Nitric Oxide 82 (2019) 25–34

Contents lists available at ScienceDirect

Nitric Oxide

journal homepage: www.elsevier.com/locate/yniox

Recent advancements in the mechanism of nitric oxide signaling associated with hydrogen sulfide and melatonin crosstalk during ethylene-induced fruit ripening in plants

Soumya Mukherjee

Department of Botany, Jangipur College, University of Kalyani, West Bengal, 742213, India

ARTICLE INFO

Keywords:
Nitric oxide
Hydrogen sulphide
Melatonin
Ethylene
Climacteric fruit ripening

ABSTRACT

The current review focuses on the significant role of nitric oxide (NO) in modulating ethylene-induced fruit ripening responses in plants. In this context, hydrogen sulfide (H_2S) and melatonin mediated crosstalk mechanisms have been discussed with recent updates. Physiological and biochemical events associated with climacteric fruit ripening involves a plethora of effects mediated by these biomolecules. In the last few years of progress in fruit ripening physiology, the involvement of hydrogen sulfide in relation to NO remains as a nascent field of research. The importance of nitric oxide as a freely diffusible and membrane permeable biomolecule leads to its applications in post-harvest fruit storage. The process of field to market transition of edible fruits involves various intermediate stages of post-harvest storage and transport. Fruits harvested in the pre-climacteric stage are intended to be stored and transported for longer durations. However, this does not confer proper development of aroma and flavor in the post-harvest stages. Nitric oxide and ethylene crosstalk is mediated by hydrogen sulfide and melatonin activity which regulate various metabolic pathways associated with fruit ripening. A surge in the reactive nitrogen species (RNS), sugar metabolism, and plastid biogenesis are the plausible effects of NO-ethylene crosstalk. NO-mediated regulations of carbon metabolism and phytohormone levels are essential components of fruit ripening process. Melatonin by the virtue of its functional group possesses strong anti-oxidative properties. Recent updates suggest crosstalk mechanisms associated with melatonin-ethylene and nitric oxide in plants. The present review briefly summarizes the current understandings of fruit ripening physiology manifested by the effects of NO, H_2S and melatonin signaling. The agri-horticultural applications of exogenous NO/H_2S donors and melatonin treatment impose major benefits for delaying postharvest fruit senescence.

1. Introduction

Physiological and biochemical events associated with climacteric fruit ripening involves a plethora of effects mediated by various biomolecules. The surge in respiration rate manifested by a burst in CO_2 levels was initially suggested to be indicative of climacteric fruit ripening [1]. However, later investigations confirmed its association with the signaling responses triggered by ethylene [2]. Ripening process in non-climacteric fruits is subject to regulation by several other endogenous factors which are yet to be deciphered with clarity. Rich literature sources are available for the understanding of fruit ripening mechanisms in response to ethylene and nitric oxide signaling. However, a lacuna lies in summarising the interactions between ethylene, nitric oxide, H_2S and melatonin in the context of fruit ripening process. Edible fruit varieties with good flavor and aroma bear agri-horticultural importance across the continents. The process of fruit ripening is regulated by various endogenous and exogenous factors like hormone activity, temperature, and light perception. In the last few years of progress in fruit ripening investigations, nitric oxide has been stated to be an important biomolecule regulating senescence in ripening fruits [3–5]. In this context, it is worth mentioning that nitric oxide delays the process of fruit ripening by inhibiting ethylene biosynthesis and blocking its downstream response [6]. The importance of nitric oxide as a freely diffusible and membrane permeable biomolecule leads to its applications in post harvest fruit storage. The process of field to market transition of edible fruits involves various intermediate stages of post-harvest storage and transport. Fruits harvested in the pre-climacteric stage are intended to be stored and transported for longer durations.

Abbreviations: Reactive oxygen species, ROS; Nitric oxide, NO; Melatonin, Mel; Ethylene response factor, ERF; Nuclear localization signal, NLS; Jasmonates, JA; γ-aminobutyric acid transaminase, GABA-T; 1-aminocyclopropane-1-carboxylic acid, ACC

E-mail address: soumobios@gmail.com.

https://doi.org/10.1016/j.niox.2018.11.003
Received 23 September 2018; Received in revised form 11 October 2018; Accepted 18 November 2018
Available online 19 November 2018

However, this does not confer proper development of aroma and flavor in the post harvest stages. Differential sensitivity of fruits to exogenous ethylene in the post-harvest stage appears to be a plausible reason for the variation in their flavor and aroma. Thus, improvement of post-harvest shelf-life and prevention of pathogen attack are the two major concerns for fruit breeders and suppliers. Nitric oxide and ethylene crosstalk regulate various metabolic pathways associated with fruit ripening. Alterations in the amount of reactive nitrogen species, sugar metabolism, and plastid biogenesis are the plausible effects of NO-ethylene crosstalk [6–8]. Hydrogen sulfide (H_2S) has emerged as an important gasotransmitter in plants [9]. Among various physiological effects regulated by H_2S, it has been reported to modulate fruit ripening associated with ethylene and NO response [10]. H_2S and NO are likely to be involved in nitrothiol formation which serves as an important source of NO reserve in the cells. Melatonin is another potent biomolecule to be considered as a putative phytohormone [11]. Many recent investigations across a couple of years have revealed interesting results in the context of melatonin regulated fruit ripening processes. Melatonin shares structural similarities to serotonin and auxin. Moreover, it bears strong antioxidant abilities attained by the virtue of its functional groups. Recent updates suggest crosstalk mechanisms associated with melatonin, ethylene and nitric oxide in plants [12]. The agri-horticultural applications of exogenous NO/H_2S donors and melatonin treatment impose major benefits for delaying post-harvest fruit senescence. The recent developments in the investigations of receptor-mediated ethylene response and gene regulation are primary factors modulating fruit development. Identification and quantification of various volatile substances have proved beneficial as commercial attributes. Metabolomic approaches have been implied to decipher multiple events associated with ethylene, H_2S, NO and melatonin-induced fruit ripening. The present review, therefore, briefly summarizes the recent developments in the aspect of fruit ripening manifested by the effect of NO-ethylene, H_2S and melatonin signaling (Fig. 1).

2. Transcriptional regulation of ethylene signaling

Ethylene responses are largely transduced by a diverse set of transcription factors namely ethylene response factor (ERF) encoded by a single gene family [13]. Liu et al. [13] also suggested the orchestration of transcriptional network regulated by ethylene. Major investigations in tomato (*Solanum lycopersicum*) have revealed latest updates on the transcriptomic regulation of ethylene-induced fruit ripening [14]. The advancements in the investigations of ethylene-mediated ripening response have deciphered gene regulation, transcriptional regulation and downstream signaling cascade associated with fruit ripening. This signaling network manifests through changes in fruit wall texture, pigmentation pattern, taste, and aroma of fruits in the course of their developmental process [15–18]. Ethylene biosynthesis in plants initiates from S-adenosyl-Methionine which further involves the conversion of 1-aminocyclopropane-1-carboxylic acid (ACC) into ethylene [19]. Ethylene biosynthesis is catalyzed by two enzymes, ACC synthase (ACS; EC 4.4.1.14) and ACC oxidase (ACO; EC 1.14.17.4). ACS catalyzes the conversion of S-adenosylmethionine to 1-aminocyclopropane-1-carboxylate followed by its further conversion to ethylene catalyzed by ACC oxidase. The regulation of ethylene biosynthesis and its activity has been reported to exhibit tissue-specific differential expression in tomato fruit [20]. The RIN-MADS element has been reported to regulate ethylene biosynthesis genes namely *LeACS2* (1-aminocyclopropane-1-carboxylic acidsynthase 2), *LeACS4*, *LeACO1* (ACCoxidase1) [21–25]. Seven receptor genes have been identified and characterized for ethylene response in tomato [25–29]. Kamiyoshihara et al. [30] reported a surge in the levels of *LeETR3* and *LeETR4* at ripening stages. Largely the ethylene receptor proteins have been suggested to be regulated by post-translational changes and phosphorylation-dephosphorylation mechanisms [30,31]. Mitogen-activated protein kinase (CTR1) is another important component which acts as a negative regulator of ethylene downstream in its action. Ethylene response factors (ERF) are a set of secondary regulators which transduce the ethylene-mediated response to various downstream ripening associated genes. Ripening-associated ERF genes have been reported to exhibit differential expression in the process of fruit developmental stages [32]. Epigenetic regulation of ethylene response involves DNA demethylation to be an essential part of the signal cascade. This further allows RIN protein binding to ethylene responsive genes [33]. Complex interactions have been suggested to be operative for hormonal associations of ethylene in the context of fruit ripening [34,35]. The onset of fruit ripening and associated chromoplast biogenesis is attained by the precise coordination of nuclear-plastid signaling [36].

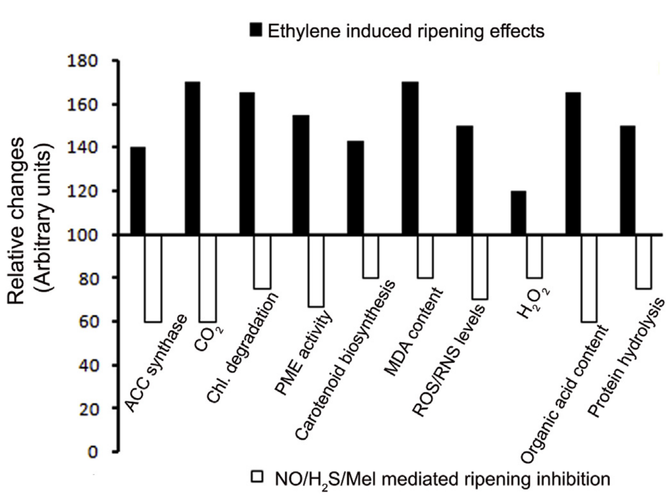

Fig. 1. Graphical representation of the antagonistic effects of NO, H_2S and Mel. in ethylene-induced fruit ripening inhibition. Relative change in the parameters have been expressed in arbitrary units.

3. Ethylene-induced regulation of fruit ripening atmosphere

Among various attributes essential for adding commercial values to fruits, aroma and sugar content are important traits. Metabolism of branched-chain fatty acids and low molecular weight amino acids (< 250 Da) are accountable for the emission of volatile aromatic substances in ripening fruits [37–39]. Advancements in the gas chromatographic analysis have led to the documentation of more than 300 volatile substances responsible for aromatic flavor in various fruits. The role of ethylene in the emission of aromatic substances at the mature stage of fruit ripening mostly depends upon the oxygen and carbon dioxide levels in the internal and external atmosphere of the fruit. Apart from that, acetaldehyde, water vapour, methyl salicylate, methyl jasmonate and nitric oxide (NO) have also been attributed to regulate the ripening process [40]. The emission of volatile substances at the fruit-atmosphere interface mostly occurs through epidermal cuticle, stomata, abscessed layers or lenticels. The sensitivity of ethylene treatment at the post-harvest stage largely regulates fruit texture, sugar-acid ratio and residual aroma [41]. A decrease in ethylene content or low oxygen in the external atmosphere of fruits inhibits the emission of volatile compounds. This results in a decreased aroma of fruits. Interesting analysis by Bangerth [41] reveals different signaling pathways to be associated with ethylene perception and aromatic substance metabolism. Thus in this context, it is important to consider the ripening-atmosphere and duration of post-harvest storage as important determinants of ripened fruit quality. Nevertheless, the age of harvested fruits regulate the threshold of ethylene sensitivity. Comparison of climacteric (apple) and non-climacteric (strawberry) fruits on the basis of volatile aroma liberation and fatty acid metabolism do not exhibit much difference. Thus respiration surge and ethylene response pathways are not intimately coupled to the volatile metabolite production. Bangerth

(2012) [41] summarizes that autocatalytic ethylene biosynthesis triggers epigenetic changes responsible for fruit ripening. Plum (*Prunus domestica* L.) fruits have been reported to exhibit differential ethylene and CO_2 emission as a climacteric response in different cultivars [42]. The differences observed were directly proportional to the skin firmness of fruits in early and late ripening cultivars. Extensive and critical review of the role of various volatiles participating in fruit ripening process has been summarized by Paul and Pandey [40]. Interesting observations in Kiwi fruits (*Actinidia* sp.) revealed certain differences in the metabolite profile of ethylene-induced natural and artificial ripening [43]. However, these observations didn't negate the possibility of obtaining a good output with exogenous ethylene treatments.

4. Peptide targeted inhibition of ethylene signaling

ETHYLENE INSENSITIVE 2 (EIN2) is an important ER-localized membrane protein which exhibits partial interaction with ETHYLENE RESPSONSE 1 component to transduce ethylene-mediated responses [44]. The success of this protein-protein interaction is regulated by a nuclear localization signal (NLS) present in the C-terminus of the EIN2 protein. Considering the fact that exogenous ethylene response provides immense commercial importance, recent developments have been reported for manipulation of fruit shelf-life extension. Bisson et al. [45] reported NOP-1 peptide to disrupt EIN2-ETR1 complex formation in tomato. The authors reported that NLS motif of EIN component in Arabidopsis helps in the coupling of EIN to downstream ethylene sensing components. In this context, EIN-ETR binding was surrogated by a small octa-peptide (NOP 1) having NLS like motif and derived from Arabidopsis EIN2 protein. Interestingly the exogenous application of this peptide reduced ethylene induced fruit ripening in tomato. The mechanism of inhibition was found to be similar in Arabidopsis and tomato plants. Surface application of NOP 1 was found to beneficial in ripening inhibition in tomato fruits thus indicating its permeability across cell membranes. Furthermore, the agricultural application of NOP-1 peptide was manifested by its better efficacy in comparison to other commercial ethylene inhibitors. This peptide did not exhibit any inhibitory effect on the pathway of ethylene biosynthesis. Considering the fact that EIN2-ETR binding event is consensus to ethylene component the authors also anticipate similar responses of the peptide in other climacteric fruits and vegetables. Kessenbrock et al. [46] reported NOP-1 induced delayed accumulation of lycopene and carotene in tomato fruit pulp which did not impose any negative impact on the fruit quality. This protein exhibited successful binding to ethylene receptors LeETR4 and NR. Protein-protein interaction in relation with ethylene signaling investigated by FRET, CD spectroscopy and other methods have thus reported the success of peptide application. The NLF motif of EIN2 is conserved among plant kingdoms. Thus stable mechanisms can be designed for peptide molecules to act as ripening inhibitors. Limitations of optimum post-harvest storage conditions often impose problem in obtaining an acceptable quality of ripened fruits. Chemical treatments used to delay ripening processes share certain backdrops like reduction in taste, less softening of fruits and poor aroma development. Peptide applications do not interfere with ethylene biosynthesis and, therefore, can be substituted with other chemical inhibitors. Tadiello et al. [47] reported the use of CTG 134 GOLVEN like peptide hormone to be necessary for maintaining auxin-ethylene balance in ripening peach fruits. Application of 1-methylcyclopropene (1-MCP) was alone, not sufficient to delay the ripening process as it increased the auxin levels. Thus CTG134 peptide circumvented the effect of 1-MCP.

5. Nitric oxide and fruit ripening

Nitric oxide is a freely diffusible membrane permeable signaling molecule in plants. It exerts diverse physiological and molecular effects associated with growth, development and cellular homeostasis [48,49]. Plants can biosynthesize NO through various enzymatic and non-enzymatic pathways [50]. Extensively studied mechanisms of NO generation involve cytosolic nitrate/nitrite reductase activity which produces nitrite from nitrate [51]. Nitrite is further metabolized to liberate NO. Mitochondrial electron transport process has also been reported to liberate NO at low oxygen conditions [52,53]. A Putative activity of nitric oxide synthase (NOS) has been detected in plant tissues [54]. The malleability of NOS activity has been tested by L-arginine-induced NO production, and counter reduction by respective NOS inhibitors [55]. Polyamine metabolism, S-nitrosoglutathione reductase activity and mitochondrial scavenging also regulate NO levels in plants [49,52,53,56].

Among various effects of NO in plants, fruit ripening has been found to be variably modulated through NO-induced signaling pathways. NO has been reported to delay senescence of ripening fruits in various plant systems. Peach fruits have been reported to retain pericarp integrity upon exposure to NO [57,58]. This has been attributed to a NO-induced reduction in cell wall loosening, maintenance of cell membrane compactness and reduced electrolyte leakage from the tissue [58]. NO has been associated with an increased shelf-life of various harvested pre-climacteric fruits as reported in banana, kiwi and tomato [6,59–61]. The effects of NO also extend to the non-climacteric process of fruit ripening [60, 63]. Ripening induced pulp degradation, pericarp browning and degradation of antioxidants have been reported to be prevented by NO applications. NO-fumigation subsequently reduced cold storage associated damage in Japanese plums (*Prunus salicina* Lindell) [64]. NO-induced reduction in pericarp browning in longan fruit primarily operates through the reduction in the activity of polyphenol oxidase [3]. NO surge in cherry tomato fruit tissue increases as a result of an application of methyl salicylate [65]. This mechanism has been associated with improved chilling tolerance. In most of the investigations sodium nitroprusside (SNP; 0.5–1 mM) has been implied as a successful NO donor. Manjunatha [5] reported a decrease in climacteric respiration in banana manifested as an effect of NO application. Interesting reports on the role of endogenous NO in fruit ripening has been investigated in mango [66]. UV-B treatment in mango fruits enhanced endogenous NO levels resulting in alleviation of chilling injuries [66]. Ripening fruits like pepper exhibit higher ascorbic acid levels attained by NO-induced elevation of the galactono-1,4-lactone dehydrogenase (GalLDH) activity [67]. NO-mediated regulation of carbon metabolism and phytohormone levels have been essential for fruit ripening in *short root* (*shr*) mutant (NO hyperaccumulation) of tomato [68]. Physiological effects of post-harvest treatment of NO have been investigated in persimmon [69]. TCA cycle intermediates for the *shr* mutant were observed to be differentially regulated in comparison with that of wild type members (68).

Nitric oxide in the course of fruit ripening largely regulates the activity of various phytohormones including ethylene. NO possess potent anti-stress properties by the virtue of its antioxidant elevation effects. Thus, SA and NO act complementary in reducing senescence during ripening fruits. NO signaling associates with SA to jointly inhibit ethylene biosynthesis. NO functioning in fruit ripening also operates as a function of ROS and free radical generation which in turn is also affected by SA action. Lipoxygenase activity is another important parameter to be accessed in relation to NO signaling in fruit ripening. The relationships of NO with auxin, GA, cytokinin, and polyamines in the context of fruit ripening are not, however, obscure.

6. Nitric oxide-ethylene crosstalk during fruit ripening operates through partial inhibition of ethylene biosynthesis

Investigations have confirmed the role of nitric oxide in modulating ethylene response during pre and post-climacteric stages of fruit ripening. Interestingly, nitric oxide binds to ACC oxidase enzyme and forms a stable ternary 'ACC-ACC oxidase-NO' complex. This signaling event results in a reduction in ethylene production in tissues [70]. Apple fruits have been observed to exhibit an exponential reduction in ethylene production manifested by linear gradation of SNP/NO gas application [71]. This ascertains the dose-dependent mechanism of NO binding with ACC oxidase. Peach fruits treated with simultaneous ethylene and NO donors led to a reduction of ethylene accumulation [57]. This reduction in ethylene content was attributed to decreased ACC levels due to NO-induced inhibition of ACC synthase. NO-induced complex transcriptional and post-transcriptional regulation of ACC synthase has been reported in the context of fruit ripening. However, NO induced regulation of ethylene biosynthesis operates through both ACC oxidase and ACC synthase activity modulation. Application of exogenous NO to pre-ripened *Mangifera indica* L. cv. 'Kensington Pride' fruits revealed changes in the levels of ACC and modulated the activity of ACC synthase and ACC oxidase, respectively [6]. Application of post-harvest NO treatment and subsequent proteomic analysis has been performed in peach fruits [72]. NO-mediated ethylene biosynthesis inhibition was manifested through retained pericarp firmness and reduced rate of respiration. Increased ACC levels were further reported to inhibit cell wall loosening enzymes [6]. Similar investigations in ripening banana revealed decreased gene expression levels for *MA-ACO1* gene as an effect of NO application [7]. Ripening associated reduction in respiration, inhibition of hydrolyzing enzymes and pericarp softness was also accessed [7]. Conversely, inhibition of endogenous NO in green tomato fruits has been reported to decrease ethylene levels [73]. Various methods of ex-planta and inplanta NO detection has been reviewed by Mur et al. [74]. A non-invasive and accurate methodology of endogenous NO and ethylene analysis has been reported by Leshem [62]. The authors reported the implication of photoacoustic spectroscopy in the measurement of NO levels associated with ripening of both climacteric and non-climacteric fruits. Application of NO synthesis inhibitor (L-Nitro-arginine methyl ester) led to the inhibition of ACO activity associated with a decrease in ethylene levels. Such NO-dependent ethylene biosynthesis was also reported to be associated with protein phosphorylation activity. An inverse correlation has been observed between NO and 1-aminocyclopropane-1-carboxylic acid (ACC) levels during mature fruit abscission in olives [75]. In this context, the expression of ethylene associated genes *(OeACS2, OeACO2, OeCTR1, OeERS1, and OeEIL2*) was observed to be under the negative regulation of polyamine biosynthesis. Thus NO-ethylene crosstalk appears to be under the secondary regulation of one, if not many other endogenous biomolecules. An important statement appears in the investigations of Tanou et al. [76] which compare SNP and ozone-mediated ripening of kiwi fruits. The authors reported a greater degree of ripening inhibition in kiwi fruits observed by ozone application. Furthermore, the effect of SNP on ethylene biosynthesis inhibition was very minor in comparison with ozone. This questions the efficiency of SNP in post-harvest storage of climacteric fruits. Complex analysis of ROS generation in fruit ripening stages of wild and rin mutants has been reported in tomato [77]. The process of fruit development was associated with a surge in the ROS levels. In continuation to such investigations, Corpas et al. [8] reported the intimate association of ROS/RNS in fruit ripening in (*Capsicum annuum* L.) and tomato (*Solanum lycopersicum* L.). NO is a dynamic molecule which exhibits interaction with ROS in multiple physiological facets. Ethylene biosynthesis is also regulated by posttranslational modification of adenosyl transferase-1. S-nitrosylation of this enzyme reduces S-adenosyl methionine levels, which in turn reduces ACC formation. Regulation of NO metabolism and associated S-nitrosoglutathione reductase (GSNOR) activity has been investigated in pepper (*Capsicum annuum* L.) [78]. Reduction in GSNOR activity and increase in total S-nitrosylated proteins were observed at mature stages of ripening. These results are indicative of the regulation of endogenous NO levels concomitantly changing with ethylene biosynthesis. NO-mediated regulation of ethylene levels also operates through the action of hydrogen peroxide which acts as an inhibitor of ethylene biosynthesis transcription proteins (Fig. 2). Thus, investigations for NO-ethylene crosstalk appear to be a promising area in the context of fruit ripening.

7. Perspectives of hydrogen sulfide-induced modulation of fruit ripening

Among various gasotransmitters involved in physiological responses, hydrogen sulfide has emerged as a potent signaling molecule exerting a plethora of effects in plants. Accumulating evidence across few years of research has revealed H_2S to act as an endogenous regulator of various other biomolecules in plants [9,79]. Plant systems have been reported to exhibit enzymatic biosynthesis of H_2S catalyzed by the activity of desulfhydrases. Arabidopsis has been investigated for the activity of cysteine desulfhydrase (**EC** 4.4.1.15) which is a plastid-localized biosynthetic enzyme for H_2S [80]. Riemenschneider et al. [81] reported a similar form of the enzyme localized in mitochondria. Evidence of H_2S acting as a signaling molecule in ethylene-mediated response has been reported in *Arabidopsis* [82]. H_2S has been deciphered to exhibit alleviating role towards fruit ripening and senescence in a wide variety of plant systems [83–85]. In most of the investigations, sodium hydrogen sulfide (NaHS) has been implied as a potent hydrogen sulfide donor. In the course of fruit ripening, H_2S has been reported to regulate the process by delaying senescence [86]. Furthermore, it also likely alters the activity of various antioxidant enzymes. These effects led to the attainment of cellular homeostasis and prevention of oxidative burst [87]. H_2S-ethylene signaling during fruit ripening at post -harvest stage has been reviewed by Ziogas et al. [88]. H_2S signaling in ethylene-induced fruit ripening thus involves interaction with reactive oxygen species (ROS), reactive nitrogen species and nitrosative stress signaling (88). The action of H_2S also operates through the post-translational modification of cysteine residues in proteins associated with fruit ripening. Precisely H_2S acts antagonistically to ethylene action during fruit ripening. Li et al. [86] reported anti-senescence activity of H_2S associated with fruit ripening in Kiwifruit (*Actinidia deliciosa*). Interestingly, the action of H_2S was operative through inhibition of polygalactouronase activity, an enzyme responsible for cell wall loosening. Furthermore, the anti-senescence activity of H_2S also involved increased activity of catalase (CAT) and ascorbate peroxidase (APX). H_2S treatment in kiwi fruits inhibited the activity of lipoxygenase (LOX) and polyphenol oxidase (PPO). The molecular mechanism of H_2S-ethylene crosstalk operates through the inhibition of ET biosynthesis genes namely *AdSAM*, *AdACS1*, *AdACS2*, *AdACO2*, and *AdACO3* [88]. Sodium hydrogen sulfide-induced modulation of endogenous H_2S levels has been reported in the post-harvest phase of mulberry fruits [89]. Natural biosynthesis of H_2S was observed to be higher at the post-harvest stage which later declined with the advent of ripening. Application of H_2S donor upregulated the activity of D-cysteine desulfhydrase and L-cysteine desulfhydrase (H_2S biosynthesizing enzymes). H_2S mediated delay in ripening process was observed to be operative through increased retention of ascorbate levels, slower protein solubilisation, and higher antioxidant activity [89]. Similar investigations on the antioxidative role of H_2S during post-harvest storage have been reported in strawberry fruits [83]. Chlorophyll degradation and biosynthesis of carotenoids are primary events associated with the onset of ripening process. Application of elemental suphur in grapes has been reported to induce a surge in the endogenous levels of H_2S in the ripening stages [90]. However, H_2S mediated down-regulation of chlorophyll degradation genes was reported in broccoli [91]. H_2S mediated ethylene biosynthesis results in improved chilling tolerance in cold-stored banana fruits [92]. The process of delayed ripening and cold-stress tolerance was associated with a decrease in malondialdehyde content and reduced electrolyte leakage. Secondary signaling components mediated by H^+-ATPase and Ca^{2+}-ATPase activity was also observed to be upregulated by H_2S [92]. This indicates that H_2S-mediated stress amelioration was primarily associated with the possible maintenance of cell membrane potential. Present evidence therefore indicates that endogenous or exogenous H_2S is primarily associated with inhibition of ethylene biosynthesis during climacteric fruit ripening processes. The fact that H_2S alleviates fruit senescence

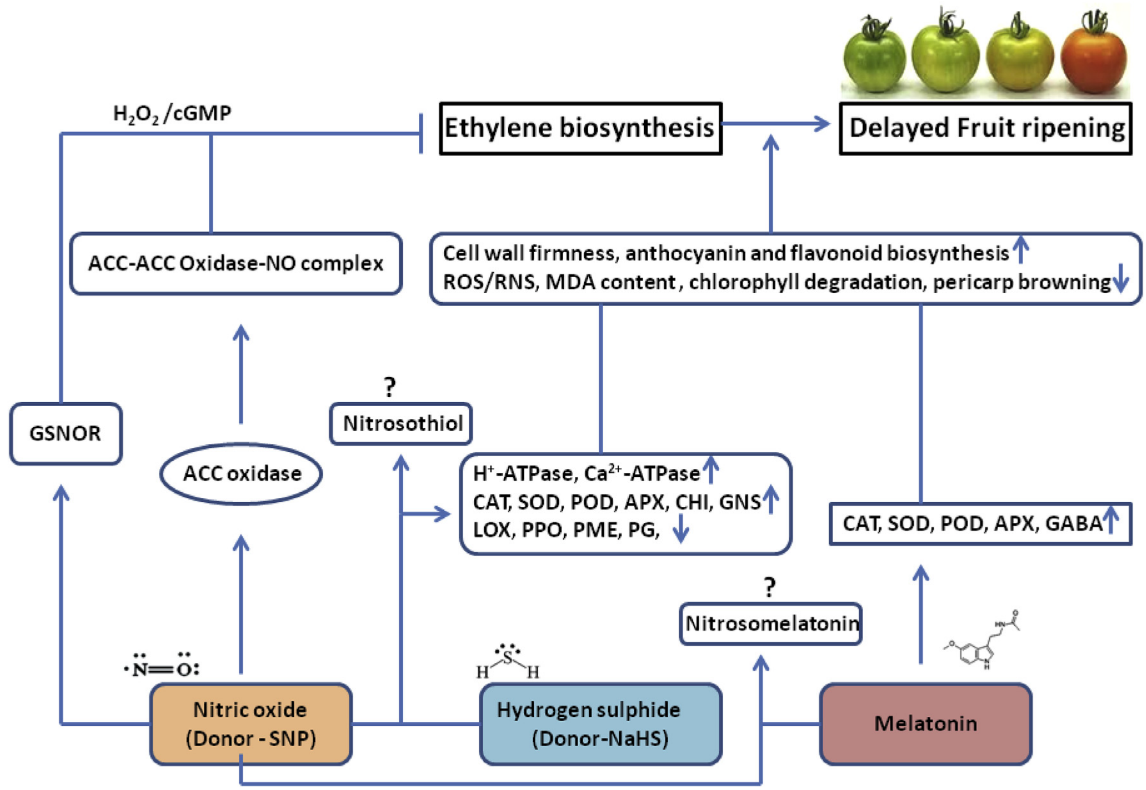

Fig. 2. Molecular crosstalk events associated with nitric oxide, hydrogen sulphide and melatonin in delaying ethylene-induced fruit ripening.

and ripening has been substantiated by the observations of decreased depigmentation and higher integrity of cell membranes. Furthermore, this biomolecule prevents the deleterious effects of oxidative burst prevalent at the onset of fruit ripening. Modulation of metabolic activities like sugar/protein hydrolysis and decreased production of organic acids are other associated outcomes of H_2S-induced delay in fruit ripening (Fig. 1).

8. Nitric oxide-hydrogen sulfide crosstalk: avenues for novel signaling response during climacteric fruit ripening

Recent investigations of climacteric fruit ripening have revealed significant insights for NO−H_2S crosstalk. Earlier investigations have established crosstalk associations of NO−H_2S associated with abiotic stress tolerance and fruit ripening in plants [92–94]. Variable reports have been obtained in regard to the correlation of NO and H_2S in abiotic stress. H_2S appears to be acting both complementary and inhibitory towards NO signaling [9,95–97]. Depending upon the dosage of exogenous H_2S and NO the two biomolecules exhibit positive or negative interactions. Lisjak et al. [98] observed a negative correlation of NO−H_2S signaling during stomatal regulation where NO levels were reported to be lower in the case of NaSH treated plant tissues. Nevertheless, NO−H_2S crosstalk exhibits a synergistic interaction towards inhibition of ethylene-induced fruit ripening. Liu et al. (2011) [82] suggest a downstream position of H_2S in the Et−NO−H_2S signaling pathway. In the context of fruit ripening, H_2S-ethylene interactions have been reported to be antagonistic in nature. Considering the fact that NO and H_2S crosstalk exhibits both positive and negative interactions it is worthwhile to mention that the nature of such interactions varies for different physiological functions. Chang et al. [10] reported that exogenous H_2S and NO applied in combination have led to enhancement of anti-ripening effects in strawberry fruits. The malleability of the test was accessed by comparisons of H_2S/NO treatment applied separately. H_2S and NO facilitated ripening inhibition by maintaining pericarp firmness and lowered the activities of pectin methylesterase (PME; EC 3.1.1.11), polygalacturonase (PG; EC 3.2.1.15) and endo-β-1,4-glucanase (EGase; EC 3.2.1.6). A success of *in-vitro* assessment of NO−H_2S cross-talk lies in the efficacy of the donors (NaSH and SNP). The combined effect of H_2S−NO has lead to better retention of the unripe colour of strawberry fruits [10]. Post-harvest management of fruits usually involves a major concern of pathogen attack [99,100]. However, H_2S supplementation has been reported to reduce the risk of fungal infection in *(Aspergillus niger* and *Penicillium expansum*) in pears (*Pyrus pyrifolia*) [101]. Additionally, Chang et al. (2014) [10] reported upregulation of biotic stress defense in strawberry fruits induced by H_2S−NO supplementation. Chitinase (CHI; EC 3.2.1.29) and beta-1,3-glucanase (GNS) activity were reported to be upregulated in presence of H_2S−NO treatments. Conversely, pectin methyl esterase (PME) an important enzyme responsible for cell wall loosening was down-regulated as a result of these treatments. These enzymes play a key role in the degradation of fungal cell walls of pathogens infesting on foliar surfaces. NO−H_2S treatments significantly reduced the effects of ethylene-induced respiratory burst in strawberry fruits. The anti-senescence effect of H_2S partially operates through the promotion of chloroplast biogenesis and modulation of thiol redox mechanism [102]. The applications of H_2S−NO, therefore, exhibit synergistic effects on anti-senescence properties which invariably delays fruit ripening in the post-harvest phase. Thus it appears that the probable involvement of H_2S−NO crosstalk finds its application in post-harvest vegetables and fruits [103]. This further extends to its applications in cut flower management and horticultural research. Further investigations are required to observe the nature of H_2S−NO crosstalk in various climacteric fruits. Monitoring of endogenous H_2S and NO levels, therefore, appear crucial to decipher their role in the course of fruit ripening-associated changes. Molecular mechanism of their action partially operates through the inhibition of ethylene biosynthesis and down-regulation of chlorophyll degradation genes. Lisjak et al. [9] suggest that the specific location of these biomolecules in the cell determines the magnitude of their signaling responses. The author also explains the possibility of H_2S competing with the protein targets of NO within the cells. Furthermore,

H_2S may regulate the bioavailability of NO possibly by modulating the activity of enzymes associated with the NO biosynthesis pathway. Unlike animal systems, it is less likely that H_2S could interact with putative nitric oxide synthase (NOS) in plants [9,104]. However, H_2S mediated modulation of nitrate reductase might be essential to regulate endogenous NO levels (Wilson et al., 2008). Interestingly enough, H_2S and NO can react among themselves to produce nitrosothiol compounds which further exhibit signaling responses (Fig. 2) [105]. Involvement of ROS in the H_2S—NO crosstalk pathway also cannot be ruled out.

9. Melatonin-induced regulation of fruit ripening

Several investigations across the last decade have established the role of phytomelatonin as a potent signaling molecule exhibiting a plethora of physiological effects. Melatonin mostly associates itself as an important antioxidant and free radical scavenger. Moreover it regulates the activity of various other plant growth regulators In this context, the role of melatonin signaling with various phytohormones and other PGRs has recently been reviewed by the author [12]. Among various physiological processes regulated by melatonin, investigations reveal its role in fruit ripening across various plant systems such as banana, strawberry, peach, grape, and tomato [106–108]. Melatonin is an indoleamine produced from L-tryptophan in plants [109]. Most of the plant systems investigated for melatonin functioning in fruits has been reported with its endogenous levels varying from picogram to micrograms levels [110–113]. Melatonin has been reported to enhance antioxidative defense mechanisms in ripening fruits (Fig. 2). This has also been associated with increased pigment biosynthesis for anthocyanins and flavonoids. Similar to nitric oxide and H_2S, exogenous melatonin application also serves as an effective option for post-harvest fruit storage. Antioxidative role of melatonin has been elucidated in various reports of abiotic stress responses [114–117]. Melatonin-induced changes during fruit ripening mostly associate with the triggering of antioxidative pathways. Xu et al. [118] reported the activity of melatonin to upregulate phenol, anthocyanin, flavonoid and proanthocyanidin biosynthesis in grape berries. Interestingly, melatonin treatment significantly altered the rate of polyphenol accumulation, carbohydrate metabolism and ethylene biosynthesis. Melatonin-induced enhancement of polyphenol and antioxidant activity was attributed to a partial increase in ethylene biosynthesis [118]. Organic acid accumulation was, however, found to be independent of melatonin-induced signaling. The authors reported that melatonin signaling largely triggered transcriptomic changes during grape berry ripening [118]. Apart from ethylene biosynthesis melatonin also regulated MAPK and nucleotide metabolism [118]. Reactive oxygen species participate in transient signaling responses associated with various physiological processes. Peach fruits treated with exogenous melatonin have been reported to exhibit cold stress tolerance acquired by redox homeostasis [119]. Melatonin treatment induced a surge in H_2O_2 levels manifested as an early response in post-harvest stage of the fruits. This transient increase in H_2O_2 levels was interpreted to be an inducer of the antioxidative system in the harvested fruits. Transcriptomic levels of enzymes associated with ascorbic acid biosynthesis and ascorbate-glutathione cycle was also observed to be increased due to melatonin treatment. Chilling stress tolerance due to melatonin supplementation was assessed by other parameters like malondialdehyde content, catalase (EC 1.11.1.6), and superoxide dismutase activity (EC 1.15.1.1). Similar investigations [120] have revealed the upregulation of catalase, peroxidase (EC 1.11.1.7), superoxide dismutase, and ascorbate peroxidase (EC 1.11.1.11) as a mechanism towards free radical detoxification. Interesting investigations in *Capsicum annuum* (pepper) and *Solanum lycopersicum* (tomato) have revealed variable level of endogenous melatonin to be associated with the advancement of ripening stages [121]. This response was, however, variable with the intensity of solar radiation and type of cultivars used. Thus, increase in melatonin content during ripening stages was not positively correlated in all the cultivars. Detailed analysis of endogenous melatonin content in various fruits has recently been reviewed [122]. Biological factors associated with the variation in melatonin content across various fruits are mostly due to different cultivars, ripening stages and growth parameters. Temporal regulation of endogenous melatonin content has been reported in veraison and ripened grape berries [110]. Melatonin levels were mostly observed to be increased at the veraison stage (induction of ripening) of early seed development. This indicates its protective role in seed development associated with the onset of fruit ripening. Zhao et al. [123] reported the induction of melatonin biosynthesis in sweet cherry varieties (*Prunus avium* L. cv. Hongdeng and *Prunus avium* L. cv. Rainier) to be triggered by darkness and oxidative stress. Climacteric rise in respiration during post-harvest stages of apples (*Malus domestica Borkh.cv.*Red) was accompanied by high accumulation of melatonin [124]. Genes for melatonin biosynthesis enzymes namely tryptophan decarboxylase (TDC; EC 4.1.1.27), tryptamine 5-hydroxylase (T5H; EC 4.1.1.28), arylalkylamine N-acetyltransferase (EC 2.3.1.87), and N-acetylserotonin methyltransferase (HIOMT; EC 2.1.1.4) were identified in apple cultivar. Tomato fruits exhibited better lycopene and ascorbate content in response to melatonin treatment [125]. Complex metabolic regulation induced by melatonin has mostly been associated with stimulation of glucose-6-phosphate dehydrogenase (EC 1.1.1.363), shikimate dehydrogenase (EC 1.1.1.25) and phenylalanine ammonia lyase (EC 4.3.1.24) in peach fruits induced by chilling stress [126]. Furthermore increased activity of γ-aminobutyric acid transaminase (GABA-T; EC 2.6.1.19) enzyme in response to melatonin provides insights to the regulation of the GABA shunt pathway in strawberry fruits *Fragaria anannasa* cv. Selva [108]. Ethylene biosynthesis was reported to be limited in the ripe resistant varieties of pear (*Pyrus communis* L.) [127]. This effect was associated with reduced senescence in the post-harvest stages. Calcium chloride supplementation in cassava has been reported to cause an increase in melatonin accumulation in the post-harvest stages [128]. Thus melatonin-calcium signaling is another important component regulating fruit ripening physiology. To summarize briefly, melatonin is mostly associated with redox homeostasis and metabolic regulation of climacteric fruit ripening in plants (Table 1). Melatonin-induced signaling partially operates through the regulation of ethylene biosynthesis. However, unlike NO or H_2S melatonin cannot be stated as an inhibitor or inducer of fruit ripening. It rather acts as a modulator of fruit ripening and regulates redox homeostatsis.

10. Probable crosstalk of nitric oxide and melatonin during fruit ripening: N-nitrosomelatonin signaling

Nitric oxide and melatonin have emerged as important signaling molecules associated with stress acclimatization, fruit ripening, and other physiological processes. Nitric oxide is a freely diffusible amphiphatic biomolecule which quickly transits across cells to bring about a rapid signaling response. Apart from the existence of NO in radical forms ($NO^{\cdot}$, NO^{+} or NO) it combines with thiol containing protein and non-protein molecules to form S-nitrosothiols [129]. Among various such NO conjugates, S-nitrosoglutathione GSNO has been reported to act as a major NO reserve in cells. Recently N-nitrosomelatonin has been stated to be an important molecule generated from nitrosation of melatonin in plant cells [129]. N-nitrosomeltonin can also act as an important antioxidant for scavenging free nitrogen species. These biomolecules have also been suggested to be involved in long -distance signaling response via xylem and phloem elements [129]. Physiological events associated with fruit ripening involve the production of reactive nitrogen species (RNS) and nitric oxide emerging from the pathways of nitro-oxidative metabolism. Corpas et al. [8] precisely explained the role of ROS/RNS and NO in signaling events associated with fruit ripening. In this context, it is worthwhile to mention that variations in endogenous melatonin levels have been investigated in major climacteric fruits. Therefore the possibilities of probable formation of N-nitrosomelatonin during fruit ripening stages cannot be ruled out (Fig. 2).

Table 1
Signaling events associated with NO, H_2S and Mel during climacteric fruit ripening.

Biomolecule	Plant system	Response	References
Nitric oxide (NO) (Donor: Sodium nitroprusside, 0.5–1 mM)	Peach	Retention of pericarp integrity	[70,72,119]
	Banana	Reduced ACC and ethylene levels	[7,92]
	Kiwi	Reduced electrolyte leakage	[5]
		Decrease in climacteric respiration Reduction on cell wall loosening	[43,76]
	Japanese plums	Reduction in cold storage mediated fruit damage	[4]
	Longan fruit	Reduction in polyphenol oxidase	[3]
	Pepper	Higher ascorbic acid levels, elevation of the galactono-1,4-lactone dehydrogenase (GalLDH) activity, modulation of GSNOR activity	[78]
	Tomato *short root* (*shr*) mutant	Regulation of primary carbon metabolism and phytohormone levels	[61,68]
	Mango	Changes in the levels of ACC and modulation of ACC synthase and ACC oxidase activity	[6]
	Olive	Inverse correlation of NO and 1-aminocyclopropane-1-carboxylic acid (ACC) levels Modulation of *OeACS2, OeACO2, OeCTR1, OeERS1, and OeEIL2*	[75]
Hydrogen sulphide (H_2S) (Donor: Sodium hydrogen sulphide 0.5–1 mM)	Kiwifruit	Inhibition of polygalactouronase, lipoxygenase (LOX) and polyphenol oxidase (PPO) activity, increased activity of catalase (CAT) and ascorbate peroxidase (APX)	[86]
	Mulberry fruits	Upregulation of D-cysteine desulfhydrase and L-cysteine desulfhydrase activity, increased retention of ascorbate levels, slower protein solubilisation and higher antioxidant activity	[89]
	Broccoli	Down-regulation of chlorophyll degradation genes	[85]
	Banana	Decrease in malondialdehyde content and reduced electrolyte leakage	[92]
H_2S + NO	Strawberry	Decreased activities of pectin methylesterase (PME) polygalacturonase (PG) and Endo-β-1,4-glucanase (EGase).	[10]
	Pears	Reduced infection risk of *(Aspergillus niger* and *Penicillium expansum*)	[101]
Melatonin (0.1–15 μM)	Grape	Upregulation of phenol, anthocyanin, flavonoid and proanthocyanidin biosynthesis Differential expression in veraison and ripening stages	[118] [110]
	Peach	Cold stress tolerance, redox homoeostasis	[119]
		Stimulation of glucose-6-phosphate dehydrogenase, shikimate dehydrogenase and phenylalanine ammonia lyase	[126]
	Sweet cherry varieties	Induction of melatonin biosynthesis	[123]
	Apple	High melatonin accumulation at ripening stages	[124]
	Tomato	Increased lycopene and ascorbate content	[125]
	Strawberry	Increased activity of γ-aminobutyric acid transaminase (GABA-T) enzyme	[108]
	Cassava	$CaCl_2$ mediated melatonin accumulation	[128]

However, the limitations exist in the lack of suitable methodologies to be implied for the detection and measurement of such transient biomolecules. Recent developments associated with the crosstalk mechanisms of NO and melatonin has been reviewed by the author [12]. Melatonin-NO crosstalk during fruit ripening is likely to operate through polyamine metabolism. Cold stress-induced fruit ripening in tomato has exhibited a surge in polyamine synthesis [130]. Polyamine synthesis during melatonin treatments is associated with endogenous nitric oxide synthesis in Arabidopsis seedlings [131]. Thus, NO-melatonin crosstalk may impart chilling stress tolerance in post-harvest fruits operative through modulation of ROS/RNS levels.

11. Nitric oxide, H_2S and melatonin: implications in the post-harvest storage of fruits

Various investigations have elucidated the applications of nitric oxide H_2S and melatonin in post harvest management of climacteric and non-climacteric fruits. Nitric oxide and H_2S act synergistically in delaying senescence events in fruits. Precise effects of the molecules have been observed in a wide variety of fruits such as strawberry, cherry, banana, apple and mango [89–92]. Sodium nitroprusside (SNP) and sodium hydrogen sulfide (NaSH) have been successfully implied as NO and H_2S donors during post-harvest storage [57,100]. Physiological investigations have clarified the fact that these biomolecules largely act as antagonists to ethylene biosynthesis. Subsequent analysis of fruit ripening parameters has revealed regulation of malondialdehyde content, ROS liberation, H_2O_2 levels, and pigment biosynthesis [3,92]. Melatonin supplementation has been reported to provide redox balance operative through the upregulation of antioxidant machinery within the cells [118,125]. Long time duration is associated with the harvest and market transition of climacteric and non-climacteric fruits. During this phase increased CO_2 burst, pericarp browning and other metabolic changes reduce the shelf life of fruits. However, newer horticultural technologies are employing the benefits of anti-ripening biomolecules (NO, H_2S) being investigated at a larger extent. Exogenous supplementation of various donor compounds to post-harvest fruits involves their application in fumigation or solutions. An initial delay in the ethylene surge and ripening shall improve the shelf life of fruits. However, these biochemical manipulations often compromise with the aroma and flavor of fruits which should be carefully considered. The concentration of nitric oxide, H_2S or melatonin applied shall reveal variations in the intensity of responses. Apart from causing delay in senescence, these biomolecules are effective in imparting tolerance towards biotic and abiotic stress factors.

12. Fruitomic approach towards the understanding of NO–H_2S-Mel crosstalk in plants: future perspectives

To elucidate the current understandings of fruit ripening physiology investigations with systems biology approach has provided sufficient insights to crosstalk mechanisms operative between nitric oxide, hydrogen sulfide and melatonin. Regulation of ACC synthase and ETR signaling in response to these biomolecules has been investigated by functional genomic approach. Ripening associated genes have been identified in various plant systems exhibiting climacteric response. RIN-MADS interaction has been a crucial aspect in the epigenetic control of fruit ripening [132,133]. TAG, TAGL1, FRUITFUL1, and FUL2 are important components of MADS-box transcription factors associated with fruit ripening [134,135]. In this context, it is necessary to investigate the transcriptomic regulation of NO, H_2S and melatonin-induced fruit ripening changes. Various candidate proteins associated with carbohydrate metabolism and cell wall loosening have been identified in the fruit ripening stages of apple, papaya, and peach [136–138]. Genotypic variations, however, lead to differential responses in protein expressions. NR receptor-mediated ethylene signaling in tomato has revealed differential expression of more than 869 genes of which 37% were affected by *nr* mutation [139]. Accumulating investigations of transcriptomic and microarray analysis have yielded plenty of data which include genes and mRNA expressions associated with fruit ripening signaling. The tomato-eco sequencing programme will deliver sufficient information on the genomic control of fruit ripening [140]. In this context it is important to consider the effects of ethylene on plastid proteome. The precise regulation of chloroplast-chromoplast conversion is a crucial response associated with the onset of ripening. Studies related to melatonin receptor have been recently reported in Arabidopsis [141]. Thus melatonin reported to be present in plastid can probably regulate one if not many downstream pathways of fruit ripening metabolism. Nitric oxide-H_2S applications exhibit synergistic effects in delaying ethylene-induced fruit ripening response. However, further investigations using microarray, transcriptomic or proteomic analysis can decipher their role in complex regulations. To summarize, genomic, transcriptomic and proteomic approach have emerged as important components of fruitomic analysis of ripening processes. In this context, nitric oxide, H_2S and melatonin should be considered for further investigations using omic approaches.

Conflicts of interest

The author declares no conflict of interest for this review article.

Contributions

The author SM has planned for the framework of the article and reviewed the topic with compilation of adequate literature.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.niox.2018.11.003.

References

[1] J.B. Biale, Growth, maturation, and senescence in fruits: recent knowledge on growth regulation and on biological oxidations has been applied to studies with fruits, Science 146 (1964) 880–808.

[2] M. Razali, Z.M. Ali, R. Othman, Effects of 1-methylcyclopropene on activities of ethylene biosynthesis and cell wall degrading enzyme during ripening of papaya"Sekaki", J. Trop. Agric. Food Sci. 41 (2013) 1–13.

[3] X. Duan, X. Su, Y. You, H. Qu, Y. Li, et al., Effect of nitric oxide on pericarp browning of harvested longan fruit in relation to phenolic metabolism, Food Chem. 104 (2007) 571–576.

[4] S.P. Singh, Z. Singh, E.E. Swinny, Post-harvest nitric oxide fumigation delays fruit ripening and alleviates chilling injury during cold storage of Japanese plums (*Prunus salicina Lindell*), Postharvest Biol. Technol. 53 (2009) 101–108.

[5] G. Manjunatha, V. Lokesh, B. Neelwarne, Nitric oxide in fruit ripening: trends and opportunities, Biotechnol. Adv. 28 (2010) 489–499.

[6] S.S. Zaharah, Z. Singh, Mode of action of nitric oxide in inhibiting ethylene biosynthesis and fruit softening during ripening and cool storage of 'Kensington Pride' mango, Postharvest Biol. Technol. 62 (2011) 258–266.

[7] G. Cheng, E. Yang, W. Lu, Y. Jia, Y. Jiang, et al., Effect of nitric oxide on ethylene synthesis and softening of banana fruit slice during ripening, J. Agric. Food Chem. 57 (2009) 5799–5804.

[8] F.J. Corpas, L. Freschi, M. Rodríguez-Ruiz, P.T. Mioto, S. González-Gordo, J.M. Palma, Nitro-oxidative metabolism during fruit ripening, J. Exp. Bot. 69 (2018) 3449–3463.

[9] M. Lisjak, T. Teklic, I.D. Wilson, M. Whiteman, J.T. Hancock, Hydrogen sulfide: environmental factor or signalling molecule? Plant Cell Environ. 36 (2013) 1607–1616.

[10] Z. Chang, S. Jingying, Z. Liqin, L. Changle, W. Qingguo, Cooperative effects of hydrogen sulfide and nitric oxide on delaying softening and decay of strawberry, Int. J. Agric. Biol. Eng. 7 (2014) 114–122.

[11] R. Hardeland, Melatonin – another phytohormone? J. Bot. Sci. 5 (2016) 20–23.

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

[13] M. Liu, J. Pirrello, Chervin, J.P. Roustan, M. Bouzayen, Ethylene control of fruit ripening: revisiting the complex network of transcriptional regulation, Plant Physiol. 169 (2015) 2380–2390.

[14] Z. Fei, X. Tang, R. Alba, J. Giovannoni, Tomato expression database (TED): a suite of data presentation and analysis tools, Nucleic Acids Res. 34 (2006) D766–D770.

[15] S.P. Burg, E.A. Burg, Role of ethylene in fruit ripening, Plant Physiol. 37 (1962) 179–189.

[16] R. Solano, J.R. Ecker, Ethylene gas: perception, signaling and response, Curr. Opin. Plant Biol. 1 (1998) 393–398.

[17] C. Ju, G.M. Yoon, J.M. Shemansky, D.Y. Lin, Z.I. Ying, et al., CTR1 phosphorylates the central regulator EIN2 to control ethylene hormone signaling from the ER membrane to the nucleus in Arabidopsis, Proc. Natl. Acad. Sci. U.S.A. 109 (2012) 19486–19491.

[18] K.N. Chang, S. Zhong, M.T. Weirauch, G. Hon, M. Pelizzola, et al., Temporal transcriptional response to ethylene gas drives growth hormone cross-regulation in Arabidopsis, eLife 2 (2013) e00675.

[19] S.F. Yang, N.E. Hoffman, Ethylene biosynthesis and its regulation in higher plants, Annu. Rev. Plant Physiol. 35 (1984) 155–189.

[20] B. Van de Poel, N. Vandenzavel, C. Smet, Nicolay, T. Bulens, et al., Tissue specific analysis reveals a differential organization and regulation of both ethylene biosynthesis and E8 during climacteric ripening of tomato, BMC Plant Biol. 14 (2014) 11.

[21] Y. Ito, M. Kitagawa, N. Ihashi, K. Yabe, J. Kimbara, et al., DNA-binding specificity, transcriptional activation potential, and the rin mutation effect for the tomato fruit-ripening regulator RIN, Plant J. 55 (2008) 212–223.

[22] M. Fujisawa, T. Nakano, Y. Shima, Y. Ito, A large-scale identification of direct targets of the tomato MADS box transcription factor RIPENING INHIBITOR reveals the regulation of fruit ripening, Plant Cell 25 (2013) 371–386.

[23] M. Fujisawa, Y. Shima, H. Nakagawa, M. Kitagawa, J. Kimbara, et al., Transcriptional regulation of fruit ripening by tomato FRUITFULL homologs and associated MADS box proteins, Plant Cell 26 (2014) 89–101.

[24] C. Martel, J. Vrebalov, P. Tafelmeyer, J.J. Giovannoni, The tomato MADS-box transcription factor RIPENING INHIBITOR interacts with promoters involved in numerous ripening processes in a COLOR LESS NON RIPENING-dependent manner, Plant Physiol. 157 (2011) 1568–1579.

[25] J.Q. Wilkinson, M.B. Lanahan, H.C. Yen, J.J. Giovannoni, H.J. Klee, An ethylene-inducible component of signal transduction encoded by never-ripe, Science 270 (1995) 1807–1809.

[26] C.C. Lashbrook, D.M. Tieman, H.J. Klee, Differential regulation of the tomato ETR gene family throughout plant development, Plant J. 15 (1998) 243–252.

[27] D.M. Tieman, H.J. Klee, Differential expression of two novel members of the tomato ethylene-receptor family, Plant Physiol. 120 (1999) 165–172.

[28] H. Klee, D. Tieman, The tomato ethylene receptor gene family: form and function, Physiol. Plantarum 115 (2002) 336–341.

[29] N.E. Gapper, R.P. McQuinn, J.J. Giovannoni, Molecular and genetic regulation of fruit ripening, Plant Mol. Biol. 82 (2013) 575–591.

[30] Y. Kamiyoshihara, D.M. Tieman, D.J. Huber, H.J. Klee, Ligand-induced alterations in the phosphorylation state of ethylene receptors in tomato fruit, Plant Physiol. 160 (2012) 488–497.

[31] B.M. Kevany, D.M. Tieman, M.G. Taylor, V.D. Cin, H. J, Klee Ethylene receptor degradation controls the timing of ripening in tomato fruit, Plant J. 51 (2007) 458–467.

[32] M. Liu, G. Diretto, J. Pirrello, J.P. Roustan, Z. Li, et al., The chimeric repressor version of an Ethylene Response Factor (ERF) family member, Sl-ERF.B3, shows contrasting effects on tomato fruit ripening, New Phytol. 203 (2014) 206–218.

[33] S. Zhong, Z. Fei, Y.R. Chen, Y. Zheng, M. Huang, et al., Single-base resolution methylomes of tomato fruit development reveal epigenome modifications associated with ripening, Nat. Biotechnol. 31 (2013) 154–159.

[34] L. Trainotti, A. Tadiello, G. Casadoro, The involvement of auxin in the ripening of climacteric fruits comes of age: the hormone plays a role of its own and has an intense interplay with ethylene in ripening peaches, J. Exp. Bot. 58 (2007) 3299–3308.

[35] M. Tatsuki, N. Nakajima, H. Fujii, T. Shimada, M. Nakano, et al., Increased levels of IAA are required for system 2 ethylene synthesis causing fruit softening in peach (Prunus persica L. Batsch), J. Exp. Bot. 64 (2013) 1049–1059.

[36] P. Pesaresi, C. Mizzotti, M. Colombo, S. Masiero, Genetic regulation and structural changes during tomato fruit development and ripening, Front. Plant Sci. 23 (2014) 124.

[37] J.K. Fellman, T.W. Miller, D.S. Mattinson, J.P. Mattheis, Factors that influence biosynthesis of volatile flavor compound in apple fruits, Hortscience 35 (2000) 1026–1033.

[38] T. Tohge, S. Alseekh, A.R. Fernie, On the regulation and function of secondary metabolism during fruit development and ripening, J. Exp. Bot. 65 (2014) 4599–4611.

[39] J.L. Rambla, Y.M. Tikunov, A.J. Monforte, A.G. Bovy, A. Granell, The expanded tomato fruit volatile landscape, J. Exp. Bot. 65 (2014) 4613–4623.

[40] V. Paul, R. Pandey, Role of internal atmosphere on fruit ripening and storability—a review, J. Food Sci. Technol. 51 (2013) 1223–1250.

[41] F. Bangerth, F. Song, J. Streif, Physiological impacts of fruit ripening and storage conditions on aroma volatile formation in apple and strawberry fruit: a review, Hortscience 47 (2012) 4–10.

[42] J. Kožiškova, J. Goliaš, Influence of ripening on the ethylene and carbon dioxide

production during storage of plum fruits, Acta Univ. Agric. Silvic. Mendelianae Brunensis 60 (2012) 133–140.
[43] S. Lim, J.G. Lee, E.J. Lee, Comparison of fruit quality and GC-MS-based metabolite profiling of Kiwifruit 'Jecy green': natural and exogenous ethylene-induced ripening, Food Chem. 234 (2017) 81–92.
[44] M.A. Bisson, G. Groth, Targeting plant ethylene responses by controlling essential protein–protein interactions in the ethylene pathway, Mol. Plant 8 (2015) 1165–1174.
[45] M.M. Bisson, M. Kessenbrock, L. Müller, A. Hofmann, F. Schmitz, et al., Peptides interfering with protein-protein interactions in the ethylene signaling pathway delay tomato fruit ripening, Sci. Rep. 6 (2016) 1–11.
[46] M. Kessenbrock, S.M. Klein, L. Müller, M. Hunsche, G. Noga, et al., Novel protein-protein inhibitor based approach to control plant ethylene responses: synthetic peptides for ripening control, Front. Plant Sci. 8 (2017) 1528.
[47] A. Tadiello, V. Ziosi, A.S. Negri, M. Noferini, G. Fiori, et al., On the role of ethylene, auxin and a GOLVEN-like peptide hormone in the regulation of peach ripening, BMC Plant Biol. 16 (2016) 44.
[48] L. Freschi, Nitric oxide and phytohormone interactions: current status and perspectives, Front. Plant Sci. 4 (2013) 398.
[49] X.G. Bai, J.H. Chen, X.X. Kong, C.D. Todd, Y.P. Yang, et al., Carbon monoxide enhances the chilling tolerance of recalcitrant Baccaurea ramiflora seeds via nitricoxide-mediated glutathione homeostasis, Free Radic. Biol. Med. 53 (2012) 710–720.
[50] K.J. Gupta, Protein S-nitrosylation in plants: photorespiratory metabolism and NO signaling, Sci. Signal. 4 (2011) jc1.
[51] Y. Morot-Gaudry-Talarmain, P. Rockel, T. Moureaux, I. Quilleré, M.T. Leydecker, et al., Nitrite accumulation and nitric oxide emission in relation to cellular signaling in nitrite reductase antisense tobacco, Planta 215 (2002) 708–715.
[52] K.J. Gupta, W.M. Kaiser, Production and scavenging of nitric oxide by barley root mitochondria, Plant Cell Physiol. 51 (2010) 576–584.
[53] K.J. Gupta, A.U. Igamberdiev, W.M. Kaiser, New insights into the mitochondrial nitric oxide production pathways, Plant Signal. Behav. 5 (2010) 999–1001.
[54] F.Q. Guo, M. Okamoto, N.M. Crawford, Identification of a plant nitric oxide synthase gene involved in hormonal signaling, Science 302 (2003) 100–103.
[55] F.J. Corpas, J.B. Barroso, A. Carreras, R. Valderrama, J.M. Palma, et al., Constitutive arginine dependent nitric oxide synthase activity in different organs of pea seedlings during plant development, Planta 224 (2006) 246–254.
[56] S. Rümer, J.G. Kapuganti, W.M. Kaiser, Oxidation of hydroxylamines to NO by plant cells, Plant Signal, Beyond Behav. 4 (2009) 853–855.
[57] S.H. Zhu, M.C. Liu, J. Zhou, Inhibition by nitric oxide of ethylene biosynthesis and lipoxygenase activity in peach fruit during storage, Postharvest Biol. Technol. 42 (2006) 41–48.
[58] F.B. Flores, P. Sanchez-Bel, M. Valdenegro, F. Romojaro, M. Concepcion Martinez-Madrid, et al., Effects of a pretreatment with nitric oxide on peach (*Prunus persica* L.) storage at room temperature, Eur. Food Res. Technol. 227 (2008) 1599–1611.
[59] Y.F. Chen, N. Etheridge, G.E. Schaller, Ethylene signal transduction, Ann. Bot. 95 (2005) 901–915.
[60] K.Q. Hong, D.Q. Gong, H.B. Xu, S.B. Wang, Z.W. Jia, et al., Effects of salicylic acid and nitric oxide pre-treatment on the expression of genes involved in the ethylene signaling pathway and the quality of postharvest mango fruit, New Z. J. Crop. Hortic. 42 (2014) 205–216.
[61] H.L. Eum, H.B. Kim, S.B. Choi, S.K. Lee, Regulation of ethylene biosynthesis by nitric oxide in tomato (*Solanum lycopersicum* L.) fruit harvested at different ripening stages, Eur. Food Res. Technol. 228 (2009) 331–338.
[62] Y.Y. Leshem, Y. Pinchasov, Non-invasive photoacoustic spectroscopic determination of relative endogenous nitric oxide and ethylene content stoichiometry during the ripeneing of strawberries *Fragaria anannasa* (Dutch.) and avocados *Persea americana* (Mill.), J. Exp. Bot. 51 (2000) 1471–1473.
[63] Y.Y. Leshem, R.B.H. Wills, Harnessing senescence delaying gases nitric oxide and nitrous oxide, a novel approach to postharvest control of fresh horticultural produce, Biol.Planta. 41 (1998) 1–10.
[64] S.P. Singh, Z. Singh, E. Swinny, Postharvest nitric oxide fumigation delays fruit ripening and alleviates chilling injury during cold storage of Japanese plums (*Prunus salicina* Lindell), Postharvest Biol. Technol. 53 (2009) 101–108.
[65] X. Zhang, L. Shen, F. Li, D. Meng, J. Sheng, Methyl salicylate-induced arginine catabolism is associated with up-regulation of polyamine and nitric oxide levels and improves chilling tolerance in cherry tomato fruit, J. Agric. Food Chem. 59 (2011) 9351–9357.
[66] J. Ruan, M. Li, H. Jin, L. Sun, Y. Zhu, et al., UV-B irradiation alleviates the deterioration of cold-stored mangoes by enhancing endogenous nitric oxide levels, Food Chem. 15 (2015) 417–423.
[67] M. Rodríguez-Ruiz, R.M. Mateos, V. Codesido, F.J. Corpas, J.M. Palma, Characterization of the galactono-1,4-lactone dehydrogenase from pepper fruits and its modulation in the ascorbate biosynthesis. Role of nitric oxide, Redox Biol 12 (2017) 171–181.
[68] R. Bodanapu, S.K. Gupta, P.O. Basha, K. Sakthivel, Sadhana, et al., Nitric oxide overproduction in tomato shr mutant shifts metabolic profiles and suppresses fruit growth and ripening, Front. Plant Sci. 7 (2016) 1714.
[69] S. Shahkoomahally, A. Ramezanian, A. Farahnaky, Postharvest nitric oxide treatment of persimmon (*Diospyros kaki* L.) improves fruit quality during storage, Fruits 70 (2015) 63–68.
[70] S.H. Zhu, M.C. Liu, J. Zhou, Inhibition by nitric oxide of ethylene biosynthesis and lipoxygenase activity in peach fruit during storage, Postharvest Biol. Technol. 42 (2006) 41–48.
[71] D.R. Rudell, J.P. Mattheis, Nitric oxide and nitrite treatments reduce ethylene evolution from apple fruit disks, Hortscience 41 (2006) 1462–1465.
[72] R. Kang, L. Zhang, L. Jiang, M. Yu, R. Ma, Z. Yu, Effect of postharvest nitric oxide treatment on the proteome of peach fruit during ripening, Postharvest Biol. Technol. 112 (2016) 277–289.
[73] Y. Yang, Y. Zheng, C. Liu, L. Chen, J. Ma, J. Inhibition of nitric oxide synthesis delayed mature-green tomato fruits ripening induced by inhibition of ethylene, Sci. Hortic. (Amst.) 211 (2016) 95–101.
[74] L.A.J. Mur, J. Mandon, S.M. Cristescu, F.J.M. Harren, E. Prats, Methods of nitric oxide detection in plants: a commentary, Plant Sci. 181 (2011) 509–519.
[75] M.C. Parra-Lobato, M.C. Gomez-Jimenez, Polyamine-induced modulation of genes involved in ethylene biosynthesis and signaling pathways and nitric oxide production during olive mature fruit abscission, J. Exp. Bot. 62 (2011) 4447–4465.
[76] G. Tanou, I.S. Minas, E. Karagiannis, D. Tsikou, S. Audebert, The impact of sodium nitroprusside and ozone in kiwifruit ripening physiology: a combined gene and protein expression profiling approach, Ann. Bot. 116 (2015) 649–662.
[77] R. Kumar, M.K. Sharma, S. Kapoor, A.K. Tyagi, A.K. Sharma, Transcriptome analysis of rin mutant fruit and in silico analysis of promoters of differentially regulated genes provides insight into LeMADS-RIN-regulated ethylene-dependent as well as ethylene-independent aspects of ripening in tomato, Mol. Genet. Genom. 287 (2012) 189–203.
[78] M. Rodríguez-Ruiz, P. Mioto, J.M. Palma, F.J. Corpas, S-nitrosoglutathione reductase (GSNOR) activity is down-regulated during pepper (*Capsicum annuum* L.) fruit ripening, Nitric Oxide 68 (2017) 51e55.
[79] M. Lisjak, T. Teklic, I.D. Wilson, M. Whiteman, J.T. Hancock, Hydrogen sulfide: environmental factor or signalling molecule? Plant Cell Environ. 36 (2013) 1607–1616.
[80] S. L'eon, B. Touraine, J.F. Briat, S. Lobr'eaux, The AtNFS2 gene from *Arabidopsis thaliana* encodes a NifS-like plastidial cysteine desulphurase, Biochem. J. 366 (2002) 557–564.
[81] A. Riemenschneider, R. Wegele, A. Schmidt, J. Papenbrock, Isolation and characterization of a d-cysteine desulfhydrase protein from *Arabidopsis thaliana*, FBES J. 272 (2005) 1291–1304.
[82] J. Liu, L.X. Hou, G.H. Liu, X. Liu, X.C. Wang, Hydrogen sulphide induced by nitric oxide mediates ethylene-induced stomatal closure of *Arabidopsis thaliana*, Chin. Sci. Bull. 56 (2011) 3547–3553.
[83] L.Y. Hu, S.L. Hu, J. Wu, Y.H. Li, J.L. Zheng, et al., Hydrogen sulfide prolongs postharvest shelf life of strawberry and plays an antioxidative role in fruits, J. Agric. Food Chem. 60 (2012) 8684–8693.
[84] S.P. Gao, K.D. Hu, L.Y. Hu, Y.H. Li, Y. Han, et al., Hydrogen sulfide delays postharvest senescence and plays an antioxidative role in fresh-cut kiwifruit, Hortic. Sci. (Calcutta) 48 (2013) 1385–1392.
[85] Z.R. Li, K.D. Hu, F.Q. Zhang, S.P. Li, L.Y. Hu, et al., Hydrogen sulfide alleviates dark-promoted senescence in postharvest broccoli, Hortic. Sci. (Calcutta) 50 (2015) 416–420.
[86] T.T. Li, Z.R. Li, K.D. Hu, L.Y. Hu, X.Y. Chen, et al., Hydrogen sulfide alleviates kiwifruit ripening and senescence by antagonizing effect of ethylene, Hortic. Sci. (Calcutta) 52 (2017) 1556–1562.
[87] Z.J. Ni, K.D. Hu, C.B. Song, R.H. Ma, Z.R. Li, et al., Hydrogen sulfide alleviates postharvest senescence of grape by modulating the antioxidant defences, Oxid. Med. Cell. Long. 2016 (2016) 4715651.
[88] V. Ziogas, A. Molassiotis, V. Fotopoulos, G. Tanou, Hydrogen sulfide: a potent tool in postharvest fruit biology and possible mechanism of action, Front. Plant Sci. (2018), https://doi.org/10.3389/fpls.2018.01375.
[89] H. Hu, W. Shen, P. Li, Effects of hydrogen sulphide on quality and antioxidant capacity of mulberry fruit, Int. J. Food Sci. Technol. 49 (2014) 399–409.
[90] M.T. Kwasniewski, G.L. Sacks, W.F. Wilcox, Persistence of elemental sulfur spray residue on grapes during ripening and vinification, Am. J. Enol. Vitic. 65 (2014) 453.
[91] S.P. Li, K.D. Hu, L.Y. Hu, Y.H. Li, A.M. Jiang, et al., Hydrogen sulfide alleviates postharvest senescence of broccoli by modulating antioxidant defense and senescence-related gene expression, J. Agric. Food Chem. 62 (2014) 1119–1129.
[92] D. Li, J. Limwachiranon, L. Li, R.X. Du, Z.S. Luo, Involvement of energy metabolism to chilling tolerance induced by hydrogen sulfide in cold-stored banana fruit, Food Chem. 208 (2016) 272–278.
[93] R. Peng, Z. Bian, L. Zhou, W. Cheng, N. Hai, et al., Hydrogen sulfide enhances nitric oxide-induced tolerance of hypoxia in maize (Zea mays L.), Plant Cell Rep. 35 (2016) 2325–2340.
[94] C.J. Da-Silva, L.V. Modolo, Hydrogen sulfide: a new endogenous player in an old mechanism of plant tolerance to high salinity, Acta Bot. Bras. 32 (2018) 150–160.
[95] A. Christou, G. Manganaris, I. Papadopoulos, V. Fotopoulos, Hydrogen sulfide confers systemic tolerance to salt and polyethylene glycol stress in strawberry plants, Abstracts Book of the 10th International Conference on Reactive Oxygen and Nitrogen Species in Plants vols. 5–8, (July 2011), p. 159 Budapest, Hungary.
[96] L. Li, Y. Wang, W. Shen, Roles of hydrogen sulfide and nitric oxide in the alleviation of cadmium-induced oxidative damage in alfalfa seedling roots, Biometals 25 (2012) 617–631.
[97] Y. Wang, L. Li, W. Ciu, S. Xu, W. Shen, Hydrogen sulfide enhances alfalfa (*Medicago sativa*) tolerance against salinity during seed germination by nitric oxide pathway, Plant Soil 351 (2012) 107–119.
[98] M. Lisjak, N. Srivastava, T. Teklic, L. Civale, K. Lewandowski, et al., A novel hydrogen sulphide donor causes stomatal opening and reduces nitric oxide accumulation, Plant Physiol. Biochem. 48 (2010) 931–935.
[99] P.V. Mahajan, O.J. Caleb, Z. Singh, C.B. Watkins, M. Geyer, Postharvest treatments of fresh produce, Philos. Trans. A Math. Phys. Eng. Sci. 372 (2017) 20130309.
[100] P. Tripathi, N.K. Dubey, Exploitation of natural products as alternative strategy to control post-harvest fungal rotting of fruits and vegetables, Postharvest Biol. Technol. 32 (2004) 235–245.

[101] K.D. Hu, Q. Wang, L.Y. Hu, S.P. Gao, J. Wu, et al., Hydrogen sulfide prolongs postharvest storage of fresh-cut pears (*Pyrus pyrifolia*) by alleviation of oxidative damage and inhibition of fungal growth, PLoS One 9 (2014) e85524.

[102] J. Chen, F.H. Wu, W.H. Wang, et al., Hydrogen sulphide enhances photosynthesis through promoting chloroplast biogenesis, photosynthetic enzyme expression, and thiol redox modification in *Spinacia oleracea* seedlings, J. Exp. Bot. 62 (2011) 4481–4493.

[103] T. Gong, C. Li, B. Bian, Y. Wu, M.M. Dawuda, et al., Advances in application of small molecule compounds for extending the shelf life of perishable horticultural products: a review, Sci. Hortic. (Amst.) 230 (2018) 25–34.

[104] T. Zemojtel, A. Fröhlich, M.C. Palmieri, et al., Plant nitric oxide synthase: a never-ending story? Trends Plant Sci. 11 (2006) 524–525.

[105] M. Whiteman, L. Li, I. Kostetski, S.H. Chu, J.L. Siau, et al., Evidence for the formation of a novel nitrosothiol from the gaseous mediators nitric oxide and hydrogen sulphide, Biochem. Biophys. Res. Commun. 343 (2006) 303–310.

[106] J.F. Meng, T. Xu, F. Song, C.Z. Yu, Y. Hu, et al., Melatonin treatment of pre-veraison grape berries to increase size and synchronicity of berries and modify wine aroma components, Food Chem. 185 (2015) 127–134.

[107] Q.Q. Sun, N. Zhang, J.F. Wang, H.J. Zhang, D.B. Li, et al., Melatonin promotes ripening and improves quality of tomato fruit during postharvest life, J. Exp. Bot. 66 (2015) 657–668.

[108] M.S. Aghdam, J.R. Fard, Melatonin treatment attenuates postharvest decay and maintains nutritional quality of strawberry fruits (*Fragaria x anannasa* cv. Selva) by enhancing GABA shunt activity, Food Chem. 221 (2017) 1650–1657.

[109] A. Galano, D.X. Tan, R.J. Reiter, Melatonin as a natural ally against oxidative stress: a physicochemical examination, J. Pineal Res. 51 (2011) 1–16.

[110] S.J. Murch, B.A. Hall, C.H. Le, P.K. Saxena, Changes in the levels of indoleamine phytochemicals during veraison and ripening of wine grapes, J. Pineal Res. 49 (2010) 95–100.

[111] S. Vitalini, C. Gardana, A. Zanzotto, G. Fico, F. Faoro, et al., From vineyard to glass: agrochemicals enhance the melatonin and total polyphenol contents and antiradical activity of red wines, J. Pineal Res. 51 (2011) 278–285.

[112] M.B. Arnao, J. Hernández-Ruiz, Melatonin: plant growth regulator and/or biostimulator during stress? Trends Plant Sci. 19 (2014) 789–797.

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

[114] S. Mukherjee, A. David, S. Yadav, F. Baluška, S.C. Bhatla, Salt stress-induced seedling growth inhibition coincides with differential distribution of serotonin and melatonin in sunflower seedling roots and cotyledons, Physiol. Plantarum 152 (2014) 714–728.

[115] H.J. Zhang, N.A. Zhang, R.C. Yang, L. Wang, Q.Q. Sun, et al., Melatonin promotes seed germination under high salinity by regulating antioxidant systems, ABA and GA4 interaction in cucumber (*Cucumis sativus* L.), J. Pineal Res. 57 (2014) 269–279.

[116] R.J. Reiter, J.C. Mayo, D.X. Tan, R.M. Sainz, M. Alatorre-Jimenez, Melatonin as an antioxidant: under promises but over delivers, J. Pineal Res. 61 (2016) 253–278.

[117] H. Li, J. Chang, H. Chen, Z. Wang, X. Gu, et al., Exogenous melatonin confers salt stress tolerance to watermelon by improving photosynthesis and redox homeostasis, Front. Plant Sci. 8 (2017) 295.

[118] L. Xu, Q. Yue, F. Bian, H. Sun, H. Zhai, et al., Melatonin enhances phenolics accumulation partially via ethylene signaling and resulted in high antioxidant capacity in grape berries, Front. Plant Sci. 8 (2017) 1426.

[119] S. Cao, J. Shao, L. Shi, L. Xu, Z. Shen, et al., Melatonin increases chilling tolerance in postharvest peach fruit by alleviating oxidative damage, Sci. Rep. 8 (2018) 806.

[120] P. Gao, W. Xing, W. Li, S.H. Shu, S. Li, et al., Effect of pumpkin rootstock on antioxidant enzyme activities and photosynthetic fluorescence characteristics of cucumber under $Ca(NO_3)_2$ stress, Acta Hortic. (Wagening.) 1086 (2015) 177–187.

[121] P. Riga, S. Medina, L.A. Garcia-Flores, A. Gil-Izquierdo, Melatonin content of pepper and tomato fruits: effects of cultivar and solar radiation, Food Chem. 156 (2014) 347–352.

[122] X. Feng, M. Wang, Y. Zhao, P. Han, Y. Dai, Melatonin from different fruit sources, functional roles, and analytical methods, Trends Food Sci. Technol. 37 (2014) 21–31.

[123] Y. Zhao, D.X. Tan, Q. Lei, et al., Melatonin and its potential biological functions in the fruits of sweet cherry, J. Pineal Res. 55 (2013) 79–88.

[124] Q. Lei, L. Wang, D.X. Tan, Y. Zhao, X.D. Zheng, et al., Identification of genes for melatonin synthetic enzymes in 'Red Fuji' apple (*Malus domestica* Borkh. cv Red) and their expression and melatonin production during fruit development, J. Pineal Res. 55 (2013) 443–451.

[125] J.L. Liu, R. Zhang, M. Sun, Y.K. Liu, Z.Y. Jin, et al., The beneficial effects of exogenous melatonin on tomato fruit properties, Sci. Hortic. 207 (2016) 14–20.

[126] H. Gao, Z.K. Zhang, H.K. Chai, Ni Cheng, Y. Yang, et al., Melatonin treatment delays postharvest senescence and regulates reactive oxygen species metabolism in peach fruit, Postharvest Biol. Technol. 118 (2016) 103–110.

[127] R. Zhai, J. Liu, F. Liu, Y. Zhao, L. Liu, et al., Melatonin limited ethylene production, softening and reduced physiology disorder in pear (*Pyrus communis* L.) fruit during senescence, Postharvest Biol. Technol. 139 (2018) 38–46.

[128] W. Hu, W. Tie, W. Ou, Y. Yan, H. Kong, et al., Crosstalk between calcium and melatonin affects postharvest physiological deterioration and quality loss in cassava, Postharvest Biol. Technol. 140 (2018) 42–49.

[129] N. Singh, H. Kaur, S. Yadav, S.C. Bhatla, Does N-nitrosomelatonin compete with S-nitrosothiols as a long distance nitric oxide Carrier in plants? Biochem. Anal. Biochem. 5 (2016) 262.

[130] F. Ding, B. Liu, S. Zhang, Exogenous melatonin ameliorates cold-induced damage in tomato plants, Sci. Hortic. (Amst.) 219 (2017) 264–271.

[131] C. Zhou, Z. Liu, L. Zhu, Z. Ma, J. Wang, et al., Exogenous melatonin improves plant iron deficiency tolerance via increased accumulation of polyamine-mediated nitric oxide, Int. J. Mol. Sci. 17 (2016) 1777.

[132] K. Manning, M. Tö r, M. Poole, et al., A naturally occurring epigenetic mutation in a gene encoding an SBP-box transcription factor inhibits tomato fruit ripening, Nat. Genet. 38 (2006) 948–952.

[133] S. Zhong, Z. Fei, Y.R. Chen, et al., Single-base resolution methylomes of tomato fruit development reveal epigenome modifications associated with ripening, Nat. Biotechnol. 31 (2013) 154–159.

[134] M. Bemer, R. Karlova, A.R. Ballester, et al., The tomato FRUITFULL homologs TDR4/FUL1 and MBP7/FUL2 regulate ethylene-independent aspects of fruit ripening, Plant Cell 24 (2012) 4437–4451.

[135] Y. Shima, M. Fujisawa, M. Kitagawa, et al., Tomato FRUITFULL homologs regulate fruit ripening via ethylene biosynthesis, Biosci. Biotechnol. Biochem. 78 (2014) 231–237.

[136] S.B. Nogueira, C.A. Labate, F.C. Gozzo, E.J. Pilau, F.M. Lajolo, et al., Proteomic analysis of papaya fruit ripening using 2DE-DIGE, J. Proteom. 75 (2012) 1428–1439.

[137] Q. Zheng, J. Song, L. Campbell-Palmer, et al., A proteomic investigation of apple fruit during ripening and in response to ethylene treatment, J. Proteom. 93 (2013) 276–294.

[138] B. Prinsi, A.S. Negri, C. Fedeli, et al., Peach fruit ripening: a proteomic comparative analysis of the mesocarp of two cultivars with different flesh firmness at two ripening stages, Phytochemistry 72 (2011) 1251–1262.

[139] R. Alba, P. Payton, Z. Fei, et al., Transcriptome and selected metabolite analyses reveal multiple points of ethylene control during tomato fruit development, Plant Cell 17 (2005) 2954–2965.

[140] J. Pirrello, F. Regad, A. Latche, J.C. Pech, M. Bouzayen, Regulation of tomato fruit ripening, CAB Reviews 4 (2009) 1–14.

[141] J. Wei, D.X. Li, J.R. Zhang, C. Shan, Z. Rengel, et al., Phytomelatonin receptor PMTR1-mediated signaling regulates stomatal closure in Arabidopsis thaliana, J. Pineal Res. (2018) e12500.