


Recent advances in melatonin regulation of drought tolerance in plants

Mingzhao Luo^{1,2#} , Dandan Zhang^{3#}, Wensi Tang^{1#}, Pierre Delaplace², Ming Chen^{1*} and Youzhi Ma^{1*}

¹ State Key Laboratory of Crop Gene Resources and Breeding, Institute of Crop Sciences, Chinese Academy of Agricultural Sciences (CAAS), Beijing 100081, China

² Plant Genetics and Rhizosphere Processes laboratory, Gembloux Agro-Bio Tech, Teaching and Research Centre (TERRA), University of Liège, Gembloux 5030, Belgium

³ Key Laboratory of Agricultural Big Data, Agricultural Information Institute, Chinese Academy of Agricultural Sciences (CAAS), Beijing 100081, China

Authors contributed equally: Mingzhao Luo, Dandan Zhang, Wensi Tang

* Corresponding authors, E-mail: chenming02@caas.cn; mayouzhi@caas.cn

Abstract

Drought stress significantly impacts crop growth, development, and productivity. However, emerging research highlights the pivotal role of melatonin as a versatile molecule in enhancing plant resilience. Studies have emphasized melatonin's ability to effectively scavenge reactive oxygen species (ROS) while also orchestrating a spectrum of physiological responses crucial for plant survival under drought conditions. Melatonin's regulatory influence extends to critical processes such as germination, root development, and leaf senescence, positioning it as a crucial agent in mitigating drought stress. Beyond its antioxidative properties, melatonin mediates drought tolerance through complex interactions with membrane receptor proteins like phyto-melatonin receptor 1 (PMTR1) and potentially activates signaling pathways, including the mitogen-activated protein kinase (MAPK) cascade and transcription factors, to regulate downstream effectors. Recent investigations have also illuminated melatonin's interactions with various phytohormones, plant microbiomes, and flavonoids, further enhancing its role in drought tolerance. This comprehensive review systematically explores the mechanisms by which melatonin modulates drought tolerance. Additionally, several promising directions are proposed for future research aimed at elucidating the multifaceted roles of melatonin and potential applications in enhancing drought tolerance in agricultural systems.

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Introduction

Drought is a primary environmental factor that adversely affects crop production. Over half of the world's crops are cultivated in arid and semi-arid regions, where drought significantly reduces crop yield and quality^[1]. Under water deficit conditions, the excessive accumulation of reactive oxidative species (ROS) can severely impair plant growth and development^[2]. In response, plants have evolved numerous sophisticated mechanisms to counteract dehydration, including regulating growth and maturation, reducing plant height, promoting root development, and accelerating leaf senescence and flowering^[3]. For example, to mitigate drought stress, plants accelerate leaf senescence and promote flowering by reallocating water and nutrition from older to younger leaves and reproduction issues^[4]. Furthermore, plant hormones, flavonoids, and microbiomes regulate drought stress resilience^[5]. During drought stress, abscisic acid (ABA) accumulation induces stomatal closure and leaf senescence through increased ROS levels^[6]. Therefore, plants modulate diverse molecular and physiological pathways to improve resilience to drought stress.

Melatonin, also known as 5-methoxy-N-acetyltryptamine, was first discovered in the pineal gland of bovine^[7] and subsequently found in plants as early as 1995^[8,9]. This multifunctional molecule is involved in plant growth and development, including germination, root architecture, flowering time, leaf senescence, and fruit ripening^[10]. Moreover, melatonin has emerged as a critical regulator of plant resilience to various biotic and abiotic stresses, including salinity, extreme temperatures, heavy metals, ultraviolet radiation, and drought^[11]. Consequently, research investigating melatonin's functions and regulatory mechanisms in plants has expanded exponentially in recent years. Numerous studies

indicated that melatonin alleviates drought stress by regulating various morphological, physiological, and biochemical processes, including seed germination, root and shoot development, leaf senescence, flowering, stomatal closure, photosynthetic efficiency, cell membrane integrity, osmotic stress, autophagy, etc^[12]. For instance, seeds pretreated with melatonin had significantly improved germination under drought stress in various species, including hexaploid triticale (*Triticale hexaploid* L.), wheat (*Triticum aestivum* L.), and cotton (*Gossypium hirsutum* L.)^[13,14]. Moreover, melatonin plays a positive role in root growth and a negative role in shoot development, facilitating water absorption and enabling plants to cope with drought stress.

These findings suggest the crucial role of melatonin on drought stress tolerance. However, comparing these studies is challenging due to the complexity of phenotypes and physiological activities under varying drought conditions. Factors such as drought treatment methods (osmotic stress or soil drought stress), duration of drought stress (hours or days), sampling positions (roots, stems, leaves, or whole plants), and culture conditions (greenhouse or field conditions) add to this complexity. Therefore, further studies are needed to explore the underlying mechanisms by which melatonin enhances drought resilience. In this review, the ROS-scavenging properties of melatonin and its metabolites are critically evaluated under drought stress conditions, alongside its regulation of growth, development, and physiological activities during drought conditions. Then, how melatonin enhances drought tolerance by regulating plant hormones, microorganisms, and flavonoids are discussed. In addition, several future research directions for melatonin are proposed that could advance agricultural production under drought conditions.

Boosting melatonin to combat drought stress in plants

Melatonin biosynthesis and its role in enhancing plant drought tolerance

Melatonin biosynthesis in plants has been extensively studied following its discovery. Initially, researchers utilized heterologous expression of animal biosynthetic genes, such as hydroxyindole-O-methyltransferase (*HIOMT*) from sheep, to enhance plant melatonin levels^[15]. Subsequent investigations revealed that melatonin can be biosynthesized in plants' chloroplasts and mitochondria^[16,17]. In plants, both melatonin and indole-3-acetic acid (IAA) are synthesized from tryptophan. As shown in Fig. 1, melatonin biosynthesis involves two distinct pathways that involve six enzymes, including tryptophan decarboxylase (TDC), tryptamine 5-hydroxylase (T5H), serotonin N-acetyltransferase (SNAT), N-acetylserotonin methyltransferase (ASMT), and caffeic acid O-methyltransferase (COMT) (Fig. 1). Then, numerous studies have established that overexpression or knockout melatonin biosynthesis genes can directly modulate melatonin levels, thereby regulating plant stress tolerance^[18–29] (Table 1). In *Arabidopsis*, overexpression of *TaCOMT* enhanced drought tolerance by promoting root growth and increasing proline content^[30]. Therefore, further studies could use genetic modification techniques, such as CRISPR-Cas9, to improve plant drought tolerance by regulating melatonin biosynthesis genes in crops.

In addition, several studies demonstrated that high melatonin content enhances stress tolerance by increasing plant flavonoid biosynthesis^[31]. On the contrary, some flavonoids, including morin and myricetin, can significantly decrease melatonin content by inhibiting the expression of *SNAT1* and *SNAT2* in rice (*Oryza sativa* L.)^[32]. Only several studies indicate that heterogeneous

overexpression of melatonin biosynthesis genes significantly enhances drought tolerance^[33]. However, no studies have demonstrated the regulation of melatonin biosynthesis genes by transcription factors under drought conditions. Hence, further studies can focus on identifying the upstream transcription factors that interact with melatonin biosynthesis genes during drought stress.

Exogenous application of melatonin enhances drought tolerance

Exogenous application of melatonin has been widely used to increase melatonin levels within the plant to enhance stress tolerance. Indeed, appropriate concentrations of melatonin can bolster drought tolerance in various plant species, including apple (*Malus domestica* Borkh.)^[34,35], alfalfa (*Medicago sativa* L.)^[36], maize (*Zea mays* L.)^[37], tomato (*Solanum lycopersicum* L.)^[38–41], wheat^[42,43], rice^[33], cotton^[44], etc. Exogenous melatonin is typically applied through foliar spraying, root application, or seed priming^[45–52] (Table 2). However, most of these studies are investigating the application of melatonin in greenhouse conditions across various species. Hence, future studies should focus on developing melatonin-related biostimulants for sustainable agricultural production in field conditions. This may involve investigating optimal application methods, timing, dosage, and other relevant factors under drought conditions. Overall, one of the research directions is to incorporate melatonin and its metabolites into crop breeding programs to enhance food production and security.

Molecular mechanisms of melatonin signaling-mediated drought tolerance

Melatonin can stabilize membrane integrity by reducing ROS content under drought conditions. Previous studies demonstrated that melatonin plays a pivotal role in maintaining ROS homeostasis,

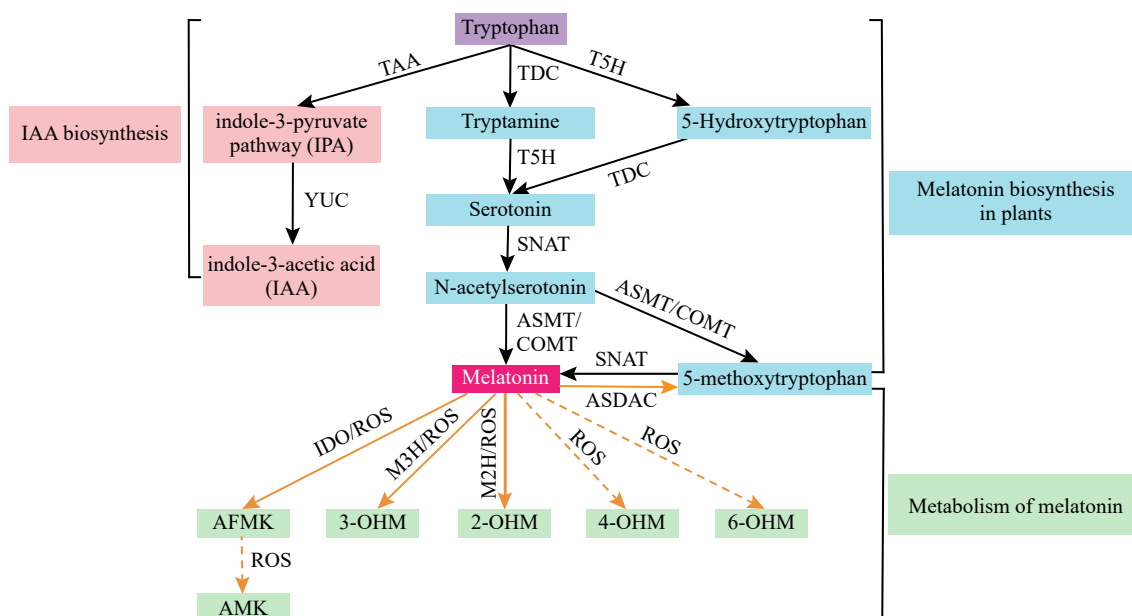


Fig. 1 Melatonin biosynthetic pathways in plants. Solid lines indicate enzymes or oxidants identified in plants, whereas dashed lines indicate enzymes or oxidants identified in animals but not yet confirmed in plants. AFMK: N1-acetyl-N2-formyl-5-methoxyknuramine, AMK: N-acetyl-5-methoxyknuramine, ASDAC: N-acetylserotonin deacetylase, ASMT: N-acetylserotonin methyltransferase, COMT: caffeic acid O-methyltransferase, IAA: indole-3-acetic acid, IDO: indoleamine 2,3-dioxygenase, IPA: indole-3-pyruvate, M2H: melatonin 2-hydroxylase, M3H: melatonin 3-hydroxylase, ROS: reactive oxygen species, RNS: reactive nitrogen species, SNAT: serotonin N-acetyltransferase, TAA: tryptophan aminotransferase of *Arabidopsis*, TDC: tryptophan decarboxylase, T5H: tryptamine 5-hydroxylase, TPH: tryptophan hydroxylase, YUC: YUCCA (the YUCCA gene encodes a flavin monooxygenase-like enzyme), 2-ODD: 2-oxoglutarate-dependent dioxygenase, 2-OHM: 2-hydroxymelatonin, 3-OHM: 3-hydroxymelatonin, 4-OHM: 4-hydroxymelatonin, 6-OHM: 6-hydroxymelatonin.

Table 1. Regulation of melatonin biosynthesis genes to enhance stress tolerance in plants.

Object species name	Melatonin biosynthesis genes	Function of melatonin	Ref.
Apple (<i>Malus domestica</i> Borkh.)	<i>MdASMT9</i>	Overexpression of <i>MdASMT9</i> also reduces abscisic acid accumulation through promoting <i>MdWRKY33</i> -mediated transcriptional inhibition of <i>MdNCED1</i> and <i>MdNCED3</i> , thus inducing stomatal opening for better heat dissipation.	[18]
<i>Arabidopsis thaliana</i> L.	<i>AtSNAT2</i>	<i>snat2</i> knockout mutant exhibits delayed flowering and reductions in leaf area and biomass.	[19]
Barley (<i>Hordeum vulgare</i> L.)	<i>HvCOMT1</i> , <i>HvCOMT2</i> , and <i>HvCOMT3</i>	Reducing thioacidolysis yields in the <i>COMT</i> RNAi lines are an indication of changes to lignin structure with a greater proportion of resistant bonds in the lignin.	[20]
Grapevine (<i>Vitis vinifera</i> L.)	<i>VvASMT1</i>	Ectopic overexpression of <i>VvASMT1</i> in <i>Nicotiana benthamiana</i> significantly enhances melatonin production and increased tolerance to salt and osmotic stresses.	[21]
<i>Malus zumi</i> Mats.	<i>MzASMT1</i>	Overexpression of <i>MzASMT1</i> increases melatonin levels and drought tolerance in <i>Arabidopsis</i> .	[22]
Rice (<i>Oryza Sativa</i> L.)	<i>OsASMT1</i> , <i>OsASMT2</i> , and <i>OsASMT3</i>	All three <i>ASMT</i> mRNAs are simultaneously induced in treatments with abscisic and methyl jasmonic acids.	[23]
Rice (<i>Oryza Sativa</i> L.)	<i>OsCOMT</i>	Overexpression of <i>OsCOMT</i> significantly delays leaf senescence at the grain-filling stage by inhibiting the degradation of chlorophyll and chloroplast. <i>OsCOMT</i> plays a positive role in the vascular development of rice. <i>OsCOMT</i> is a positive regulator of grain yield.	[24]
Rice (<i>Oryza Sativa</i> L.)	<i>OsSNAT1</i>	<i>OsSNAT1</i> -overexpressing rice plants increases resistance to cadmium and senescence stresses.	[25]
Rice (<i>Oryza Sativa</i> L.)	<i>OsSNAT2</i>	<i>SNAT2</i> RNAi lines indicates a decrease in melatonin and a dwarf phenotype with erect leaves by exhibiting photomorphogenic phenotypes such as inhibition of internodes and increased expression of light-inducible <i>CAB</i> genes in the dark.	[26]
Tobacco (<i>Nicotiana tabacum</i> L.)	<i>NtCOMT1</i>	Overexpression of <i>NtCOMT1</i> promotes drought resistance by increasing melatonin content.	[27]
Watermelon (<i>Citrullus lanatus</i> L.)	<i>CICOMT1</i>	Overexpression of <i>CICOMT1</i> enhances transgenic <i>Arabidopsis</i> tolerance against cold, drought, and NaCl.	[28]
Tomato (<i>Solanum lycopersicum</i> L.)	<i>SICOMT1</i>	Overexpression of <i>COMT1</i> significantly enhances the capacity of the tomato to reduce fungicide carbendazim phytotoxicity and residue.	[29]
Wheat (<i>Triticum aestivum</i> L.)	<i>TaCOMT</i>	Overexpression of the wheat <i>TaCOMT</i> gene enhances drought tolerance and increases the content of melatonin in transgenic <i>Arabidopsis</i> .	[30]
Cassava (<i>Manihot esculenta</i> Crantz)	<i>MeTDC2</i> , <i>MeASMT2</i> , and <i>MeASMT3</i>	<i>MeWRKY20/75</i> interacts with 3 melatonin synthesis enzymes (<i>MeTDC2</i> , <i>MeASMT2/3</i>) and positively regulates endogenous melatonin accumulation.	[55]
Cassava (<i>Manihot esculenta</i> Crantz)	<i>MeTDC2</i> , <i>MeTSH</i> , <i>MeASMT1</i> , <i>MeTDC1</i> , <i>MeASMT2</i> , <i>MeASMT3</i> , and <i>MeSNAT</i>	<i>MeRAV1</i> and <i>MeRAV2</i> positively regulate 7 melatonin biosynthesis genes (<i>MeTDC2</i> , <i>MeTSH</i> , <i>MeASMT1</i> , <i>MeTDC1</i> , <i>MeASMT2</i> , <i>MeASMT3</i> , and <i>MeSNAT</i>) and the endogenous melatonin level in plant disease resistance against cassava bacterial blight.	[56]

regulating plant growth, and enhancing plant stress resilience^[53]. On the one hand, melatonin reduces ROS levels by increasing antioxidant systems under stress conditions. On the other hand, melatonin also directly interacts with ROS/RNS to produce various metabolites, including 2-hydroxymelatonin (2-OHM), 3-hydroxymelatonin (3-OHM), 4-hydroxymelatonin (4-OHM), 6-hydroxymelatonin (6-OHM), 5-methoxytryptamine (5-MT), N1-acetyl-N2-formyl-5-methoxykynuramine (AFMK), and N-acetyl-5-methoxykynuramine (AMK) (Fig. 1). In addition, several plant enzymes involved in melatonin metabolism have been identified, including melatonin 2-hydroxylase (M2H), melatonin 3-hydroxylase (M3H), indoleamine 2,3-dioxygenase (IDO), and N-acetylserotonin deacetylase (ASDAC), which produce 2-OHM, 3-OHM, AFMK, and 5-MT, respectively. Further studies have indicated that these metabolites exhibit higher antioxidant activity than melatonin under stress conditions. For example, 2-OHM could mitigate cadmium stress in cucumber (*Cucumis sativus* L.) and increase drought stress tolerance by regulating the antioxidant system^[54]. Additionally, various transcription factors and flavonoids directly regulate melatonin biosynthesis genes in cassava (*Manihot esculenta* Crantz.). For example, the transcription factor *MeWRKY20/75* interacts with three melatonin biosynthesis enzymes (*MeTDC2*, *MeASMT2/3*) to enhance melatonin levels^[55]. These authors also revealed that *MeRAV1* and *MeRAV2* positively regulate melatonin biosynthesis genes to improve disease resilience against cassava bacterial blight^[56]. However, further studies are required to elucidate the function and the mechanisms by which these melatonin metabolites mitigate drought stress by decreasing ROS levels.

Studies on drought also indicate that transcription factors, such as *DEHYDRATION-RESPONSIVE ELEMENT-BINDING PROTEIN (DREB)*, *NAC*, *MYBs*, *bZIPs*, and *WRKYs*, play an important role in plant resilience^[57].

Melatonin has been shown to modulate various physiological processes and developmental growth to enhance plant stress tolerance by interacting synergistically with key phytohormones, such as ABA and gibberellic acid (GA)^[58]. These interactions are often mediated through intricate signaling networks and transcription factors, such as *NAC* and *MYB*, which regulate gene expression in response to various environmental factors^[59]. Additionally, several studies have reported that melatonin delays flowering time by stabilizing DELLA proteins or promoting the transcription of flowering locus C (FLC) to inhibit flowering locus T (FT)^[60]. However, the regulatory mechanisms of melatonin on leaf senescence and flowering transition under drought conditions require further investigation. In addition, autophagy is activated to degrade and recycle drought-induced proteins, reducing their toxicity. Previous studies demonstrated that melatonin regulates autophagy by an ABA-independent pathway to enhance drought tolerance. For example, Wang et al. initially discovered that melatonin regulates autophagy to mitigate the accumulation of oxidized proteins during oxidant stress (methyl viologen)^[61]. In wheat, rab-related proteins (RAB5C and RAB11A) related to autophagy activation were accumulated by applying melatonin during osmotic stress conditions^[62]. Subsequently, studies revealed that melatonin enhances drought tolerance by upregulating *ATG8* and *ATG8-PE* expression related to autophagosomes in cotton^[63]. Hence, plants regulate ABA-dependent or independent pathways to improve drought stress tolerance.

Preliminary findings indicate that melatonin regulates stomatal conductance enhances drought tolerance by accumulating the osmolytes, and improves water use efficiency. This regulatory mechanism also underpins the observed increase in photosynthetic efficiency under drought conditions^[64]. For example, melatonin can mitigate the reduction of stomatal conductance to enhance photosyn-

Table 2. Exogenous melatonin enhances drought tolerance in plants.

Species name	Melatonin concentration	Function of exogenous melatonin under drought stress	Ref.
Apple (<i>Malus domestica</i> Borkh.)	Root application (100 μ M)	Helping to maintain the better function of PSII and controlling the burst of hydrogen peroxide to delay the leaf senescence under drought.	[3]
Cotton (<i>Gossypium hirsutum</i> L.)	Foliar spray (100 μ M)	Down-regulating chlorophyll degradation-related genes and senescence marker genes (<i>GhNAC12</i> and <i>GhWRKY27/71</i>). Improving photosynthetic efficiency, reducing chlorophyll degradation and ROS accumulation, and inhibiting ABA synthesis, thereby delaying drought-induced leaf senescence in cotton.	[4]
Wheat (<i>Triticum aestivum</i> L.)	Root application (100 μ M)	Alleviating photosynthetic and cell membrane damage by maintaining low levels of hydrogen peroxide.	[13]
Rice (<i>Oryza Sativa</i> L.)	Seed priming (100 μ M)	Promoting the germination rate and improving the biomass of rice seed shoots and roots. Alleviating the oxidative damage of rice seeds caused by drought stress.	[33]
Alfalfa (<i>Medicago sativa</i> L.)	Foliar spray (100 μ M)	Boosting antioxidant enzyme activities, improving photosynthetic performance, and accumulating total soluble sugar and proline content.	[36]
Maize (<i>Zea mays</i> L.)	Foliar spray (100 μ M), and root application (50 μ M)	Reducing the reactive oxygen species burst and enhancing the photosynthetic activity.	[37]
Pepper (<i>Capsicum annum</i> L.)	Foliar spray (100 μ M)	Reducing oxidative stress and improving nitrogen metabolism by activating various enzymes such as nitrate reductase, nitrite reductase, glutamine synthetase, and glutamine dehydrogenase activities.	[38]
Tomato (<i>Solanum lycopersicum</i> L.)	Seed priming (100 μ M)	Increasing stomatal conductance, photochemical efficiency, and the antioxidant system, and also reducing the cellular content of toxic substances.	[39]
Tomato (<i>Solanum lycopersicum</i> L.)	Foliar spray (100 μ M), and root application (100 μ M)	Alleviating the inhibition of drought stress on the gas exchange parameters and the leaf net photosynthetic rate, protecting the thylakoid membrane from damage, and strengthening the ATP-synthase activity.	[40]
Two Citrus cultivars	Foliar spray (100 μ M)	Increasing total flavonoid and total phenolic contents under severe drought stress.	[41]
Wheat (<i>Triticum aestivum</i> L.)	Root application (500 μ M)	Decreasing membrane damage, more intact grana lamella of chloroplast, higher photosynthetic rate, and maximum efficiency of photosystem II, as well as higher cell turgor and water-holding capacity.	[42]
Wheat (<i>Triticum aestivum</i> L.)	Root application (100 μ M)	Improving fine root, lateral root, and root hair, plant height, dry weight, net photosynthesis, and stomatal aperture of leaves.	[43]
Cotton (<i>Gossypium hirsutum</i> L.)	Foliar spray (100 and 200 μ M)	Improving the translocation of carbon assimilates to drought-stressed anthers, regulating the carbohydrate balance of drought-stressed anthers to improve male fertility.	[44]
Kiwifruit (<i>Actinidia chinensis</i> Planch)	Root application (100 μ M)	Improving photosynthesis by inhibiting stomatal closure, enhancing light energy absorption, and promoting electron transport in PSII.	[45]
Maize (<i>Zea mays</i> L.)	Foliar spray (100 μ M)	Increasing the accumulation of flavonoid metabolites, particularly apigenin, luteolin, and quercetin. Upregulating the expression of genes related to flavonoid biosynthesis (<i>PAL</i> , <i>C4H</i> , <i>4CL</i> , <i>HCT</i> , <i>CHS</i> , <i>CHI</i> , <i>F3'5'H</i> , and <i>DFR</i>), activates drought-responsive transcription factors (<i>ERFs</i> , <i>NACs</i> , <i>MYBs</i> , and <i>bHLHs</i>).	[46]
Moldavian balm (<i>Dracocephalum moldavica</i>)	Foliar spray (100 μ M)	Increasing soluble sugar content, malondialdehyde content, and lipoxygenase activity, non-enzyme antioxidants (including flavonoid, polyphenol compounds, and anthocyanin) under moderate and severe drought stress.	[47]
Maize (<i>Zea mays</i> L.)	Root application (100 μ M)	Improving the photosynthetic activities and alleviated the oxidative damages of maize seedlings under the drought stress.	[48]
Rapeseed (<i>Brassica napus</i> L.)	Root application (50 μ M)	Alleviating the seedling growth inhibition and increasing the leaf area and fresh and dry weights of roots and shoots under drought stress.	[49]
Rice (<i>Oryza Sativa</i> L.)	Root application (100 μ M)	Promoting root, shoot length, fresh and dry weight, and increasing chlorophyll contents.	[50]
Soybean (<i>Glycine max</i> L.)	Foliar spray or root application (50 and 100 μ M)	Improving photosynthetic activity, reduction of abscisic acid and drought-induced oxidative damage.	[51]
Tomato (<i>Solanum lycopersicum</i> L.)	Root application (150 μ M)	Affecting stomatal conductance and the activity of ROS scavenging enzymes.	[52]
Tomato (<i>Solanum lycopersicum</i> L.)	Root application (100 and 500 μ M)	Carbon monoxide is a downstream signal molecule of melatonin-enhanced drought resistance by promoting chlorophyll biosynthesis.	[59]
Cotton (<i>Gossypium hirsutum</i> L.)	Seed priming (10 μ M)	Increasing photosynthetic activity, water-use efficiency, and nitrogen metabolism. Upregulating the expression of the autophagosome marker [lipidated (ATG8-PE)].	[63]
Tomato (<i>Solanum lycopersicum</i> L.)	Root application (100 μ M)	Improving the seedlings growth, root characteristics, leaf photosynthesis and antioxidant machinery.	[64]
Creeping bentgrass (<i>Agrostis stolonifera</i>)	Foliar spray (20 μ M)	Increasing visual quality, photochemical efficiency, chlorophyll content, and relative water content. Up-regulating and chlorophyll-degradation genes, and cytokinin-signaling and synthesis genes.	[82]
Naked oats (<i>Avena nuda</i> L.)	Foliar spray (100 μ M)	Increasing the chlorophyll content and photosynthetic rate of leaves, increasing expression of <i>PYL</i> , <i>PP2C</i> , <i>ABF</i> , <i>SNRK2</i> , and <i>IAA</i> .	[84]
Barley (<i>Hordeum vulgare</i> L.)	Root application (2 mM)	Exogenous melatonin increases the relative abundance of the bacterial community in carbohydrate and carboxylate degradation while decreasing the relative abundance in the pathways of fatty acid and lipid degradation and inorganic nutrient metabolism under drought.	[89]

thetic efficiency in various plants under drought conditions^[65]. In addition, melatonin was also shown to prevent disruption of the photosystems within the thylakoids and the reduction of chlorophyll, rubisco protein, etc., under drought conditions^[66]. For example, Ye et al. report that melatonin alleviates chlorophyll degradation and disruption of fluorescence parameters caused by drought stress^[67]. Exogenous application of melatonin could improve photosynthetic efficiency and grain filling rate, thereby enhancing grain yield poten-

tial under drought stress conditions in soybean (*Glycine max* L.)^[68] and maize^[69]. Melatonin can also protect the photosynthetic electron transport in photosystems (PSI and PSII) and restore the fluorescence parameters to increase photosynthetic capacity^[70]. However, the regulatory mechanism of melatonin on photosynthesis under drought stress conditions remains largely unknown.

In addition, identifying receptor proteins is vital for studying melatonin's regulation and signal pathways in plants. The first

phyto-melatonin receptor1 (Cand2/PMTR1), a putative G protein-coupled melatonin receptor-like protein, was identified in Arabidopsis^[71]. In the study by Wei et al., melatonin was shown to regulate stomatal closure by inducing ROS and Ca²⁺ signaling pathways or activating mitogen-activated protein kinase (MAPK) cascades in guard cells^[71]. The melatonin receptor mutant, *cand2*, exhibited reduced osmotic stress tolerance with ROS accumulation and exogenous melatonin could not revert this osmotic stress phenotype in Arabidopsis^[71]. Subsequently, homologs of PMTR1 have been identified in other plants. For instance, overexpressing *ZmPMTR1* in Arabidopsis enhanced osmotic stress tolerance by reducing the rate of transpiration^[72]. However, Lee & Back argued that PMTR1 is not a G protein-coupled melatonin receptor as, under stress conditions, melatonin-activated MAPK (MPK3/6) cascades without the need for PMTR1^[73]. In addition, it is noteworthy that previous studies have identified at least two receptors (MT1 and MT2) in animals^[74]. Therefore, further investigations are necessary to confirm the receptor function of PMTR1 or identify new melatonin receptors and elucidate its signal transduction pathways.

Additionally, MAPK cascades are essential signal transduction pathways that respond to various environmental stresses, such as drought, salt, and pathogens. Previous studies have demonstrated that melatonin activates MAPK signaling in response to plant pathogens^[75]. In addition, melatonin regulated chloroplast protein quality control (CPQC), which is critical for starch synthesis and reducing DNA damage by activating the plant MAPK pathways^[76]. Recent studies have further elucidated melatonin's role in MAPK pathways under stress conditions. For example, in apples, melatonin-activated *MdMPK3* and *MdMPK6* upregulate the melatonin biosynthesis gene, *MdASMT7*, by phosphorylating the transcription factor *MdWRKY17*^[77]. Similarly, in Sour jujube (*Ziziphus jujuba* var. *spinose*), melatonin could enhance salt resilience by upregulating *MKK3* in the MAPK signaling pathway^[78]. Despite these findings, the specific mechanisms by which melatonin activates the MAPK cascade to alleviate drought stress in plants remain underexplored. Therefore, further studies are needed to elucidate MAPK cascade pathways regulating drought resilience.

Melatonin regulates other pathways to enhance drought tolerance

Melatonin cross-talks with other plant hormones to enhance drought tolerance

Recent studies have shown that melatonin enhances drought tolerance by modulating other plant hormones, microbiome communities, and flavonoids. Plant hormones are vital for drought resilience in plants through their regulation of growth, development, and numerous physiological processes. In contrast, melatonin promotes stomatal reopening by decreasing ROS and ABA levels under drought conditions^[79]. New studies have suggested that melatonin achieves this by downregulating ABA biosynthesis genes and upregulating ABA catabolism genes^[80]. Other studies have demonstrated that melatonin can inhibit ABA transport from roots to shoots during drought stress^[81]. Melatonin can synergistically interact with cytokinin (CTK) to increase drought tolerance by upregulating dehydration-responsive genes (*JUB1* and *DREB2A*) and alleviate drought-induced leaf senescence by increasing endogenous CTK content^[82]. Additionally, melatonin increased brassinosteroid (BR) content by upregulating biosynthesis genes, including *CYP750A1*, *CYP707A5*, *CYP707A7*, *CYP87A3*, and *CYP90D2*, thereby improving drought and cold tolerance^[83]. The exogenous application of melatonin increased salicylic acid (SA), GA, and IAA under imposed water deficit conditions^[84,85]. Jasmonic acid (JA) levels, which are increased by drought stress and contribute to drought tolerance, were positively regulated by melatonin during drought conditions^[86]. Overall, these studies demonstrate that melatonin plays a central role by modulating these plant hormones and reducing ROS concentration caused by water deficit conditions (Table 3). Although these studies illustrated that melatonin can regulate plant growth, development, and physiological processes to enhance drought resilience by changing plant hormones' content, its interactions with other plant hormones under drought conditions remain largely unexplored. Therefore, further detailed omics studies are essential to identify the transcription factors and regulatory elements involved in this signaling cascade.

Table 3. Melatonin regulatory pathways under drought conditions.

Species name	Regulation objects	Function of melatonin under drought conditions	Ref.
Cotton (<i>Gossypium hirsutum</i> L.)	Decreased ABA	Melatonin can effectively enhance the antioxidant enzyme system, improve photosynthetic efficiency, reduce chlorophyll degradation and ROS accumulation, and inhibit ABA synthesis, thereby delaying drought-induced leaf senescence in cotton.	[4]
Wheat (<i>Triticum aestivum</i> L.)	Increased JA	Up-regulating jasmonic acid biosynthesis genes and increasing jasmonic acid contents to mitigate drought stress.	[13]
Maize (<i>Zea mays</i> L.)	Increased GA and IAA; decreased ABA	Melatonin increases GA and IAA while reducing the ABA levels in leaves under drought conditions.	[69]
Apple (<i>Malus domestica</i> Borkh.)	Decreased ABA	Melatonin scavenges H ₂ O ₂ and reduces ABA by upregulating <i>MdNCED3</i> and downregulating <i>MdCYP707A1</i> and <i>MdCYP707A2</i> to re-open stomatal under drought conditions.	[79]
Maize (<i>Zea mays</i> L.)	Reduced ABA	Reducing ABA accumulation and inducing stomatal reopening by inhibiting up-regulation of <i>NCED1</i> , and up-regulating ABA catabolic genes <i>ABA8ox1</i> and <i>ABA8ox3</i> .	[80]
Soybean (<i>Glycine max</i> L.)	Decreased ABA in leaves and increased ABA in roots	Melatonin-received plant leaves accumulates less ABA but roots content higher ABA. Melatonin significantly suppresses ABA biosynthesis and signaling gene expression in soybean exposed to drought stress.	[81]
Creeping bentgrass (<i>Agrostis stolonifera</i>)	Increased CTK	Melatonin synergistically interacts with cytokinins to suppress drought-induced leaf senescence. Increasing endogenous cytokinins content and upregulating cytokinins signal transduction genes and transcription factors.	[82]
Perennial ryegrass (<i>Lolium perenne</i> L.)	Increased BR	Brassinosteroid plays a critical role in the melatonin-mediated mitigation of cold and drought stress by triggering antioxidant activities as well as enhancing the photosynthetic capacities. Brassinosteroid biosynthesis and its signaling pathway are induced by melatonin.	[83]
Barley (<i>Hordeum vulgare</i> L.)	Increased SA, GA, CK, and IAA; decreased ABA	Melatonin increases levels of SA, GA, CK, and IAA, as well as a decrease in abscisic acid to enhance stress tolerance in barley.	[84]
Cotton (<i>Gossypium hirsutum</i> L.)	Increased GA and reduced ABA	Increasing the germination rate, germination potential, radical length, and fresh weight, as well as the activities of superoxide dismutase (SOD), peroxidase (POD), and α -amylase. Melatonin alleviates drought stress by reducing ABA content and increasing GA ₃ content.	[85]
Maize (<i>Zea mays</i> L.)	Increased JA	Up-regulating jasmonic acid biosynthesis genes and increasing jasmonic acid contents to mitigate drought stress.	[86]

Melatonin regulates microbes to enhance drought stress

Plants can manipulate and recruit beneficial microbial communities to produce various compounds, including phytohormones, osmolytes, antioxidants, and volatile organic compounds (VOCs), that mediate in alleviating drought stress^[87]. Under drought conditions, plant microbiomes also influence the expression of drought-related genes. For instance, a *B. subtilis* strain can induce the expression of drought-related genes, such as *RD29* and *DREB2*, to mitigate drought stress in rapeseed (*Brassica napus* L.) and *Arabidopsis*^[88]. Melatonin can also interact, synergistically, with arbuscular mycorrhizal fungi (AMF) to improve drought tolerance. Applying melatonin to roots can alter the composition of rhizosphere microbiomes, promoting bacteria involved in carbohydrate and carboxylate degradation, which was shown to help alleviate drought stress in barley^[89]. In addition, melatonin affects the structure of microbial communities, including soil fungi and bacteria, leading to improved soil nitrogen content and utilization efficiency, thereby enhancing drought resilience^[90]. Currently, the mechanism(s) by which melatonin interacts with the plant microbes to mitigate drought stress remains largely unknown. This is the new future research direction for improving plant drought tolerance. Future research should focus on elucidating the communication mechanisms between

melatonin and microbial communities to mitigate drought stress in plants. Identifying specific bacterial or fungal communities that enhance melatonin's function in improving drought resilience represents a promising direction for the enhancement of global agriculture.

Melatonin regulates flavonoids to enhance drought tolerance

Flavonoids, such as anthocyanins, kaempferol, and quercetin, are specialized secondary metabolites known for their roles as phytoalexins or antioxidants, through their ROS-scavenging trait. Such flavonoids are crucial for protecting plants against both biotic and abiotic stress, including drought, as their accumulation has been demonstrated to significantly enhance drought tolerance. In addition, both melatonin and flavonoids have multifunctional roles in the plant and interact with plant microbes to regulate drought tolerance, as previously established.

Metabolomics analyses have shown that melatonin can regulate a variety of metabolites in the flavonoid biosynthesis pathway during drought stress conditions. For example, melatonin improves tolerance to salt, drought, and heat stresses, by upregulating the luteolin biosynthesis genes^[91]. It also enhances stem strength by increasing lignin content and secondary cell wall thickness in herbaceous peonies^[92]. Here, in particular, melatonin can increase the

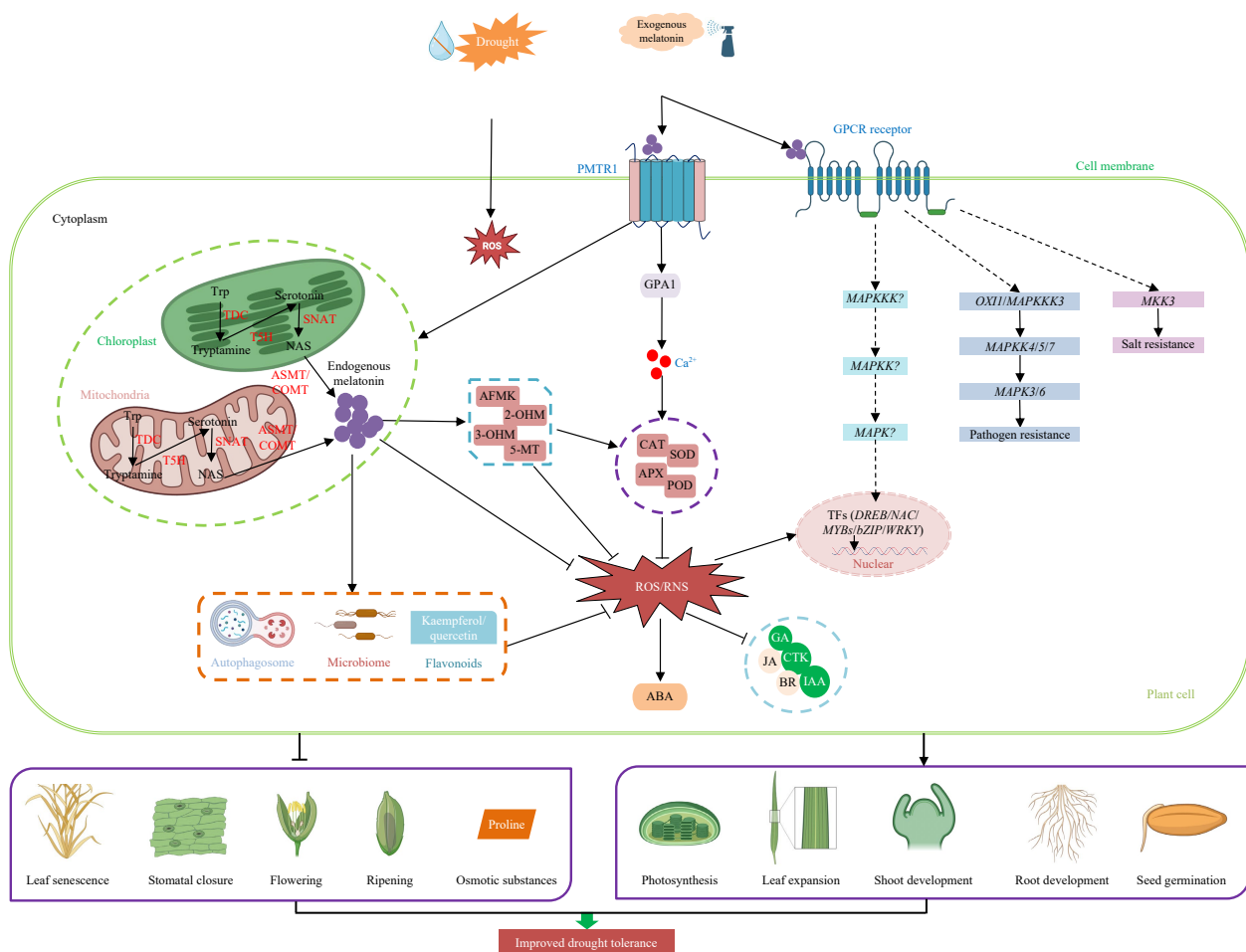


Fig. 2 Schematic illustrating plant growth, development, and physiological activities regulated by melatonin under drought conditions. ABA: abscisic acid, AFMK: N1-acetyl-N2-formyl-5-methoxynuramine, APX: ascorbate peroxidase, BR: brassinosteroids, CAT: catalase, CTK: cytokinin, DREB: dehydration-responsive element-binding protein, GA: gibberellic acid, GPA: G protein alpha subunit, GPX: glutathione peroxidase, IAA: indole-3-acetic acid, JA: jasmonic acid, MAPK: mitogen-activated protein kinase, MKK: MAPK kinase, MAPKKK: MKK kinase, PMTR1: phyto-melatonin receptor 1, RNS: reactive nitrogen species, ROS: reactive oxygen species, SA: salicylic acid, SOD: superoxide dismutase, TFs: transcription factors, 2-OHM: 2-hydroxymelatonin, 3-OHM: 3-hydroxymelatonin, 5-MT: 5-methoxytryptamine.

accumulation of apigenin, luteolin, and quercetin, under drought-stress conditions. In tobacco (*Nicotiana tabacum* L.), kaempferol, a type of flavonol, has also been reported to interfere with melatonin's regulation of ROS and stomatal closure^[93]. Therefore, these recent studies confirmed that melatonin accumulates several different flavonoids to enhance drought tolerance. However, further studies are warranted to explore the relationship between melatonin and flavonoids in regulating drought tolerance. Especially the lack of molecular mechanisms between melatonin and different flavonoids under drought conditions.

Conclusions and future prospects

In conclusion, current evidence indicates that melatonin, whether through the regulation of its biosynthesis genes or exogenous application, primarily functions by scavenging ROS. This activity helps to maintain ROS homeostasis and alleviates drought-induced stress. This pivotal role protects plants from drought-induced damage, including compromised seed germination, inhibited root growth, stomatal closure, decreased photosynthesis, etc. Moreover, melatonin mediates drought tolerance through intricate signal transduction pathways, potentially interacting with membrane receptors such as PMTR1 or activating mitogen-activated protein kinases (MAPKs) like *MdMPPK3* and *MdMPPK6*. Additionally, recent investigations have elucidated melatonin's interactions with various phytohormones, plant microbes, and flavonoids, which further augment its role in drought tolerance (Fig. 2). For instance, melatonin synergizes with AMF to improve drought tolerance and modulates microbial community structures to enhance nutrient uptake and utilization. Metabolomics analyses have revealed that melatonin regulates differentially expressed metabolites in flavonoid biosynthesis, during drought stress, increasing the accumulation of key flavonoid metabolites, such as apigenin, luteolin, and quercetin.

Despite these advancements, the mechanisms through which melatonin interacts with these various pathways to confer drought tolerance remains to be fully elucidated. Future research programs should focus on characterizing the detailed molecular and biochemical pathways involved in melatonin-mediated drought resilience. Identifying transcription factors and regulatory elements that interact with melatonin, as well as the role of melatonin in modulating plant microbiomes and other phytohormones are promising avenues for exploration. Hence, advanced omics approaches, such as transcriptomics, proteomics, and metabolomics will be instrumental in uncovering these complex interactions.

In summary, melatonin is a multifaceted molecule with significant potential in enhancing plant drought tolerance. By deepening our understanding of its underlying mechanisms, we can better harness melatonin's capabilities to mitigate drought stress in agricultural settings, thereby improving crop resilience and productivity in the face of climate change.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Luo M, Chen M; data collection: Luo M, Zhang D, Tang W; analysis and interpretation of results: Delaplace P, Ma Y; draft manuscript preparation: Luo M, Zhang D. All authors reviewed the results and approved the final version of the manuscript.

Data availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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Conflict of interest

The authors declare that they have no conflict of interest.

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References

- Gu Z, Hu C, Gan Y, Zhou J, Tian G, et al. 2024. Role of microbes in alleviating crop drought stress: A review. *Plants* 13(3):384
- Gu Q, Xiao Q, Chen Z, Han Y. 2022. Crosstalk between melatonin and reactive oxygen species in plant abiotic stress responses: An update. *International Journal of Molecular Sciences* 23(10):5666
- He Z, Zhang P, Jia H, Zhang S, Nishawy E, et al. 2024. Regulatory mechanisms and breeding strategies for crop drought resistance. *New Crops* 1:100029
- Yang K, Sun H, Liu M, Zhu L, Zhang K, et al. 2023. Morphological and physiological mechanisms of melatonin on delaying drought-induced leaf senescence in cotton. *International Journal of Molecular Sciences* 24(8):7269
- Salvi P, Mahawar H, Agarrwal R, Kajal, Gautam V, et al. 2022. Advancement in the molecular perspective of plant-endophytic interaction to mitigate drought stress in plants. *Frontiers in Microbiology* 13:981355
- Huang X, Hou L, Meng J, You H, Li Z, et al. 2018. The antagonistic action of abscisic acid and cytokinin signaling mediates drought stress response in Arabidopsis. *Molecular Plant* 11(7):970–82
- Lerner AB, Case JD, Takahashi Y, Lee TH, Mori W. 1958. Isolation of melatonin, the pineal gland factor that lightens melanocytes. *Journal of the American Chemical Society* 80(10):2587
- Hattori A, Migita H, Iigo M, Itoh M, Yamamoto K, et al. 1995. Identification of melatonin in plants and its effects on plasma melatonin levels and binding to melatonin receptors in vertebrates. *Biochemistry and Molecular Biology International* 35(3):627–34
- Dubbels R, Reiter RJ, Klenke E, Goebel A, Schnakenberg E, et al. 1995. Melatonin in edible plants identified by radioimmunoassay and by high performance liquid chromatography-mass spectrometry. *Journal of Pineal Research* 18(1):28–31
- Pan Y, Xu X, Li L, Sun Q, Wang Q, et al. 2023. Melatonin-mediated development and abiotic stress tolerance in plants. *Frontiers in Plant Science* 14:1100827
- Ahmad I, Zhu G, Zhou G, Liu J, Younas MU, et al. 2023. Melatonin role in plant growth and physiology under abiotic stress. *International Journal of Molecular Sciences* 24(10):8759
- Supriya L, Dake D, Muthamilarasan M, Padmaja G. 2024. Melatonin-mediated regulation of autophagy is independent of ABA under drought stress in sensitive variety of *Gossypium hirsutum* L. *Plant Physiology and Biochemistry* 207:108409
- Luo M, Wang D, Delaplace P, Pan Y, Zhou Y, et al. 2023. Melatonin enhances drought tolerance by affecting jasmonic acid and lignin biosynthesis in wheat (*Triticum aestivum* L.). *Plant Physiology and Biochemistry* 202:107974
- Hu W, Zhang J, Yan K, Zhou Z, Zhao W, et al. 2021. Beneficial effects of abscisic acid and melatonin in overcoming drought stress in cotton (*Gossypium hirsutum* L.). *Physiologia Plantarum* 173(4):2041–54
- Yuan S, Guan C, Liu S, Huang Y, Tian D, et al. 2016. Comparative transcriptomic analyses of differentially expressed genes in transgenic melatonin biosynthesis ovine *HIOMT* gene in switchgrass. *Frontiers in Plant Science* 7:1613
- Tan DX, Manchester LC, Liu X, Rosales-Corral SA, Acuna-Castroviejo D, et al. 2013. Mitochondria and chloroplasts as the original sites of melatonin synthesis: a hypothesis related to melatonin's primary function and evolution in eukaryotes. *Journal of Pineal Research* 54(2):127–38

17. Back K, Tan DX, Reiter RJ. 2016. Melatonin biosynthesis in plants: multiple pathways catalyze tryptophan to melatonin in the cytoplasm or chloroplasts. *Journal of Pineal Research* 61(4):426–37
18. Gao T, Zhang D, Shen W, Xu S, Jia X, et al. 2024. MdASMT9-mediated melatonin biosynthesis enhances basal thermotolerance in apple plants. *Plant, Cell & Environment* 47(3):751–64
19. Lee HY, Lee K, Back K. 2019. Knockout of Arabidopsis serotonin N-acetyltransferase-2 reduces melatonin levels and delays flowering. *Biomolecules* 9(11):712
20. Daly P, McClellan C, Maluk M, Oakey H, Lapierre C, et al. 2019. RNAi-suppression of barley caffeic acid O-methyltransferase modifies lignin despite redundancy in the gene family. *Plant Biotechnology Journal* 17(3):594–7
21. Yu Y, Ni Y, Qiao T, Ji X, Xu J, et al. 2022. Overexpression of VvASMT1 from grapevine enhanced salt and osmotic stress tolerance in *Nicotiana benthamiana*. *PLoS One* 17(6):e0269028
22. Zuo B, Zheng X, He P, Wang L, Lei Q, et al. 2014. Overexpression of MzASMT improves melatonin production and enhances drought tolerance in transgenic *Arabidopsis thaliana* plants. *Journal of Pineal Research* 57(4):408–17
23. Park S, Byeon Y, Back K. 2013. Functional analyses of three ASMT gene family members in rice plants. *Journal of Pineal Research* 55(4):409–15
24. Huangfu L, Chen R, Lu Y, Zhang E, Miao J, et al. 2022. OsCOMT, encoding a caffeic acid O-methyltransferase in melatonin biosynthesis, increases rice grain yield through dual regulation of leaf senescence and vascular development. *Plant Biotechnology Journal* 20(6):1122–39
25. Lee K, Back K. 2017. Overexpression of rice serotonin N-acetyltransferase 1 in transgenic rice plants confers resistance to cadmium and senescence and increases grain yield. *Journal of Pineal Research* 62(3):e12392
26. Hwang OJ, Back K. 2018. Melatonin is involved in skotomorphogenesis by regulating brassinosteroid biosynthesis in rice plants. *Journal of Pineal Research* 65(2):e12495
27. Yao Z, Zhang X, Liang Y, Zhang J, Xu Y, et al. 2022. NtCOMT1 responsible for phytomelatonin biosynthesis confers drought tolerance in *Nicotiana tabacum*. *Phytochemistry* 202:113306
28. Chang J, Guo Y, Yan J, Zhang Z, Yuan L, et al. 2021. The role of watermelon caffeic acid O-methyltransferase (CICOMT1) in melatonin biosynthesis and abiotic stress tolerance. *Horticulture Research* 8(1):210
29. Choi GH, Lee HY, Back K. 2017. Chloroplast overexpression of rice caffeic acid O-methyltransferase increases melatonin production in chloroplasts via the 5-methoxytryptamine pathway in transgenic rice plants. *Journal of Pineal Research* 63(1):e12412
30. Yang WJ, Du YT, Zhou YB, Chen J, Xu ZS, et al. 2019. Overexpression of TaCOMT improves melatonin production and enhances drought tolerance in transgenic Arabidopsis. *International Journal of Molecular Sciences* 20(3):652
31. Yue L, Kang Y, Zhong M, Kang D, Zhao P, et al. 2023. Melatonin delays postharvest senescence through suppressing the inhibition of BrERF2/BrERF109 on flavonoid biosynthesis in flowering chinese cabbage. *International Journal of Molecular Sciences* 24(3):2933
32. Bai Y, Wei Y, Yin H, Hu W, Cheng X, et al. 2022. PP2C1 fine-tunes melatonin biosynthesis and phytomelatonin receptor PMTR1 binding to melatonin in cassava. *Journal of Pineal Research* 73(1):e12804
33. Li Y, Sun Y, Cui H, Li M, Yang G, et al. 2022. *Carex rigescens* caffeic acid O-methyltransferase gene CrCOMT confer melatonin-mediated drought tolerance in transgenic tobacco. *Frontiers in Plant Science* 13:971431
34. Wang P, Sun X, Li C, Wei Z, Liang D, et al. 2013. Long-term exogenous application of melatonin delays drought-induced leaf senescence in apple. *Journal of pineal research* 54(3):292–302
35. Liang B, Ma C, Zhang Z, Wei Z, Gao, T et al. 2018. Long-term exogenous application of melatonin improves nutrient uptake fluxes in apple plants under moderate drought stress. *Environmental and experimental botany* 155:650–661
36. Roy M, Niu J, Irshad A, Kareem HA, Hassan MU, et al. 2021. Exogenous melatonin protects alfalfa (*Medicago sativa* L.) seedlings from drought-induced damage by modulating reactive oxygen species metabolism, mineral balance and photosynthetic efficiency. *Plant Stress* 2:100044
37. Ahmad S, Kamran M, Ding R, Meng X, Wang H, et al. 2019. Exogenous melatonin confers drought stress by promoting plant growth, photosynthetic capacity and antioxidant defense system of maize seedlings. *PeerJ* 2019(10):e7793
38. Kaya C, Shabala S. 2023. Melatonin improves drought stress tolerance of pepper (*Capsicum annuum*) plants via upregulating nitrogen metabolism. *Functional Plant Biology* 51(1):FP23060
39. Liu J, Wang W, Wang L, Sun Y. 2015. Exogenous melatonin improves seedling health index and drought tolerance in tomato. *Plant Growth Regulation* 77(3):317–26
40. Yang X, Xu H, Li T, Wang R. 2017. Effects of exogenous melatonin on photosynthesis of tomato leaves under drought stress. *Scientia Agricultura Sinica* 50(16):3186–95
41. Jafari M, Shahsavari A. 2021. The effect of foliar application of melatonin on changes in secondary metabolite contents in two *Citrus* species under drought stress conditions. *Frontiers in Plant Science* 12:692735
42. Cui G, Zhao X, Liu S, Sun F, Zhang C, et al. 2017. Beneficial effects of melatonin in overcoming drought stress in wheat seedlings. *Plant Physiology and Biochemistry* 118:138–49
43. Zhang Z, Guo L, Sun H, Wu J, Liu L, et al. 2023. Melatonin increases drought resistance through regulating the fine root and root hair morphology of wheat revealed with RhizoPot. *Agronomy* 13(7):1881
44. Hu W, Cao Y, Loka DA, Harris-Shultz KR, Reiter RJ, et al. 2020. Exogenous melatonin improves cotton (*Gossypium hirsutum* L.) pollen fertility under drought by regulating carbohydrate metabolism in male tissues. *Plant Physiology and Biochemistry* 151:579–88
45. Liang D, Ni Z, Xia H, Xie Y, Lv X, et al. 2019. Exogenous melatonin promotes biomass accumulation and photosynthesis of kiwifruit seedlings under drought stress. *Scientia Horticulturae* 246:34–43
46. Wang Y, Wang J, Guo H, Wu X, Hao M, et al. 2023. Integrative transcriptome and metabolome analysis reveals the mechanism of exogenous melatonin alleviating drought stress in maize roots. *Plant Physiology and Biochemistry* 199:107723
47. Naghizadeh M, Kabiri R, Hatami A, Oloumi H, Nasibi F, et al. 2019. Exogenous application of melatonin mitigates the adverse effects of drought stress on morpho-physiological traits and secondary metabolites in Moldavian balm (*Dracocephalum moldavica*). *Physiology and Molecular Biology of Plants* 25(4):881–94
48. Huang B, Chen YE, Zhao YQ, Ding CB, Liao JQ, et al. 2019. Exogenous melatonin alleviates oxidative damages and protects photosystem ii in maize seedlings under drought stress. *Frontiers in Plant Science* 10:677
49. Li J, Zeng L, Cheng Y, Lu G, Fu G, et al. 2018. Exogenous melatonin alleviates damage from drought stress in *Brassica napus* L. (rapeseed) seedlings. *Acta Physiologiae Plantarum* 40(3):43
50. Khan Z, Jan R, Asif S, Farooq M, Jang YH, et al. 2024. Exogenous melatonin induces salt and drought stress tolerance in rice by promoting plant growth and defense system. *Scientific Reports* 14:1214
51. Imran M, Latif Khan A, Shahzad R, Aaqil Khan M, Bilal S, et al. 2021. Exogenous melatonin induces drought stress tolerance by promoting plant growth and antioxidant defence system of soybean plants. *AoB PLANTS* 13(4):plab026
52. Jensen NB, Ottosen CO, Zhou R. 2023. Exogenous melatonin alters stomatal regulation in tomato seedlings subjected to combined heat and drought stress through mechanisms distinct from ABA signaling. *Plants* 12(5):1156
53. Ahammed GJ, Li Z, Chen J, Dong Y, Qu K, et al. 2024. Reactive oxygen species signaling in melatonin-mediated plant stress response. *Plant Physiology and Biochemistry* 207:108398
54. Lee HJ, Back K. 2019. 2-Hydroxymelatonin confers tolerance against combined cold and drought stress in tobacco, tomato, and cucumber as a potent anti-stress compound in the evolution of land plants. *Melatonin Research* 2(2):35–46
55. Wei Y, Liu G, Chang Y, Lin D, Reiter RJ, et al. 2018. Melatonin biosynthesis enzymes recruit WRKY transcription factors to regulate melatonin accumulation and transcriptional activity on W-box in cassava. *Journal of Pineal Research* 65:e12487
56. Wei Y, Chang Y, Zeng H, Liu G, He C, et al. 2018. RAV transcription factors are essential for disease resistance against cassava bacterial blight via activation of melatonin biosynthesis genes. *Journal of Pineal Research* 64:e12454
57. Li B, Liu R, Liu J, Zhang H, Tian Y, et al. 2024. ZmMYB56 regulates stomatal closure and drought tolerance in maize seedlings through the transcriptional regulation of ZmTOM7. *New Crops* 1:100012

58. Arnao MB, Hernández-Ruiz J. 2021. Melatonin as a regulatory hub of plant hormone levels and action in stress situations. *Plant Biology* 23(S1):7–19
59. Liu H, Song S, Zhang H, Li Y, Niu L, et al. 2022. Signaling transduction of ABA, ROS, and Ca²⁺ in plant stomatal closure in response to drought. *International Journal of Molecular Sciences* 23(23):14824
60. Arnao MB, Hernández-Ruiz J. 2020. Melatonin in flowering, fruit set and fruit ripening. *Plant Reproduction* 33(2):77–87
61. Wang P, Sun X, Wang N, Tan DX, Ma F. 2015. Melatonin enhances the occurrence of autophagy induced by oxidative stress in Arabidopsis seedlings. *Journal of Pineal Research* 58(4):479–89
62. Cui G, Sun F, Gao X, Xie K, Zhang C, et al. 2018. Proteomic analysis of melatonin-mediated osmotic tolerance by improving energy metabolism and autophagy in wheat (*Triticum aestivum* L.). *Planta* 248(1):69–87
63. Supriya L, Durgeshwar P, Muthamilarasan M, Padmaja G. 2022. Melatonin mediated differential regulation of drought tolerance in sensitive and tolerant varieties of upland cotton (*Gossypium hirsutum* L.). *Frontiers in Plant Science* 13:821353
64. Altaf MA, Shahid R, Ren MX, Naz S, Altaf MM, et al. 2022. Melatonin improves drought stress tolerance of tomato by modulation plant growth, root architecture, photosynthesis, and antioxidant defense system. *Antioxidants* 11(2):309
65. Talaat NB. 2023. Drought stress alleviator melatonin reconfigures water-stressed barley (*Hordeum vulgare* L.) plants' photosynthetic efficiency, antioxidant capacity, and endogenous phytohormone profile. *International Journal of Molecular Sciences* 24(22):16228
66. Ahmad S, Muhammad I, Wang GY, Zeeshan M, Yang L, et al. 2021. Ameliorative effect of melatonin improves drought tolerance by regulating growth, photosynthetic traits and leaf ultrastructure of maize seedlings. *BMC Plant Biology* 21(1):368
67. Ye J, Wang S, Deng X, Yin L, Xiong B, et al. 2016. Melatonin increased maize (*Zea mays* L.) seedling drought tolerance by alleviating drought-induced photosynthetic inhibition and oxidative damage. *Acta Physiologiae Plantarum* 38(2):48
68. Zou JN, Jin XJ, Zhang YX, Ren CY, Zhang MC, et al. 2019. Effects of melatonin on photosynthesis and soybean seed growth during grain filling under drought stress. *Photosynthetica* 57(2):512–20
69. Ahmad S, Wang GY, Muhammad I, Farooq S, Kamran M, et al. 2022. Application of melatonin-mediated modulation of drought tolerance by regulating photosynthetic efficiency, chloroplast ultrastructure, and endogenous hormones in maize. *Chemical and Biological Technologies in Agriculture* 9(1):1–14
70. Guo YY, Li HJ, Liu J, Bai YW, Xue JQ, et al. 2020. Melatonin alleviates drought-induced damage of photosynthetic apparatus in maize seedlings. *Russian Journal of Plant Physiology* 67(2):312–22
71. Wei J, Li DX, Zhang JR, Shan C, Rengel Z, et al. 2018. Phytomelatonin receptor PMTR1-mediated signaling regulates stomatal closure in Arabidopsis thaliana. *Journal of Pineal Research* 65(2):e12500
72. Wang LF, Lu KK, Li TT, Zhang Y, Guo JX, et al. 2022. Maize PHYTOMELATONIN RECEPTOR1 functions in plant tolerance to osmotic and drought stress. *Journal of Experimental Botany* 73(17):5961–73
73. Lee HY, Back K. 2020. The phytomelatonin receptor (PMRT1) Arabidopsis Cand2 is not a bona fide G protein-coupled melatonin receptor. *Melatonin Research* 3(2):177–86
74. Zlotos DP, Jockers R, Cecon E, Rivara S, Witt-Enderby PA. 2014. MT1 and MT2 melatonin receptors: Ligands, models, oligomers, and therapeutic potential. *Journal of Medicinal Chemistry* 57(8):3161–85
75. Lee HY, Back K. 2017. Melatonin is required for H₂O₂- and NO-mediated defense signaling through MAPKKK3 and OX11 in Arabidopsis thaliana. *Journal of Pineal Research* 62(2):e12379
76. Maity S, Guchhait R, Pramanick K. 2022. Melatonin mediated activation of MAP kinase pathway may reduce DNA damage stress in plants: a review. *BioFactors* 48(5):965–71
77. Song H, Sun Y, Shan D, Zhang T, Wang C, et al. 2023. MdMPK3 and MdMPK6 fine-tune MdWRKY17-mediated transcriptional activation of the melatonin biosynthesis gene MdASMT7. *Journal of Pineal Research* 75(1):e12891
78. Zhu W, Cao H, Wang Q, Niu Y, Sadeghnezhad E, et al. 2023. Transcriptome analysis revealed MAPK and hormone pathway involving in exogenous melatonin-regulated salt tolerance in sour jujube. *Fruit Research* 3:19
79. Li C, Tan DX, Liang D, Chang C, Jia D, et al. 2015. Melatonin mediates the regulation of ABA metabolism, free-radical scavenging, and stomatal behaviour in two Malus species under drought stress. *Journal of Experimental Botany* 66(3):669–80
80. Li Z, Su X, Chen Y, Fan, X, He, L et al. 2021. Melatonin improves drought resistance in maize seedlings by enhancing the antioxidant system and regulating abscisic acid metabolism to maintain stomatal opening under PEG-induced drought. *Journal of Plant Biology* 64(4):299–312
81. Jahan MS, Zhao CJ, Shi LB, Liang, XR, Jabborova D, et al. 2023. Physiological mechanism of melatonin attenuating to osmotic stress tolerance in soybean seedlings. *Frontiers in Plant Science* 14:1193666
82. Ma X, Zhang J, Burgess P, Rossi S, Huang B. 2018. Interactive effects of melatonin and cytokinin on alleviating drought-induced leaf senescence in creeping bentgrass (*Agrostis stolonifera*). *Environmental and Experimental Botany* 145:1–11
83. Fu J, Zhang S, Jiang H, Zhang X, Gao H, et al. 2022. Melatonin-induced cold and drought tolerance is regulated by brassinosteroids and hydrogen peroxide signaling in perennial ryegrass. *Environmental and Experimental Botany* 196:104815
84. Zhang X, Liu W, Lv Y, Bai J, Li T, et al. 2022. Comparative transcriptomics reveals new insights into melatonin-enhanced drought tolerance in naked oat seedlings. *PeerJ* 10:e13669
85. Bai Y, Xiao S, Zhang Z, Zhang Y, Sun H, et al. 2020. Melatonin improves the germination rate of cotton seeds under drought stress by opening pores in the seed coat. *PeerJ* 2020(7):e9450
86. Zhao C, Yang M, Wu X, Wang Y, Zhang R. 2021. Physiological and transcriptomic analyses of the effects of exogenous melatonin on drought tolerance in maize (*Zea mays* L.). *Plant Physiology and Biochemistry* 168:128–42
87. Afridi MS, Javed MA, Ali S, De Medeiros FHV, Ali B, et al. 2022. New opportunities in plant microbiome engineering for increasing agricultural sustainability under stressful conditions. *Frontiers in Plant Science* 13:899464
88. Poudel M, Mendes R, Costa LAS, Bueno CG, Meng Y, et al. 2021. The role of plant-associated bacteria, fungi, and viruses in drought stress mitigation. *Frontiers in Microbiology* 12:743512
89. Ye F, Jiang M, Zhang P, Liu L, Liu S, et al. 2022. Exogenous melatonin reprograms the rhizosphere microbial community to modulate the responses of barley to drought stress. *International Journal of Molecular Sciences* 23(17):9665
90. Du P, Cao Y, Yin B, Zhou S, Li Z, et al. 2022. Improved tolerance of apple plants to drought stress and nitrogen utilization by modulating the rhizosphere microbiome via melatonin and dopamine. *Frontiers in Plant Science* 13:980327
91. Song Z, Yang Q, Dong B, Li N, Wang M, et al. 2022. Melatonin enhances stress tolerance in pigeon pea by promoting flavonoid enrichment, particularly luteolin in response to salt stress. *Journal of Experimental Botany* 73(17):5992–6008
92. Zhao D, Luan Y, Shi W, Tang Y, Huang X, et al. 2022. Melatonin enhances stem strength by increasing lignin content and secondary cell wall thickness in herbaceous peony. *Journal of Experimental Botany* 73(17):5974–91
93. Xiao L, Ma W, Zhang J, Pu X, Rengel Z, et al. 2023. Phytomelatonin interferes with flavonols biosynthesis to regulate ROS production and stomatal closure in tobacco. *Journal of Plant Physiology* 284:153977



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