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EFFECT OF 1-METHYLCYCLOPROPENE AND STORAGE TEMPERATURE ON POSTHARVEST FRUIT QUALITY: A REVIEW

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ABSTRACT

1-Methylcyclopropene (1-MCP) is a strong ethylene inhibitor with important applications in postharvest quality control, maintaining the freshness of fresh fruits and vegetables for longer periods. It works by binding to ethylene receptors, effectively blocking ethylene action and delaying the processes of ripening and senescence. Its effectiveness depends significantly on storage conditions, especially temperature. Keeping temperatures at optimum levels in combination with 1-MCP treatment increases the capacity to maintain fruit quality, as temperature control reduces metabolic activity that leads to degradation. This combination positively impacts key physicochemical characteristics such as respiration rate, ethylene evolution rate, fruit firmness, total soluble solids, titratable acidity, and antioxidant activity, all of which are critical for maintaining postharvest freshness. This review gives a thorough review of the 1-MCP synergistic effect in combination with storage temperature on fruit physiology and considers its real-life applications for decreasing postharvest losses, enhancing fruit quality, and guaranteeing economic stability in the fresh produce market.

***Key words*: 1-MCP, postharvest quality, storage temperature, ethylene, ripening.**

Introduction

Postharvest quality management of horticultural produce is essential for meeting consumer expectations and reducing food waste. Horticultural crops, including fruits, vegetables, and flowers, are highly perishable and prone to rapid deterioration under storage conditions due to ripening and ageing. Ethylene, a key plant hormone, plays a significant role in catalysing physiological changes that accelerate postharvest quality deterioration. By changing skin colour and cell turgor and promoting structural changes that lead to texture loss, ethylene contributes to the rapid loss of produce quality. In addition, ethylene increases respiration rates and activates degradation enzymes that destroy cell walls, adding to the loss of quality (Asrey *et al*., 2023).

Various methods have been devised to maintain the quality of produce in postharvest storage. In these, safe chemicals such as ethylene inhibitors appear to hold the potential for minimising postharvest losses. Ethylene inhibitors check the formation of ethylene and thereby delay the ripening of produce. A notable example is 1-methylcyclopropene (1-MCP), a novel ethylene action inhibitor that effectively prolongs the storage life of certain fruits and vegetables. By competing with ethylene for binding sites on ethylene receptors, 1-MCP regulates ethylene responses, delaying ripening and associated physiological changes (Sisler and Serek, 1997). Its non-toxic mode of action, minimal residue levels, and high efficacy at extremely low doses make 1-MCP an ideal tool for postharvest quality management of fruits (Watkins and Miller, 2005). Temperature is another critical factor influencing the postharvest storage life of horticultural produce. Maintaining optimum storage temperatures is fundamental for minimising product deterioration. Effective temperature control is one of the most basic yet crucial methods to preserve quality. Proper temperature management delays ageing, softening, and texture loss in produce. Low-temperature storage further inhibits ethylene-related activities, enhances the expression of stress-responsive genes, and modulates both primary and secondary metabolic pathways, thereby preserving quality (Brizzolara *et al*., 2020).

Combining 1-methylcyclopropene treatment with optimal storage temperature has shown synergistic effects in reducing respiration rates, ethylene production, ripening, ageing, and other metabolic processes. Although there are many studies on the separate effects of 1-MCP treatment and temperature control with respect to postharvest fruit quality, we found no review to date that has integrated the information on the combined effects of 1-MCP and optimal storage temperature across a variety of fruit crops and storage conditions. There is also very little understanding of the interactive effect of 1-MCP under varying temperature regimes, with the protocols of application being inconsistent in the amount of dosage, timing and application. These limitations should be addressed to create more comprehensive strategies to improve the postharvest quality and shelf life of fruits. This review aims to provide information on the combined effects of 1-MCP and optimal storage temperatures, to aid in understanding how they interact to affect the physicochemical qualities of fruits under storage.

Ethylene biosynthesis and action

Ethylene is a natural gaseous hormone in plants that serves as a key signal for triggering fruit ripening and various metabolic processes. This hormone is synthesised within plants through a biochemical pathway called the ethylene biosynthesis pathway.

The process begins with methionine (MET), a common amino acid acting as the precursor for ethylene production. Methionine is energised by adenosine triphosphate (ATP), forming S-adenosyl methionine (SAM), a pivotal intermediate in the pathway. SAM is then converted into 1-aminocyclopropane-1-carboxylic acid (1-ACC), the direct precursor of ethylene, via the action of the pathway's key enzyme, ACC synthase. Finally, the enzyme ACC oxidase catalyses the conversion of 1-ACC into ethylene (Dhall, 2013) (Fig. 1). Once produced, ethylene binds to specific receptors in plant cells. During normal development, these receptors remain active in the absence of ethylene, allowing the fruit to grow without initiating ripening. However, when ripening begins, the released ethylene binds to the receptors, deactivating them and initiating the ripening process (Asrey *et al*., 2023).

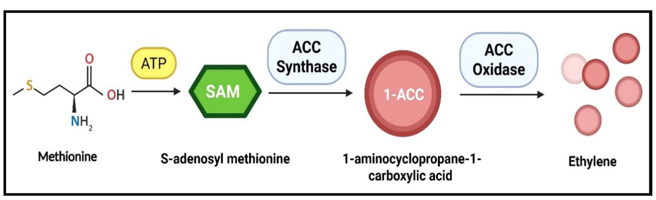

Fig. 1: Ethylene biosynthesis pathway.

Two distinct systems of ethylene biosynthesis have been identified in fruits. System 1 functions during the development and ripening of non-climacteric fruits and is also responsible for the low levels of ethylene produced during the pre-climacteric phase of climacteric fruits. In contrast, System 2 is an auto-catalytic process unique to climacteric fruits, characterised by a significant surge in ethylene production during ripening (Bapat *et al*., 2010).

Effect of 1-MCP in postharvest quality management

1-Methylcyclopropene delays the ripening and senescence activities in fruits and vegetables, thereby improving the shelf life of the produce under storage. It is a gaseous compound with a molecular weight of 54 and of formula C_4H_6 at standard temperature and pressure (Blankenship and Dole, 2003). 1-MCP binds to the ethylene receptors present in the plant cells, thereby preventing the deteriorative action due to ethylene binding (Sisler and Serek, 1997) (Fig. 2). When 1-MCP binds to the receptors, ethylene biosynthesis enzymes, including ACC oxidase and ACC synthase, are suppressed. Because of the ten-fold greater affinity for ethylene binding receptors, 1-MCP exhibits remarkable efficacy even at very low concentrations (Blankenship and Dole, 2003). 1-Methylcyclopropene is a powerful tool in delaying fruit ripening by binding permanently to ethylene receptors in plant cells. However, ripening can eventually occur as plants produce new receptors over time.

The commercial adoption of 1-MCP has been driven by its numerous advantages over traditional preservation methods. One of the primary benefits is its non-toxic nature and safety profile, making it suitable for use on food products without leaving harmful residues. The compound demonstrates excellent efficiency even at low application volumes, requiring minimal amounts to achieve significant preservation effects while producing no environmental pollution (Kumar *et al*., 2023). Commercially, 1-MCP is marketed under various trade names, including EthylBloc®, SmartFreshTM, and AgroFresh. It is approved for use on horticultural produce by the Environmental Protection Agency (EPA) (Watkins, 2006). The Food and Drug Administration (FDA) has also categorised 1-MCP as a GRAS (Generally

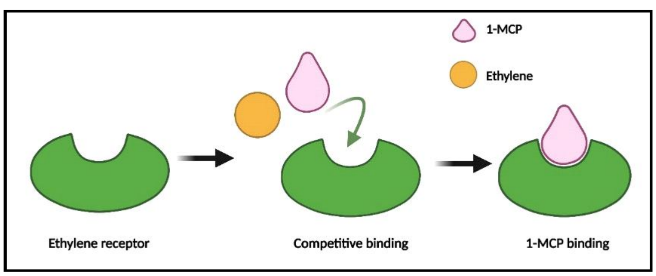

Fig. 2: Ripening inhibition mechanism of 1-MCP.

Recognised As Safe) chemical, due to its non-toxic mode of action.

Effect of storage temperatures in postharvest quality management

Temperature is a critical environmental factor that decides the postharvest storage life of horticultural produce. All physiological functions, including transpiration and respiration, continue after harvest since fruits remain alive. However, since the produce is no longer connected to the parent plant, it is impossible to give nutrients and water. Produce deteriorates with respiration, losing weight through transpiration, changing texture and flavour, and losing nutritional content. Although these processes cannot be prevented, they can be considerably slowed down by carefully controlling storage temperature and relative humidity (Bekele, 2018).

Low-temperature storage is generally preferred to improve the keeping quality of produce. Cold storage postpones the ripening and senescence processes by reducing the general metabolism and decreasing the catalytic activity of many enzymes, including those engaged in the various respiration phases (Brizzolara *et al*., 2020). Singh *et al*., (2021) stored dragon fruit at three different temperatures (4, 8, and 12°C) and found that the fruits exhibited a longer shelf life up to 24 days under refrigerated storage of 4°C. Similarly, in another study Careli-Gondim *et al*., (2020) revealed that a cold storage temperature of 7-10°C is optimal for preserving ‘Quintal’ avocados without any chilling injury symptoms.

While low temperatures generally preserve fruit quality, certain sensitive fruits, mainly tropical fruits, are prone to chilling injuries when exposed to cold conditions. Bananas stored at 7°C temperature exhibited serious chilling injury symptoms like peel browning and pitting within 3 days of storage (Tian *et al*., 2022). Conversely, higher storage temperatures can accelerate ripening, reduce shelf life, and increase the risk of spoilage and nutrient loss. To balance shelf life and quality retention across various fruit varieties, ideal storage conditions must be carefully implemented.

Influence of storage temperatures on 1-MCP treatments

Storage temperatures significantly influence 1-MCP treatments, and together, they determine the postharvest quality of the harvested produce. Studies indicated that lower storage temperatures improve 1-MCP’s effectiveness, resulting in decreased respiration rates, weight loss, and enhanced sensory attributes (Wan *et al*., 2023). Álvarez-Herrera *et al*., (2023) conducted a study where they subjected feijoa fruits to different 1-MCP doses and storage temperatures. Compared to fruits held at 16 °C, those stored at 4 °C showed the highest levels of soluble solids and antioxidant activity and the lowest levels of mass loss and respiration rate (Álvarez-Herrera *et al*., 2023). In another experiment where guava fruits were stored at two different cold storage temperatures (8 and 12°C), the 1-MCP treatments maintained the quality and freshness of fruits for up to 3 weeks at 12°C storage and up to 4 weeks at 8°C storage (Sachin *et al*., 2024).

In the persimmon cultivar (cv.) ‘Giombo’, 1-MCP treatment combined with a storage temperature of 1°C enhances the efficacy of 1-MCP, and it alleviates chilling injury and reduces astringency, improving the storage life of fruits (Tessmer *et al*., 2019). In tropical fruits, exposure to a lower temperature can lead to significant chilling injury and related defects. In such cases, 1-MCP treatment should be augmented with ambient temperature conditions for quality preservation and shelf-life extension. When banana fruits were stored at a temperature of 25°C after being treated with 400 nL/L of 1-MCP, they showed a significant reduction in ripening rate with extension of shelf life (Zhu *et al*., 2015). Qiu *et al*. (2009) examined the effects of 1-MCP on ‘Sunrise’ apples at various temperature ranges and found that 1-MCP was more successful at lowering ethylene production and softening at higher temperatures (22°C) than at lower temperatures (5°C). This contradictory effect may be ascribed to the cold stress resistance of genotypes, and as a result, chilling-sensitive fruits may not respond to 1-MCP treatment under lower temperatures (Satekge and Magwaza, 2022).

In certain scenarios, apart from the lowest or highest temperatures, an optimal storage temperature is ideal for postharvest quality maintenance. In a study conducted by Hasan *et al*. (2023), 1-MCP-treated mango fruits in a developed storage structure (10 ± 1°C and 90 % RH) had an extended storage life of 40 days compared to storage under cold and ambient temperatures. In light of these findings, there is a need to emphasise the importance of ideal storage conditions to optimise the advantages of 1-MCP treatments.

Physicochemical and physiological changes in produce induced by postharvest application of 1-MCP

Respiration rate:

The respiration rate of a fruit is closely linked to its ripening process. Respiration is the metabolic process where the reserved substrate breaks down in the presence of oxygen to produce energy. A higher respiration rate correlates with faster utilisation of the fruit's energy reserves, shortening its shelf life (Saltveit, 2019). Application of 1-MCP has been found to reduce the respiration rate of fruits during storage. This reduction is attributed to 1-MCP's ability to slow down metabolic activities by inhibiting ethylene action, thereby delaying the ripening process and extending shelf life.

Postharvest treatment of 1-MCP on peach cv. Dorado has significantly lowered the respiration rate on extended storage, subsequently maintaining its keeping quality (Mariño-González *et al*., 2019). Lv *et al*., (2020), found that apple cv. Golden Delicious exhibited a delayed respiratory peak on treatment with 1-MCP compared to the respiratory peak of 21 days in control fruits. When mango variety Amrapali was treated with 1-MCP, the respiratory peak was delayed up to 9 days, while in control, it took place within 6 days (Reddy *et al*., 2017). Postharvest treatment of 500 ppb 1-MCP on guava cv. Arka Mridula under ambient temperature substantially lowered respiration and, in turn, the ripening rate (Sachin *et al*., 2021).

Treatment with 1-MCP was the primary factor influencing the respiration rate. However, the rate of respiration was also significantly influenced by the maturity stage and storage temperature. When pear fruits were treated with 500 ppb 1-MCP and stored at 0^oC, the respiratory rate decreased noticeably, and storage life was extended up to 8 months (Kuruba and Erkan, 2018). 1-MCP treatment on Royal Gala apples under different storage temperatures (0.5-3 °C) revealed that maximum suppression of respiration rate was observed at 0.5 °C temperature (Lee *et al*., 2016). In sweet melon, 1-MCP fumigation with 3.0 µL/L concentration coupled with low-temperature storage (8 ± 1^oC) was found to be the best combination for inhibiting respiratory intensity in sweet melon fruit during storage (Wang *et al*., 2025). 'Honggeum' apple fruits treated with 1-MCP (1.0 µL/L) and stored at cold temperatures (0°C) exhibited significantly reduced respiration rates compared to untreated fruits, effectively delaying the climacteric respiratory peak by approximately 15-20 days (Yoo *et al*., 2020). However, in bananas, cool room temperatures are used instead of refrigerated storage due to the incidence of chilling injury. 1-MCP treatment considerably delayed the respiratory peak in banana cv. Ambul with a more substantial impact at 14 °C cool room temperature than the ambient temperature (Wasala *et al*., 2024).

Ethylene evolution rate:

1-MCP blocks and delays the ripening and senescence activity of ethylene by binding irreversibly to the ethylene receptors in plant cells (Sisler and Serek, 1997). As a result, 1-MCP has been used extensively as a potential ethylene inhibitor to reduce ethylene evolution rates and enhance keeping quality (Blankenship and Dole, 2003). In a study where mango fruits were treated with 1-MCP at ambient temperatures, control fruits showed a climacteric ethylene peak on day 4 at 25°C, while 1-MCP-treated fruits peaked later, on day 6, indicating a 2-day delay in ethylene peak (Li *et al*., 2020). Similarly, the guava variety Arka Mridula treated with 500 ppb 1-MCP and stored under ambient conditions showed a significant decrease in ethylene production rates compared to untreated fruits (Sachin *et al*., 2021). 1-MCP treatment in Bartlett Pear revealed that the ethylene evolution rate after 1-MCP treatment is not only dependent on the treatment itself but also significantly influenced by the ethylene levels present during the treatment (Villalobos Acuña *et al*., 2011). Higher ethylene levels substantially reduce the effectiveness of 1-MCP.

Even while 1-MCP effectively lowers ethylene generation, if proper storage temperatures are not maintained, extended storage may result in quality degradation. Wan *et al*., (2023) studied the effect of 1-MCP treatment on five pomegranate varieties stored under 4 ± 0.5^oC and found that the ethylene production was cut down and the respiratory peak was decreased in whole fruits . Rizzolo *et al*., (2015), stored 1-MCP treated Abbé Fétel' pears at 0.5^oC and found a drastic decrease in ethylene production, less than ten times the ethylene produced in control fruits. 1-MCP treatment effectively reduced the rise in ethylene production in kiwifruits during cold storage (0^oC), maintaining levels around 12–13 µL/kg/h for 6 months (Liu *et al*., 2021). Sachin *et al*., (2022), treated guava cv. Arka Mridhula with 500 ppb 1-MCP followed by storage at 12 ± 1 °C temperature. 1-MCP-treated fruits exhibited reduced ethylene production (5.02 µl/kg/h) after 21 days of storage, compared to untreated fruits, which reached a maximum rate of 40.96 µl/kg/h on the same day. This suppression of ethylene production, in turn, decelerated the rate of ripening and respiration in fruits.

Texture and firmness:

The firmness of fruits and vegetables is one indicator of their quality and is related to the maturity of many agricultural goods. Generally speaking, fruit firmness diminishes with maturity and rapidly declines with ripening. 1-MCP tends to delay this fruit softening process with its ability to retard cell wall degradation. In ripening, ethylene induces the synthesis of cell wall-degrading enzymes, such as polygalacturonase (PG), pectin methylesterase (PME), cellulase, β-galactosidase, and α-L-arabinofuranosidase.

1-MCP treatment significantly inhibits the activities of these enzymes in retaining architectural integrity and firmness (Win *et al.*, 2019).

Treatment and storage of avocado cv. Pollock with 1-MCP under the tropical ambient temperature of 27 ± 2°C substantially postponed the softening of fruits, leading to increased firmness retention due to the diminished activity of cell wall disintegrating enzymes, specifically polygalacturonase and cellulase (Daulagala and Daundasekera, 2016). Zhao *et al.*, (2024) treated 3 varieties of kiwifruits, namely Xuxiang, Hayward and Huayou with 1-MCP and stored under ambient conditions of 20°C and observed that 1.0 µL/L of 1-MCP was found to be effective for maximum firmness retention in Xuxiang and Hayward varieties, whereas, for the Huayou variety, 0.5 µL/L of 1-MCP was ideal. 1-MCP treatment combined with cold storage further improved the firmness and keeping quality of fruits. Ting *et al.*, (2023), studied the effect of 1-MCP on 4 different varieties of apple under cold storage (2°C) and found that 1-MCP treated apples maintained quality comparable to untreated apples for at least an additional six weeks. Under cold storage, 'Hwangok' and 'Picnic' apples treated with 1-MCP retained the firmness and texture of fruit by delaying the alteration of cell wall pectin, which in turn delayed fruit softening (Win *et al.*, 2021). Physiological markers associated with firmness in climacteric fruits were considerably lowered by 1-MCP treatment. It was determined that 1-MCP is a valuable tool for preserving fruit firmness and that concentration, environmental factors, and possible combination with other treatments control its effectiveness.

Total soluble solids (TSS):

One characteristic of fruit ripening is the hydrolysis of starch reserves into sugars (glucose, fructose, or sucrose), which imparts sweetness to the fruits. During ripening, there is a drastic reduction in starch and an increase in TSS, mainly sugars, in fruits. The postharvest treatment of 1-MCP significantly delays the increase in TSS contents of fruits. This effect is attributed to the slowing of general metabolic activity and the suppression of ethylene-mediated starch-to-sugar conversion pathways.

In an experiment, two varieties of mango, 'Tommy Atkins' and 'Apple Mango' were treated with one ppm 1-MCP and stored under ambient temperatures. The study found that 1-MCP treatment reduced the TSS by postponing the biochemical alterations associated with ripening in mango fruits (bekele *et al.*, 2013). Similarly, studies on Kent mango revealed that 1-MCP prevented the rise in TSS during storage, and the 400 mg/L concentration sustained this effect throughout the marketing simulation until the stage of consumption (Osuna-Garcia *et al.*, 2015). Tomato cv. Vaishali treated with 2.5 µL/L of 1-MCP showed a slow progression of TSS from 1.6 to 3.8 with a storage life of 34 days under 20 ! storage, whereas the untreated controls exhibited a quicker increase in TSS from 1.7 to 3.1 within their significantly shorter 12-day shelf life (Chavan *et al.*, 2023).

1-MCP delayed the metabolic responses related to TSS in nectarines stored at 0°C, improving their storage life (Jiang *et al.*, 2024). Ilea *et al.* (2025) treated strawberry fruits with a commercial concentration of 1-MCP (250 µL/L) followed by cold storage at 2°C temperature, and found that 1-MCP treated fruits exhibited a slower reduction in total soluble solids content, which was notably observed after 6 days of cold storage.

Titratable acidity (TA):

Organic acids are essential constituents of fruits, and they play an important role in the metabolism, flavour, and quality of the fruit. Organic acids such as malate and citrate are present in high amounts in the early stages of fruit development, but decrease as the fruit ripens (Batista-Silva *et al.*, 2018). 1-MCP treatment has different effects on the level of organic acids due to the diversity of fruit cultivars and different storage conditions.

When the guava variety 'Allahabad Safeda' was treated with 1-MCP and stored under ambient and cold storage conditions, there was considerable improvement in the fruit quality parameters. The greater titratable acidity (TA) levels in fruit immediately following 25 days of storage at 10 °C suggested a delayed ripening process (Singh and Pal, 2008). During the course of 32 weeks of storage, 'Bramleys Seedling' apples treated with 626 ppb 1-MCP kept at 3°C in modified atmosphere packaging displayed noticeably higher TA levels than untreated fruits (Zangeneh and Hennerty, 2008). Preharvest and postharvest 1-MCP treatment in Fuji apples and storage under cold storage (0.5°C) temperature retained more TA compared to the untreated control (Lee *et al.*, 2019). Similarly, in apple cultivars 'Colorpple' and 'Manhong', higher retention of titratable acidity was observed in 1-MCP treated fruit kept at cold storage rather than the one stored at ambient storage temperature (Kwon *et al.*, 2024).

Tegan Blue plums treated with 1-MCP (1 µL/L) showed higher TA levels, particularly under cold storage temperatures (0 ± 1°C), extending storage life up to 6 weeks (Khan *et al.*, 2009). Research conducted by Calvo

(2003), on the pear cv. Williams revealed that a higher concentration of 1-MCP treatment (400-600 ppb) was more effective in maintaining the titratable acidity levels in the fruits. From the studies conducted by Faasema *et al*., (2014), on 3 different varieties of mango (Peter, Brokin and Julie), it was revealed that the effect of 1-MCP on acidity levels depends upon storage temperatures. Fruits stored at 20°C showed maximum retention of titratable acidity with delayed ripening and extended storage up to 25 days compared to 32°C storage. Harvest maturity of the fruit also affects the effectiveness of 1-MCP on titratable acidity. The loss of titratable acidity in Larry Ann plums, especially in early-harvested fruits, was successfully decreased by 1-MCP treatment. However, the treatment's ability to maintain acidity decreased with an increase in harvest ripeness (Candan and Calvo, 2021).

Antioxidant activity:

The US Food and Drug Administration (FDA) defines antioxidants as compounds that help preserve food by delaying oxidation-induced deterioration, rancidity, or discolouration (Kaur and Kapoor, 2001). Antioxidant activity in fruits is associated with phenolic compounds, ascorbic acid and other bioactive compounds. However, the effects of 1-MCP treatment on these compounds are complex, and different patterns may emerge based on fruit species and storage conditions.

When loquat fruits were treated with 1-MCP and stored under cold storage conditions, they exhibited high DPPH radical scavenging activity. It also maintained high phenolic and flavonoid content in fruits during storage (Cao *et al*., 2011). Similarly, 1-MCP treated peach fruits, accompanied by cold storage conditions, exhibited a high antioxidant activity caused by the retention of high polyphenols in the fruits (Tang *et al*., 2020). In mango cv. Amrapali treatment with 1000 ppb 1-MCP retained maximum ascorbic acid content in the fruits. The fruits exhibited highest antioxidant activity of 692.47 μmol Trolox g^{-1} Fresh Weight on 9th day of storage (Reddy *et al*., 2017).

It has been reported that 1-MCP treatment causes increased activities of several antioxidant enzymes, including SOD, CAT, and APX, in several fruits. In a study conducted by Loh *et al*., (2024), the antioxidant response of papaya fruits to postharvest treatment of 1-MCP and geranium oil was assessed. It was found that Papaya's total phenolic and flavonoid content, DPPH scavenging ability, and the activities of antioxidant enzymes like SOD, CAT, APX, and POD were all found to be significantly increased by the treatment during cold storage. Combining 1-MCP with other treatments, such as chitosan or controlled-atmosphere storage, further enhances antioxidant capacity and fruit quality. The Controlled Atmospheric (CA) storage of 1-MCP treated blueberries showed a significant increase in the antioxidant enzymes, including APX, CAT, and SOD, which decreased the accumulation of ROS and enhanced the antioxidant capacity in postharvest blueberries during storage (Ba *et al*., 2022).

Economic and practical considerations of 1-MCP treatment

Extended postharvest life achieved through the application of 1-MCP facilitates long-distance transport as well as off-season availability of fruits. Because of the ease of the technique involved in 1-MCP treatment, it can give an effective and viable solution in the supply chain of perishable commodities (Paul and Pandey, 2017). Its effectiveness, even at minute concentrations, makes it a cost-effective solution in postharvest management compared to other traditional methods of quality management (Watkins and Miller, 2005). The 1-MCP market is expected to develop significantly, with a compound annual growth rate (CAGR) of 7.1 %, from USD 1.2 billion in 2023 to over USD 2.3 billion by 2032 (DataIntelo, 2024). The global need for cutting-edge postharvest technology to increase shelf life and decrease food waste is fueling this trend.

The practical application of 1-Methylcyclopropene needs careful consideration of several factors. It can be applied either in gaseous or liquid form, but the gaseous method is generally preferred due to its ease of application. For commercial implementation, consideration of facility needs such as sealed treatment chambers, gas monitors, and proper ventilation is necessary. The timing of application is also critical, as greater results are obtained in earlier postharvest applications before the fruit reaches its climacteric peak (Satekge and Magwaza, 2022). Maintenance of optimal temperatures in storage also increases the effectiveness of 1-MCP (Álvarez-Herrera *et al*., 2023). Commodity-specific elements such as ethylene sensitivity, maturity, and genotype, as well as interactions with other treatments, are also important in determining the effectiveness of 1-MCP treatment (Satekge and Magwaza, 2022).

Limitations of 1-MCP

Even though 1-MCP is a powerful tool in delaying ripening and senescence activities during the postharvest quality management of fruits, it also suffers certain limitations. A major concern is the possibility of irreversible inhibition of ripening, commonly referred to as the 'evergreen' effect, where fruits fail to develop their characteristic aroma, colour, and flavour as 1-MCP blocks the normal progression of their ripening process (Chiriboga *et al*., 2011). This effect persists even after extended storage, necessitating post-storage ethylene treatments to restore softening capacity, which increases operational costs and complicates supply chain logistics.

1-MCP also causes negative impacts on the aroma and flavour profile of treated fruits, leading to a condition called ‘flavour dilution’, reducing their market appeal. This phenomenon correlates with 1-MCP’s suppression of alcohol acyltransferase enzymes involved in ester biosynthesis pathways (Ferenczi *et al*., 2006).

Despite the fact that 1-MCP blocks ethylene action by binding to the receptors irreversibly, plants are able to produce new ethylene receptors. Over time, the 1-MCP block may be overcome by this receptor renewal, decreasing the efficacy of a single treatment. Limitations can also be observed regarding the efficacy of its commercial formulations. Conventional powder formulations of 1-MCP require enclosed spaces to prevent gas leakage. Although liquid and non-volatile formulations have been created, their application is still very limited (Naing *et al*., 2022).

Future prospects

In the near future, 1-MCP technology is anticipated to take the lead in regulating ethylene in perishables. This is because of its high efficacy, low concentration requirements, prolonged protection, odourless nature, and especially non-toxicity. Studies are being conducted about the biochemical factors that regenerate ethylene receptors, which help in reviving the ripening of fruits after the storage period. The discovery of improved commercial formulations of 1-MCP will greatly help to improve its global demand in postharvest quality management of horticultural crops.

Recent studies highlight the potential of machine learning to optimise 1-MCP dosing and timing. Research demonstrates that convolutional neural networks (CNNs) can predict fruit ethylene sensitivity with 92 % accuracy, and they can enable cultivar-specific 1-MCP protocols, addressing current limitations of uniform treatment strategies (Fadiji *et al*., 2023). IoT-enabled systems can also be combined with 1-MCP application with real-time environmental monitoring. Edge computing devices in storage facilities can analyse ethylene emission patterns (0-5 ppm resolution) to trigger automated 1-MCP fogging when thresholds exceed cultivar-specific limits (Barnavo Das *et al*., 2025).

Failure of 1-MCP treatments can be visualised effectively through computer vision systems. Thermal imaging can be used to detect residual ethylene activity, whereas RGB cameras can be used to spot incomplete chlorophyll degradation, and NIR spectroscopy to map uneven receptor binding (Fadiji *et al*., 2023). Incorporation of machine learning, computer vision, and AI approaches into 1-MCP treatments facilitates real-time tracking, predictive modelling, and automatic decision support, resulting in improved treatment procedures, better fruit quality, decreased postharvest losses, and a more efficient and sustainable supply chain.

Conclusion

1-Methylcyclopropene (1-MCP) is a potent ethylene inhibitor that has become a valuable asset for the postharvest quality management of fruit. The retention of important physicochemical properties of fruits due to 1-MCP is attributed to slowing down ripening and senescence, ultimately enhancing the shelf life and preserving the nutritional value of fruits. By maintaining optimum storage temperature, 1-MCP effectiveness can be maximised. This powerful combination works synergistically to extend the shelf life of fruits. Proper storage temperatures are critical to the effective functioning of 1-MCP since deviations from ideal conditions can greatly reduce its effectiveness and cause a faster deterioration in quality. Standardisation of application time and temperatures according to varietal differences is also a major constraint.

In the future, the inclusion of Artificial Intelligence (AI) and machine learning technologies in postharvest practices is an evident breakthrough in the field of fruit quality management. These advances offer predictive, real-time processing that can be used to optimise 1-MCP treatment and storage options and create an opportunity for personalised and dynamic post-harvest treatment that minimises waste and increases marketing value. As demand for fresh produce continues to grow worldwide, the integration of 1-MCP with optimal storage practices offers a sustainable and efficient solution for the fresh produce industry, benefiting farmers, retailers, and consumers alike.

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