Vol. 14, No. 6 (2025): 2458 - 2472 http://dx.doi.org/10.23960/jtepl.v14i6.2458-2472

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Mechanisms and Application of Fruit and Vegetable Shelf Life Extension Using 1-MCP, NO, and Melatonin: Systematic Review

Melati Pratama[1,✉], Daniel Saputra[1], Gatot Priyanto[1], Anny Yanuriati[1]

[1] Doctoral Program in Agricultural Sciences, Faculty of Agriculture, Sriwijaya University, Jl. Padang Selasa No. 524, Bukit Besar 30139, Palembang, South Sumatra, INDONESIA.

Article History:

Received : 20 April 2025
Revised : 28 April 2025
Accepted : 30 August 2025

Keywords:

Ethylene,
MCP,
Melatonin,
NO,
Respiration.

Corresponding Author:
✉ melatipratama07002@gmail.com
(Melati Pratama)

ABSTRACT

Fruits and vegetables are perishable commodities after harvest. Fruit and vegetable damage occurs due to post-harvest metabolic processes that can result in the formation of ROS and ethylene, bacteria, fungi, chilling injury and mechanical damage (wounds). New technologies were discovered to inhibit ripening, aging and post-harvest fruit damage, namely the use of Methylcyclopropene (MCP), Nitric Oxide (NO) and Melatonin. The purpose of this paper is to analyze the mechanism of the three inhibitors, their applications, advantages and disadvantages so that they can be used effectively and efficiently. The method used is systematic review, data are collected and analyzed systematically. A review of 106 articles shows that MCP, NO, and melatonin have different mechanisms. MCP works by inhibiting ethylene receptors, NO through four pathways (S-nitrosylation, limiting SAM formation, forming MACC, binding NO-ACC-ACC), and melatonin through four pathways (slowing ripening, reducing cold damage, as an antioxidant, as an antibacterial agent).

1. INTRODUCTION

Fruits and vegetables are horticultural commodities that have a role as suppliers of vitamins and minerals (Maharani *et al*., 2023), fiber, folic acid (Chandra & Aisah, 2023), carbohydrates (Sulaiman *et al*., 2024) and water as much as 55-85% (Waryat & Handayani, 2020). Apart from containing various nutrients, fruits, vegetables can be harvested after ripening. During the ripening process, physiological changes and biochemical (metabolic) reactions occur. This Process involves several biomolecular compounds and ethylene production. For climacteric fruits, this process is still ongoing and even increases after harvest (Widodo *et al*., 2019; Yuniastri *et al*., 2020; Prayitno, 2023) so fruits and vegetables are easily damaged (perishable) (Nofiyanto *et al*., 2024) for 2 - 4 days (Waryat & Handayani, 2020). Vegetable damage is characterized by yellowing of the leaves, foul smell, fungus and fly attack (Harnanik, 2018). While in the fruit, the texture of the flesh becomes tender, black-brown in color, and juicy (Adirahmanto *et al*., 2013). In some other fruits, the appearance of wounds on the surface of the fruit, necrosis and dents (spots on the skin and dark brown spots on the fruit), abnormal discoloration of the surface and inside of the fruit, leakage of damaged microorganisms, especially metabolites that promote fungal growth (Sunarso *et al*., 2023).

Fruit and vegetable spoilage is caused by several things including excess free radicals (Habibah *et al*., 2023), mold and bacteria growth (Ansiska *et al*., 2023), as well as physical damage of chilling injury (Ifmalinda *et al*., 2023). Habibah *et al*. (2023) said that excess free radicals such as reactive oxygen species (ROS), reactive nitrogen species (RNS), and reactive sulfur species (RSS) can cause cell damage, thus accelerating aging and degenerative diseases. Pathogenic fungi in fruits, namely *Botrytis cinerea* and *Colletotrichum acutatum*, cause anthracnose rot and rot on the skin of the fruit (Asharo *et al*., 2022). Meanwhile, chilling injury occurs due to cell damage or cell death in plant tissues that are sensitive to cold temperatures. At cold temperatures, toxic metabolites such as ethanol, acetaldehyde, and oxaloacetate accumulate (Sunarso *et al*., 2023).

Various studies have been conducted to extend the shelf life of fruits and vegetables including using MCP (Methylcyclopropene) (Haloho, 2023; Prabasari, 2024; Lata *et al*., 2017; Candan & Calvo, 2021; Lv *et al*., 2023; Peng & Fu, 2023; Hasan *et al*., 2024), Nitric oxide (Sukasih & Setyadjit, 2019; Liu *et al*., 2023; Corpas *et al*., 2023; Lu *et al*., 2023), and Melatonin (Wei *et al*., 2022; Shah *et al*., 2024; Mandal *et al*., 2024; Boonsiriwit *et al*., 2021; Arshad & Haghshenas, 2025; Fan *et al*., 2022; Borthakur *et al*., 2024), by various methods, namely by immersion (Badiche-El Hilali *et al*., 2023), spraying (Wang *et al*., 2023), and soaking (Sun *et al*., 2020). However, it is not yet known which of the three technologies (MCP, NO, and Melatonin) is the most effective and efficient. Therefore, a study on the mechanism of action, application, advantages and disadvantages of each technology is needed.

2. METHODS

The method used in this paper was the Systematic Literature Review (SLR). The SLR method was used to identify, review, evaluate and interpret all available research with the topic area of the phenomenon of interest, with certain relevant questions. In this study, SLR was conducted by adopting Carrera-Rivera *et al*. (2022) and Sauer & Seuring (2023) stages, including:

1. Determining the initial idea or interest in a topic. The phenomenon being discussed is the mechanisms of technology (MCP, NO, and Melatonin) in extending the shelf life of fruits and vegetables, as well as the advantages and disadvantages of each technology.
2. The SLR continued by searching for relevant literature through Google Scholar.
3. The obtained literatures was then read to determine the direction of the review and the formulation of questions.
4. Once the focus was established, research results were selected specifically. The selection of research results was reviewed through several questions, such as how do these technologies maintain the freshness of fruits and vegetables? What are the advantages and disadvantages of each technology?
5. Data from literatures, including process mechanisms, technologies, applications, gaps, and challenges, were analyzed critically.
6. The analysis results are evaluated and reported.

3. RESULTS AND DISCUSSION

3.1. Technological Mechanisms to Extend Shelf Life

Fruits and vegetables are still metabolizing after harvest (Sari *et al*., 2018) in the form of respiration and enzymatic reactions (Kurniawan & Deglas, 2022). Respiration that occurs in post-harvest fruits is carried out through the skin of the fruit (Mudyantini *et al*., 2016). Respiration is a chemical reaction that breaks down complex compounds into simpler ones (Nur Fauziah *et al*., 2021) through glycolysis, tricarboxylic acid cycle, Krebs and electron transfer. During respiration, all substrates are utilized (Kandasamy, 2022; Mudyantini *et al*., 2016). Glycolysis is the initial stage in carbohydrate metabolism by breaking down glucose into energy in the form of ATP (Adenosine Triphosphate). Figure 1 is the reactions of glycolysis, Krebs and electron transfer:

ATP is the main source of energy for cells in metabolism (Marpaung & Prasetyo, 2024). Jiang *et al*. (2024) added ATP is also the energy used to form ethylene together with the precursor. Ethylene is a hydrocarbon compound with the chemical formula C_2H_4 that plays an important role in the fruit ripening process. Ethylene is also a plant hormone that affects the rate of respiration. High respiration rate leads to short shelf life of fruits and vegetables (Giyanto *et al*., 2022). Ethylene is formed through three stages, namely the formation of S-adenosyl methionine (SAM) from methionine with the help of SAM synthase which requires 1 molecule of ATP. Next, SAM is converted to ACC (1-aminocyclopropane -1-carboxylic acid) catalyzed by ACC synthase. Methylthiadenosine (MTA) is also produced in the process of ACC formation and will be reused for methionine formation so that cellular methionine concentration is

Glycolysis (Chandel, 2021)
Glucose + 2ADP + $2P_i$ + $2NAD^+$ → 2Pyruvic acid + 2ATP + 2NADH

↓

Krebs cycle (Gasmi *et al*., 2021)
Pyruvic acid + CoA + NAD^+ → Acetil-CoA + CO_2 + NADH
Acetil-CoA + O_2 → CO_2 + ATP + NADH + $FADH_2$

↓

Electron transfer (Hardianti *et al*., 2023)
NADH + O_2 → H_2O + ATP

Figure 1. Glycolysis, Krebs cycle and electron transfer reactions

always available despite increased ethylene formation. The last stage is the oxidation of ACC to ethylene (Pradani, 2020; Giyanto *et al*., 2022). In addition to ethylene, fruit and vegetable respiration also forms free radicals or reactive oxygen species (ROS). ROS are formed from the incomplete reduction of oxygen in the electron transfer chain (ETC) (Situmorang & Zulham, 2020). Accumulation of ROS can lead to cell damage, protein structure damage and tissue aging (Li *et al*., 2023).Post-harvest deterioration of fruits and vegetables can be slowed down by using MCP (Methylcyclopropene), Nitric oxide (NO) and Melatonin.

3.1.1. MCP (Methylcyclopropene)

1-MCP is a gas with a molecular weight of 54 and a formula of C_4H_6 at standard temperature and pressure (Blankenship & Dole, 2003). 1-MCP is used to inhibit the reaction of ethylene in providing plant physiological effects (Fauzi *et al*., 2018; Chang & Brecht, 2023). Kolniak-Ostek *et al*. (2014) added the ability of 1-MCP to extend shelf life is achieved by blocking ethylene receptor capture. The mechanism of ethylene receptor blocking by 1-MCP can be seen in the Figure 2.

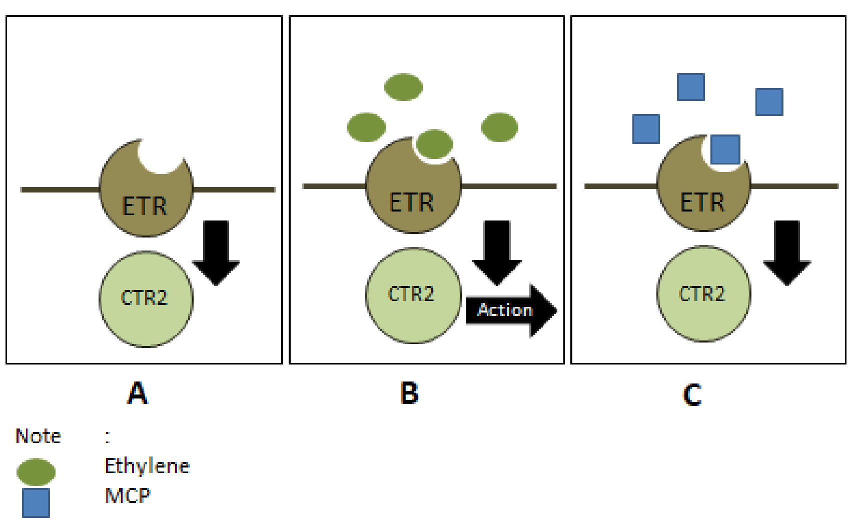

Figure 2. Receptor blocking by 1-MCP, source : (Alabboud *et al*., 2017)

The process of blocking ethylene receptors involves ETR and CTR. Figure 2 explains that ETR is ethylene receptor, while CTR2 (Constitutive Triple Signaling) is protein kinase (in certain organs). Protein kinase is an enzyme that signals intracellularly (Hidayat, 2020). The analogy is that CTR acts as a brake that inhibits the response of the cellular signal pathways, while ETR (ethylene receptor) is a gate sensor. As long as the sensor does not detect ethylene, the door remains tightly closed. This sensor is directly connected to the CTR (brake). CTR prevent the ripening machine from working. As long as the brake (CTR) is active, the ripening machine cannot run.

Figure 2A show in the absence of ethylene, CTR2 to be active so ripening machine does not run. The kinase activity of the receptor (ETR-1) shuts down the first step in the cascade response (CTR). If sensor detect ethylene, the door remains opened. The brake is released (CTR2 is inactive), then the machine immediately starts working sequentially. Figure 2B, the ethylene binds to the receptor (ETR-1) the kinase activity is inhibited and the cascade begins to respond.

The prevention of ethylene binding to the receptor in Figure 2C shows when 1-MCP binds to the receptor (ETR-1), 1-MCP binds irreversibly. That caused ethylene fails to bind to it (Alabboud *et al*., 2017). Blocking of the receptor by ethylene is done by 1-MCP filling the receptor position that ethylene normally occupies. The existence of this bond causes ethylene to be unable to bind to the receptor. The mechanism of 1-MCP in blocking receptors occurs, 1-MCP in gaseous form enters plant tissues. 1-MCP has a similar structure to ethylene, but 1-MCP has a greater affinity and is active at low concentrations than ethylene (Blankenship & Dole, 2003). This causes 1-MCP to bind strongly to the ethylene receptor. Once bound, the receptor cannot recognize ethylene anymore (Dong *et al*., 2021a). To prevent direct precursors in the ethylene biosynthetic pathway, S-AdoMet is converted to ACC. 1-MCP then binds to the ACC synthase enzyme, preventing ethylene formation and inhibiting ethylene-induced signal transduction (Kumar *et al*., 2023). There are several factors that affect the effect of 1-MCP use, namely commodity, developmental level of the plant, 1-MCP concentration, ambient temperature at application, and duration of application. 1-MCP is generally applied at low concentrations 2.5 nL/L to 1 µL/L for 12–24 h at room temperature 20–25 ºC (Nanthachai *et al*., 2007).

3.1.2. Nitric Oxide

Ethylene has an important role in plant development and physiology. Ethylene biosynthesis involves two specialized enzymatic reactions. Bioethylene synthesis in fruits and vegetables is initiated from methionine (MET) which is converted to S-adenosylmethionine (SAM). SAM is then converted to 1-amino cyclopropene 1-carboxylate (ACC) by 1-carboxylate synthase (ACC synthase). ACC is again converted to ethylene, carbon dioxide, and cyanide by the enzyme ACC oxidase (ACO) (Gardjito & Adnan, 2006). Inhibition of ethylene biosynthesis in fruits and vegetables can be done by applying nitric oxide (NO). Inhibition of ethylene biosynthesis by NO occurs through ethylene signal transduction with several directions, namely S-nitrosylation, diversion of SAM to polyene synthesis, conversion of ACC to MACC, and formation of NO-ACC-ACCO in Figure 3.

Nitric oxide (NO) is a free radical obtained from various oxidative stress conditions (Norazizah *et al*., 2020). Besides being obtained through endogenous, NO can also be obtained through exogenous, namely from the atmosphere or soil that is fixed through nitrification. Endogenous NO formation occurs non-enzymatically and enzymatically. Non-enzymatic NO formation is the conversion of NO_2 to NO in an acidic or alkaline environment, while enzymatic is through oxidative reductive by nitrite reductase (NR). NR uses various cofactors to convert nitrate to nitrite in mitochodria, peroxisomes and plant chloroplasts in the electron transport pathway (Figure 3). This gas is stable, can signal plants in the process of development, has anti-aging and maturation properties (Duan *et al*., 2007).

According to Pols *et al*. (2022), the inhibition of ethylene synthesis in fruits and vegetables by nitric oxide (NO) occurs in four stages. The First, signaling (S-nitrosylation) occurs when NO is attached to the cysteine (Cys) thiol (SH) of proteins to form S-nitrosothiol (SNO). S-nitrosothiols reversibly regulate various biological signals and processes. (Broniowska & Hogg, 2012). S-nitrosothiol regulates methionine adenosyltransferase (MAT) through S-nitrosylation, thus inhibiting the activity of MAT enzyme, which catalyzes the biosynthesis of SAM (S-adenosylmethionine). Secondly, inhibited MAT activity will limit the biosynthesis of SAM, an important precursor in ethylene and PA biosynthesis. Third, in addition to helping SAM biosynthesis, the presence of high concentrations of

NO in the cell will cause the formation of 1-malonyl aminocyclopropane-1-carboxylic acid (MACC) so that the concentration of ACC becomes low and this is irreversible. Fourth, in maturity inhibition, the presence of NO in cells affects ethylene formation. NO binds to ACC and ACC oxidase resulting in the formation of NO-ACC-ACO. The formation of NO-ACC-ACO causes the conversion of ACC to ethylene to be disrupted (Kaniawati *et al*., 2024);. The mechanism can be seen in Figure 3.

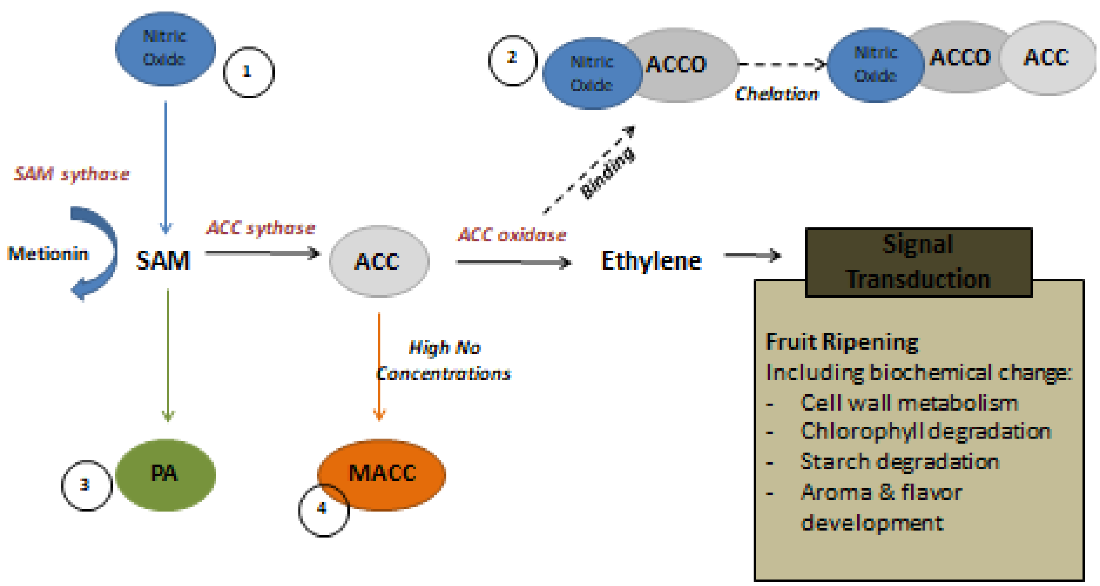

Figure 3. Mechanism of NO as an inhibitor of ACC conversion. The ethylene signal is indirectly inhibited by NO through S-nitrosylation of MAT that catalyzes SAM biosynthesis (1), signal inhibition can also occur by the binding of NO with ACC and ACO to form NO-ACC-ACO which causes ethylene not to be formed (2), SAM is diverted into polyamine synthesis from ACC formation (3), and the conversion of ACC to MACC has occurred, source : (Pols *et al*., 2022)

3.1.3. Melatonin

Melatonin is a peptide hormone of the indolamine class produced by the pineal gland. This hormone is commonly found in humans which functions to make a person fall asleep and restore physical energy during sleep (Husna & Puspita, 2020). According to Hidayat *et al*. (2020) melatonin is a lipophilic hormone that has antioxidant-like activity in fighting free radicals. Melatonin can also be classified as a vitamin and antioxidant. Melatonin is found in vegetables, fruit, rice, wheat and herbal remedies (Kesanda *et al*., 2016). Initially used as a therapy for sleep disorders, melatonin has recently become a key modulator in post-harvest preservation of fruits and vegetables. Endogenously, melatonin plays an important role in post-harvest ripening of fruits and vegetables. Exogenously, melatonin eliminates excessive reactive oxygen species (ROS) by increasing antioxidant enzymes, non-enzymatic antioxidants and enzymes related to oxidized proteins (Xu *et al*., 2019). In extending the shelf life of fruits and vegetables, melatonin has four mechanism pathways, namely slowing down ripeness, reducing chilling injury, as an antioxidant and antibacterial (Feng *et al*., 2022).

In the post-harvest aging process, fruits and vegetables undergo chlorophyll degradation by chlorophyll enzymes. During post-harvest aging, fruits and vegetables undergo chlorophyll degradation by chlorophyll enzymes. Chlorophyll degradation can be delayed by applying melatonin. The mechanism of inhibition of chlorophyll enzyme catabolic activity by melatonin occurs through the inhibition of PAO (Pheophorbide a oxygenase) activity. Melatonin, in the form of indoleamine (indole group), captures free radicals (hydroxyl, superoxide, and peroxyl) (An *et al*., 2025).

The capture of free radicals by the indole group causes the activation of PAO (Pheophorbide a oxygenase) to be inhibited, thereby reducing chlorophyll degradation (Hörtensteiner, 2013; Hörtensteiner & Kräutler, 2011). The reduction in degradation affects the stability of photosynthetic pigments. Photosynthesis becomes stable, so the energy supply from chloroplasts remains stable. This ensures that the supply of organic carbon entering the TCA cycle is maintained, resulting in optimal energy metabolism (Wang *et al*., 2025). Beside delayed chlorophyll degradation, the mechanism of melatonin in inhibiting aging is by blocking ABA (abscisic acid) signaling by reducing ABA (abscisic acid) content and inhibiting signal transduction. Melatonin also inhibits the activity of pectin methylesterase, polygalacturonase, cellulase, and β-Glucosidase thus keeping pectin water insoluble thus inhibiting fruit softening (Feng *et al*., 2022; Li *et al*., 2023).

In terms of chilling injury, there are some fruits that are sensitive to low temperatures (<10-15 ºC) such as bananas, papayas, mangoes, tomatoes and eggplants. Low temperature can cause physiological such as surface appearance changes such as brown spots on the skin and pulp, skin wrinkling, impaired ripening, abnormal softening, and increased susceptibility to pathogen infection. Cold damage can also cause discoloration, wilting, stiffness, and brittleness (Dahlan *et al*., 2024). At the molecular level, cold damage causes changes in composition, lipid membrane flexibility, ion and metabolite leakage, substance transport disruption, and tissue damage (loss of cell integrity which triggers localized cell death) (Purwanto *et al*., 2012).

In addition, there is stress caused by the accumulation of reactive oxygen species (ROS). Cold temperature triggers metabolic stress that increases the production of ROS such as superoxide (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radicals (▪OH). This accumulation causes oxidative damage to fat, protein and DNA, increasing malondialdehyde (MDA) and decreasing sulfhydryl content (Mirshekari *et al*., 2020; Zhang *et al*., 2018a). Cold temperatures also inactivate or denature important enzymes such as dehydrogenase, ATPase and antioxidant enzymes which worsen metabolism resulting in decreased enzyme activity and accelerated tissue damage (Feng *et al*., 2022). The addition of melatonin can also inhibit chilling injury.

The mechanism of melatonin in inhibiting chilling injury is by increasing the accumulation of putrescine, spermidine (Spd), spermine (Spm), and conjugated Polyamines (PAs) which regulate cell metabolism such as division, differentiation, and neutralizing ROS. Melatonin also increases gamma-aminobutyric acid (GABA) and proline which play a role in regulating cell osmotic pressure, releasing toxins from ROS and free radicals (H_2O_2), putrescine conversion, and signal transduction in the cell. The addition of melatonin provides succinic acid and NADH for the TCA cycle and electron transfer chain in the mitochondria (Feng *et al*., 2022). As an antioxidant, melatonin creates an antioxidative system as in studies (Wei *et al*., 2022; Fan *et al*., 2022). Wei *et al*. (2022) reported that exogenous melatonin application prevented browning in rambutan fruits. In the study (Fan *et al*., 2022), melatonin in guava creates an efficient non enzymatic and enzymatic antioxidative system to prevent ROS and protect oxidative damage. Oxidative damage is caused by the presence of CAT, APX, PPO, peroxidase (POD), dehydroascorbate reductase, SOD, GR and GPX, which are important for ROS homeostasis in fruits. The application of exogenous melatonin effectively reduces ROS in fruits by inducing antioxidant systems, including enzymatic and non-enzymatic antioxidants which then delays the fruit ripening process. In the study (Arshad & Haghshenas, 2025), melatonin in banana has limited ROS accumulation and inhibited oxidative damage; catalase and superoxide dismutase by creating antioxidants. Research (Boonsiriwit *et al*., 2021) increases the activity of the CAT enzyme (catalase enzyme). Research (Charoenphun *et al*., 2025) increases the activity of antioxidant enzymes such as superoxide dismutase (SOD) and ascorbate peroxidase (APX). Figure 4 shows the mechanism of melatonin in maintaining the shelf life of fruits and vegetables through antioxidative.

In Figure 4, three routes are as follow. (1) Red lines and arrows indicate ROS elimination pathways. Melatonin acts mainly as a powerful free radical scavenger by increasing the content of antioxidant enzymes, non-enzymatic antioxidants, and enzymes related to oxidative protein repair, removing excess active oxygen from post-harvest fruits and vegetables. Furthermore, the content of hydroxyl radicals and hydrogen peroxide is reduced, the degree of membrane lipid peroxidation is reduced, thereby protecting cells from oxidative damage and extending the shelf life. (2) Blue lines and arrows indicate pathogen response-dependent pathways. Exogenous melatonin increases the level of JA and SA, triggers plant pathogen responses, enhances pathogen resistance, and extends shelf life. (3) Green lines and arrows indicate postharvest fruit and vegetable spoilage. Disease or postharvest aging of fruits and vegetables generates a lot of ROS, causes lipid peroxidation, and leads to postharvest spoilage. Red arrows indicate increased levels of each component.

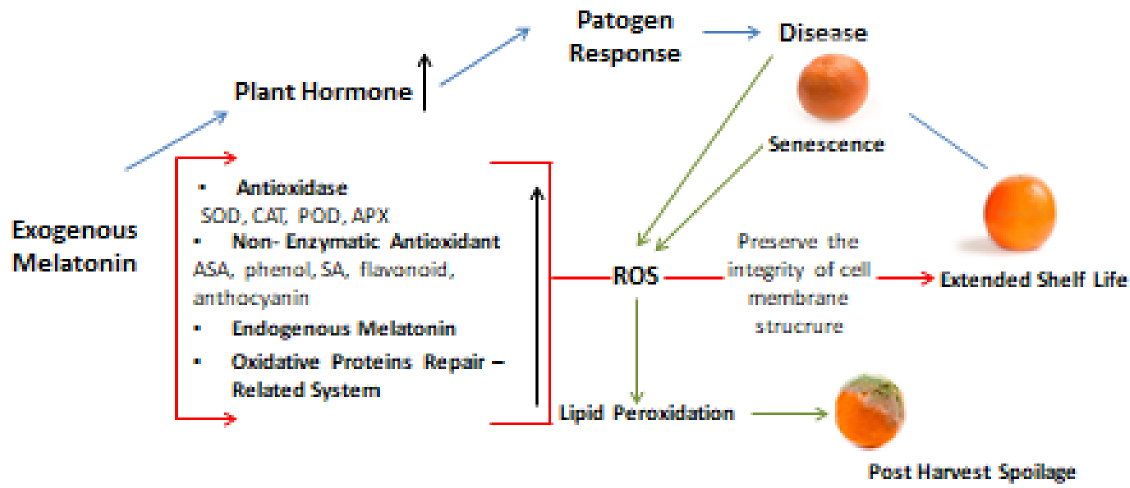

Figure 4. Model mechanism of exogenous melatonin-mediated postharvest preservation in fruits and vegetables (Xu *et al*., 2019)

Melatonin has good antibacterial activity and can be used to reduce the use of pesticides. The activity of melatonin as an anti-bacterial is carried out by enhancing the defense system of fruits and vegetables, inhibiting microbial growth and providing fungicidal effects. The mechanism of melatonin in improving the defense system of fruits and vegetables is by channeling pathogen-resistant signals to induce the biosynthesis of nitric oxide, jasmonic acid (JA) and salicylic acid (SA); where JA is an organic compound formed through the biosynthesis of free linolenic acid by the lipoxygenase enzyme which is used as a key signal compound in the plant's defense response (Manullang *et al*., 2013), whereas salicylic acid induces the formation of pathogenesis related (PR) proteins that increase resistance to plant infection (Gunaeni *et al*., 2015). Melatonin also circulates glucose in plant leaves and roots, increases the accumulation of cellulose, xylose, galactose and kallose in the cell wall by increasing the activity of cell wall invertase (CWI) and vacuolar invertase (VI) to increase the thickness of the cell wall (Feng *et al*., 2022).

In inhibiting bacterial growth and functioning as a pesticide, melatonin interferes with the amino acid metabolism of pathogens by targeting rapamycin (TOR) thereby causing death. Melatonin downregulates genes encoding rate limitation of the enzymes pyruvate kinase, fructose diphosphate aldolase and isocitrate dehydrogenase and reduces the rate of amine acid metabolism (He *et al*., 2021; Feng *et al*., 2022). Based on the explanations of MCP (sub-subchapter 3.1.1), Nitric Oxide (sub-subchapter 3.1.2), and melatonin (sub-subchapter 3.1.3) have different mechanisms and reaction forms. The differences between the three technologies can be seen in Table 1.

3.2. Application of MCP, NO and Melatonin on Fruits and Vegetables

The application of MCP, NO and Melatonin on fruits and vegetables varies in both concentration and application method. MCP application on fruits and vegetables depends on the concentration used. The use of MCP 300 - 1000 nL can reduce the weight loss of tomatoes, 400 - 600 nL can delay the maturity of bananas, MCP application on tomatoes and bananas is done by fumigation (Satekge & Magwaza, 2022). Table 2 details of the application and its effects.

Table 1. Comparison of MCP, NO and Melatonin mechanisms

Technology	MCP (Methylcyclopropene)	Nitric oxide	Melatonin
Mechanism	Blocking ethylene capture receptors	Through 4 mechanism pathways, namely: 1) S-nitrosylation, 2) Limiting the formation of SAM, 3) Forming MACC, and 4) Binding NO-ACC-AC	Through 4 paths, namely: 1) Slows down maturity, 2) Reduces chilling injury, 3) As an antioxidant 4) and antibacterial
Reaction form	Volatile gas	Free radicals	Hormone

Table 2. Effect of inhibitors on shelf life of fruits, vegetables, or flowers at various concentrations

Inhibitory Ingredients	Commodities	Concentration	Application form	Influence
MCP (Methylcyclopropene)	Tomato (Horváth-Mezőfi *et al.*, 2024)	2%	Gas	Tomato color change within 2 weeks
	Chrysanthemum flower (Salsabilla & Kartika, 2013)	0.3 ppm	Gas	Extend chrysanthemum cut flowers 1.2 - 1.8 times
	Guava (Widodo *et al.*, 2016)	0.01 g/mL	Gas	Able to maintain the sweetness level of guava
	Kiwi (Zhao *et al.*, 2024)	0.5 μL^{-1}	Gas	Influence on carbohydrate metabolism
	Mango (Hasan *et al.*, 2024)	1 μL^{-1}	Gas	slowing down fruit weight loss, firmness, soluble solids, and acidity
Nitric oxide (NO)	Tomato (Shu *et al.*, 2025)	0.2 mM	Dipping	inhibits ethylene production
	Apricot (Abd Elwahab *et al.*, 2024)	25 µM	Spraying	delay fruit ripening and maintain fruit quality
	Orange (Yang *et al.*, 2021)	15 μL^{-1}	Gas	inducing disease resistance to P. italicum in citrus fruits
Melatonin	Apple (Verde *et al.*, 2022)	500 µM	Spraying	melatonin stimulates fruit ripening
	Blueberries (Shang *et al.*, 2021)	0.05 $mmoL^{-1}$	Spraying	maintain the content of ascorbic acid, anthocyanins, total phenols, reduce the accumulation of ROS and lipid peroxides
	Mango (Dong *et al.*, 2021b)	200 µM	Dipping	inhibits the maturation process
	Papaya (Wang *et al.*, 2022)	1.5 mM	Spraying	reducing postharvest aging and maintaining fresh quality of papaya fruit in cold storage
	Avocado (Yılmaz *et al.*, 2025)	0.5 mM 1.0 mM	Spraying	maintaining the quality of stored avocados

It can be summarized from the table that various biochemical inhibitors—including methylcyclopropene (MCP), nitric oxide (NO), and melatonin—have been shown to significantly enhance the shelf life and postharvest quality of different fruits, vegetables, and flowers. MCP, applied mainly in gaseous form, delays ripening, maintains sweetness, improves firmness, and even extends the longevity of cut flowers across commodities such as tomatoes, guava, kiwi, mango, and chrysanthemums. Nitric oxide, delivered through dipping, spraying, or gas exposure, effectively suppresses ethylene production, delays ripening, maintains fruit quality, and enhances disease resistance in tomatoes, apricots, and citrus fruits. Melatonin treatments—applied via spraying or dipping—either stimulate or inhibit ripening depending on concentration and commodity, while also preserving antioxidant content and reducing oxidative stress in fruits like apples, blueberries, mangoes, papayas, and avocados. Overall, the use of these inhibitors demonstrates a broad potential to modulate physiological processes and prolong freshness across a wide range of horticultural products.

3.3. Disadvantages and Advantages of MCP, NO and Melatonin

All inhibitors have the same ability to prevent damage of fruits and vegetables, extend shelf life and maintain quality. However, they have advantages and disadvantages as summarized in Table 3.

3.4. Prospect and Challenges

MCP, NO, and melatonin also have prospects and challenges. Based on Tables 2 and 3, the prospects and challenges of MCP, NO, and melatonin are summarized in Table 4.

Table 3. Advantages and disadvantages of MCP, NO and Melatonin

Inhibitory material	MCP (Methylcyclopropene)	Nitric oxide (NO)	Melatonin
Advantages	• Already commercial and safe, applied at room temperature (20-25oC) for 12-24 hours (Watkins, 2006) • Can be applied with other materials such as chitosan (You *et al*., 2022)	• Can reduce cold damage (Zhong *et al*., 2024) • Can be applied as fumigation to control pests (Liu, 2013) • Can be applied to bruised/injured fruit (Gardjito & Adnan, 2006)	• Provides antioxidant effects (Zhang *et al*., 2018b) • Delays in fruit maturity and quality do not involve ethylene (Zhao *et al*., 2020) • Can be applied to fruits and vegetables prone to cold temperatures (Azadshahraki *et al*., 2018) • Can be a substitute for pesticides (Feng *et al*., 2022)
Disadvantages	The response to 1-MCP may vary depending on the species and cultivar of the fruit or vegetable. Some varieties may show lower effectiveness to 1-MCP treatment (Watkins, 2006)	Too high a concentration of NO can cause toxic effects (Granella *et al*., 2022)	The use of melatonin at high concentrations may cause negative effects. For example, postharvest treatment of strawberries with melatonin at a concentration of 1,000 µM was reported to cause rotting and reduced fruit quality (Xu *et al*., 2019)

Table 4. Prospects and challenges

Inhibitory material	MCP (Methylcyclopropene)	Nitric oxide (NO)	Melatonin
Prospect	• More effective on climacteric fruits	• Can be widely applied to fruits, flowers, and vegetables	• Can be widely applied to fruits, flowers, and vegetables • Tends to be safe
Challenges	• MCP only delays, it does not fix	• Unstable • Toxic	• Unstable • Quite expensive

MCP, NO, and melatonin are classified as food additives (BTP) in their application. The Ministry of Health has determined that the use of BTP in foodstuffs is subject to certain conditions, namely that it is not treated as a raw material, that the additive has an effect on the foodstuff to which it is added, and that it is not a contaminant or harmful (Kementerian Kesehatan RI, 2012). Table 4 shows that the use of NO in fruits and vegetables poses a risk to these conditions. NO has toxic properties if used in excess. NO also has reversible/unstable effects, where its function will disappear if NO in food is lost. NO only disrupts communication; it does not lock like MCP. MCP is also synthetic and more effective on climacteric fruits. This is because MCP's mechanism of action is to block ethylene receptors. Based on these limitations, MCP and NO have limited prospects for use, while the limitation of melatonin is its relatively high cost. However, melatonin has greater potential due to the concentration used, which ranges from 200 µM to 1.5 mM.

4. CONCLUSIONS

Based on the literature study, it was found that MCP, NO and Melatonin have different reaction mechanisms when applied as inhibitors. The mechanism of MCP is on the blocking of ethylene receptors, while NO through a four-path mechanism that prevents the formation of ethylene, and melatonin by various functions, namely slowing maturity, reducing chilling injury, as an antioxidant and antibacterial. The application of the three inhibitors also varies, with MCP using more gassing methods, NO and melatonin immersion and spraying with different concentrations. The three inhibitors also have their own advantages and disadvantages, where the use of MCP is more effective on climacteric and safe fruits, NO can be used in fumigation and melatonin can provide antioxidant effects. However, NO can cause toxins if used in excessive concentrations. Therefore, selecting the most suitable inhibitor should be based on its mechanism of action, as well as its respective advantages and limitations.

REFERENCES

Adirahmanto, K.A., Hartanto, R., & Novita, D.D. (2013). Perubahan kimia dan lama simpan buah salak pondoh (*Salacca edulis* Reinw.) dalam penyimpanan dinamis udara–CO_2. *Jurnal Teknik Pertanian Lampung, **2***(3), 123–132.

Abd Elwahab, S.M., Abdallatif, A.M., & El-Saeed, S.A.E. (2024). Improving the postharvest shelf life of apricot fruits (*Prunus armeniaca* L. cv. Amal) using preharvest application of spermidine, salicylic acid and sodium nitroprusside. *Journal of Applied Horticulture, **26***(4), 493–499. https://doi.org/10.37855/jah.2024.v26i04.92

Alabboud, M., Mohi-Alden, K., & Alhaj Alali, F. (2017). Using 1-methylcyclopropene (1-MCP) as an ethylene inhibitor in horticultural crops storage (a review). *Proceedings of the 3rd International Conference on Sustainable Development, Strategies and Challenges with a Focus on Agriculture, Natural Resources, Environment and Tourism*, 1–12. https://civilica.com/doc/639981

An, W., Wang, G., Dou, J., Zhang, Y., Yang, Q., He, Y., Tang, Z., & Yu, J. (2025). Protective mechanisms of exogenous melatonin on chlorophyll metabolism and photosynthesis in tomato seedlings under heat stress. *Frontiers in Plant Science, **16**,* 1519950. https://doi.org/10.3389/fpls.2025.1519950

Ansiska, P., Anggraini, S., Sari, I.M., Windari, E.H., & Oktoyoki, H. (2023). *Isolasi dan identifikasi jamur patogen buah stroberi selama penyimpanan*. *Jurnal Ilmu-Ilmu Pertanian Indonesia, **25***(1), 34–39. https://doi.org/10.31186/jipi.25.1.34-39

Arshad, M., & Haghshenas, M. (2024). Melatonin and chitosan coating effects on banana postharvest life and physiological traits. *International Journal of Horticultural Science & Technology, **12***(1), 31. https://doi.org/10.22059/ijhst.2024.364005.687

Asharo, R.K., Indrayanti, R., Damayanti, A.P., Putri, H.A.E., Nabilah, S., & Pasaribu, P.O. (2022). Isolation and characterization of pathogenic microbes origin in strawberry (*Fragaria sp.*) based on Koch's Postulates. *Jurnal Ilmiah Biologi Eksperimen dan Keanekaragaman Hayati (J-BEKH), **9***(2), 51-61. https://doi.org/10.23960/jbekh.v9i2.269

Azadshahraki, F., Jamshidi, B., & Mohebbi, S. (2018). Postharvest melatonin treatment reduces chilling injury and enhances antioxidant capacity of tomato fruit during cold storage. *Advances in Horticultural Science, **32***(3), 299–309. https://doi.org/10.13128/ahs-22260

Badiche-El Hilali, F., Valverde, J.M., García-Pastor, M.E., Serrano, M., Castillo, S., & Valero, D. (2023). Melatonin postharvest treatment in leafy 'Fino' lemon maintains quality and bioactive compounds. *Foods, **12***(15), 2979. https://doi.org/10.3390/foods12152979

Blankenship, S.M., & Dole, J.M. (2003). 1-Methylcyclopropene: A review. *Postharvest Biology and Technology, **28***(1), 1–25. https://doi.org/10.1016/S0925-5214(02)00246-6

Boonsiriwit, A., Lee, M., Kim, M., Itkor, P., & Lee, Y.S. (2021). Exogenous melatonin reduces lignification and retains quality of green asparagus (*Asparagus officinalis* L.). *Foods, **10***(9), 2111. https://doi.org/10.3390/foods10092111

Borthakur, P., Chinnasamy, K., Paramasivam, S.K., Venkatachalam, S., Alagarswamy, S., Iruthayasamy, J., Thiyagarajan, E., & Muthusamy, S. (2024). Exogenous melatonin as pre- and postharvest application on quality attributes, antioxidant capacity, and extension of shelf life of papaya. *Horticulturae, **10***(10), 1099. https://doi.org/10.3390/horticulturae10101099

Broniowska, K.A., & Hogg, N. (2012). The chemical biology of S-nitrosothiols. *Antioxidants and Redox Signaling*, ***17***(7), 969–980. https://doi.org/10.1089/ars.2012.4590

Candan, A.P., & Calvo, G. (2021). Treatment with 1-MCP: An alternative to extend storage in plums harvested with advanced maturity. *Agrociencia Uruguay, **25***(NE1), 402. https://doi.org/10.31285/AGRO.25.402

Carrera-Rivera, A., Ochoa, W., Larrinaga, F., & Lasa, G. (2022). How-to conduct a systematic literature review: A quick guide for computer science research. *MethodsX, **9**,* 101895. https://doi.org/10.1016/j.mex.2022.101895

Chandel, N.S. (2021). Glycolysis. *Cold Spring Harbor Perspectives in Biology*, ***13***(5), 1–12. https://doi.org/10.1101/CSHPERSPECT.A040535

Chandra, F., & Aisah, A. (2023). Peningkatan pengetahuan konsumsi buah dan sayur untuk mencegah anemia pada remaja putri SMA Negeri 11 Kota Jambi. *Jurnal Abdimas Kesehatan (JAK), **5***(2), 219. https://doi.org/10.36565/jak.v5i2.455

Chang, L.-Y., & Brecht, J.K. (2023). Responses of 1-methylcyclopropene (1-MCP)−treated banana fruit to pre− and post−treatment ethylene exposure. *Scientia Horticulturae, **309**,* 111636. https://doi.org/10.1016/j.scienta.2022.111636

Charoenphun, N., Lekjing, S., & Venkatachalam, K. (2025). Effect of exogenous melatonin application on maintaining physicochemical properties, phytochemicals, and enzymatic activities of mango fruits during cold storage. *Horticulturae, **11***(2), 222. https://doi.org/10.3390/horticulturae11020222

Corpas, F.J., Muñoz-Vargas, M.A., González-Gordo, S., Rodríguez-Ruiz, M., & Palma, J.M. (2025). Nitric oxide (NO) and hydrogen sulfide (H_2S): New potential biotechnological tools for postharvest storage of horticultural crops. *Journal of Plant Growth Regulation, 44,* 1203–1220. https://doi.org/10.1007/s00344-023-11150-5

Dahlan, S.A., Saman, W.R., Limonu, M., Panggi, H., & Amelia, D.C. (2024). Pengaruh penyimpanan pada suhu ruang dan suhu dingin terhadap karakter fisik pisang. *Jurnal JTPG, **9***(1), 1342. https://doi.org/10.30869/jtpg.v9i1.1342

Dong, J., Kebbeh, M., Yan, R., Huan, C., Jiang, T., & Zheng, X. (2021a). Melatonin treatment delays ripening in mangoes associated with maintaining the membrane integrity of fruit exocarp during postharvest. *Plant Physiology and Biochemistry, **169**,* 22–28. https://doi.org/10.1016/j.plaphy.2021.10.038

Dong, M., Wen, G., Li, J., Wang, T., Huang, J., Li, Y., Tang, H., Sun, Q., & Wang, W. (2021b). Determination of 1-methylcyclopropene residues in vegetables and fruits based on iodine derivatives. *Food Chemistry, **358**,* 129854. https://doi.org/10.1016/j.foodchem.2021.129854

Duan, X., Su, X., You, Y., Qu, H., Li, Y., & Jiang, Y. (2007). Effect of nitric oxide on pericarp browning of harvested longan fruit in relation to phenolic metabolism. *Food Chemistry, **104***(2), 571–576. https://doi.org/10.1016/j.foodchem.2006.12.007

Fan, S., Xiong, T., Lei, Q., Tan, Q., Cai, J., Song, Z., Yang, M., Chen, W., Li, X., & Zhu, X. (2022). Melatonin treatment improves postharvest preservation and resistance of guava fruit (*Psidium guajava* L.). *Foods, **11***(3), 262. https://doi.org/10.3390/foods11030262

Fauzi, A.A., Kusumiyati, K., Mubarok, S., & Rufaidah, F. (2018). Beberapa catatan pemanfaatan 1-Methylcyclopropene pada krisan (*Chrysanthemum morifolium* Ram.). *Jurnal Pertanian Terpadu, **6***(1), 1–10. https://doi.org/10.36084/jpt..v6i1.137

Feng, B.-S., Kang, D.-C., Sun, J., Leng, P., Liu, L.-X., Wang, L., Ma, C., & Liu, Y.-G. (2022). Research on melatonin in fruits and vegetables and the mechanism of exogenous melatonin on postharvest preservation. *Food Bioscience, **50***(Part B), 102196. https://doi.org/10.1016/j.fbio.2022.102196

Gardjito. (2006). Biosintetis etilen luka pada irisan mesokarp labu kuning. *agriTECH, **26***(1), 8–13.

Gasmi, A., Peana, M., Arshad, M., Butnariu, M., Menzel, A., & Bjørklund, G. (2021). Krebs cycle: Activators, inhibitors and their roles in the modulation of carcinogenesis. *Archives of Toxicology, **95**,* 1161–1178. https://doi.org/10.1007/s00204-021-02974-9

Giyanto, G., Damanik, G., & Aisyah, S. (2022). Kajian perbedaan metode aplikasi ethephon 60% terhadap efisiensi pembrondolan serta nilai dobi, beta karoten dan vitamin E pada tandan buah segar kelapa sawit. *Jurnal Agroteknologi dan Farming, **4***(2), 48-59. https://doi.org/10.47199/jaf.v4i2.110

Granella, S.J., Bechlin, T.R., Christ, D., & Coelho, S.R.M. (2022). A potential role of nitric oxide in postharvest pest control: A review. *Journal of the Saudi Society of Agricultural Sciences, **21***(7), 452–459. https://doi.org/10.1016/j.jssas.2021.12.002

Gunaeni, N., Wulandari, A.W., & Hudayya, A. (2015). Pengaruh bahan ekstrak tanaman terhadap pathogenesis related protein dan asam salisilat dalam menginduksi resistensi tanaman cabai merah terhadap virus kuning keriting. *Jurnal Hortikultura, **25***(2), 160–170.

Habibah, R.A., Ferdinal, F., & Yulianti, E. (2023). Uji fitokimia, kapasitas total antioksidan, uji toksisitas dan kadar metabolit sekunder ekstrak buah aprikot (*Prunus armeniaca*). *Tarumanagara Medical Journal, **5***(2), 354–360. https://doi.org/10.24912/tmj.v5i2.24718

Haloho, J.D. (2023). Inovasi teknologi untuk memperpanjang masa simpan buah naga. *Prosiding Seminar Nasional Pertanian*, ***3***(2), 12–19.

Hardianti, B., Anwar, I., Sida, N.A., Sumiati, E., Rita, R.S., Amin, A., Suherman, S., Jati, M.A.S., Nasruddin, N.I., Larasati, M.D., Salman, Y.R.D. (2023). *Biokimia advance*. Eureka Media Aksara.

Harnanik, S. (2018). Kajian perubahan karakteristik mutu sawi segar selama penyimpanan dengan pencucian air berozon pada suhu dan kemasan berbeda. *Jurnal Riset Industri*, ***1***(1), 74-82.

Hasan, M.K., Alam, A., Islam, M.R., Akhtaruzzaman, M., & Biswas, M. (2024). Evaluating the potential of 1-methylcyclopropene treatments on physicochemical properties, bioactive compounds, and shelf life of mango fruits under different storage conditions. *Heliyon, **10***(15), e34695. https://doi.org/10.1016/j.heliyon.2024.e34695

He, F., Wu, X., Zhang, Q., Li, Y., Ye, Y., Li, P., Chen, S., Peng, Y., Hardeland, R., & Xia, Y. (2021). Bacteriostatic potential of melatonin: Therapeutic standing and mechanistic insights. *Frontiers in Immunology, **12***, 683879. https://doi.org/10.3389/fimmu.2021.683879

Hidayat, C., Sopiyana, S., & Rahman, R. (2020). Review: Pengaruh pakan terhadap kualitas semen ayam. *Jurnal Ilmiah Peternakan Halu Oleo, 7*(3), 218. https://doi.org/10.33772/jitro.v7i3.11695

Hidayat, R. (2020). *Mekanisme Komunikasi Sel*. NoerFikri Palembang. ISBN 978-602-447-614-4

Hörtensteiner, S. (2013). The pathway of chlorophyll degradation: Catabolites, enzymes and pathway regulation. *Plastid development in leaves during growth and senescence*, 363–392. https://doi.org/10.1007/978-94-007-5724-0_16

Hörtensteiner, S., & Kräutler, B. (2011). Chlorophyll breakdown in higher plants. *Biochimica et Biophysica Acta (BBA) - Bioenergetics, **1807***(8), 977–988. https://doi.org/10.1016/j.bbabio.2010.12.007

Horváth-Mezőfi, Z., Baranyai, L., Nguyen, L.L.P., Dam, M.S., Ha, N.T.T., Göb, M., Sasvár, Z., Csurka, T., Zsom, T., & Hitka, G. (2024). Evaluation of color and pigment changes in tomato after 1-methylcyclopropene (1-MCP) treatment. *Sensors, **24***(8), 2426. https://doi.org/10.3390/s24082426

Husna, D.S., & Puspita, I.D. (2020). Hubungan intensitas penggunaan media sosial terhadap durasi tidur dan status gizi mahasiswa S-1 Ilmu Gizi. *Jurnal Riset Gizi*, ***8***(1), 76–84. https://doi.org/10.31983/jrg.v8i2.6273

Ifmalinda, I., Fahmy, K., & Zein, N.L. (2023). Studi penambahan ekstrak daun randu (*Ceiba pentandra*) pada edible coating gel lidah buaya (*Aloe vera* L.) terhadap mutu mentimun (*Cucumis sativus* L.). *Jurnal Teknologi Pertanian dan Biosistem, **11***(1). https://doi.org/10.21776/ub.jkptb.2023.011.01.05

Jiang, Y., Liu, Z., Peydayesh, M., Zhang, B., Jia, X., & Huang, Q. (2024). Ethylene control in fruit quality assurance: A material science perspective. *Aggregate, **5***(5), e565. https://doi.org/10.1002/agt2.565

Kandasamy, P. (2022). Respiration rate of fruits and vegetables for modified atmosphere packaging: A mathematical approach. *Journal of Postharvest Technology, **10***(1), 88–102.

Kaniawati, M., Sulaeman, A., Nurfazri, A., Susilawati, E., Auliyaa, M., & Freitas, F.M. de F. (2024). Efek pemberian ekstrak etanol bunga rosella (*Hibiscus sabdariffa* L.) terhadap inflamasi dan disfungsi endotel. *Jurnal Farmasi Indonesia, **16***(1). https://doi.org/10.35617/jfionline.v16i1.238

Kementerian Kesehatan Republik Indonesia. (2012). *Peraturan Menteri Kesehatan RI Nomor 033 Tahun 2012 tentang Bahan Tambahan Pangan*. Kementerian Kesehatan RI.

Kesanda, I.M.P., Widyadharma, I.P.E., & Adnyana, I.M.O. (2016). Peranan melatonin pada nyeri kepala migren, klaster, dan hipnik. *E-Jurnal Medika Udayana, **47***(3), 30–36.

Kolniak-Ostek, J., Wojdyło, A., Markowski, J., & Siucińska, K. (2014). 1-Methylcyclopropene postharvest treatment and their effect on apple quality during long-term storage time. *European Food Research and Technology, **239***, 603–612. https://doi.org/10.1007/s00217-014-2256-2

Kumar, H., Gupta, N., Bandral, J.D., Sood, M., Bhat, A., Reshi, M., & Singh, J. (2023). Role of 1-MCP on post-harvest quality of fruits and vegetables. *The Pharma Innovation Journal, **12***(4), 1785–1788.

Kurniawan, T.W., & Deglas, W. (2022). Pengaruh etilen pada buah pepaya terhadap pematangan buah pisang kepok (*Musa paradisiaca* L.). *Agrofood, **4***(1), 10–16.

Lata, D., Kuchi, V.S., & Nayik, G.A. (2017). 1-methyl cyclopropene (1-MCP) for quality preservation of fresh fruits and vegetables. *Journal of Postharvest Technology, **5***(3), 9–15. https://journals.acspublisher.com/index.php/jpht/article/view/15692

Li, C., Shen, X., Fan, Z., Chen, J., Tao, N., & Tan, X. (2023). Melatonin retards leaf senescence by modulating phytohormone metabolism in stored Chinese flowering cabbage. *Food Quality and Safety, **7***, fyad037. https://doi.org/10.1093/fqsafe/fyad037

Li, N., Zhai, K., Yin, Q., Gu, Q., Zhang, X., Melencion, M. G., & Chen, Z. (2023). Crosstalk between melatonin and reactive oxygen species in fruits and vegetables post-harvest preservation: An update. *Frontiers in Nutrition, **10***. https://doi.org/10.3389/fnut.2023.1143511

Liu, Y., Chen, T., Tao, N., Yan, T., Wang, Q., & Li, Q. (2023). Nitric oxide is essential to keep the postharvest quality of fruits and vegetables. *Horticulturae, **9***(2), 135. https://doi.org/10.3390/horticulturae9020135

Liu, Y.-B. (2013). Nitric oxide as a potent fumigant for postharvest pest control. *Journal of Economic Entomology, **106***(6), 2267–2274. https://doi.org/10.1603/EC13249

Lu, X., Yin, F., Liu, C., Liang, Y., Song, M., & Shang, F. (2023). Nitric oxide alleviates chilling injury in cucumber (*Cucumis sativus* L.) fruit by regulating membrane lipid and energy metabolism. *International Journal of Food Properties, **26***(1), 1047–1061. https://doi.org/10.1080/10942912.2023.2199948

Lv, Y., Fu, A., Song, X., Wang, Y., Chen, G., & Jiang, Y. (2023). 1-Methylcyclopropene and UV-C treatment effect on storage quality and antioxidant activity of 'Xiaobai' apricot fruit. *Foods, **12***(6), 1296. https://doi.org/10.3390/foods12061296

Maharani, M.P., Panggabean, N.H.G., & Dianty, Z.P. (2023). Analisis impor komoditi buah dan sayuran China di Indonesia 2018–2022. *ARMADA: Jurnal Penelitian Multidisiplin, **1***(12). https://doi.org/10.55681/armada.v1i12.1101

Mandal, D., Ennio, N., Lalhruaitluangi, N., Lalrinchhani, & Fanai, A.V. (2024). Response of melatonin on postharvest qualities and shelf life of pineapple cv. Kew at ambient storage. *Journal of Applied and Natural Science, **16***(2), 5562. https://doi.org/10.31018/jans.v16i2.5562

Manullang, W.W., Napitupulu, J.A., Mariati, M., & Sv, N. (2013). Respons pertumbuhan dan produksi biomassa tanaman obat pegagan (*Centella asiatica* (L.) Urb.) dengan pemberian fosfor dan metil jasmonat. *Jurnal Agroekoteknologi Universitas Sumatera Utara, **2***(1), 474-486.

Marpaung, M.P., & Prasetyo, D. (2024). Analisis efek penambahan asam dan suhu terhadap glikolisis dalam sel ragi pada metabolisme karbohidrat. *Innovative: Journal of Social Science Research, **4***(1), 5765–5773.

Mirshekari, A., Madani, B., Yahia, E.M., Golding, J. B., & Haji Vand, S. (2020). Postharvest melatonin treatment reduces chilling injury in sapota fruit. *Journal of the Science of Food and Agriculture, **100***(5), 1897–1903. https://doi.org/10.1002/jsfa.10198

Mudyantini, W., Anggarwulan, E., & Rahayu, P. (2015). Penghambatan pemasakan buah srikaya (*Annona squamosa* L.) dengan suhu rendah dan pelapisan kitosan. *Agriculture: Jurnal Ilmu Pertanian, **27***(1), 23–29. https://doi.org/10.24246/agric.2015.v27.i1.p23-29

Nanthachai, N., Ratanachinakorn, B., Kosittrakun, M., & Beaudry, R.M. (2007). Absorption of 1-MCP by fresh produce. *Postharvest Biology and Technology, **43***(3), 291–297. https://doi.org/10.1016/j.postharvbio.2006.10.003

Nofiyanto, E., Waluyo, T.S., & Larasati, D. (2024). Perendaman dalam larutan asam askorbat untuk meningkatkan mutu edamame segar (Glycine max L.). *Jurnal Agrointek, **18***(2), 487–495. https://doi.org/10.21107/agrointek.v18i2.19368

Norazizah, S., Wibisono, N., & Wahyuningsih, D. (2021). Studi pustaka sistematis: Delima memperbaiki kadar nitric oxide pada berbagai kondisi stres oksidatif. *Jurnal Kedokteran Komunitas, **9***(1), 1–16.

Nur Fauziah, I.A., Zackiyah, Z., & Solihin, H. (2021). Pengaruh penggunaan 1-metilsiklopropena terhadap kualitas buah klimaterik pasca panen. *Chemica Isola*, ***1***(2), 49–57.

Peng, Z., & Fu, D. (2023). Effects of 1-methylcyclopropene treatment on the quality of red 'Fuji' apples fruit during short-term storage. *Food Quality and Safety, **7***, fyac074. https://doi.org/10.1093/fqsafe/fyac074

Pols, S., Van de Poel, B., Hertog, M.L.A.T.M., & Nicolaï, B.M. (2022). The regulatory role of nitric oxide and its significance for future postharvest applications. *Postharvest Biology and Technology, **188***, 111869. https://doi.org/10.1016/j.postharvbio.2022.111869

Prabasari, I. (2024). Kombinasi perlakuan 1-MCP dan suhu dingin dalam mempertahankan kualitas buah jambu biji (*Psidium guajava* L) selama penyimpanan. *Agrohita: Jurnal Agroteknologi, **9***(1), 57–64. https://doi.org/10.31604/jap.v9i1.15774

Pradani, H.R. (2020). Peran ethylene dalam pertumbuhan dan pengembangan tanaman. *Anterior Jurnal*, ***19***(2), 123–129.

Prayitno, S.A. (2023). Effect of ethylene compounds on banana ripening and post-harvest packaging (storage) of citrus fruits. *Agroindustrial Technology Journal*, ***7***(2), 71–85.

Purwanto, Y.A., Oshita, S., Makino, Y., & Kawagoe, Y. (2012). Indikasi kerusakan dingin pada mentimun Jepang (*Cucumis sativus* L.) berdasarkan perubahan ion leakage dan pH. *Jurnal Keteknikan Pertanian, **26***(1), 33–37.

Salsabilla, I., & Kartika, J.G. (2013). Aplikasi 1-methylcyclopropene untuk meningkatkan vase life bunga potong *Tapeinochilos anannaceae* K. Schum. *Bul. Agrohorti, **1***(4), 101–110. https://doi.org/10.29244/agrob.1.4.101-110

Sari, D.P., Harlita, H., & Dyah, K. (2018). Modifikasi penanganan pasca panen melalui inovasi sayur siap saji di Desa Segoro Gunung, Kecamatan Ngargoyoso, Kabupaten Karanganyar, Jawa Tengah. *Prosiding Seminar Nasional SIMBIOSIS III*, 364-371.

Satekge, T.K., & Magwaza, L.S. (2022). Postharvest application of 1-methylcyclopropene (1-MCP) on climacteric fruits: Factors affecting efficacy. *International Journal of Fruit Science, **22***(1), 595–607. https://doi.org/10.1080/15538362.2022.2085231

Sauer, P.C., & Seuring, S. (2023). How to conduct systematic literature reviews in management research: A guide in 6 steps and 14 decisions. *Review of Managerial Science, 17*, 1899–1933. https://doi.org/10.1007/s11846-023-00668-3

Shah, H.M., Singh, Z., Afrifa-Yamoah, E., Hasan, M.U., Kaur, J., & Woodward, A. (2024). Insight into the role of melatonin in mitigating chilling injury and maintaining the quality of cold-stored fruits and vegetables. *Food Reviews International, **40***(5), 1238–1264. https://doi.org/10.1080/87559129.2023.2212042

Shang, F., Liu, R., Wu, W., Han, Y., Fang, X., Chen, H., & Gao, H. (2021). Effects of melatonin on the components, quality and antioxidant activities of blueberry fruits. *LWT, **147***, 111582. https://doi.org/10.1016/j.lwt.2021.111582

Shu, P., Sheng, J., Qing, Y., & Shen, L. (2025). SlATG5 is crucial for the accumulation of ROS in postharvest tomato fruit resistance to *B. cinerea* mediated by nitric oxide. *Postharvest Biology and Technology, **219***, 113204. https://doi.org/10.1016/j.postharvbio.2024.113204

Situmorang, N., & Zulham, Z. (2020). Malondialdehyde (MDA) (zat oksidan yang mempercepat proses penuaan). *Jurnal Keperawatan dan Fisioterapi (JKF), **2***(2). https://doi.org/10.35451/jkf.v2i2.338

Sukasih, E., & Setyadjit, S. (2019). Teknologi penanganan buah segar stroberi untuk mempertahankan mutu. *Jurnal Penelitian dan Pengembangan Pertanian, **38***(1), 47–54. bikin no spasi

Sulaiman, D., Huturlukitaningtyas, D.F., Sari, A.L.R., & Ulva, S.M. (2024). Uji karakteristik bioetanol campuran kulit nanas dan buah pisang hutan. *Jurnal Energi Baru dan Terbarukan, **5***(3), 1–8. https://doi.org/10.14710/jebt.2024.24059

Sun, Y.D., Guo, D.L., Yang, S.D., Zhang, H.C., Wang, L.L., Min, L., & Yu, Y.H. (2020). Melatonin treatment improves the shelf-life and postharvest quality of table grape (*Vitis labrusca* L. cv. 'Fengzao'). *Journal of Berry Research, **10***(4), 665-676. https://doi.org/10.3233/JBR-200569

Sunarso, M.P., Fithriyah, N.H., & Nugrahani, R.A. (2023). Pengaruh formulasi edible coating dari pati pisang raja bulu terhadap penghambatan gejala chilling injury pada tomat merah. *Jurnal Teknologi, **15***(1), 73–80.

Verde, A., Míguez, J.M., & Gallardo, M. (2022). Role of melatonin in apple fruit during growth and ripening: Possible interaction with ethylene. *Plants, **11***(5), 688. https://doi.org/10.3390/plants11050688

Wang, D., Randhawa, M.S., Azam, M., Liu, H., Ejaz, S., Ilahy, R., Qadri, R., Khan, M.I., Umer, M.A., Khan, M.A., & Wang, K. (2022). Exogenous melatonin treatment reduces postharvest senescence and maintains the quality of papaya fruit during cold storage. *Frontiers in Plant Science, **13***, 1039373. https://doi.org/10.3389/fpls.2022.1039373

Wang, M., Xu, J., Ding, Z., & Xie, J. (2023). Prolong the postharvest shelf life of spinach through the antioxidative ability of melatonin. *Food Chemistry: X, **19***, 100769. https://doi.org/10.1016/j.fochx.2023.100769

Wang, Y., Jin, X., & Zhang, Y. (2025). Dual melatonin enhances coordination between carbon and nitrogen assimilation in soybean. *Agriculture, **15***(7), 681. https://doi.org/10.3390/agriculture15070681

Waryat, W., & Handayani, Y. (2020). Implementasi jenis kemasan untuk memperpanjang umur simpan sayuran pakcoy. *Jurnal Ilmiah Respati, **11***(1), 33–45. https://doi.org/10.52643/jir.v11i1.847

Watkins, C.B. (2006). The use of 1-methylcyclopropene (1-MCP) on fruits and vegetables. *Biotechnology Advances, **24***(4), 389–409. https://doi.org/10.1016/j.biotechadv.2006.01.005

Wei, D., Yang, J., Xiang, Y., Meng, L., Pan, Y., & Zhang, Z. (2022). Attenuation of postharvest browning in rambutan fruit by melatonin is associated with inhibition of phenolics oxidation and reinforcement of antioxidative process. *Frontiers in Nutrition, **9***. https://doi.org/10.3389/fnut.2022.905006

Widodo, S.E., Kamal, M., Zulferyenni, Z., & Aprianti, D. (2016). Pengaruh 1-methylcyclopropene (1-MCP), kitosan, dan suhu simpan terhadap masa simpan dan mutu jambu biji (*Psidium guajava* L.) 'Crystal'. *Jurnal Agrotek Tropika, **4***(1), 29–35.

Widodo, W.D., Suketi, K., & Rahardjo, R. (2019). Evaluasi kematangan pascapanen pisang barangan untuk menentukan waktu panen terbaik berdasarkan akumulasi satuan panas. *Buletin Agrohorti*, ***7***(2), 162–171.

https://doi.org/10.29244/agrob.7.2.162-171

Xu, T., Chen, Y., & Kang, H. (2019). Melatonin is a potential target for improving post-harvest preservation of fruits and vegetables. *Frontiers in Plant Science, **10***, 1388. https://doi.org/10.3389/fpls.2019.01388

Yang, R., Du, H., Sun, Y., Zhang, F., Zhang, W., Wan, C., Chen, J., & Zhu, L. (2021). Effects of nitric oxide on the alleviation of postharvest disease induced by *Penicillium italicum* in navel orange fruits. *International Journal of Food Science and Technology, **56***(10), 5259–5267. https://doi.org/10.1111/ijfs.15054

Yılmaz, K.F., Gündoğdu, M., & Taş, A. (2025). Effect of post-harvest melatonin application on quality characteristics of avocado fruit. *Applied Fruit Science, **67**,* 57. https://doi.org/10.1007/s10341-025-01284-z

You, M., Duan, X., Li, X., Luo, L., Zhao, Y., Pan, H., Gong, W., Yang, L., Xiang, Z., & Li, G. (2022). Effect of 1-methylcyclopropene combined with chitosan-coated film on storage quality of passion fruit. *Sustainable Chemistry and Pharmacy, **27***, 100679. https://doi.org/10.1016/j.scp.2022.100679

Yuniastri, R., Ismawati, I., Atkhiyah, V.M., & Al Faqih, K. (2020). Karakteristik kerusakan fisik dan kimia buah tomat. *Journal of Food Technology and Agroindustry, **2***(1). https://doi.org/10.24929/jfta.v2i1.954

Zhang, H., Liu, X., Chen, T., Ji, Y., Shi, K., Wang, L., Zheng, X., & Kong, J. (2018a). Melatonin in apples and juice: Inhibition of browning and microorganism growth in apple juice. *Molecules, **23***(3), 521. https://doi.org/10.3390/molecules23030521

Zhang, Y., Huber, D.J., Hu, M., Jiang, G., Gao, Z., Xu, X., Jiang, Y., & Zhang, Z. (2018b). Delay of postharvest browning in litchi fruit by melatonin via the enhancing of antioxidative processes and oxidation repair. *Journal of Agricultural and Food Chemistry, **66***(28), 7475–7484. https://doi.org/10.1021/acs.jafc.8b01922

Zhao, Y., Yan, M., Zhang, K., Wu, X., Wang, Z., Shao, T., Lei, J., Chen, X., & Liu, H. (2024). Effects of 1-methylcyclopropene treatment on postharvest quality and metabolism of different kiwifruit varieties. *Foods, **13***(22), 3632. https://doi.org/10.3390/foods13223632

Zhao, Y., Zhu, X., Hou, Y., Wang, X., & Li, X. (2020). Postharvest nitric oxide treatment delays the senescence of winter jujube (*Zizyphus jujuba* Mill. cv. Dongzao) fruit during cold storage by regulating reactive oxygen species metabolism. *Scientia Horticulturae, **261***, 109009. https://doi.org/10.1016/j.scienta.2019.109009

Zhong, Y., Wu, X., Zhang, L., Zhang, Y., Wei, L., & Liu, Y. (2024). The roles of nitric oxide in improving postharvest fruits quality: Crosstalk with phytohormones. *Food Chemistry, **455***, 139977. https://doi.org/10.1016/j.foodchem.2024.139977