Chapter

Recent Development in the Preharvest 1-MCP Application to Improve Postharvest Fruit Quality

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Abstract

1-Methylcyclopropene (1-MCP), an ethylene action inhibitor, is routinely applied to fruit as a postharvest treatment prior to cold storage to extend fruit storability and posterior shelf life. Nevertheless, preharvest 1-MCP applied as a liquid spray to trees is a novel treatment for maintaining fruit quality throughout the postharvest in some crops and can be a very useful tool for improving handling operations in packing houses. This chapter aims to provide an overview of not only employing 1-MCP as a preharvest treatment in different crops, but also of its effect on the biochemical and physico-chemical parameters that influence fruit postharvest quality, storage capacity, and chilling injury development. It also intends to address the main factors related to the preharvest 1-MCP application effect, such as application time, optimum concentrations, and its combination with other preharvest treatments.

Keywords: 1-methylcyclopropene, Harvista, fruit storage, field treatment, ethylene

1. Introduction

Ethylene is the simplest natural plant ripening hormone that is involved in the regulation of many growth and development processes of horticultural crops. This hormone acts by linking itself to its action site in the cell to promote a succession of events, such as leaf abscission, fruit maturation, and the ripening process [1–3].

Fruits are generally divided into two categories: climacteric and non-climacteric [4]. It has been clearly established that all fruits produce minimal amounts of ethylene during their development. However, the ripening of climacteric fruit is characterized by an increased respiration rate and a burst of ethylene biosynthesis. Non-climacteric fruits have a different ripening pattern. They do not show a drastic change in respiration rate and the ethylene production remains at a very low level. Climacteric and non-climacteric fruits can be differentiated by not only their pattern of ethylene production during ripening but also by their response to exogenous ethylene.

The postharvest quality of horticultural crops is also influenced by ethylene, whose effect can be beneficial or detrimental depending on a number of factors like fruit type (climacteric or non-climacteric), ripening stage, and intended use [5].

The application of exogenous ethylene is often used to promote uniform ripening in climacteric fruits like bananas or apples [6, 7]. Ethylene is also applied on non-climacteric fruits to bring about certain different effects, such as accelerating citrus fruits color change (degreening) [8]. However, ethylene can negatively influence the quality of both climacteric and non-climacteric fruits by inducing the development of physiological disorders or accelerating senescence processes, especially during storage and shelf life.

Therefore, many strategies have been studied to control ethylene production or its action during the postharvest life of fruits and vegetables. Of the available methods, 1-methylcyclopropene (1-MCP) is a competitive inhibitor of ethylene perception that prevents ethylene binding and the eliciting of subsequent signal transduction and translation. As a consequence, 1-MCP applied at very low concentrations (0.5–1.0 $\mu L\ L^{-1}$) can delay ripening and senescence events of horticultural products that are mediated by ethylene [9–11].

Postharvest 1-MCP application has become a successful technology for controlling ripening and senescence processes to maintain fruit quality and to reduce different postharvest physiological disorders in many climacteric and non-climacteric horticultural products [9, 12]. 1-MCP is also used as an excellent tool to explore ethylene-mediated responses of plant systems, especially those involved in ripening and senescence processes.

It is known that 1-MCP lowers the highest peak value of respiration and ethylene production and delays their emergence during storage [1]. There are two known systems for regulating ethylene production in higher plants: system-1 and system-2. Auto-inhibitory system-1 functions during normal vegetative growth and is responsible for producing the basal ethylene levels detectable in all tissues in both climacteric and non-climacteric fruits. Autostimulatory system-2 is responsible for the upsurge of ethylene production that occurs during the ripening of climacteric fruits [13, 14]. The transition from system-1 to system-2 is believed to be an important step during fruit ripening [3]. For different fruits, such as apples, bananas, and tomatoes [13, 15, 16], there are reports that the expression of the genes responsible for the transition from system-1 to system-2 can be blocked by postharvest 1-MCP application.

To date, a large amount of information has been acquired about the effect of postharvest treatment with 1-MCP on many fruits and vegetables. Protocols have been developed to optimize the benefits of 1-MCP for different horticultural products because its effect depends on factors like concentration, exposure time, or application time after harvest.

Some commercial names of 1-MCP are EthylBloc®, SmartFresh®, SmartTabs®, and EthylBloc® Sachet, which contain different 1-MCP concentrations. When the product is mixed with water or buffer solution, 1-MCP gas is released to the chambers where it is applied. 1-MCP is used in combination with proper temperature and relative humidity management and can replace or be utilized in combination with controlled atmospheres.

Despite postharvest 1-MCP application being able to present lots of benefits in many fruits and vegetables, preharvest 1-MCP treatment emerges as a novel option, and one that has been tested in several crops with different effects, for example, reducing fruit drop, delaying color development and softening, ethylene production, ripening, maintaining fruit quality throughout the postharvest, and replacing the postharvest treatment in some crops [9, 17, 18].

Preharvest 1-MCP treatments can offer some advantages over conventional postharvest exposure. Besides, treatments allow a more flexible harvesting time to be obtained for some apple cultivars and might be a good option because they respond poorly or inconsistently to 1-MCP gas exposure as a postharvest treatment [19, 20].

As the preharvest 1-MCP application is considerably limited, a sprayable formulation has been developed for its utilization that facilitates its field application and is marketed as Harvista® (AgroFresh Solutions Inc., Philadelphia, PA, USA). This product allows 1-MCP to be dissolved in water and applied as a fumigation product. Today, it is the only 1-MCP formulation available for preharvest use purposes.

In some cases like bananas, the preharvest 1-MCP treatment has been tested by submerging the stem of the bunch still attached to trees in 1-MCP aqueous solution [21]. In another study conducted with figs, preharvest treatment was applied through a plastic bag with gaseous 1-MCP [22]. Despite having positive effects, these application modes would be very limited for commercial use.

Relatively few reports exist about the preharvest 1-MCP treatment effect on fruits. Most studies have focused mainly on apples and pears, since Harvista® treatment is authorized for these fruits in some countries. However, the interest generated by this treatment has led to further studies being conducted in recent years to search for a possible benefit on other fruits [23]. This chapter reports a review of the main findings of the preharvest 1-MCP application on different fruits.

2. Climacteric fruit

Increased respiration in climacteric fruit is associated with autocatalytic ethylene production, which mediates fruit ripening processes [24]. As 1-MCP inhibits ethylene perception, its field application in climacteric fruits affects fruit ripening and senescence processes, mainly by delaying harvest time and prolonging postharvest fruit quality [9]. However, effects vary according to different aspects, such as fruit cultivar, application time, and concentration.

2.1 Apple (*Malus domestica* Borkh)

1-MCP is commonly used as a postharvest treatment to prolong apple eating quality by maintaining fruit firmness, crispness, sweetness, acidity, and juiciness of cold-stored fruits. It is a proven effective treatment in many cultivars [25–27]. In recent years, and as a novel application method, numerous studies have been conducted on the effect of 1-MCP applied at preharvest on delaying maturation on trees and to maintain postharvest quality in different scenarios.

Most studies generally suggest that the preharvest 1-MCP treatment positively influences apple quality attributes. The differences observed in fruits response may vary among cultivars, mostly in relation to the ability of some cultivars to rapidly generate new ethylene receptors when fruits remain attached to trees [17, 28, 29].

Recent studies have demonstrated that preharvest 1-MCP can retard the activation of system-2 ethylene biosynthesis in apples [14]. The MdACS1 gene is necessary for system-2 activation during apple climacteric ripening. The molecular mechanisms that control the delay and suppression of the expression of MdACS1 and receptor genes after regular postharvest 1-MCP treatment are not well defined. However, the preharvest 1-MCP application is effective in suppressing its expression in the "Delicious" and "Golden Delicious" varieties, which results in the delayed activation of system-2 ethylene biosynthesis [1, 6, 14].

One effect of 1-MCP applied in the preharvest has been reported on fruit cuticular wax biosynthesis and regulation, composition, and structure for regulating ethylene biosynthesis and signaling [1]. The preharvest 1-MCP application at 150 g hm^2 lowers the contents of alcohols, acids, and esters in apple cuticular wax by reducing fruit superficial scald and decay and by maintaining fruit cuticular wax functions, such as disease resistance and water retention, after 1 cold storage month.

The preharvest 1-MCP effect on carbohydrate metabolism in apples has also been studied at harvest and during cold storage. The authors observed that the treatment at 150 g AI ha^{-1} applied 7 days before harvest inhibited starch degradation, retarded soluble sugar increase, and reduced sucrose, glucose, and fructose in "Starkrimson" apples. This was related to the ethylene regulation of related gene expressions and enzyme activities during cold storage [30].

The combined application of pre- and postharvest 1-MCP treatments has also been evaluated in apples. In this case, Harvista® was applied 10 days before harvest at 60 mg L^{-1} and, 1 day after harvest, fruits were subjected to the Smartfresh® treatment at 1 μL L^{-1}. This combination resulted in greater fruit firmness retention and longer ethylene suppression in "Golden Delicious" apples throughout cold storage [14]. The preharvest or postharvest 1-MCP treatment application led to different expression patterns of ethylene biosynthesis genes (MdACS3 and MdACS1) and receptor genes, which could result in differential effects by 1-MCP treatments.

A common preharvest treatment for apples is to apply ethephon to accelerate maturity to bring forward the harvest period and to improve color development [31, 32]. However, ethephon application leads to the activation of ethylene autocatalysis in fruit tissues, which is reflected as a drastically shortened harvest period and reduced storability. It can also lead to undesired fruit abscission before harvest and accelerated flesh firmness loss during the commercialization period [30, 33, 34]. Nevertheless in "Anna" apples treated with ethephon (50 ppm), preharvest 1-MCP treatment (1–2 mM) in the mature green stage reduced preharvest abscission and preserved fruit firmness. This treatment also mitigated the adverse influence of ethephon on flesh firmness loss during fruit cold storage at 1°C.

In order to delay fruit ripening and preharvest drop in apple, treatments with naphthaleneacetic acid (NAA), a synthetic auxin, and aminoethoxyvinylglycine (AVG), an inhibitor of ethylene biosynthesis, are applied in some production areas. Comparative studies have been conducted on the application of these treatments and the preharvest 1-MCP application [6]. In this way, sprayable 1-MCP at 396 mg L^{-1} applied 1 week before harvest to "Golden Delicious" apples had a stronger effect on delayed fruit drop than AVG or NAA [24]. Similarly with "Delicious" apples, the application of 1-MCP 15 or 7 days before harvest at a concentration of 160 or 320 mg L^{-1} delayed preharvest fruit drop more effectively than AVG or NAA used alone and had a similar effect compared to the fruit to which both AVG and NAA had been applied. In that study, the best results were obtained when 1-MCP was applied 15 days before harvest and the concentration did not affect its efficacy in reducing fruit drop [6].

Scolaro et al. [35] also compared preharvest treatments with 1-MCP or AGV on "Royal Gala" apples. They observed that the 1-MCP application had similar effects to the AVG treatment on delaying fruit ripening and also on decreasing ethylene production, starch degradation, loss of flesh firmness and acidity, epidermal yellowing, soluble solid accumulation, and red color development. The authors concluded that preharvest 1-MCP can be an alternative method to the commonly applied AVG for fruit maturation and harvest management purposes.

With "Golden Delicious" and "Law Rome" apples, 1-MCP applied 7 days or 1 day before harvest at concentrations between 75 and 155 mg L^{-1} has also been reported as an effective emergency stop treatment, similarly to NAA, and without the potential loss of firmness caused by NAA [20].

Preharvest 1-MCP application, used as a treatment to reduce the incidence of different disorders during storage, has been reported for some apple cultivars [20, 27, 36, 37]. In "Honeycrisp" apples, preharvest 1-MCP sprays reduced the incidence of both soft scald, a skin disorder characterized by brown lesions, and soggy breakdown, a flesh disorder characterized by brown and soft internal tissue [36]. In "Law Rome" apples, preharvest 1-MCP application also lowered the superficial scald incidence during prolonged cold storage (up to 120 days) [20].

Stem-end flesh browning, another disorder that develops around the shoulders of apples, is frequently manifested in some cultivars during storage. In cv. Gala, postharvest 1-MCP treatment had no effect on this disorder, while the preharvest 1-MCP application significantly reduced it, but did not prevent its development [37].

In "Fuji" apples at harvest, watercore incidence and severity, besides starch pattern indices, were lower in the fruits that underwent the preharvest 1-MCP treatment [27]. This study also evaluated the combined application of preharvest and postharvest 1-MCP treatments on fruit quality and the incidence of disorders. The incidences of flesh greasiness and watercore diminished more when the combination of both treatments was applied than by either treatment alone. Besides, preharvest and postharvest 1-MCP applications contribute to maintain fruit quality attributes during cold storage and at 20°C. The effects of preharvest 1-MCP were more consistent when the interval between spraying and harvest was 10 days compared to its application at 4 days before harvest.

The traditional postharvest 1-MCP treatment has been reported to increase the risk of certain stress-related storage disorders in apples, such as CO_2 injury, a physiological disorder that can be manifested externally and/or internally, and both injury type and susceptibility were strongly affected by apple cultivar and growing conditions [38]. A study carried out with the cv. McIntosh and cv. Empire revealed that 40 to 160 mg L^{-1} of preharvest 1-MCP applied 7 or 11 days before harvest also increased the development of external CO_2 injury during storage in a controlled atmosphere.

2.2 Pear (*Pyrus communis* L.)

Similarly to apples, in pears the effect of the sprayable preharvest 1-MCP application has been studied mainly on fruit drop, extension of the harvest window, quality maintenance during cold storage, and reduction of the incidence of different disorders [39–41].

Prevention of fruit drop with the preharvest 1-MCP application has been reported in "Santa Maria" pears, but the effect on fields was dose-dependent [40]. The most effective treatment was achieved at 150 and 200 g ha^{-1}. In this cultivar, the ripening period could be prolonged up to 4 weeks.

A similar preharvest 1-MCP treatment effect on fruit drop has been reported for "Barlett" pears [42]. In this study, the 1-MCP application was as effective as NAA in reducing premature fruit drop. 1-MCP significantly delayed ripening immediately after harvest, but this effect diminished after storing fruit at −1°C for 3.5 months. No differences in pear fruit maturity were found between the highest (100 mg L^{-1}) and the lowest (28 mg L^{-1}) applied doses. The strongest 1-MCP effect occurred when fruits were harvested soon after treatment (7 days after application). The 1-MCP preharvest application also lowered internal browning incidence during storage.

A recent study performed with the “Bartlett” and “d ‘Anjou” cultivars found that the preharvest 1-MCP treatment extended the harvest window by 3–4 days without reducing the storage potential or eating quality [41]. This treatment also lowered ethylene synthesis and respiration rates, maintained fruit firmness and green color during cold storage, and retarded melting texture development in both cultivars. 1-MCP also reduced the incidence of flesh disorders by alleviating membrane lipid peroxidation, maintaining antioxidant capacity, and enhancing superoxide dismutase, catalase, and ascorbate peroxidase activity in both cultivars.

When combining the effect of the pre- and postharvest 1-MCP treatments on “Barlett” pears, the applications of 160 μL L^{-1} of Harvista® and 0.15 μL L^{-1} of Smartfresh® were capable of extending the melting texture life of pears up to 5 months of cold storage [43]. When the effects of Harvista® and Smarfresh® were compared in relation to the fruit firmness maintenance during the cold storage of “Abate Feel” pears, a positive result of both treatments was obtained, but the postharvest application was more effective [44]. The Harvista® application time influenced its effect on fruit firmness, since applying Harvista® 7 days before the commercial harvest time was more effective in maintaining fruit firmness after harvest than when applied before.

In “Chuhwangbae” pears, the preharvest 1-MCP application had no effect on postharvest quality attributes during cold storage and shelf life because most fruit quality attributes and specific targeted metabolites were not affected by preharvest 1-MCP application, but by storage duration [19]. Nevertheless, the sprayable preharvest 1-MCP treatment enhanced the incidence of physiological disorders compared to that of the untreated fruits.

2.3 Persimmon (*Diospyros kaki* Thunb)

The postharvest 1-MCP (Smartfresh®) application is routinely performed to allow persimmon cold storage, since it has been widely reported that it reduces flesh firmness loss as the main chilling injury symptom [45, 46]. Nevertheless, very little information is available on the preharvest 1-MCP application effect on persimmon.

In cv. Rojo Brillante, the preharvest 1-MCP application effect has been evaluated on maintaining flesh firmness in two different scenarios: 1) early in the season on the fruit treated with ethephon to advance maturity; and 2) at the end of the season on the fruit destined for cold storage, treated with gibberellic acid to delay fruit ripening [18]. The preharvest 1-MCP treatment (22 g L^{-1}) delayed fruit firmness loss induced by ethephon, extending the harvest window, and proved to be the most effective treatment when 1-MCP was applied 1 day after ethephon treatment. The preharvest 1-MCP application also maintained fruit firmness during the marketing period and applying the postharvest 1-MCP treatment was not necessary. Nevertheless, the pre- and postharvest 1-MCP combination maintained greater flesh firmness during the commercialization period than the single postharvest application.

In the fruit treated with gibberellic acid at the end of the season, the 1-MCP application performed 3 days before harvest maintained fruit firmness during cold storage to the same extent as the traditional postharvest 1-MCP application [18]. Hence in this situation, replacing the postharvest 1-MCP application with preharvest treatment can be a very useful alternative.

A positive preharvest 1-MCP treatment effect has also been observed on “Fuyu” persimmon [47]. Spraying 150 mg L^{-1} of 1-MCP in the first commercial harvest week reduced not only premature flesh softening but also the occurrence of the translucent stain disorder at postharvest without altering fruit maturation on trees. Better results were found on fruit harvest 1 day after 1-MCP treatment, when similar efficacy of the pre- or postharvest application on both fruit firmness and the incidence of disorders was observed during storage.

2.4 Banana (*Musa spp.*)

The main postharvest banana losses are due to a short postharvest life, which is the main problem in the banana industry. The postharvest 1-MCP application has been well studied in this fruit to delay the ripening process and maintain postharvest quality [21]. Numerous studies have reported that 1-MCP applied at the 5–500 nL L^{-1} and 0.1 μL L^{-1}concentrations delays fruit ripening and skin color change during the postharvest life [48–50].

The postharvest 1-MCP treatment regulates ethylene synthesis by inhibiting the genes that regulate the aminocyclopropane-1-carboxylic acid synthase (ACS) and aminocyclopropane carboxylate oxidase (ACO) enzymes [51, 52]. The inhibition of these enzymes results in reduced fruit softening, which extends green life. Moreover, 1-MCP enhances superoxide dismutase and catalase activities and inhibits peroxidase activity, playing an important role in growth and plant development and disease resistance [11, 53]. It is noteworthy that the postharvest 1-MCP treatment effect depends on different factors such as cultivar, maturity stage, previous ethylene exposures, crop conditions, and the part of the bunch [21].

Negative 1-MCP postharvest application effects have also been reported in bananas such as irregular peel coloration, reduced volatile compound production, and delayed sugar accumulation [21, 50]. 1-MCP treatment in bananas can increase the development of chilling-related disorders, which can be trigged by the inhibition of ethylene production [10, 54]. These negative effects limit its commercial application [11].

To date, very few studies on preharvest 1-MCP applications in bananas exist. Only Manigo et al. [55] has studied the effect of preharvest 1-MCP treatment with "Cavendish" on postharvest fruit quality to identify the best and most cost-efficient application method. Three preharvest 1-MCP application methods have been evaluated: Stalk End Immersion (SEI), where the edge of bunch stalks is immersed in an aqueous solution of 1-MCP; bunch spraying (BS); and the combination of both methods (SEI-BS). In all cases, the applied dose was 400 nL L^{-1}. These treatments had a significant effect on delaying fruit ripening, retarding peel color change and fruit softening, and maintaining visual quality during storage. The fruit treated with 1-MCP by the SEI-BS method displayed lesser accumulated weight loss, and the degree of shriveling and the finger drop incidence were lower compared to the BS and SEI methods followed separately. The combined method is useful for prolonging the banana shelf life up to 19 days.

2.5 Stone fruits

Stone fruits are a diverse group, mostly of the genus Prunus, that includes peach, apricot, among others. This group is characterized by a lignified endocarp, a fleshy mesocarp and a thin exocarp or skin [56]. In "Madoka" peach (*Prunus persica* L.), the 1-MCP application in fields has been investigated with regard to fruit physiological and biochemical responses and quality attributes. Lee et al. [57] have observed not only delayed firmness loss but also an inhibition of ethylene production and respiration during the storage of the peach fruit preharvest-treated with 1-MCP. The inhibition of the expression of the genes related to sugar accumulation and cell wall softening, and of the genes responsive to ethylene receptors, has also been found. These findings suggest that the preharvest 1-MCP application can extend the shelf life of peaches by the inhibition of ethylene production and respiration.

Another assay, which compared the effect of preharvest sprayable 1-MCP (Harvista®) or postharvest fumigable 1-MCP (Smartfresh®) treatments on the quality attributes and enzymatic activities of cell wall hydrolases during the cold storage of "Hetsal Haunkeybee" peaches, has reported that fruit flesh firmness was significantly enhanced by SmartFresh®, but not by Harvista® [58]. The SmartFresh® treatment significantly reduced the enzymatic activities of α-galactosidase, β-galactosidase, β-glucosidase, β-arabinosidase, β- xylosidase, and α-mannosidase during cold storage compared to the untreated and Harvista-treated fruits.

A study on apricot (*Prunus armeniaca* L.) cv. Canino has been conducted to evaluate the effect of preharvest 1-MCP and other field treatments ($CaCl_2$ and AGV), and their combination, on fruit quality parameters during cold storage. This study showed that treatment not only improved fruit postharvest quality but also lowered the incidence of disorders throughout storage. The combination of the three compounds was the most effective treatment in maintaining fruit quality and prolonging storability up to 30 days [2].

2.6 Other fruits

With mango (*Mangifera indica* L.), the postharvest 1-MCP treatment is necessary for delaying the fast ripening that initiates before fruit harvest maturity. In this situation, preharvest treatment would be a good option for prolonging fruit storability and allow exportation [59]. In mango cv. "Carabao," the preharvest 1-MCP treatment at 10 ppm is effective in slowing external color evolution, delaying ethylene peak, and controlling both ripening and deteriorated visual quality at harvest and during storage at 13°C. However, fruit firmness does not significantly vary among treatments [60]. The fruits treated twice with 1-MCP (10 and 5 days before harvest) obtain the best results than those treated once. The authors concluded that the second application time is crucial because of the variation in the biochemical composition of fruit tissues.

Application time is also critical for the proper response of preharvest 1-MCP in Mangosteen (*Garcinia mangostana* L.). Lerslerwong et al. [61] observed that when treatment was applied in the fruit climacteric stage, it delayed the ripening process by about 1 week. This shows its potential use to retard the harvest period. However, treatment had no effect on fruit ripening when applied before the climacteric peak.

Figs (*Ficus carica* L.) are a postharvest technology challenge because of their very short shelf life and high susceptibility to diseases. The fig ripening process is classified as climacteric, with higher respiration rates and ethylene production at the beginning of the ripening phase. Yet unlike most climacteric fruits harvested before ripening onset, it does not ripen after harvest [62]. The postharvest 1-MCP treatment does not affect the ripening parameters of treated fruits (unlike other climacteric fruits), but applications to fruit on trees improve fruit storage capacity by inhibiting deterioration with minor effects on fruit growth and ripening [63, 64]. The 1-MCP application before or after harvest has also been used as a tool for studying the ethylene-related genes involved in the natural ripening process of attached fruit [22], and a possible feedback reaction has been proposed. This downstream component of ethylene signal transduction can play a role in regulating ethylene synthesis during the reaction to 1-MCP, which causes the non-climacteric behavior of fig ethylene production.

The preharvest 1-MCP influence on the development of fruit on trees and storage capacity has been studied in "Brown Turkey" figs [22]. Treatment was applied as gas in plastic bags 3 days before harvest at preclimacteric stage, which delayed fruit senescence and improved storage life up to 7 days as manifested by fruit color, firmness, internal texture, weight, size, shriveling, and decay.

Yellow pitahaya (*Selenicereus megalanthus* Haw) is a tropical fruit that undergoes physiological damage associated with cold storage, including peel browning and necrosis [65, 66]. In addition, fruit quality loss during storage has been associated with ethylene production and fruit respiration. Therefore, postharvest 1-MCP applications are done to extend fruit shelf life. Cock et al. [65] observed that the 1-MCP application 15 days before harvest in yellow pitahaya produced significant beneficial effects on chemical, physical, and sensory properties and extended fruit shelf life by 5 days with no large differences between treatment concentrations (200 or 400 μg L^{-1}). Another study conducted with yellow pitahaya under the same preharvest 1-MCP conditions showed that treatment accelerated epicarp coloration, maintained firmness, and delayed weight loss and the maturity index [66]. However, the higher applied concentration led fruit to show undesirable signs of senescence. The authors suggested that the preharvest 1-MCP application in this fruit could trigger the metabolic processes responsible for shortening fruit preservation, which has been related to both the magnitude and sensitivity to ethylene rises because fewer receptors are evaluable, and effects depend on the compound concentration, application time, and storage time.

Melon (*Cucumis melo* L.) presents a high diversity of ripening behaviors, including climacteric and non-climacteric genotypes [67, 68]. Cantaloupe melons possess typical climacteric behavior with ethylene playing a major role in the regulation of the ripening process and by affecting the ripening rate. Nevertheless, Pech et al. [3] have reported that climacteric (ethylene-dependent) and non-climacteric (ethylene-independent) regulation coexist during climacteric fruits ripening. In two cantaloupe melon cultivars (cv. Caravelle and cv. Mission), the effect of the preharvest 1-MCP application was evaluated in relation to fruit quality, harvest synchrony, and maturity [69]. Treatment was applied at a concentration between 5 and 25 g ha^{-1} and from 22 to 7 days before harvest. It presented very little or no effect on fruit quality at harvest or after cold storage. Only the cv. Mission treated with the highest concentration presented greater firmness than the other treatments after 9 storage days.

Despite most studies on preharvest and postharvest 1-MCP applications showing positive beneficial effects on maintaining fruit firmness and overall postharvest quality, in blueberry (*Vaccinium corymbosum* L.) the 1-MCP treatment applied at both the pre- and postharvests had negative effects on fruit firmness at harvest and during storage. Previous studies have demonstrated that the postharvest 1-MCP application to "Rabbiteye" blueberry led to increased ethylene production, which caused fruit softening [70]. On to the preharvest treatment, Blaker and Olmstead [71] observed in cv. 'Star" and "Sweetcrisp" that the 1-MCP application 5 days prior to harvest decreased fruit firmness, while the fruit treated 9 days before harvest did not differ from the control. However, the authors are still unclear why the preharvest treatment could result in firmness loss.

3. Non-climacteric fruits

As opposed to climacteric fruits, non-climacteric fruits are characterized by ripening transitions that do not strictly depend on a significant increase in ethylene production and an associated rise in the respiration rate [72, 73]. Although the ripening process of climacteric fruits is well documented, it is not very accurate for non-climacteric fruits. Recent studies using metabolomics, proteomics, and transcriptomics have significantly increased knowledge about molecular processes during non-climacteric fruits ripening [72]. These studies have demonstrated the involvement of different hormones, such as abscisic acid (ABA), auxin, gibberellins, among others. However, the complex mechanisms underlying the regulation and crosstalk between these hormones during fruit development and ripening require further research.

In non-climacteric fruits, applying 1-MCP at the postharvest for ripening control does not make sense because these fruits do not have a response to ethylene for maturation. However, 1-MCP has been applied to some non-climacteric fruits for other purposes to, for instance, provide insights into the occurrence of ethylene-dependent and ethylene-independent events during ripening, including changes in genes expression [10]. A positive effect of the postharvest 1-MCP application on the inhibition of senescence processes has been reported in some non-climacteric fruits, such as reducing rachis browning in grapes and delaying leaf senescence in "Shatangju" mandarins marketed with attached leaves [74, 75].

The postharvest 1-MCP treatment has also been reported to inhibit the development of some physiological disorders, such as scald development in pomegranate, pericarp browning in litchi, water soaking in watermelon, internal browning in loquat, and internal flesh browning of pineapple [76, 77]. Inhibition of degreening and color change are observed in several citrus fruits, strawberry, and olive when 1-MCP has been applied [76].

Very few studies report the preharvest effects of 1-MCP applications on non-climacteric fruits. In citrus fruits (*Citrus spp*.), the preharvest 1-MCP treatment has been reported to result in reduced undesirable tree defoliation when ethephon is applied to diminish fruit removal force [22, 78]. In "Washington" navel oranges, a higher yield per tree and increased fruit elongation have been found when a combination of preharvest 1-MCP and gibberellic acid (GA3) was applied [79]. Besides, fruit drop considerably reduced when fruits were treated with 1-MCP alone or combined with either NAA or GA3. The combination of 1-MCP with either NAA or GA3 also enhanced the maturity index compared to untreated fruits.

In "Bing" sweet cherry (*Prunus avium* L.), reduced flesh firmness during postharvest life occurred when ethephon was applied to stimulate fruit abscission during mechanical harvest. The 1-MCP treatment performed 3 days after the ethephon application counteracted ethephon-induced flesh firmness loss without inhibiting fruit removal force reduction [80].

4. Summary of the effect of preharvest 1-MCP application on different fruits

See **Table 1**

Fruits	Effect of preharvest 1-MCP application	References
Apple	Reduce fruit drop Delay color development and flesh softening Retard starch degradation Delay ethylene production and ripening Maintain soluble solids and titratable acidity Reduce disorders incidence during cold storage	[1, 6, 14, 17, 20, 24–38]
Pear	Reduce fruit drop Extend the harvest window Reduce ethylene production Maintain firmness and color during cold storage	[19, 39–44]
Persimmon	Extend the harvest window Maintain firmness and color during cold storage Reduce disorders incidence during cold storage	[18, 47]
Banana	Delay ripening, color change, softening, weight loss, and finger drop during storage	[55]
Peach	Retard flesh softening Reduce ethylene production and ripening Extend shelf life	[57, 58]
Apricot	Maintain quality and prolong storability Reduce disorders incidence during cold storage	[2]
Mango	Delay ripening and peel color change Reduce ethylene production	[60]
Mangosteen	Delay ripening and extend the harvest window	[61]
Fig	Delay fruit senescence and improved storability	[22]
Pitahaya	Extend shelf life	[65, 66]
Melon	Maintain firmness during storage	[69]
Blueberry	Decrease firmness	[71]
Citrus	Reduce fruit and leaves abscission	[22, 78, 79]
Cherry	Reduce flesh firmness during postharvest life	[80]

Table 1.
Summary of different fruits in which 1-MCP has been applied as a preharvest treatment.

5. Future research trends and new perspectives

The preharvest 1-MCP treatment has shown remarkable benefits for different fruit crops, which clearly come over for apples. Further research is needed to allow its application to a larger number of climacteric fruits, mainly those for which the postharvest 1-MCP treatment has a positive effect on delaying ripening and maintaining fruit quality. In these cases, replacing the postharvest treatment with the preharvest 1-MCP application would be a very useful tool for improving handling operations in packing houses.

In non-climacteric fruits, further studies are necessary to elucidate the role of the preharvest 1-MCP treatment in maintaining or improving different fruits quality aspects.

Besides, continued research is required on metabolic paths, gene expression, and enzyme activities on the preharvest effects of 1-MCP on fruit metabolism.

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Conflict of interest

The authors declare no conflict of interest.

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