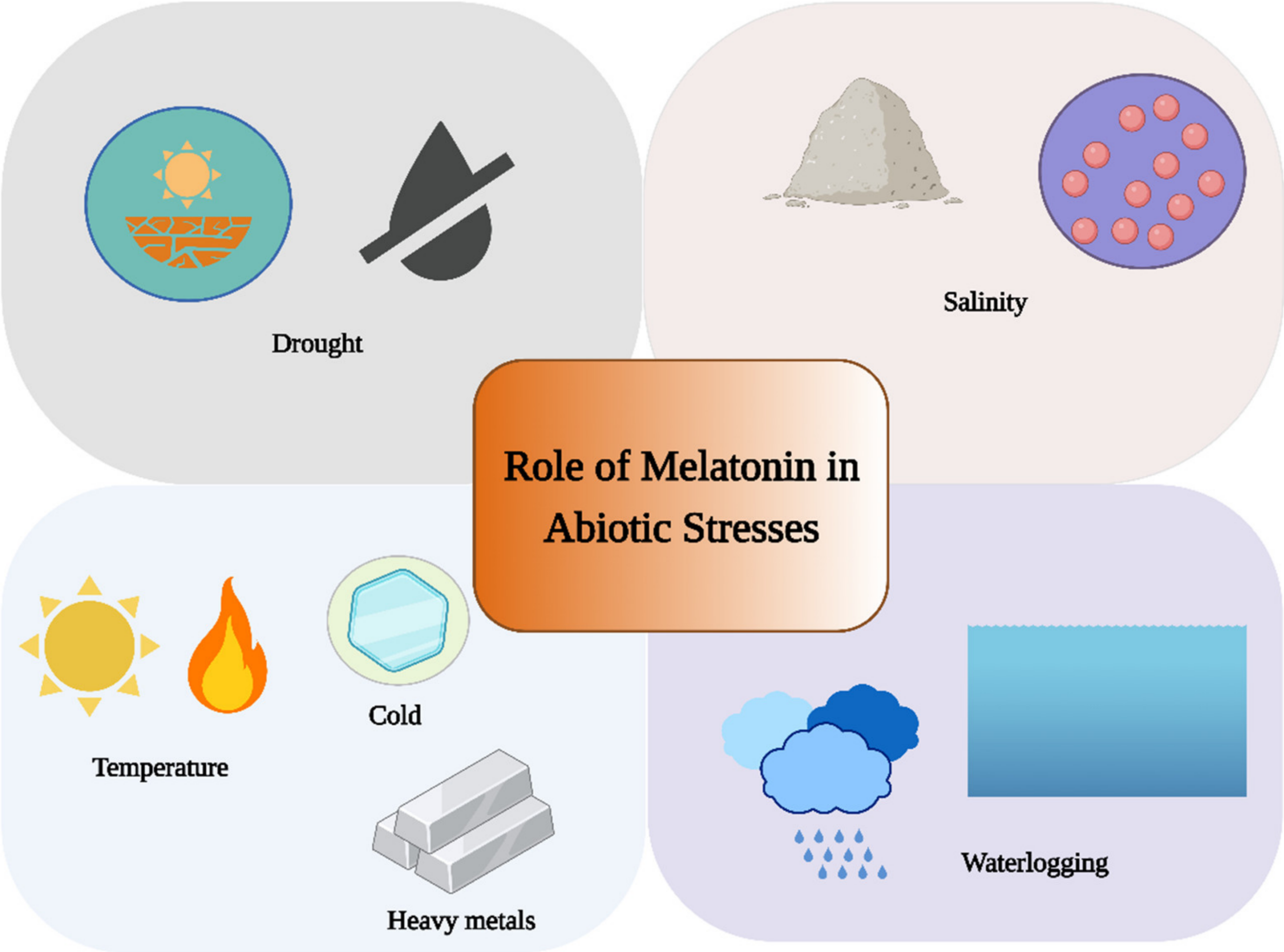

Figure 3. Role of melatonin under abiotic stress. This figure was created with BioRender.com (accessed on 7 September 2022).

3.1. Role of Melatonin under Water Stress

Drought stress dramatically reduces plant growth and development [17]. The morphological, physiological, biochemical, and molecular properties of plants are altered by drought stress, which poses a major threat to agricultural productivity and quality [18]. Under abiotic stress, endogenous melatonin levels are increased [19]. The Arabidopsis plant's ability to withstand drought was significantly improved by the overexpression of the melatonin production gene, MzASMT1 [20]. Thus, exogenous melatonin could be used to alleviate abiotic stresses. For example, melatonin application improved drought tolerance in drought-sensitive and drought-resistant species of apple plants [21]. Similarly, melatonin supplementation reduced the adverse effects of drought stress on the photosynthetic and antioxidant systems of grapes [22].

Waterlogging adversely affects plant growth and development. This process substantially restricts gas diffusion, causing hypoxic stress brought on by anaerobic respiration in the roots and encouraging the buildup of reactive oxygen species (ROS) [23]. Melatonin takes a role in the control of plant reactions to waterlogging. In plants, in response to waterlogging stress conditions, the transcript accumulation of the genes involved in melatonin is dramatically increased [24]. Under waterlogging conditions, exogenously applied melatonin significantly increased seedling viability in apples [25]. Furthermore, melatonin was found to be able to improve cucumber and *Prunus persica* resistance to waterlogging by stimulating root development, increasing antioxidant enzyme activity, and improving photosynthetic efficiency [25].

3.2. Role of Melatonin under Extreme Temperature

Cold stress adversely affects plant growth and survival. It may cause an excessive ROS buildup and redox imbalance. Melatonin tends to accumulate in extreme cold conditions to shield plants from deadly injuries. For instance, melatonin plays a protective role in plants' ability to withstand low temperatures, as shown by SNAT transgenic rice, which is less sensitive to cold than wild-type plants [26]. Exogenously applied melatonin may improve the cold and drought tolerance of tobacco, tomato, and cucumber [27]. The application of melatonin significantly enhanced the germination rate of cucumber seeds from 4% to 83% at 10 °C [28]. Wheat seedlings supplemented with melatonin showed increased levels of osmoprotectants and antioxidant enzyme activity, indicating that melatonin may increase the plant's ability to withstand low temperatures by scavenging ROS and regulating redox equilibrium [29]. Exogenously applied melatonin can sustain the quality of fruits, vegetables, and cut flowers by conferring chilling tolerance. For instance, pre-treating loquat fruit with melatonin before storage causes a buildup of phenolic chemicals and a decrease in lignin, relieving taste and nutrient loss brought on by chilling damage when exposed to cold storage [30].

Heat stress also adversely affects the growth and survival of plants and is becoming a worldwide concern because of global warming. Heat stress adversely affects the physical, biochemical, and molecular properties of the plants [31]. Additionally, by raising endogenous melatonin, ASMT and SNAT overexpression dramatically enhances thermotolerance [32]. Melatonin concentration was significantly enhanced when the plants were challenged by heat stress [33]. Thus, melatonin treatment might improve the plant's resistance to heat stress. Exogenously applied melatonin dramatically improved the germination percentage of *Arabidopsis thaliana* [34]. Melatonin therapy increased heat stress tolerance in tomato seedlings by maintaining redox homeostasis while regulating polyamine and nitric oxide production [35]. Melatonin treatment improved the production of SA and lowered the concentration of ABA in soybean seedlings to decrease fatal heat-induced injuries [36].

3.3. Role of Melatonin under Salt Stress

Salt stress has emerged as a serious global issue, restricting agricultural output and causing significant economic losses globally [37]. Melatonin has reportedly been linked to an increase in plants' resistance to salt stress in recent years. Melatonin treatment increased salt tolerance in several plants, including barley, wheat, cucumbers, soybeans, bermudagrass, and apples [38]. Similarly, in cucumber plants, the adverse effects of salt stress on the root system were significantly reduced via the application of melatonin [39]. Furthermore, melatonin treatment increased salt tolerance and regulated transcript accumulation of the genes related to salt stress [9]. Melatonin application also increased the expression of the genes related to the production and catabolism of abscisic acid (ABA) and gibberellic acid (GA) in cucumber plants during salt-induced stress [40].

3.4. Role of Melatonin under Heavy Metal Stress

Pollution from heavy metals (HMs) poses a major threat to all types of living things, notably to plants [41][42]. HMs application, including cadmium, lead, and zinc, significantly increased the production of endogenous melatonin in algae, and exogenous melatonin application improved the algae's ability to withstand cadmium stress [33][43]. Furthermore, exogenous melatonin application dramatically induced the tolerance of the plants to HMs stress [35]. For example, exogenously applied melatonin substantially reduced the toxicity caused by cadmium in tomatoes [44]. Melatonin and nitrogen oxide interaction enhanced Pb and Cd stress tolerance [38]. Melatonin treatments at concentrations of 1 and 10 µM boosted seed germination and seedling growth when exposed to copper stress, whereas the application of 100 µM melatonin showed opposite effects and increased copper's harmful effects [45].

Melatonin controls antioxidant levels as well as the uptake and sequestration of heavy metals, which helps to modulate the tolerance to heavy metals. For example, vanadium was excluded or sequestered from the plants via melatonin application [46].

3.5. Role of Melatonin under Light-Induced Stress

Plants are harmed by light-induced oxidative bursts. In plants, UV radiation can cause the production of free radicals [47]. After exposure to UV-B light for a brief period, endogenous melatonin concentration was shown to increase in plants, indicating that it plays a role in the UV-B response [48]. Under UV-B exposure, exogenous melatonin increased the number of isoflavone monomers in 4-day-old germinated soybeans [49]. In Arabidopsis, melatonin application induced UV-B tolerance [50].

4. Role of Melatonin in Biotic Stress

To combat biotic stressors, plants often have a highly developed immune system. First, physical barriers to plants, including waxes, thick cuticles, and unique trichomes, prevent pathogens or insects from adhering to them [51][52][53]. Plants have two pathways that they can use to recognize pathogens and launch defense mechanisms. The first one is the pattern recognition receptors (PRRs), which recognize pathogen-associated molecular patterns (PAMPs) such as flagellin to induce PAMP-triggered immunity (PTI) [54]. Plant resistance (R) proteins, the second route of the immune system, detect the specific effectors of pests or pathogens (avirulent proteins) and trigger the plant defense response through a mechanism known as effector-triggered immunity (ETI) [54][55]. ETI induces a hypersensitive response (HR), an intentional cell suicide of the infected cells [54]. A number of plant hormones, including ethylene (ET), jasmonic acid (JA), and salicylic acid, are particularly prominent in the signaling pathways induced by PTI and ETI (SA). Plants frequently induce the ET and JA pathways in response to chewing insects and necrotrophic infections, but the SA mechanism enhances resistant protection against hemi-biotrophic and biotrophic pathogens [54][56]. The first is known as systemic acquired resistance (SAR), which becomes active during primary infection with a necrotizing pathogen and is associated with rising concentrations of SA and related pathogenesis proteins [54]. The second type of plant resistance is induced systemic resistance (ISR), which is triggered by particular strains of nonpathogenic root-colonizing bacteria and requires JA and ET for signaling [51][57]. By identifying the conserved herbivore-associated elicitors of the invading insect, phytophagous insects force plants to exhale volatiles to attract their foes and warn their neighbor plants of impending hazards [58][59].

Melatonin may be a cost-effective alternative method to induce plant protection against biotic stress because it is an eco-friendly chemical (**Figure 4**). Animal studies have shown that melatonin possesses immunomodulatory, antioxidant, anti-inflammatory, and neuroprotective properties [60], making it a potential therapeutic alternative for the treatment of microbial illnesses. Similarly, several significant discoveries have recently demonstrated the positive role that melatonin plays in plant–pathogen interactions. In this context, extra pertinent information is covered in-depth in the following subsections.

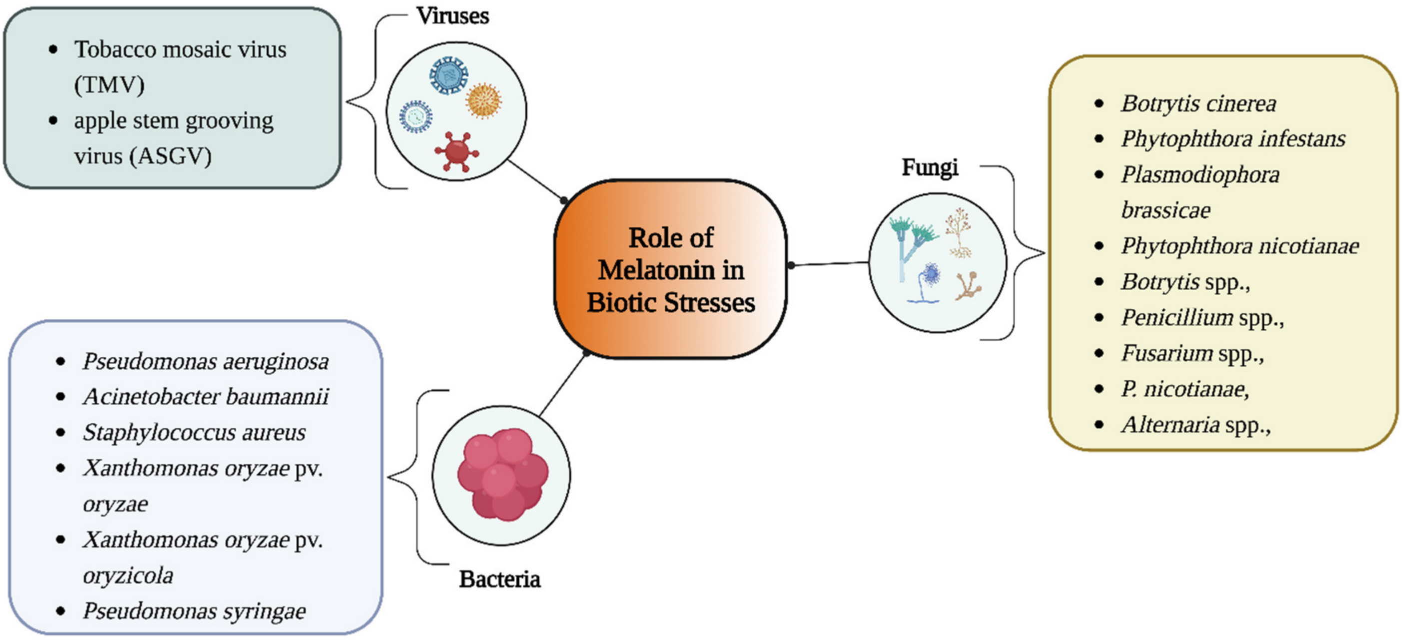

Figure 4. Role of melatonin in biotic stress. This figure was created with BioRender.com (accessed on 7 September 2022).

4.1. Antiviral Effects of Melatonin

Melatonin's antiviral activity in animals has been proven in numerous studies. In comparison with infected control mice, melatonin therapy drastically reduced blood and brain viruses [61]. Similarly, mice infected with the influenza virus survived longer when given melatonin along with the antiviral medication ribavirin [62]. Melatonin's great antioxidation efficacy and capacity to reduce endoplasmic reticulum stress make it a candidate in this situation for regulating the autophagy process during various viral infections [63][64][65]. Few researchers have examined the antiviral properties of melatonin in plants up until this point. Tobacco mosaic virus (TMV) viral RNA and virus concentration were reduced in infected *Nicotiana glutinosa* and *Solanum lycopersicum* seedlings after treatment with exogenous melatonin. The rise in SA concentrations in the NO-dependent pathway was thought to be the cause of melatonin's beneficial effects [66]. Additionally, the apple stem grooving virus (ASGV) of "Gala" apple shoots that had been infected in vitro was successfully destroyed by melatonin, suggesting that it may be possible to grow plants devoid of viruses [67].

4.2. Antibacterial Effects of Melatonin

Both in vitro and in vivo studies have been conducted to examine the defense mechanisms of melatonin against bacterial infections in animals. Melatonin's ability to kill bacteria that are resistant to many drugs, including carbapenem-resistant *Pseudomonas aeruginosa*, *Acinetobacter baumannii*, and methicillin-resistant *Staphylococcus aureus*, has been demonstrated in vitro [68]. Melatonin application also showed a strong inhibitory action against Mycobacterium TB (H37Rv strain) [51]. Melatonin has demonstrated efficient antibacterial activity against phytobacterial pathogens in plant–bacteria interactions. One study found that melatonin application reduced the occurrence of a bacterial leaf streak (BLS) in rice [69].

Melatonin, along with nitric oxide, increased the transcript accumulation of SA pathway-related genes [70]. Additionally, in *Pseudomonas syringae* pathovar tomato (Pst)-DC3000-infected *Arabidopsis thaliana*, melatonin can trigger MAPK cascades to induce SA production [71]. Transcriptomic data have recently shown that melatonin application triggers ETI- and PTI-associated genes in watermelon and Arabidopsis [72].

4.3. Antifungal Effects of Melatonin

Melatonin was shown to have therapeutic advantages in animal models of *Candida sepsis* and conventional antimycotic therapy, where it could reduce interleukin-6 concentrations and shorten the amount of time needed for recovery from *Candida sepsis* in rats [73]. Melatonin promoted tomato fruit resistance to *Botrytis cinerea* by controlling the production of H_2O_2 and the jasmonic acid signaling pathway [74]. In watermelon and other cucurbits, a rise in melatonin accumulation in plants increases resistance to foliar diseases, such as powdery mildew and soil-borne oomycetes, through alterations in the transcript accumulation of the genes linked to PTI and ETI [72]. The prevalence of *Plasmodiophora brassicae* infection of *A. thaliana* and the number of pathogen sporangia decreased following melatonin treatment. This decrease was ascribed to the high expression of the JA-responsive *PR3* and *PR4* genes [51].

Melatonin and ethylicin, an oomycete antifungal, work synergistically to prevent the growth of *Phytophthora nicotianae* in vitro and in vivo by disrupting the fungus' amino acid metabolic homeostasis [75]. Melatonin is exogenously applied to replant soil to promote apple seedling growth, boost potassium levels, and induce photosynthesis, all of which alleviate replant disease [76]. Other fungi, such as *Botrytis* spp., *Penicillium* spp., *Fusarium* spp., *P. nicotianae*, and *Alternaria* spp., also showed similar results [51]. Additionally, several studies have examined the function of endophytic rhizobacteria in enhancing plants' capacity to synthesize melatonin [77]. A number of different theories have explained melatonin's preventive function against plant fungal infections. For example, some scientists have suggested that melatonin's defense mechanism involves its capacity to maintain H_2O_2 cellular concentrations and the production and control of antioxidant enzyme activities [78].

Transcriptomic data have recently shown that exogenous melatonin administration activates PTI- and ETI-related genes in watermelon and *A. thaliana* [72]. Additionally, melatonin is essential for controlling the levels of ROS and reactive nitrogen species (RNS) in plants, which are signals for numerous cellular and physiological responses to biotic and abiotic stresses. These responses can be triggered directly by ROS/RNS scavengers or indirectly by genes that control the redox network [79].

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