



REVIEW PAPER

# Phytomelatonin: a universal abiotic stress regulator

Yanping Wang<sup>1</sup>, Russel J. Reiter<sup>2</sup> and Zhulong Chan<sup>1,\*</sup>

<sup>1</sup> Key Laboratory of Horticultural Plant Biology, Ministry of Education, College of Horticulture and Forestry Sciences, Huazhong Agricultural University, Wuhan, 430070, China

<sup>2</sup> Department of Cellular and Structural Biology, University of Texas Health Science Center, San Antonio, TX 78229, USA

\* Correspondence: [zlchan@mail.hzau.edu.cn](mailto:zlchan@mail.hzau.edu.cn)

Received 12 September 2017; Editorial decision 7 December 2017; Accepted 11 December 2017

Editor: Christine Raines, University of Essex, UK

## Abstract

Melatonin, a derivative of tryptophan, was first detected in plant species in 1995 and it has been shown to be a diverse regulator during plant growth and development, and in stress responses. Recently, great progress has been made towards determining the detailed functions of melatonin in plant responses to abiotic stress. Melatonin priming improves plant tolerance to cold, heat, salt, and drought stresses through regulation of genes involved in the *DREB/CBF*, *HSF*, *SOS*, and *ABA* pathways, respectively. As a scavenger of free radicals, melatonin also directly detoxifies reactive oxygen species, thus alleviating membrane oxidation. Abiotic stress-inhibited photosynthesis is partially recovered and metabolites accumulate in the presence of melatonin, leading to improved plant growth, delayed leaf senescence, and increased stress tolerance. In this review, we summarize the interactions of melatonin with phytohormones to regulate downstream gene expression, protein stabilization, and epigenetic modification in plants. Finally, we consider the need for, and approaches to, the identification of melatonin receptors and components during signaling transduction pathways.

**Keywords:** Abscisic acid, abiotic stress, auxin, leaf senescence, melatonin, osmolytes, phytohormone, reactive oxygen species.

## Introduction

Environmental stresses adversely affect plant growth and development. As sessile organisms, plants develop different approaches to cope with harsh environmental conditions. Abiotic stress tolerance is a complex trait. Phytohormones including abscisic acid (ABA), ethylene (ETH), gibberellic acid (GA), jasmonic acid (JA), salicylic acid (SA), indole acetic acid (IAA), strigolactone (SL), brassinosteroids (BR), and cytokinins (CTK) play key roles during stress responses and plant development (Balbi and Devoto, 2008; Lee *et al.*, 2013; Kapulnik and Koltai, 2014; Zhao *et al.*, 2016). Additionally, several other small molecules such as melatonin (MT) and polyamines (PA) are involved in plant

stress responses (Chan and Shi, 2015; Huang *et al.*, 2015; Reiter *et al.*, 2015).

Melatonin (N-acetyl-5-methoxytryptamine), a derivative of the essential amino acid tryptophan, was identified in bovine pineal tissue and structurally identified by Lerner and co-workers (Lerner *et al.*, 1958). It was initially shown to be an important molecule in animals that regulates reproductive physiology, circadian rhythms, sleep, retinal physiology, mood, antioxidative activity, sexual behavior, temperature homeostasis, and immunological enhancement (Galano *et al.*, 2011; Venegas *et al.*, 2012; Calvo *et al.*, 2013). In 1995, pioneer studies independently conducted by Dubbels *et al.* (1995) and

Hattori *et al.* (1995) verified that melatonin is also ubiquitously present in higher plants and plant products. Since then, melatonin has been found in leaves, roots, stems, fruits, and seeds of various plant species, including crops (rice, wheat, barley, corn, tobacco, grass, carrot, and oats) and fruit (sweet cherry, grape, cucumber, and apple), as well as plant products used to make popular beverages (tea, coffee, beer, and wine) (Manchester *et al.*, 2000; Chen *et al.*, 2003; Garcia-Parrilla *et al.*, 2009; Huang and Mazza 2011; Stürtz *et al.*, 2011; Arnao and Hernández-Ruiz 2013, 2015, 2017a; Arnao, 2014; Feng *et al.*, 2014; Kocadağh *et al.*, 2014; Hernández-Ruiz and Arnao 2016). Evidence has shown that melatonin is involved in flowering, circadian rhythms, photosynthesis, senescence (Byeon *et al.*, 2012; Wang *et al.*, 2012, 2013a, 2013b; Lee *et al.*, 2014; Shi *et al.*, 2015b), root system architecture (Arnao and Hernández-Ruiz, 2007; Pelagio-Flores *et al.*, 2012; Zhang *et al.*, 2014b; Arnao and Hernández-Ruiz, 2017b), seed germination (Posmyk *et al.*, 2009), and in response to various environmental stresses (Table 1).

To date, melatonin has been shown to be a diverse regulator during plant growth and development, and in stress responses (Arnao and Hernández-Ruiz, 2014; Reiter *et al.*, 2015; Zhang *et al.*, 2015). Recently, great progress has been made towards determining the detailed functions of melatonin in plant responses to abiotic stress, and a number of reviews related to this have been published. In this review, we focus on how melatonin interacts with phytohormones and affects transcriptomic and proteomic changes in plants, and we summarize how melatonin modulates plant abiotic stress signaling pathways. We also consider the need for, and approaches to, the identification of melatonin receptors and signaling transduction pathways.

## Melatonin detoxifies free radicals and alleviates oxidative stress

In plant cells, reactive oxygen species (ROS) such as the hydroxyl radical ( $\cdot\text{OH}$ ), the superoxide anion ( $\text{O}_2^{\cdot-}$ ), singlet oxygen ( $^1\text{O}_2$ ), and hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) are produced continuously and coincidentally. To scavenge ROS, plants have developed an efficient enzymatic and non-enzymatic antioxidative system to protect against oxidative damage, together with fine modulation of low levels of ROS for signal transduction. Enzymatic antioxidants in plants include superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), glutathione reductase (GR), dehydroascorbate reductase (DHAR), glutathione S-transferase (GST), and peroxiredoxin (PRX) (Noctor *et al.*, 2014; Song *et al.*, 2014). Non-enzymatic antioxidants including glutathione (GSH), ascorbic acid (AsA), carotenoids, tocopherols, and flavonoids are also crucial for ROS homeostasis in plants (Gill and Tuteja, 2010).

Melatonin in both animals and plants is a direct free radical scavenger and an indirect antioxidant (Tan *et al.*, 2007, 2012; Manchester *et al.*, 2015). Melatonin controls the burst of hydrogen peroxide in plants associated with pathogen attack and harsh environmental conditions, possibly by directly

scavenging excessive ROS and by enhancing the activities of antioxidative enzymes and the capacity of the ascorbate–glutathione cycle (Wang *et al.*, 2013b). It is estimated that via the cascade reaction, one melatonin molecule potentially scavenges 10 free radicals, which contrasts with the classic antioxidants because they typically detoxify one radical per molecule (Tan *et al.*, 2007). Therefore, it has been deduced that the initial function of melatonin in organisms was to serve as an antioxidant to scavenge a variety of ROS and reactive nitrogen species (RNS), and to protect plants from oxidative stress (Dubbels *et al.*, 1995; Hardeland *et al.*, 1995; Tan *et al.*, 2007; Manchester *et al.*, 2015). Exogenous application of melatonin increases antioxidant enzyme activities, while it decreases superoxide, hydrogen peroxide, and malondialdehyde concentrations in apple, grape, maize, sunflower, tomato, and wheat (Wang *et al.*, 2013b; Meng *et al.*, 2014; Turk *et al.*, 2014; Li *et al.*, 2015; Liu *et al.*, 2015; Ye *et al.*, 2016; Arora and Bhatla, 2017). Moreover, melatonin treatment reduces the accumulation of oxidized proteins, enhances the occurrence of oxidative stress-induced autophagy, and alleviates photo-oxidation damage in Arabidopsis (Wang *et al.*, 2015). Pre-treatment with melatonin significantly alleviates  $\text{H}_2\text{O}_2$ -modulated plant growth, cell damage, and ROS accumulation in bermudagrass (Shi *et al.*, 2015d), and reduces paraquat-induced oxidative stress in Arabidopsis (Weeda *et al.*, 2014) and cadmium-mediated oxidative stress in rice (Byeon *et al.*, 2015). Melatonin possibly interacts with nitric oxide (NO) to modulate the production of  $\text{O}_2^{\cdot-}$  and the peroxynitrite anion ( $\text{ONOO}^-$ ), the accumulation of tyrosine-nitrated proteins, and the activity and spatial localization of SOD isoforms (Arora and Bhatla, 2017).

Transcriptomic analysis has shown that a large proportion of differentially expressed genes are involved in oxidation–reduction process after melatonin treatment. Several classes of antioxidant-related genes are significantly regulated by melatonin (Liang *et al.*, 2015; Shi *et al.*, 2015a; Wei *et al.*, 2015). *NOE1* encodes a rice catalase, and the *noe1* mutant accumulates high amounts of  $\text{H}_2\text{O}_2$ , leading to leaf cell death and senescence (Lin *et al.*, 2012). Melatonin-treated *noe1* mutants show significantly reduced leaf cell death and a decrease in  $\text{H}_2\text{O}_2$  when compared to the wild-type, indicating that melatonin directly participates in regulating the cellular  $\text{H}_2\text{O}_2$  detoxification system (Liang *et al.*, 2015). Studies have also shown that not only exogenously applied but also endogenously produced melatonin in plants possess a similar antioxidant capacity (Table 1). Transgenic plants rich in endogenous melatonin have a higher total antioxidative capacity and lower oxidatively damaged products compared with the wild-type (Wang *et al.*, 2014a). Arabidopsis plants with transgenic apple *ASMT1* (encoding N-acetylserotonin methyltransferase) or *MzSNAT5* (encoding serotonin N-acetyltransferase) have significantly lower intrinsic ROS than the wild-type and hence these plants exhibit greater tolerance to drought stress (Zuo *et al.*, 2014; Wang *et al.*, 2017). Melatonin-rich transgenic rice plants treated with ROS-generating herbicide also have reduced lipid peroxidation due to scavenging of ROS and stimulation of antioxidative enzymes

**Table 1.** Exogenous application of melatonin or modulation of exogenous melatonin regulates plant abiotic stress tolerance

Abiotic stress	Concentration of melatonin or transgene*	Plant species	Changes and mechanisms	Reference	
Cold	10, 30 $\mu$ M	<i>Arabidopsis thaliana</i>	Modulation of <i>CBF</i> , <i>COR</i> , <i>ZAT10</i> and ROS genes	Bajwa <i>et al.</i> , 2014	
	20 $\mu$ M	<i>Arabidopsis thaliana</i>	Modulation of <i>ZAT6</i> and <i>CBFs</i>	Shi and Chan, 2014	
	50 $\mu$ M	<i>Arabidopsis thaliana</i>	Modulation of <i>CBFs</i> , <i>COR</i> , <i>RD</i> and <i>KIN</i> genes	Shi <i>et al.</i> , 2015c	
	43, 86 nM	Carrot ( <i>Daucus carota</i> )	ROS scavenger; Polyamine metabolism	Lei <i>et al.</i> , 2004	
	0.05–800 $\mu$ M	<i>Citrullus lanatus</i>	ROS; Hormones; Stress-responsive genes	Li <i>et al.</i> , 2017a	
	25, 50, 100, and 500 mM	Cucumber ( <i>Cucumis sativus</i> )	Membrane structure; Protein oxidative changes	Posmyk <i>et al.</i> , 2009	
	200 $\mu$ M	Cucumber ( <i>Cucumis sativus</i> )	<i>ZAT12</i> ; Polyamine; ABA	Zhao <i>et al.</i> , 2017	
	50 $\mu$ M	<i>Elymus nutans</i>	ROS changes; ABA	Fu <i>et al.</i> , 2017	
	1 mM	Barley ( <i>Hordeum vulgare</i> )	ROS changes; ABA; Photosynthesis	Li <i>et al.</i> , 2016c	
	1 mM	Maize ( <i>Zea mays</i> )	Mineral elements; ROS	Turk and Erdal, 2015	
	50 and 500 $\mu$ M	Maize ( <i>Zea mays</i> )	Stress-related proteins	Kolodziejczyk <i>et al.</i> , 2016	
	1 mM	Wheat ( <i>Triticum aestivum</i> )	ROS changes; Osmoprotectants	Turk <i>et al.</i> , 2014	
	100 $\mu$ M	Bermudagrass ( <i>Cynodon dactylon</i> )	Photosynthesis; Metabolites	Hu <i>et al.</i> , 2016	
	150 $\mu$ M	Watermelon ( <i>Citrullus lanatus</i> )	siRNA, miRNA, Cold-responsive genes	Li <i>et al.</i> , 2016b	
	100 $\mu$ M	Tomato ( <i>Solanum lycopersicum</i> )	Alleviation of photoinhibition	Ding <i>et al.</i> , 2017	
	Suppression of <i>SNAT</i> or <i>ASMT</i>	Rice ( <i>Oryza sativa</i> )	Growth; Yield; Gene expression	Byeon and Back, 2016	
	Overexpression of human <i>SNAT</i>	Rice ( <i>Oryza sativa</i> )	Elevated chlorophyll synthesis	Kang <i>et al.</i> , 2010	
	Drought	10 $\mu$ M	Alfalfa ( <i>Medicago sativa</i> )	Nitric oxide; Proline	Antoniou <i>et al.</i> , 2017
		100 $\mu$ M	Apple ( <i>Malus prunifolia</i> )	ABA; ROS	Li <i>et al.</i> , 2015
		100 $\mu$ M	Apple ( <i>Malus prunifolia</i> )	Photosynthesis; Modulation of <i>SAG12</i> and <i>PAO</i>	Wang <i>et al.</i> , 2013b
50, 100, 300, 500 mM		Cucumber ( <i>Cucumis sativus</i> )	Photosynthesis; ROS; Cell membrane	Zhang <i>et al.</i> , 2013	
50 nM		Grape ( <i>Vitis vinifera</i> )	Photosynthesis; ROS	Meng <i>et al.</i> , 2014	
100 $\mu$ M		Maize ( <i>Zea mays</i> )	Photosynthesis; Transpiration rates; ROS	Ye <i>et al.</i> , 2016	
50, 100 $\mu$ M		Soybean ( <i>Glycine max</i> )	Growth; Seed production; Gene expression	Wei <i>et al.</i> , 2015	
100 $\mu$ M		Tomato ( <i>Solanum lycopersicum</i> )	Photosynthesis; ROS	Liu <i>et al.</i> , 2015	
Overexpression of apple <i>ASMT</i>		<i>Arabidopsis thaliana</i>	ROS	Zuo <i>et al.</i> , 2014	
Overexpression of apple <i>MzSNAT5</i>		<i>Arabidopsis thaliana</i>	ROS	Wang <i>et al.</i> , 2017	
Salt		100 $\mu$ M	Apple ( <i>Malus hupehensis</i> )	CBL-CIPK; ROS	Li <i>et al.</i> , 2016a
		1 $\mu$ M	<i>Arabidopsis thaliana</i>	Ion homeostasis; ROS	Chen <i>et al.</i> , 2017
	1 $\mu$ M	Citrus ( <i>Citrus aurantium</i> )	ROS; Metabolites; Ion accumulation	Kostopoulou <i>et al.</i> , 2015	
	50, 100, 150, and 200 $\mu$ M	Cucumber ( <i>Cucumis sativus</i> )	Growth; Photosynthetic capacity	Wang <i>et al.</i> , 2016a	
	1 $\mu$ M	Cucumber ( <i>Cucumis sativus</i> )	Antioxidant systems, ABA and GA4	Zhang <i>et al.</i> , 2014a	
	1 $\mu$ M	Cucumber ( <i>Cucumis sativus</i> )	157 proteins	Zhang <i>et al.</i> , 2017b	
	0.1 $\mu$ M	<i>Malus hupehensis</i>	Ion homeostasis; ROS	Li <i>et al.</i> , 2012	
	10, 20 $\mu$ M	Rice ( <i>Oryza sativa</i> )	Photosynthesis; Senescence; ROS	Liang <i>et al.</i> , 2015	
	75 $\mu$ M	Rice ( <i>Oryza sativa</i> )	Ion homeostasis; ROS	Li <i>et al.</i> , 2017b	
	15 $\mu$ M	Sunflower ( <i>Helianthus annuus</i> )	Root growth; Hypocotyl elongation	Mukherjee <i>et al.</i> , 2014	
	15 $\mu$ M	Sunflower ( <i>Helianthus annuus</i> )	Cu/Zn SOD, Mn SOD; Tyrosine-nitration of proteins	Arora and Bhatla, 2017	
	0, 50, and 100 $\mu$ M	Soybean ( <i>Glycine max</i> )	Growth; Seed production; Gene expression	Wei <i>et al.</i> , 2015	
	Suppression of <i>SNAT</i> or <i>ASMT</i>	Rice ( <i>Oryza sativa</i> )	Growth; Yield; Gene expression	Byeon and Back, 2016	
Heat	5 and 20 $\mu$ M	<i>Arabidopsis thaliana</i>	Expression of <i>HSF</i> and <i>HSP</i>	Shi <i>et al.</i> , 2015d	
	20 $\mu$ M	Perennial ryegrass ( <i>Lolium perenne</i> )	ABA and cytokinin pathway; Photosynthesis	Zhang <i>et al.</i> , 2017a	
	20 $\mu$ M	Tomato ( <i>Solanum lycopersicum</i> )	HSP abundance and expression	Xu <i>et al.</i> , 2016	
	Overexpression of tomato <i>ASMT</i>	Tomato ( <i>Solanum lycopersicum</i> )	HSP abundance and expression	Xu <i>et al.</i> , 2016	
	0.3, 1, 6, 12, 30, 60, 90 $\mu$ M	<i>Phacelia tanacetifolia</i>	Seed germination	Tiryaki and Keles, 2012	

\* *SNAT*, serotonin N-acetyltransferase; *ASMT*, N-acetylserotonin methyltransferase.

(Park *et al.*, 2013). These results indicate that melatonin functions as a powerful antioxidant to detoxify free radicals and thus improve the oxidative stress tolerance in plants.

Melatonin alleviates electrolyte leakage (EL) and lipid peroxidation caused by malondialdehyde (MDA) during plant stress responses. Abiotic stresses including drought, salt, and cold increase MDA and ROS levels, which have a direct impact on cell membranes, resulting in increased EL in bermudagrass (Shi *et al.*, 2015a), and probably other plants as well. Pre-treatment with melatonin decreases both EL and MDA under abiotic stress conditions (Shi *et al.*, 2015a, 2015d). Cold stress results in disrupted membranes and a collapsed nucleus, while melatonin pre-treatment alleviates cold-induced cell damage in suspended carrot cells (Lei *et al.*, 2004). In tomato, pre-treatment prevents cadmium (Cd)-induced increases in EL and MDA to varying degrees (Hasan *et al.*, 2015). Treatment with 200 mM NaCl increases EL and MDA in cucumber plants, while melatonin-treated plants show significantly lower EL and MDA than the control in the presence of NaCl (Wang *et al.*, 2016a). These results are consistent with the ability to prevent the oxidation of membrane lipids in particular.

## Melatonin improves plant photosynthesis and delays leaf senescence

In plants, photosynthesis is the key biological process that determines plant survival and productivity. Generally, abiotic stress conditions inhibit photosynthesis and reduce growth, resulting in decreased transpiration and elevated water use efficiency (Gururani *et al.*, 2015). In tomato, pre-treatment with 0.1 mM melatonin significantly increases drought tolerance. Pre-treated tomato plants show elevated net photosynthetic rate, transpiration rate, stomatal conductance, quantum yield of PSII, electron transport, and maximum quantum yield ( $F_v/F_m$ ) (Liu *et al.*, 2015). Exposure to moderate light under chilling causes substantial reduction of  $F_v/F_m$  and of the effective photochemical efficiency ( $F'_v/F'_m$ ) in tomato, while melatonin mitigates the photoinhibition (Ding *et al.*, 2017). Chlorophyll is extremely sensitive to water deficit, and reduction in pigment levels caused by drought stress has been reported in several plant species. However, these pigments are largely preserved after melatonin pre-treatment (Li *et al.*, 2012, 2015; Wang *et al.*, 2013a, 2013b; Zhang *et al.*, 2013). Long-term supplement of 100  $\mu$ M melatonin to the soil increases photosynthetic activity, chlorophyll content, and sugar contents in apple leaves (Wang *et al.*, 2013a). In *Chara australis* (Characeae), supplementing melatonin in the water growth medium increases the quantum yield of PSII by 34% (Lazár *et al.*, 2013). In addition, exogenous application of melatonin under stressed conditions helps maintain the chlorophyll content in rice (Liang *et al.*, 2015), grape (Meng *et al.*, 2014), cherry (Sarropoulou *et al.*, 2012a), and turfgrass (Shi *et al.*, 2015a; Zhang *et al.*, 2017a). Transgenic rice seedlings with the human *SNA* gene exhibit high levels of melatonin and elevated chlorophyll synthesis under cold stress conditions (Kang *et al.*, 2010). As noted above, melatonin is a

direct free radical scavenger that attenuates ROS/RNS formation and protects against stress-induced damage at multiple levels. In photosynthetic organisms, ROS/RNS are continuously produced that can damage key macromolecules, in particular DNA, lipids, and proteins, and that can severely inhibit photosynthesis. Melatonin synthesized on-site might relieve chloroplasts from stress-induced damage and thus help to maintain photosynthesis under stress conditions. Hence, melatonin effectively alleviates decomposition of chlorophyll and preserves chloroplast physiology when plants are subjected to abiotic stresses.

Melatonin is known to regulate phloem-loading of sucrose in plants. Application of 10  $\mu$ M melatonin accelerates starch catabolism at night, whereas 100  $\mu$ M significantly suppresses this process and leads to starch accumulation in photosynthetic tissues (Zhao *et al.*, 2015). Melatonin alleviates the decline in content of carotenoids and chlorophyll during leaf senescence in apple. Concentrations of nitrogen, total soluble proteins, and Rubisco decrease in parallel with the aging process, but the levels of these metabolites are significantly higher in melatonin-treated plants. In addition, the contents of starch, sorbitol, sucrose, fructose, and glucose tend to increase after melatonin treatment (Wang *et al.*, 2013a, 2013b). Using an 'omics' approach, 54 metabolites were examined in bermudagrass plants before or after melatonin treatment. Interestingly, without abiotic stress treatments, melatonin was only found to affect a small portion of the detected metabolites, while under stressed conditions, a much larger number of metabolites showed increased contents after melatonin pre-treatment, especially those involved in the carbon metabolic pathway (Shi *et al.*, 2015a; Hu *et al.*, 2016). These results indicate that melatonin might function as a regulator of plant sugar metabolism in response to abiotic stress. The stomata are important passages through which air and water vapor are conveyed in plant leaves. Melatonin pre-treatment leads to greater stomatal conductance in apple and grape (Meng *et al.*, 2014; Li *et al.*, 2015). In apple, the imposition of drought results in significantly shorter and narrower stomata and also causes stomatal closure. Apple plants pre-treated with melatonin have longer and wider stomata than the control plants. After melatonin pre-treatment, stomata remain open under stress conditions; however, stomatal density in apple leaves is not altered by melatonin (Li *et al.*, 2015). In grape, drought conditions decrease the length and width of stomata in mature leaves, as well as the degree to which they open. Pre-treatment with melatonin leads to greater stomatal length and width, and the degree of opening of stomata is greater than that in control plants (Meng *et al.*, 2014). Hence, pre-treatment with melatonin results in greater stomatal conductance and improves photosynthetic capacity because of the ability of melatonin to maintain the stomata in an open state.

Leaf senescence is a type of programmed cell death that results in the degradation of macromolecules including chlorophyll and the subsequent mobilization of components to other parts of the plant (Liang *et al.*, 2014). Melatonin pre-treatment suppresses the up-regulation of *senescence-associated gene 12* (*SAG12*) and *phosphoribide a oxygenase*



(*PAO*) in apple, and helps to maintain better function of PSII under drought conditions (Wang *et al.*, 2013b). In addition, Arnao and Hernández-Ruiz (2009) found that melatonin pre-treatment significantly slowed the senescence process in barley leaves, with the maximal chlorophyll content being observed after application of 1 mM melatonin. In rice, Liang *et al.* (2015) also found that melatonin significantly inhibited chlorophyll degradation, suppressed the expression of senescence-associated genes, and delayed leaf senescence. Several transcription factors including senescence-related *SGR* and *NAC* are regulated by melatonin in rice, as shown by high-throughput RNA sequencing, indicating that a reduction in melatonin is an essential feature of plant senescence (Liang *et al.*, 2015). Using proteomic approaches, senescence-related protein has been shown to exhibit decreased intensity after melatonin pre-treatment (Sun *et al.*, 2016). In perennial ryegrass, melatonin reduces transcript levels of senescence-associated genes (*LpSAG12.1* and *Lph36*) and alleviates heat-induced leaf senescence (Zhang *et al.*, 2017a).

## Melatonin modulates plant growth and development

Melatonin affects plant growth partially through photosynthesis and metabolism pathways. Transgenic rice seedlings expressing sheep serotonin N-acetyltransferase (*NAT*) showed enhanced seminal root growth and an elevated number of adventitious roots. Moreover, exogenous melatonin treatment promoted seminal root growth of the wild-type rice under continuous light (Park and Back, 2012). Melatonin priming increased yield of corn (*Zea mays*), mung bean (*Vigna radiata*), and cucumber (Janas and Posmyk, 2013; Wang *et al.*, 2016a; Ye *et al.*, 2016). Melatonin-treated soybean plants produced more pods and seeds than the controls, although the 100-seed weight was not significantly influenced (Wei *et al.*, 2015). In addition, many genes involved in cell division, photosynthesis, carbohydrate metabolism, fatty acid biosynthesis, and ascorbate metabolism were differentially regulated by melatonin. In etiolated lupin (*Lupinus albus*), melatonin promotes the growth of hypocotyls at micromolar concentrations, while it inhibits the same process at higher concentrations (Hernández-Ruiz *et al.*, 2004). Recent research on Arabidopsis and soybean seedlings has shown that high melatonin concentrations adversely affect whole-plant growth (Bajwa *et al.*, 2014; Wei *et al.*, 2015). In tomato, application of melatonin at 50  $\mu$ M promotes fruit ripening and increases fruit softening, pigment accumulation, water loss, and flavor formation (Sun *et al.*, 2015). Further proteomics analysis has shown that melatonin increases the intensity of proteins involved in ripening-related pathways and in the anthocyanin accumulation pathway (Sun *et al.*, 2016).

In roots, melatonin modulates growth in a concentration-dependent manner, as reported in mustard (Chen *et al.*, 2009), cherry (Sarropoulou *et al.*, 2012b), sunflower (Mukherjee *et al.*, 2014), tomato (Wen *et al.*, 2016), and several monocot species (Hernández-Ruiz *et al.*, 2005; Liang *et al.*, 2017). A stimulatory effect was observed during root growth of

mustard after treatment with low concentrations of melatonin, while an inhibitory effect was found with high concentrations (Chen *et al.*, 2009). Salt stress inhibits primary root growth and hypocotyl elongation in sunflower seedlings, but melatonin-treated seedlings exhibited 13% and 58% increases for primary root length and hypocotyl elongation, respectively, in the presence of NaCl (Mukherjee *et al.*, 2014). Melatonin promotes the rooting of several sweet cherry rootstocks at a relative low concentration, but inhibits root growth at high concentrations (Sarropoulou *et al.*, 2012b). Wen *et al.*, (2016) observed that the effects of melatonin on formation of adventitious root in tomato seedlings are dose-dependent. Application of an NO scavenger removed the function of melatonin, but a melatonin biosynthesis inhibitor had little effect in abolishing the function of NO during the formation of adventitious root. Hernández-Ruiz *et al.* (2005) found that the optimum growth-promoting concentration for melatonin in several monocot plants was  $10^{-7}$  M. In rice, 10–50  $\mu$ M melatonin treatments inhibit embryonic root growth, but promote lateral root formation and development (Liang *et al.*, 2017).

## Putative target genes of melatonin

Melatonin modulates a wide range of stress-responsive genes. The expression of C-repeat-binding factors (*CBFs*)/drought response element binding factors (*DREBs*), a downstream cold responsive gene (*COR15a*), and transcription factors involved in freezing- and drought-stress tolerance, including *CAMTA1*, *ZAT6*, *ZAT10*, and *ZAT12* are up-regulated by melatonin (Bajwa *et al.*, 2014; Shi and Chan 2014; Shi *et al.*, 2015b; Zhao *et al.*, 2017). In Arabidopsis, a low concentration of melatonin (100 pM) changed the expression level of 81 genes, while a high concentration (1 mM) influenced the expression of 1308 genes, including the transcription factors (TFs) *WRKY*, *NAC*, and *MYB* (Weeda *et al.*, 2014). Based on the classification of the gene ontology (GO) 'slim' term, the majority of genes were involved in stress response and signal transduction. The same results were found in cucumber where 10  $\mu$ M melatonin affected fewer genes (113) than 500  $\mu$ M melatonin (317), and expression levels of the *WRKY*, *MYB*, and *NAC* genes were significantly changed by melatonin (Zhang *et al.*, 2014b). In bermudagrass, genome-wide transcriptomic profiling identified 3933 transcripts that were differentially expressed after melatonin treatment. Pathway enrichment analysis showed that pathways related to nitrogen metabolism, major carbohydrate metabolism, hormone metabolism, metal handling, redox, and secondary metabolism were over-represented. Transcription factors including *DREB*, *HSF*, *WRKY*, and *MYB* are highly induced by melatonin (Shi *et al.*, 2015a). Melatonin treatment also up-regulates expression of genes inhibited by salt stress, and hence alleviates the inhibitory effects of the stress on gene expression. Genes involved in fatty acid biosynthesis, cell division, carbohydrate metabolism, photosynthesis, and ascorbate metabolism are activated after melatonin pre-treatment in soybean (Wei *et al.*, 2015). Exogenous melatonin treatment affected 457 genes in rice, with 191 being up-regulated and 266 being

down-regulated. The functions of these genes were mainly involved in response to stress and responses to other stimuli (Liang *et al.*, 2015). Several miRNAs, such as *miR159-5p*, *miR858*, *miR8029-3p*, and *novel-m0048-3p*, are down-regulated upon melatonin treatment in watermelon. The target genes of these miRNA, including *CDPK*, *bHLH*, *WRKY*, *MYB*, and *DREB*, consistently show increased expression in the presence of melatonin (Li *et al.*, 2016b). In melatonin-rich transgenic rice, 260 and 204 genes are up- and down-regulated, respectively, when compared with the wild-type. Representative up-regulated genes include those for signaling and transcription factors such as the leucine-rich repeat and zinc-finger genes. In contrast, jasmonate-induced and senescence-associated genes are significantly down-regulated. Further GO analysis reveals that melatonin is positively involved in plant reproductive development (Byeon *et al.*, 2013). Ovine *HIOMT* and *AANAT* genes were transformed into switchgrass and modulated the expression of 405 and 946 genes, respectively. Among them, 186 unigenes were co-regulated by both transgenes, which might be the candidate targets of melatonin (Yuan *et al.*, 2016a, 2016b).

Using comparative proteomic technologies, 40 and 34 proteins in bermudagrass were found to be affected by melatonin in the absence and presence, respectively, of H<sub>2</sub>O<sub>2</sub>. MapMan pathway analysis showed that several pathways were enhanced by melatonin and H<sub>2</sub>O<sub>2</sub> treatments, including polyamine metabolism, major carbohydrate (CHO) metabolism, photosynthesis, redox status, and amino acid metabolism (Shi *et al.*, 2015d). Through use of NanoLC-MS/MS, 622 and 309 proteins were found to be altered by senescence and melatonin, respectively. The functions of these proteins were mainly classified into several senescence-related categories, including degradation of macromolecules, transport, photosynthesis, development, redox, and stress responses (Wang *et al.*, 2014b). GO analysis has shown that melatonin-modulated proteins in cucumber are mainly involved in lipid metabolism, ribosome biosynthesis, and carbohydrate metabolism (Zhang *et al.*, 2017b). In corn plants, proteins involved in the ABA pathway, stress response, ROS, and energetic metabolism show intensity changes after melatonin priming (Kołodziejczyk, *et al.*, 2016). Exogenous melatonin treatment and overexpression of tomato *ASMT* genes increased the expression level of *HSPs* and the protein abundance in tomato. Proteomics analysis showed decreased accumulation of aggregated proteins (Xu *et al.*, 2016). Melatonin pre-treatment also reduces protein degradation through inhibition on the expression of autophagy-related genes (*ATGs*) in apple and tomato (Wang *et al.*, 2013a; Xu *et al.*, 2016). These results indicate that melatonin is involved in plant stress responses at both transcriptional and post-transcriptional levels. Several genes, including *DREB/CBF*, *WRKY*, and *MYB*, might function as melatonin targets. The detailed function of these genes in response to melatonin needs to be further examined.

## Melatonin integrates with phytohormones

Many melatonin-affected genes are involved in different hormone signaling pathways, such as auxin, ABA, SA, ETH,

and JA, indicating possible crosstalk between melatonin and other phytohormones, as noted above (Weeda *et al.*, 2014). Interactions between melatonin and other phytohormones have been well reviewed by Arnao and Hernández-Ruiz (2017b, 2017c). One of the first roles proposed for melatonin in plants was its possible action as a growth regulator. Melatonin promotes root and vegetative growth in a number of plant species (Arnao and Hernández-Ruiz, 2007, 2014, 2015; Erland *et al.*, 2015; Nawaz *et al.*, 2015). Melatonin modulates root system architecture by stimulating lateral and adventitious root formation, but it minimally affects primary root growth or root-hair development in Arabidopsis (Pelagio-Flores *et al.*, 2012; Koyama *et al.*, 2013). In addition, melatonin neither activates the expression of the auxin-inducible gene marker *DR5::GUS*, nor induces the degradation of *HS::AXR3NT-GUS*. Therefore, melatonin is proposed to modulate lateral root development through IAA-independent pathways (Pelagio-Flores *et al.*, 2012; Koyama *et al.*, 2013). However, melatonin and IAA are structurally related, and therefore it is suggested that melatonin applied exogenously could be metabolized to IAA or to an IAA agonist (Kolár and Machácková, 2005); however, this has not been demonstrated so far. Tryptophan is the precursor for both melatonin and IAA. Arylalkylamine N-acetyltransferase (*AANAT*), which encodes a rate-limiting enzyme catalysing melatonin biosynthesis in animals, has also been identified in plants (Kang *et al.*, 2013). Tomato plants overexpressing the homologous sheep *oAANAT* exhibited higher melatonin levels and lower IAA contents than controls due to competition for the precursor (Wang *et al.*, 2014a). It is reported that exogenously applied melatonin acts as a rooting promoter and its action is similar to that of IAA (Sarropoulou *et al.*, 2012a). Exogenous melatonin treatment increases the contents of IAA and IBA in tomato and mustard seedlings (Chen *et al.*, 2009; Wen *et al.*, 2016). At a relatively low concentration (50 μM), melatonin has been shown to enhance the expression levels of auxin signaling-transduction genes (*IAA19* and *IAA24*) and auxin efflux genes (*PIN1*, *PIN3*, and *PIN7*) and to accelerate adventitious root formation in tomato (Wen *et al.*, 2016). In contrast, a high concentration of melatonin (600 μM) repressed auxin synthesis and transportation pathways, as evidenced by decreased expression of *YUC1*, *YUC2*, *YUC5*, *YUC6*, *TAA1*, *TAR2*, *PIN1*, *PIN3*, and *PIN7* (Wang *et al.*, 2016b). In rice, 10–20 μM melatonin treatment up-regulates the expression of *Os01g08320* (*OsIAA1*), *Os02g56120* (*OsIAA9*), *Os02g57250* (*OsIAA10*), *Os06g07040* (*OsIAA20*), and *Os011g11410* (*OsIAA27*) (Liang *et al.*, 2017). These data indicate that melatonin at low concentrations might partially function as an IAA mimic.

Melatonin affects ABA biosynthesis and catabolism during cucumber (*Cucumis sativus*) seed germination under salt-stress conditions. Pre-treatment with 1 μM melatonin down-regulates the ABA biosynthesis gene *NCED2* and up-regulates ABA catabolism genes including *CYP707A1* and *CYP707A2*. As a result, the ABA content significantly decreases after melatonin treatment (Zhang *et al.*, 2014a). Evidence shows that 100 μM melatonin selectively down-regulates *MdNCED3* and up-regulates *MdCYP707A1* and

*MdCYP707A2*, leading to reduced ABA content in drought-stressed apple plants (Li *et al.*, 2015). The same results have been observed in perennial ryegrass, with ABA biosynthesis and signaling genes being down-regulated and ABA content declining after 20  $\mu\text{M}$  melatonin treatment under heat-stress conditions (Zhang *et al.*, 2017a). However, Jia and Zhang (2000) reported that pretreatment with 50–500  $\mu\text{M}$  melatonin had no effect on water stress-induced ABA accumulation in maize. In chilling-stressed *Elymus nutans* and cucumber, ABA production was reported to increase after 50 and 200  $\mu\text{M}$  melatonin treatments, respectively (Fu *et al.*, 2017; Zhao *et al.*, 2017). The effect of melatonin on ABA content is therefore still controversial. Interestingly, the ABA-biosynthesis inhibitor fluridone significantly suppresses melatonin-induced ABA accumulation. However, ABA and fluridone pre-treatments do not affect the endogenous melatonin content (Fu *et al.*, 2017), indicating that melatonin functions upstream of the ABA pathways (Arnao and Hernández-Ruiz 2017c). Further transcriptomic analysis has shown that the ABA receptor (PYL5) and PP2C are highly induced by melatonin in bermudagrass (Shi *et al.*, 2015a), while PYL8 of *Citrullus lanatus* is suppressed by melatonin under cold-stress conditions (Li *et al.*, 2017a). These results indicate that the ABA signaling transduction pathway is modulated by melatonin, but the detailed mechanisms need to be further examined.

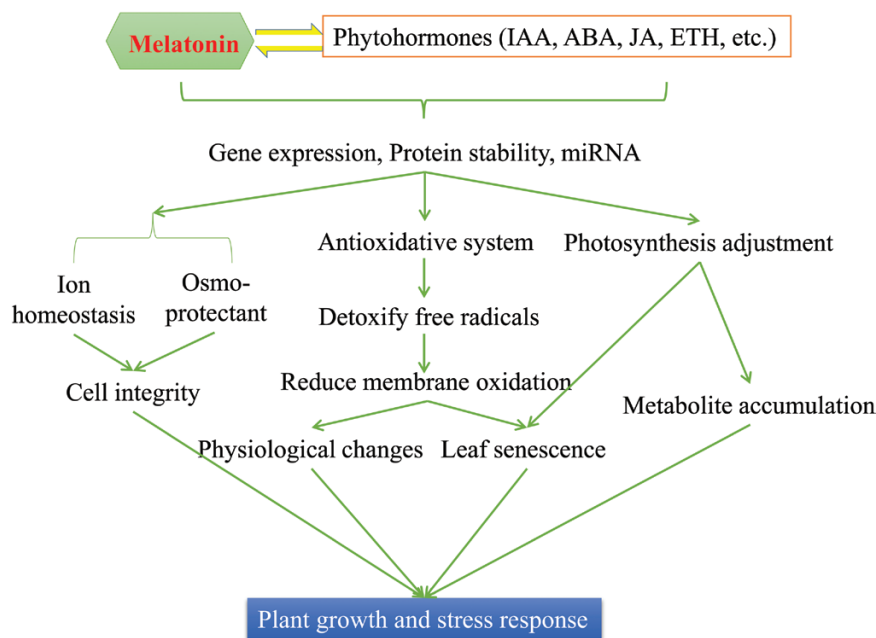
Melatonin also modulates the expression level of genes involved in the ETH, SA, and JA pathways (Arnao and Hernández-Ruiz 2017c). In harvested tomato fruit, melatonin treatment increases ethylene production through up-regulation of the biosynthesis gene *SIACS4* during fruit ripening (Weeda *et al.*, 2014). The ethylene receptor genes *NR* and *ETR4* and the signal transduction elements *EIL1*, *EIL3*,

and *ERF2* are up-regulated by melatonin (Sun *et al.*, 2015). Melatonin influences GA biosynthesis and catabolism during seed germination (Zhang *et al.*, 2014a). Notable increases in putrescine and spermidine levels have been observed in melatonin-treated carrot suspension cells and cucumber seedlings (Lei *et al.*, 2004; Zhao *et al.*, 2017). These data suggest that the actions of melatonin may involve other phytohormones.

## Conclusions and perspectives

Increasing evidence shows that melatonin functions as a universal defensive signal to alleviate damage induced by different stressful conditions. In Fig. 1 a model is proposed to characterize the potential roles of melatonin during plant abiotic stress responses. Melatonin might interact with other phytohormones such as ABA, IAA, ETH, and GA to regulate gene expression, protein stabilization, and epigenetic modification caused by miRNA. Furthermore, downstream stress-responsive pathways are activated, including those for enhancing antioxidant systems, decreasing free radicals, increasing osmoprotectants, recovering ionic disorder, alleviating membrane oxidation, and delaying leaf senescence. Stress-inhibited photosynthesis is partially recovered in the presence of melatonin. Plants thus exhibit improved growth and increased stress tolerance after melatonin priming (Fig. 1).

Under abiotic stress conditions, plants have developed different strategies to buffer the harmful effects on growth and development. The key roles of the *DREB/CBF* pathway for cold, the *HSF-HSP* pathway for heat, the *SOS3-SOS2-SOS1/NHX* pathway for salt, and the ABA



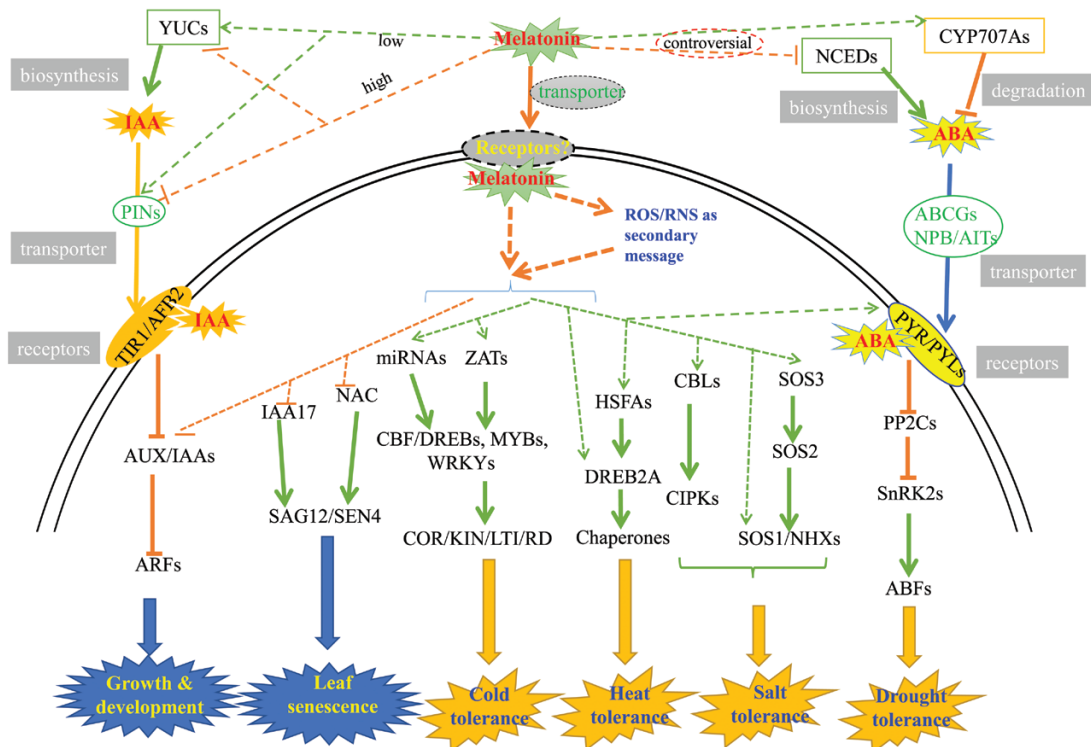
**Fig. 1.** Proposed model depicting melatonin-mediated plant abiotic stress responses. Melatonin interacts with other phytohormones and modulates gene expression, protein stability, and epigenetic modification directed by miRNA. Activated stress-responsive genes further detoxify free radicals, alleviate membrane oxidation, and delay leaf senescence. Stress-inhibited photosynthesis is partially recovered and metabolites accumulate in the presence of melatonin. The production of osmoprotectants is increased and ion disorders are balanced to maintain cell integrity. Plant tolerances to abiotic stress are hence improved and damage to plant growth is reduced after melatonin treatment.



(*PYR/PYL-PP2C-SnRK2-ABF*) pathway for drought have been well characterized. Melatonin functions as a general regulator during plant responses to abiotic stress through modulation of stress-responsive genes directly or indirectly (Fig. 2). We hypothesize that the perception of melatonin activates downstream signaling transduction pathways. Alternatively, melatonin-modulated ROS/RNS function as secondary messengers during plant growth and stress responses. Melatonin or a downstream signaling component induces the expression of *DREB/CBF* genes and other cold stress-responsive transcription factors such as *CAMTA3*, *ZAT6*, *ZAT10*, and *ZAT12* to improve plant/cold tolerance (Bajwa et al., 2014; Shi and Chan, 2014; Shi et al., 2015b; Zhao et al., 2017). Expression of *HSF* and *HSP* is readily induced by melatonin treatment, leading to enhanced heat tolerance (Shi et al., 2015c). Moreover, salt overly sensitive 1 (*SOS1*), *SOS2*, *SOS3*, *NHX* Na<sup>+</sup>/H<sup>+</sup> antiporters (*NHXs*), *CBL1*, and *CIPK23* are significantly up-regulated after melatonin treatment (Li et al., 2012, 2016a, 2017b; Chen et al., 2017), resulting in an activated SOS pathway and elevated salt tolerance. Exogenous melatonin changes the ABA content by modulating its biosynthesis and metabolism pathways. Increased expression levels of ABA receptors are induced by melatonin and ABA signaling transduction pathways are then activated, resulting in increased drought tolerance (Jia and Zhang, 2000; Zhang et al., 2014a; Li et al., 2015; Shi et al., 2015a). However, the

effect of melatonin on ABA is still controversial, as noted above. ABA is a stress-induced hormone and how melatonin integrates with the ABA signal remains unclear. Low concentrations of melatonin activate the IAA pathway, while high concentrations repress it (Wang et al., 2016b; Wen et al., 2016; Liang et al., 2017). In addition, melatonin inhibits expression of *IAA17/AXR3* and *NAC*, leading to reduced *SEN4* and *SAG12* and delayed leaf senescence (Wang et al., 2013b; Liang et al., 2015; Shi et al., 2015b).

Although progress has been made to characterize the functions of melatonin in plants, numerous questions remain unanswered. Firstly, whilst the receptors and signaling transduction pathways of other phytohormones have been identified, including auxin, cytokinin, gibberellins, ethylene, brassinosteroids, jasmonic acid, and abscisic acid, no information is available regarding melatonin receptors in plants. Currently, two melatonin membrane receptors, namely *MT1* and *MT2* (originally denoted as *Mella*, *Mellb*), have been identified in mammalian vertebrates, and two, *MT3* or *Mellc*, in non-mammalian vertebrates (Hardeland, 2009), but the perception of melatonin by plant cells and the signaling transduction pathways remain to be determined. Secondly, ROS are important signaling molecules during the plant stress response. Melatonin acts as an effective free radical scavenger and antioxidant to alleviate oxidative stress caused by drought, salt, cold, and heat amongst others (Tan et al.,



**Fig. 2.** Melatonin modulates plant stress-signaling pathways, regulates plant growth, and delays leaf senescence. Based on identification of melatonin receptors in mammalian and non-mammalian vertebrates (Hardeland, 2009), we hypothesize that the perception of melatonin by receptors either directly modulates expression of stress-responsive genes or indirectly through melatonin signaling components or secondary messengers such as ROS/RNS. Melatonin up-regulates C<sub>2</sub>H<sub>2</sub>-type zinc finger transcription factor ZATs and miRNAs, which act as upstream regulators of the CBFs/DREBs pathway during plant responses to cold stress. Melatonin regulates heat and salt stresses through the *HSF-DREB2A* and *SOS* pathways, respectively. The ABA signaling transduction pathway (*PYR/PYL-PP2C-SnRK2-ABF*) is modulated by melatonin to regulate the plant drought-stress response. Melatonin activates/represses the IAA pathway in a concentration-dependent manner. The senescence-related genes *IAA17/AXR3* and *NAC* are inhibited by melatonin, leading to delayed leaf senescence. Dashed lines show pathways possibly regulated by melatonin, as summarized in the text.



2007, 2012; Reiter *et al.*, 2015) Therefore, it is not surprising that melatonin improves plant tolerance to most abiotic stresses. However, further work is needed to characterize how melatonin interacts with other hormones and how it regulates stress-signaling pathways.

Melatonin-mediated transcriptomic changes have been identified in bermudagrass, rice, *Arabidopsis*, soybean, and cucumber (Byeon *et al.*, 2013; Weeda *et al.*, 2014; Zhang *et al.*, 2014b; Shi *et al.*, 2015d; Wei *et al.*, 2015). However, relatively little is known about the downstream target genes and regulatory networks. Bioinformatics analysis of genes commonly modulated by melatonin would be an effective approach to answer this question. Finally, homologous genes involved in plant melatonin biosynthesis have been cloned in several crop species (Zuo *et al.*, 2014; Byeon and Back, 2016). Overexpression of biosynthesis-related genes increase the endogenous content of melatonin and improve plant abiotic stress tolerance. Several Chinese medicinal herbs constitutively exhibit very high melatonin contents, especially Chantui (*Periostracum cicadae*), which has 3.7  $\mu\text{g g}^{-1}$  dry mass melatonin (Chen *et al.*, 2003). In beans of *Coffea* species, melatonin content even reaches 5.8–9.6  $\mu\text{g g}^{-1}$  dry mass, which is much higher than in edible plants (Ramakrishna *et al.*, 2012). Functional analysis of the genes involved in melatonin biosynthesis and metabolism pathways in these plants might provide more efficient genetic resources to increase the endogenous melatonin content in crops. In conclusion, melatonin is an important stress-signaling molecule that functions as a general abiotic stress regulator.

## Acknowledgments

We apologize to those colleagues who have contributed to this field but who were not cited because of space limitations. This research was supported by a National Key Research and Development Program grant (2017YFD0201305) to ZC and YW, Huazhong Agricultural University Scientific & Technological Self-innovation Foundation (Program No.2016RC010) and the Chutian Scholars Fund Project to ZC, and Huazhong Agricultural University Scientific & Technological Self-innovation Foundation (Program No.2016QD026) to YW.

## References

- Antoniou C, Chatzimichail G, Xenofontos R, Pavlou JJ, Panagiotou E, Christou A, Fotopoulos V. 2017. Melatonin systemically ameliorates drought stress-induced damage in *Medicago sativa* plants by modulating nitro-oxidative homeostasis and proline metabolism. *Journal of Pineal Research* **62**, e12401.
- Arnao MB. 2014. Phytomelatonin: discovery, content, and role in plants. *Advances in Botany* **2014**, e815769.
- Arnao MB, Hernández-Ruiz J. 2007. Melatonin promotes adventitious- and lateral root regeneration in etiolated hypocotyls of *Lupinus albus* L. *Journal of Pineal Research* **42**, 147–152.
- Arnao MB, Hernández-Ruiz J. 2009. Protective effect of melatonin against chlorophyll degradation during the senescence of barley leaves. *Journal of Pineal Research* **46**, 58–63.
- Arnao MB, Hernández-Ruiz J. 2013. Growth conditions determine different melatonin levels in *Lupinus albus* L. *Journal of Pineal Research* **55**, 149–155.
- Arnao MB, Hernández-Ruiz J. 2014. Melatonin: plant growth regulator and/or biostimulator during stress? *Trends in Plant Science* **19**, 789–797.

- Arnao MB, Hernández-Ruiz J. 2015. Phytomelatonin: searching for plants with high levels as a natural source of nutraceuticals. In: Atta-ur-Rahman FRS, ed. *Studies in natural products chemistry (bioactive natural products)*, vol. **46**. Amsterdam, Netherlands: Elsevier Science Publishers, 519–545.
- Arnao MB, Hernández-Ruiz J. 2017a. Phyto-melatonin: a natural substance from plants with interesting nutraceutical properties. In: Motohashi N, ed. *Nutraceuticals: prospects, sources and role in health and disease*. New York: NOVA Science Publ., 123–157.
- Arnao MB, Hernández-Ruiz J. 2017b. Growth activity, rooting capacity, and tropism: three auxinin precepts fulfilled by melatonin. *Acta Physiologiae Plantarum* **39**, 127.
- Arnao MB, Hernández-Ruiz J. 2017c. Melatonin and its relationship to plant hormones. *Annals of Botany*. In press, doi:10.1093/aob/mcx114.
- Arora D, Bhatla SC. 2017. Melatonin and nitric oxide regulate sunflower seedling growth under salt stress accompanying differential expression of *Cu/Zn SOD* and *Mn SOD*. *Free Radical Biology & Medicine* **106**, 315–328.
- Bajwa VS, Shukla MR, Sherif SM, Murch SJ, Saxena PK. 2014. Role of melatonin in alleviating cold stress in *Arabidopsis thaliana*. *Journal of Pineal Research* **56**, 238–245.
- Balbi V, Devoto A. 2008. Jasmonate signalling network in *Arabidopsis thaliana*: crucial regulatory nodes and new physiological scenarios. *New Phytologist* **177**, 301–318.
- Byeon Y, Back K. 2016. Low melatonin production by suppression of either serotonin *N*-acetyltransferase or *N*-acetylserotonin methyltransferase in rice causes seedling growth retardation with yield penalty, abiotic stress susceptibility, and enhanced coleoptile growth under anoxic conditions. *Journal of Pineal Research* **60**, 348–359.
- Byeon Y, Lee HY, Hwang OJ, Lee HJ, Lee K, Back K. 2015. Coordinated regulation of melatonin synthesis and degradation genes in rice leaves in response to cadmium treatment. *Journal of Pineal Research* **58**, 470–478.
- Byeon Y, Park S, Kim YS, Back K. 2013. Microarray analysis of genes differentially expressed in melatonin-rich transgenic rice expressing a sheep serotonin *N*-acetyltransferase. *Journal of Pineal Research* **55**, 357–363.
- Byeon Y, Park S, Kim YS, Park DH, Lee S, Back K. 2012. Light-regulated melatonin biosynthesis in rice during the senescence process in detached leaves. *Journal of Pineal Research* **53**, 107–111.
- Calvo JR, González-Yanes C, Maldonado MD. 2013. The role of melatonin in the cells of the innate immunity: a review. *Journal of Pineal Research* **55**, 103–120.
- Chan Z, Shi H. 2015. Improved abiotic stress tolerance of bermudagrass by exogenous small molecules. *Plant Signaling & Behavior* **10**, e991577.
- Chen G, Huo Y, Tan DX, Liang Z, Zhang W, Zhang Y. 2003. Melatonin in Chinese medicinal herbs. *Life Sciences* **73**, 19–26.
- Chen Q, Qi WB, Reiter RJ, Wei W, Wang BM. 2009. Exogenously applied melatonin stimulates root growth and raises endogenous indoleacetic acid in roots of etiolated seedlings of *Brassica juncea*. *Journal of Plant Physiology* **166**, 324–328.
- Chen Z, Xie Y, Gu Q, Zhao G, Zhang Y, Cui W, Xu S, Wang R, Shen W. 2017. The *AtrbohF*-dependent regulation of ROS signaling is required for melatonin-induced salinity tolerance in *Arabidopsis*. *Free Radical Biology & Medicine* **108**, 465–477.
- Ding F, Wang M, Liu B, Zhang S. 2017. Exogenous melatonin mitigates photoinhibition by accelerating non-photochemical quenching in tomato seedlings exposed to moderate light during chilling. *Frontiers in Plant Science* **8**, 244.
- Dubbels R, Reiter RJ, Klenke E, Goebel A, Schnakenberg E, Ehlers C, Schiwara HW, Schloot W. 1995. Melatonin in edible plants identified by radioimmunoassay and by high performance liquid chromatography-mass spectrometry. *Journal of Pineal Research* **18**, 28–31.
- Erland LAE, Murch SH, Reiter RJ, Saxena PK. 2015. A new balancing act: the many roles of melatonin and serotonin in plant growth and development. *Plant Signaling & Behavior* **10**, e1096469.
- Feng X, Wang M, Zhao Y, Han P, Dai Y. 2014. Melatonin from different fruit sources, functional sources, and analytical methods. *Trends in Food Science & Technology* **37**, 21–31.
- Fu J, Wu Y, Miao Y, *et al.* 2017. Improved cold tolerance in *Elymus nutans* by exogenous application of melatonin may involve

- ABA-dependent and ABA-independent pathways. *Scientific Reports* **7**, 39865.
- Galano A, Tan DX, Reiter RJ.** 2011. Melatonin as a natural ally against oxidative stress: a physicochemical examination. *Journal of Pineal Research* **51**, 1–16.
- Garcia-Parrilla MC, Cantos E, Troncoso AM.** 2009. Analysis of melatonin in foods. *Journal of Food Composition and Analysis* **22**, 177–183.
- Gill SS, Tuteja N.** 2010. Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. *Plant Physiology and Biochemistry* **48**, 909–930.
- Gururani MA, Venkatesh J, Tran LS.** 2015. Regulation of photosynthesis during abiotic stress-induced photoinhibition. *Molecular Plant* **8**, 1304–1320.
- Hardeland R.** 2009. Melatonin: signaling mechanisms of a pleiotropic agent. *BioFactors* **35**, 183–192.
- Hardeland R, Balzer I, Poeggeler B, Fuhrberg B, Uria H, Behrmann G, Wolf R, Meyer TJ, Reiter RJ.** 1995. On the primary functions of melatonin in evolution: mediation of photoperiodic signals in a unicell, photooxidation, and scavenging of free radicals. *Journal of Pineal Research* **18**, 104–111.
- Hasan MK, Ahammed GJ, Yin L, Shi K, Xia X, Zhou Y, Yu J, Zhou J.** 2015. Melatonin mitigates cadmium phytotoxicity through modulation of phytochelatin biosynthesis, vacuolar sequestration, and antioxidant potential in *Solanum lycopersicum* L. *Frontiers in Plant Science* **6**, 601.
- Hattori A, Migita H, Iigo M, Itoh M, Yamamoto K, Ohtani-Kaneko R, Hara M, Suzuki T, Reiter RJ.** 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**, 627–634.
- Hernández-Ruiz J, Arnao MB.** 2016. Phytomelatonin, an interesting tool for agricultural crops. *Focus on Science* **2**, 1–7.
- Hernández-Ruiz J, Cano A, Arnao MB.** 2004. Melatonin: a growth-stimulating compound present in lupin tissues. *Planta* **220**, 140–144.
- Hernández-Ruiz J, Cano A, Arnao MB.** 2005. Melatonin acts as a growth-stimulating compound in some monocot species. *Journal of Pineal Research* **39**, 137–142.
- Hu Z, Fan J, Xie Y, Amombo E, Liu A, Gitau MM, Khaldun AB, Chen L, Fu J.** 2016. Comparative photosynthetic and metabolic analyses reveal mechanism of improved cold stress tolerance in bermudagrass by exogenous melatonin. *Plant Physiology and Biochemistry* **100**, 94–104.
- Huang X, Mazza G.** 2011. Application of LC and LC-MS to the analysis of melatonin and serotonin in edible plants. *Critical Reviews in Food Science and Nutrition* **51**, 269–284.
- Huang XS, Zhang Q, Zhu D, Fu X, Wang M, Zhang Q, Moriguchi T, Liu JH.** 2015. ICE1 of *Poncirus trifoliata* functions in cold tolerance by modulating polyamine levels through interacting with arginine decarboxylase. *Journal of Experimental Botany* **66**, 3259–3274.
- Janas KM, Posmyk MM.** 2013. Melatonin, an underestimated natural substance with great potential for agricultural application. *Acta Physiologicae Plantarum* **35**, 3285–3292.
- Jia W, Zhang J.** 2000. Water stress-induced abscisic acid accumulation in relation to reducing agents and sulfhydryl modifiers in maize plant. *Plant, Cell & Environment* **23**, 1389–1395.
- Kang K, Lee K, Park S, Byeon Y, Back K.** 2013. Molecular cloning of rice serotonin N-acetyltransferase, the penultimate gene in plant melatonin biosynthesis. *Journal of Pineal Research* **55**, 7–13.
- Kang K, Lee K, Park S, Kim YS, Back K.** 2010. Enhanced production of melatonin by ectopic overexpression of human serotonin N-acetyltransferase plays a role in cold resistance in transgenic rice seedlings. *Journal of Pineal Research* **49**, 176–182.
- Kapulinik Y, Koltai H.** 2014. Strigolactone involvement in root development, response to abiotic stress, and interactions with the biotic soil environment. *Plant Physiology* **166**, 560–569.
- Kocadağlı T, Yılmaz C, Gökmen V.** 2014. Determination of melatonin and its isomer in foods by liquid chromatography tandem mass spectrometry. *Food Chemistry* **153**, 151–156.
- Kolár J, Machácková I.** 2005. Melatonin in higher plants: occurrence and possible functions. *Journal of Pineal Research* **39**, 333–341.
- Kołodziejczyk I, Dzitko K, Szewczyk R, Posmyk MM.** 2016. Exogenous melatonin improves corn (*Zea mays* L.) embryo proteome in seeds subjected to chilling stress. *Journal of Plant Physiology* **193**, 47–56.
- Kostopoulou Z, Therios I, Roumeliotis E, Kanellis AK, Molassiotis A.** 2015. Melatonin combined with ascorbic acid provides salt adaptation in *Citrus aurantium* L. seedlings. *Plant Physiology and Biochemistry* **86**, 155–165.
- Koyama FC, Carvalho TL, Alves E, da Silva HB, de Azevedo MF, Hemerly AS, Garcia CR.** 2013. The structurally related auxin and melatonin tryptophan-derivatives and their roles in *Arabidopsis thaliana* and in the human malaria parasite *Plasmodium falciparum*. *The Journal of Eukaryotic Microbiology* **60**, 646–651.
- Lazár D, Murch SJ, Beilby MJ, Al Khazaaly S.** 2013. Exogenous melatonin affects photosynthesis in Characeae *Chara australis*. *Plant Signaling & Behavior* **8**, e23279.
- Lee HY, Byeon Y, Lee K, Lee HJ, Back K.** 2014. Cloning of *Arabidopsis* serotonin N-acetyltransferase and its role with caffeic acid O-methyltransferase in the biosynthesis of melatonin *in vitro* despite their different subcellular localizations. *Journal of Pineal Research* **57**, 418–426.
- Lee SC, Lim CW, Lan W, He K, Luan S.** 2013. ABA signaling in guard cells entails a dynamic protein–protein interaction relay from the *PYL-RCAR* family receptors to ion channels. *Molecular Plant* **6**, 528–538.
- Lei XY, Zhu RY, Zhang GY *et al.*** 2004. Attenuation of cold induced apoptosis by exogenous melatonin in carrot suspension cells: the possible involvement of polyamines. *Journal of Pineal Research* **36**, 126–131.
- 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**, 2587.
- Li C, Liang B, Chang C, Wei Z, Zhou S, Ma F.** 2016a. Exogenous melatonin improved potassium content in *Malus* under different stress conditions. *Journal of Pineal Research* **61**, 218–229.
- Li C, Tan DX, Liang D, Chang C, Jia D, Ma F.** 2015. Melatonin mediates the regulation of ABA metabolism, free-radical scavenging, and stomatal behaviour in two *Malus* species under drought stress. *Journal of Experimental Botany* **66**, 669–680.
- Li C, Wang P, Wei Z, Liang D, Liu C, Yin L, Jia D, Fu M, Ma F.** 2012. The mitigation effects of exogenous melatonin on salinity-induced stress in *Malus hupehensis*. *Journal of Pineal Research* **53**, 298–306.
- Li H, Chang J, Zheng J, *et al.*** 2017a. Local melatonin application induces cold tolerance in distant organs of *Citrullus lanatus* L. via long distance transport. *Scientific Reports* **7**, 40858.
- Li H, Dong Y, Chang J, *et al.*** 2016b. High-throughput MicroRNA and mRNA sequencing reveals that MicroRNAs may be involved in melatonin-mediated cold tolerance in *Citrullus lanatus* L. *Frontiers in Plant Science* **7**, 1231.
- Li X, Tan DX, Jiang D, Liu F.** 2016c. Melatonin enhances cold tolerance in drought-primed wild-type and abscisic acid-deficient mutant barley. *Journal of Pineal Research* **61**, 328–339.
- Li X, Yu B, Cui Y, Yin Y.** 2017b. Melatonin application confers enhanced salt tolerance by regulating Na<sup>+</sup> and Cl<sup>-</sup> accumulation in rice. *Plant Growth Regulation* **83**, 441–454.
- Liang C, Li A, Yu H, Li W, Liang C, Guo S, Zhang R, Chu C.** 2017. Melatonin regulates root architecture by modulating auxin response in rice. *Frontiers in Plant Science* **8**, 134.
- Liang C, Wang Y, Zhu Y, *et al.*** 2014. *OsNAP* connects abscisic acid and leaf senescence by fine-tuning abscisic acid biosynthesis and directly targeting senescence-associated genes in rice. *Proceedings of the National Academy of Sciences, USA* **111**, 10013–10018.
- Liang C, Zheng G, Li W, *et al.*** 2015. Melatonin delays leaf senescence and enhances salt stress tolerance in rice. *Journal of Pineal Research* **59**, 91–101.
- Lin A, Wang Y, Tang J, *et al.*** 2012. Nitric oxide and protein S-nitrosylation are integral to hydrogen peroxide-induced leaf cell death in rice. *Plant Physiology* **158**, 451–464.
- Liu J, Wang W, Wang L, Sun Y.** 2015. Exogenous melatonin improves seedling health index and drought tolerance in tomato. *Plant Growth Regulation* **77**, 317–326.
- Manchester LC, Coto-Montes A, Boga JA, Andersen LP, Zhou Z, Galano A, Vriend J, Tan DX, Reiter RJ.** 2015. Melatonin: an ancient

molecule that makes oxygen metabolically tolerable. *Journal of Pineal Research* **59**, 403–419.

**Manchester LC, Tan DX, Reiter RJ, Park W, Monis K, Qi W.** 2000. High levels of melatonin in the seeds of edible plants: possible function in germ tissue protection. *Life Sciences* **67**, 3023–3029.

**Meng JF, Xu TF, Wang ZZ, Fang YL, Xi ZM, Zhang ZW.** 2014. The ameliorative effects of exogenous melatonin on grape cuttings under water-deficient stress: antioxidant metabolites, leaf anatomy, and chloroplast morphology. *Journal of Pineal Research* **57**, 200–212.

**Mukherjee S, David A, Yadav S, Baluška F, Bhatla SC.** 2014. Salt stress-induced seedling growth inhibition coincides with differential distribution of serotonin and melatonin in sunflower seedling roots and cotyledons. *Physiologia Plantarum* **152**, 714–728.

**Nawaz MA, Huang Y, Bie Z, Ahmed W, Reiter RJ, Niu M, Hameed S.** 2015. Melatonin: current status and future perspectives in plant science. *Frontiers in Plant Science* **6**, 1230.

**Noctor G, Mhamdi A, Foyer CH.** 2014. The roles of reactive oxygen metabolism in drought: not so cut and dried. *Plant Physiology* **164**, 1636–1648.

**Park S, Back K.** 2012. Melatonin promotes seminal root elongation and root growth in transgenic rice after germination. *Journal of Pineal Research* **53**, 385–389.

**Park S, Lee DE, Jang H, Byeon Y, Kim YS, Back K.** 2013. Melatonin-rich transgenic rice plants exhibit resistance to herbicide-induced oxidative stress. *Journal of Pineal Research* **54**, 258–263.

**Pelagio-Flores R, Muñoz-Parra E, Ortiz-Castro R, López-Bucio J.** 2012. Melatonin regulates Arabidopsis root system architecture likely acting independently of auxin signaling. *Journal of Pineal Research* **53**, 279–288.

**Posmyk MM, Bałabusta M, Wieczorek M, Sliwinska E, Janas KM.** 2009. Melatonin applied to cucumber (*Cucumis sativus* L.) seeds improves germination during chilling stress. *Journal of Pineal Research* **46**, 214–223.

**Ramakrishna A, Giridhar P, Sankar KU, Ravishankar GA.** 2012. Melatonin and serotonin profiles in beans of *Coffea* species. *Journal of Pineal Research* **52**, 470–476.

**Reiter RJ, Tan DX, Zhou Z, Cruz MH, Fuentes-Broto L, Galano A.** 2015. Phytomelatonin: assisting plants to survive and thrive. *Molecules* **20**, 7396–7437.

**Sarropoulou V, Dimassi-Theriou K, Therios I, Koukourikou-Petridou M.** 2012a. Melatonin enhances root regeneration, photosynthetic pigments, biomass, total carbohydrates and proline content in the cherry rootstock PHL-C (*Prunus avium* × *Prunus cerasus*). *Plant Physiology and Biochemistry* **61**, 162–168.

**Sarropoulou VN, Therios IN, Dimassi-Theriou KN.** 2012b. Melatonin promotes adventitious root regeneration in *in vitro* shoot tip explants of the commercial sweet cherry rootstocks CAB-6P (*Prunus cerasus* L.), Gisela 6 (*P. cerasus* × *P. canescens*), and MxM 60 (*P. avium* × *P. mahaleb*). *Journal of Pineal Research* **52**, 38–46.

**Shi H, Chan Z.** 2014. The cysteine2/histidine2-type transcription factor ZINC FINGER OF ARABIDOPSIS THALIANA 6-activated C-REPEAT-BINDING FACTOR pathway is essential for melatonin-mediated freezing stress resistance in *Arabidopsis*. *Journal of Pineal Research* **57**, 185–191.

**Shi H, Jiang C, Ye T, Tan DX, Reiter RJ, Zhang H, Liu R, Chan Z.** 2015a. Comparative physiological, metabolomic, and transcriptomic analyses reveal mechanisms of improved abiotic stress resistance in bermudagrass [*Cynodon dactylon* (L.) Pers.] by exogenous melatonin. *Journal of Experimental Botany* **66**, 681–694.

**Shi H, Reiter RJ, Tan DX, Chan Z.** 2015b. *INDOLE-3-ACETIC ACID INDUCIBLE 17* positively modulates natural leaf senescence through melatonin-mediated pathway in *Arabidopsis*. *Journal of Pineal Research* **58**, 26–33.

**Shi H, Tan DX, Reiter RJ, Ye T, Yang F, Chan Z.** 2015c. Melatonin induces class A1 heat shock factors (*HSFA1s*) and their possible involvement of thermotolerance in *Arabidopsis*. *Journal of Pineal Research* **58**, 335–342.

**Shi H, Wang X, Tan DX, Reiter RJ, Chan Z.** 2015d. Comparative physiological and proteomic analyses reveal the actions of melatonin in the reduction of oxidative stress in Bermuda grass (*Cynodon dactylon* (L.) Pers.). *Journal of Pineal Research* **59**, 120–131.

**Song Y, Miao Y, Song CP.** 2014. Behind the scenes: the roles of reactive oxygen species in guard cells. *New Phytologist* **201**, 1121–1140.

**Stürtz M, Cerezo AB, Cantos-Villar E, Garcia-Parrilla MC.** 2011. Determination of the melatonin content of different varieties of tomatoes (*Lycopersicon esculentum*) and strawberries (*Fragaria ananassa*). *Food Chemistry* **127**, 1329–1334.

**Sun Q, Zhang N, Wang J, Cao Y, Li X, Zhang H, Zhang L, Tan DX, Guo YD.** 2016. A label-free differential proteomics analysis reveals the effect of melatonin on promoting fruit ripening and anthocyanin accumulation upon postharvest in tomato. *Journal of Pineal Research* **61**, 138–153.

**Sun Q, Zhang N, Wang J, et al.** 2015. Melatonin promotes ripening and improves quality of tomato fruit during postharvest life. *Journal of Experimental Botany* **66**, 657–668.

**Tan DX, Hardeland R, Manchester LC, Korkmaz A, Ma S, Rosales-Corral S, Reiter RJ.** 2012. Functional roles of melatonin in plants, and perspectives in nutritional and agricultural science. *Journal of Experimental Botany* **63**, 577–597.

**Tan DX, Manchester LC, Terron MP, Flores LJ, Reiter RJ.** 2007. One molecule, many derivatives: a never-ending interaction of melatonin with reactive oxygen and nitrogen species? *Journal of Pineal Research* **42**, 28–42.

**Tiryaki I, Keles H.** 2012. Reversal of the inhibitory effect of light and high temperature on germination of *Phacelia tanacetifolia* seeds by melatonin. *Journal of Pineal Research* **52**, 332–339.

**Turk H, Erdal S.** 2015. Melatonin alleviates cold-induced oxidative damage in maize seedlings by up-regulating mineral elements and enhancing antioxidant activity. *Journal of Plant Nutrition and Soil Science* **178**, 433–439.

**Turk H, Erdal S, Genisel M, Atici O, Demir Y, Yanmis D.** 2014. The regulatory effect of melatonin on physiological, biochemical and molecular parameters in cold-stressed wheat seedlings. *Plant Growth Regulation* **74**, 139–152.

**Venegas C, García JA, Escames G, et al.** 2012. Extrapineal melatonin: analysis of its subcellular distribution and daily fluctuations. *Journal of Pineal Research* **52**, 217–227.

**Wang L, Feng C, Zheng X, Guo Y, Zhou F, Shan D, Liu X, Kong J.** 2017. Plant mitochondria synthesize melatonin and enhance the tolerance of plants to drought stress. *Journal of Pineal Research* **63**, e12429.

**Wang L, Zhao Y, Reiter RJ, et al.** 2014a. Changes in melatonin levels in transgenic ‘Micro-Tom’ tomato overexpressing ovine AANAT and ovine HIOMT genes. *Journal of Pineal Research* **56**, 134–142.

**Wang LY, Liu JL, Wang WX, Sun Y.** 2016a. Exogenous melatonin improves growth and photosynthetic capacity of cucumber under salinity-induced stress. *Photosynthetica* **54**, 19–27.

**Wang P, Sun X, Chang C, Feng F, Liang D, Cheng L, Ma F.** 2013a. Delay in leaf senescence of *Malus hupehensis* by long-term melatonin application is associated with its regulation of metabolic status and protein degradation. *Journal of Pineal Research* **55**, 424–434.

**Wang P, Sun X, Li C, Wei Z, Liang D, Ma F.** 2013b. Long-term exogenous application of melatonin delays drought-induced leaf senescence in apple. *Journal of Pineal Research* **54**, 292–302.

**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**, 479–489.

**Wang P, Sun X, Xie Y, Li M, Chen W, Zhang S, Liang D, Ma F.** 2014b. Melatonin regulates proteomic changes during leaf senescence in *Malus hupehensis*. *Journal of Pineal Research* **57**, 291–307.

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

**Wang Q, An B, Wei Y, Reiter RJ, Shi H, Luo H, He C.** 2016b. Melatonin regulates root meristem by repressing auxin synthesis and polar auxin transport in *Arabidopsis*. *Frontiers in Plant Science* **7**, 1882.

**Weeda S, Zhang N, Zhao X, Ndip G, Guo Y, Buck GA, Fu C, Ren S.** 2014. Arabidopsis transcriptome analysis reveals key roles of melatonin in plant defense systems. *PLoS ONE* **9**, e93462.

**Wei W, Li QT, Chu YN, et al.** 2015. Melatonin enhances plant growth and abiotic stress tolerance in soybean plants. *Journal of Experimental Botany* **66**, 695–707.

**Wen D, Gong B, Sun S, Liu S, Wang X, Wei M, Yang F, Li Y, Shi Q.** 2016. Promoting roles of melatonin in adventitious root development of



*Solanum lycopersicum* L. by regulating auxin and nitric oxide signaling. *Frontiers in Plant Science* **7**, 718.

**Xu W, Cai SY, Zhang Y, et al.** 2016. Melatonin enhances thermotolerance by promoting cellular protein protection in tomato plants. *Journal of Pineal Research* **61**, 457–469.

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

**Yuan S, Guan C, Liu S, Huang Y, Tian D, Cui X, Zhang Y, Yang F.** 2016a. Comparative transcriptomic analyses of differentially expressed genes in transgenic melatonin biosynthesis ovine *H1OMT* gene in switchgrass. *Frontiers in Plant Science* **7**, 1613.

**Yuan S, Huang Y, Liu S, Guan C, Cui X, Tian D, Zhang Y, Yang F.** 2016b. RNA-seq analysis of overexpressing ovine *AANAT* gene of melatonin biosynthesis in switchgrass. *Frontiers in Plant Science* **7**, 1289.

**Zhang HJ, Zhang N, Yang RC, et al.** 2014a. Melatonin promotes seed germination under high salinity by regulating antioxidant systems, ABA and GA<sub>4</sub> interaction in cucumber (*Cucumis sativus* L.). *Journal of Pineal Research* **57**, 269–279.

**Zhang J, Shi Y, Zhang X, Du H, Xu B, Huang B.** 2017a. Melatonin suppression of heat-induced leaf senescence involves changes in abscisic acid and cytokinin biosynthesis and signaling pathways in perennial ryegrass (*Lolium perenne* L.). *Environmental and Experimental Botany* **138**, 36–45.

**Zhang N, Sun Q, Zhang H, Cao Y, Weeda S, Ren S, Guo YD.** 2015. Roles of melatonin in abiotic stress resistance in plants. *Journal of Experimental Botany* **66**, 647–656.

**Zhang N, Zhang HJ, Sun QQ, Cao YY, Li X, Zhao B, Wu P, Guo YD.** 2017b. Proteomic analysis reveals a role of melatonin in promoting cucumber seed germination under high salinity by regulating energy production. *Scientific Reports* **7**, 503.

**Zhang N, Zhang HJ, Zhao B, et al.** 2014b. The RNA-seq approach to discriminate gene expression profiles in response to melatonin on cucumber lateral root formation. *Journal of Pineal Research* **56**, 39–50.

**Zhang N, Zhao B, Zhang HJ, Weeda S, Yang C, Yang ZC, Ren S, Guo YD.** 2013. Melatonin promotes water-stress tolerance, lateral root formation, and seed germination in cucumber (*Cucumis sativus* L.). *Journal of Pineal Research* **54**, 15–23.

**Zhao H, Su T, Huo L, Wei H, Jiang Y, Xu L, Ma F.** 2015. Unveiling the mechanism of melatonin impacts on maize seedling growth: sugar metabolism as a case. *Journal of Pineal Research* **59**, 255–266.

**Zhao H, Zhang K, Zhou X, Xi L, Wang Y, Xu H, Pan T, Zou Z.** 2017. Melatonin alleviates chilling stress in cucumber seedlings by up-regulation of *CsZat12* and modulation of polyamine and abscisic acid metabolism. *Scientific Reports* **7**, 4998.

**Zhao Y, Chan Z, Gao J, et al.** 2016. The ABA receptor *PYL9* promotes drought resistance and leaf senescence. *Proceedings of the National Academy of Sciences, USA* **113**, 1949–1954.

**Zuo B, Zheng X, He P, et al.** 2014. Overexpression of *MzASMT* improves melatonin production and enhances drought tolerance in transgenic *Arabidopsis thaliana* plants. *Journal of Pineal Research* **57**, 408–417.