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Review Article on:

1-Methylcyclopropene (1-MCP) a Breakthrough to Delay Ripening and Extend Shelf-Life of Horticultural Crops

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1. Ethylene gas in horticulture

1.1. Ethylene effects

Ethylene gas ($CH_2=CH_2$) is a simple organic compound physiologically active in plants. It is thought of as the aging and ripening hormone and is physiologically active in trace amounts. It causes a wide range of effects in plants, depending on the age of the plant and its sensitivity to ethylene. Ethylene effects can be desirable or undesirable, depending on the commodity you work with. These effects include: fruit ripening, degreening of citruses, harvest aids in mechanical harvesting, flower initiation, change sex expression (increases female flowers on cucurbits), yellowing and senescence of vegetative tissues (leafy vegetables) and immature fruits (cucumber, squash), leaf abscission (dropping) and quick senescence of most flowers (Abu-Goukh 1993).

1.2. Control of fruit ripening

Control of fruit ripening, initiation or delay, is generally dependent on factors that affect ethylene production or action. Treatment of pre-climacteric fruits with exogenous ethylene advances the onset of ripening. This response is used widely in commercial practices to achieve controlled ripening of fruits that are picked and transported in a mature, but unripe state and ripened just before marketing (Wills *et al.* 1998). Delay of fruit ripening and prolonging shelf-life can be achieved by different post-harvest procedures related to ethylene production or action, including:

1. Low Temperature: Low temperature can be used to achieve a delay in the onset of ripening in climacteric fruits. Lowering the temperature not only reduces the production of ethylene by the tissues, but also minimizes the rate of response of the tissue to ethylene action (Wills *et al.* 1998).
2. Ethylene Exclusion and Removal: The removal of ethylene from the atmosphere surrounding the commodity is the preferable method of preventing deterioration of produce sensitive to the gas. Simple ventilation of ripening rooms can reduce ethylene concentration. (Kader 2002). Removal of endogenous ethylene was the first benefit ascribed to the hypobaric or low-pressure system, of storage. The shelf-life of banana can be extended considerably by low pressure system (Abu-Goukh 1986; Burg and Burg 1966). Abu-Goukh (1986) reported that ethylene production and respiration activity of banana held in hypobaric storage at 20˚C with gas mixtures of 1 to 10% O_2 under one-fifth atmospheric pressure were considerably depressed. No climacteric rise of respiration was apparent and fruit remained green and firm until the end of the 14-days storage period. The fruit showed a rapid increase in ethylene production and respiration activity and started to ripen normally almost immediately after being transferred to air. Apelbaum *et al.* (1977) found that slowing of banana ripening is inversely proportional to atmospheric pressure of storage.
3. Inhibition of Effect of Ethylene: Delaying of fruit ripening can be achieved by modified atmosphere (MA) or controlled atmosphere (CA) storage. Ethylene production and respiratory activity of banana fruits held in CA storage at 20˚C in gas mixtures of 1 to 10% O_2 were greatly depressed. No climacteric was apparent and fruits remained green and firm until they were removed to air after 18 days, where they showed a rapid increase in ethylene production and respiratory activity and start to ripen immediately (Abu-Goukh 1986). Many of the beneficial results of modified atmosphere storage cannot simply be attributed to a reduction in respiration. The greatly increased storage life was attributed to a reduction in the rate of natural ethylene production by the bananas, decreased sensitivity of the fruit to ethylene and inhibition of ethylene action by CO_2 (Wills *et al*. 1998). The use of plastic films in achieving modified atmosphere is increase-ing. Polyethylene film liners, sealed or perforated, significantly delayed fruit ripening, maintained quality and extended shelf-life of bananas (Osman and Abu-Goukh

2008; Elamin and Abu-Goukh 2009) and papaya (Shattir and Abu-Goukh 2012).

4. Chemical Removal of Ethylene: Removal of ethylene gas can have additional benefit on extending shelf-life of bananas, under both ambient and modified atmosphere conditions (Scott *et al.* 1970; Abu-Goukh 1986). Ethylene can be removed by a number of chemical processes.

Potassium permanganate ($KMnO_4$) is an oxidizing agent quite effective in reducing ethylene levels by oxidizing it to CO_2 and H_2O (Kader 2002). Potassium permanganate is a chemical, which has long been used to remove ethylene from the storage atmosphere (Salunkhe and Desai 1984). Abu-Goukh (1986) reported that 'Purafil' (alkaline $KMnO_4$ on silicate carrier) lowered the rate of ethylene production by about 15 to 30% in CA storage even after the 'Purafil' had been removed and fruits transferred to air. The reduction of ethylene was reflected on a slight delay in ripening. The use of $KMnO_4$ in conjunction with modified atmosphere storage in polyethylene films or bags significantly delayed fruit ripening in banana (Scott *et al.* 1970; Elamin and Abu-Goukh 2009) and mango (Elsoofi 2012).

Silver ions, applied in aqueous solution as $AgNO_3$, inhibit ethylene synthesis and ripening of mature banana slices (Saltveit *et al.* 1978). The inhibition of ripening and ethylene synthesis by the silver ion was evident in tissues treated with sufficient exogenous ethylene to elicit both responses in control tissue. However, several parameters of banana ripening were not inhibited at concentrations of the silver ion, others were severely inhibited.

The ornamentals industry has inhibited the undesirable effects of ethylene with a complex of silver and thiosulfate (Silver thiosulfate, STS), which has a very low stability constant and therefore moves readily from the vase solution to the head of cut flowers. Flowers pulsed with this material last two to three times as long as control flowers. Potted flowering plants do not lose their flowers during transportation if they are first sprayed with STS (Kader 2002).

Recently, an ethylene analog, 1-methylcyclopropene (1-MCP) was shown to be a very effective inhibitor of ethylene action in ornamentals plants, fruits and vegetables (Kader 2002).

1.3. Mode of action of ethylene

Ethylene is a plant hormone that acts in concert with other plant hormones (auxins, gibberellins, kinins and abscisic acid). Most is known about the relation of ethylene to fruit ripening because the availability of the sensitive gas chromatographic method for measurement of ethylene has enabled detailed studies of this relationship. The relationship of the other plant hormones to ripening is as yet not clearly defined (Wills *et al.* 1998).

As in the case of other plant hormones, ethylene is believed to bind to specific receptor(s) to form a complex that then triggers ripening. Ethylene's action can be affected by altering the amount of receptor(s) or by interfering with the binding of ethylene to its receptor(s). Detailed studies of the structural requirements for biological activity of ethylene receptors led to the proposal that binding takes place reversibly at a site containing a metal. From kinetic studies on the responses of plant tissue to added ethylene, it has been proposed that the affinity of the receptor for ethylene is increased by the presence of oxygen and decreased by carbon dioxide. The occurrence of a metal-containing receptor has not been confirmed, but the proposition is supported by studies with silver ion. Treatment of fruits, flowers and other tissues with silver ion has been shown to inhibit the action of ethylene. The need for specific structural requirements for ethylene action has been demonstrated by treating tissues with analogues and antagonists of ethylene. The gaseous cyclic olefins, 2, 5-norbornadiene and 1-methylcyclopropene (1-MCP), have been shown to be highly effective inhibitors of ethylene action. 1-methylcyclopropene has been shown to bind irreversibly to the ethylene receptors in sensitive plant tissues and a single treatment with low concentrations for a few hours at ambient temperatures confers protection against ethylene for several days (Wills *et al.* 1998).

2. 1-Methylcyclopropene (1-MCP) as inhibitor of ethylene gas

1-Methylcyclopropene (1-MCP) is an innocuous gas used at very low concentration which inhibit ethylene action by blocking ethylene receptors (Candan *et al.* 2006). By binding to ethylene receptors, 1-MCP acts as an efficient ethylene antagonist and its effect can persist for long time (Sisler *et al.* 2003). It can therefore slow down the ripening process as well as senescence of the fruit (Sisler and Serek 1997). In recent years an intensive work has been done in describing the effect of 1-MCP in fruit ripening (Blankenship and Dole 2003). It has been employed to increase the shelf-life of some horticultural commodities. 1-methylcyclopropene is being described as a breakthrough in shipping and storage technology that can maintain the 'fresh-picked' quality of ethylene sensitive commodities (Bates and Warner 2001).

At a standard temperature and pressure, 1-MCP is a gas with a molecular weight of 54 and a formula of C_4H_6. 1-methylcyclopropene is thought to occupy ethylene receptors such that ethylene cannot bind and elicit action. Sisler and Serek (1997) proposed a model of how 1-MCP reacts with the ethylene receptor. The affinity of 1-MCP for the receptor is approximately 10 times greater than that of ethylene. Compared with ethylene, 1-MCP is active at much lower concentrations. 1-methylcyclopropene also influences ethylene biosynthesis in some species through feedback inhibition (Sisler and Blankenship 1996).

The background work for the discovery of 1-MCP as an ethylene inhibitor came out of the laboratories of Edward Sisler and Sylvia Blankenship, Departments of Biochemistry and Horticultural Science, respectively, North Carolina State University. These workers jointly hold the patent on the use of cyclopropenes to inhibit ethylene action (Sisler and Blankenship 1996).

1-methylcyclopropene (1-MCP) has been added to the list of options for extending the shelf-life and quality of plant products. Not only does commercial use of 1-MCP promise to advance commercial agriculture, but also using 1-MCP in research programs promises to advance our understanding and provide new insights into plant ethylene responses.

Watkins (2002) has summarized the effects of 1-MCP on fruit and how it relates to ethylene physiology.

3. Commercialization of 1-MCP

Commercialization of 1-MCP was first under-taken by Floralife, Inc. (Walterboro, SC) for use on ornamental crops. Floralife formulated a α-cyclodextrin powder that releases 1-MCP when mixed with water (Blankenship and Dole 2003). This chemically nontoxic substance is environmental friendly and harmless to the public health was approved by the United States Environmental Protection Agency (USEPA) in 1999 for ornamentals and is sold under the trade name EthylBloc® (USEPA 2002; Liu *et al.*, 2010). Commercial application of 1-MCP to edible crops was undertaken by AgroFresh, Inc., a subsidiary of Rohm and Haas (Spring House, PA), under the trade name SmartFresh® since 2002. Both EthylBloc® and SmartFresh® are approved for use in the United States (USEPA 2002; Liu *et al.*, 2010). In addition to the fumigant application method, liquid spray application is being researched and may be added to the label in the United States (Hamrick 2001).

At standard temperature and pressure, 1-MCP is released from EthylBloc® powder in approximately 20-30 minutes. Complete release may take longer at lower temperatures. The concentration of 1-MCP gas in a sealed container with plant material declines with time. Only about one third of the initial amount of 1-MCP remains in the container after 24 h at 5°C. Up to 10% carbon dioxide in the same container atmosphere does not inhibit binding effectiveness of 1-MCP on apples. Because of the greater affinity of 1-MCP for the ethylene receptor, approximately 100 µl/l or greater concentration of ethylene is required to compete effectively for the receptor in apples (Blankenship and Dole 2003).

Diffusion of 1-MCP out of plant material is rapid. No 1-MCP was detected in the core area of individual apples approximately 8 h after application (Blankenship and Dole 2003). Measurable 1-MCP was not detected in sealed polyethylene bags 15 days after introducing 1 µl/l of 1-MCP to bananas (Jiang *et al.* 1999b). 1-methylcyclopropene appears to readily pass through plastic bags and fiberboard boxes. 1-MCP analysis can be conducted using gas chromatography with isobutylene often being used as a standard.

The safety, toxicity and environmental profiles of 1-MCP in regard to humans, animals and the environment are extremely favorable (USEPA 2002). The compound is used at low rates, has a non-toxic mode of action and is chemically similar to naturally occurring substances.
1-methylcyclopropene will protect plant products from both endogenous and exogenous sources of ethylene. Studies of 1-MCP have been conducted in the presence of applied ethylene and/or in the presence of endogenous ethylene. Responses to the two types of tests vary with commodity. Some crops will benefit from 1-MCP regardless of the presence of exogenous ethylene. Other crops show little benefit from 1-MCP application unless exogenous ethylene is present (Tian *et al.* 2000; Jiang *et al.* 2001b).

4. Mode of action of 1-MCP

1-methylcyclopropene blocks ethylene binding to its receptor. The fruit (plant) may still produce some ethylene, but without any response to ethylene, regardless of source (Blankenship 2001). In a normal plant response, ethylene (C_2H_4) attaches to a receptor molecule and a response occurs (Fig.1).

Ethylene attachment to the receptor is much like a 'key' fitting in a 'lock', with ethylene as the 'key' and the receptor as the 'lock'. When ethylene attaches to the receptor, it is like the lock turns and a door opens. A cascade of events then takes place, such as the fruit begins to soften, leaves turn yellow, or flowers drop off (Blankenship 2001).
Another gas, 1-MCP (C_4H_6), is also able to attach to the ethylene receptor. It also can act as a 'key' that goes into the 'lock', but it is unable to turn on the 'lock' and open the door. When the 1-MCP 'key' is in the 'lock' it is not possible for the ethylene 'key' to go in the 'lock'. The 1-MCP stops the 'lock' from turning so the door can't open (Fig. 2). It is in this way, 1-MCP acts as an ethylene inhibitor in plants (Blankenship 2001).

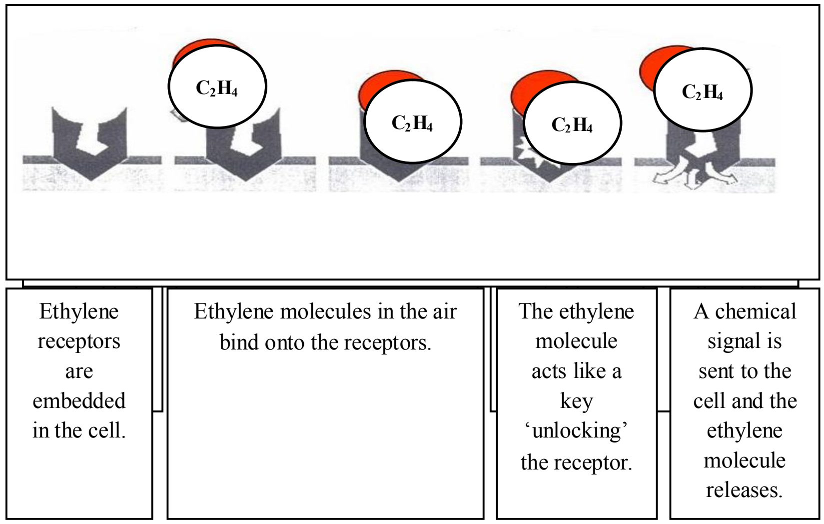
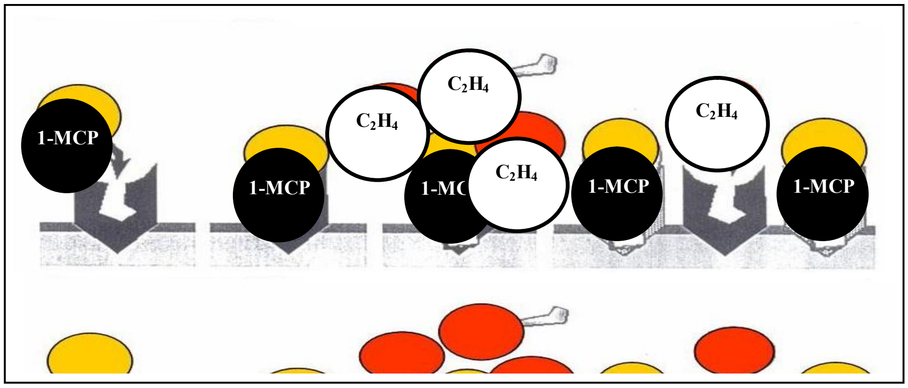


Figure 1: Binding of ethylene molecule with the receptor 'unlocks' the receptor and leads to a chemical reaction in the plant tissue (Blankenship 2001).

The assumption has been made that 1-MCP binds permanently to receptors present at the time of treatment and any return of ethylene sensitivity is due to appearance of new sites. While this may be true, there is little direct supporting data. Plant tissues vary greatly in their ability to regenerate sites. In avocado, ripening was delayed by about 2 weeks after 1-MCP treatment, and then the fruit ripened normally (Feng *et al.* 2000). Pesis *et al.* (2002) found that two applications of 300 nl/l made 10 days apart, were enough to prevent softening in avocado, whereas one application would allow fruit to soften normally. Binding sites appear to develop after treatment of broccoli as continuous application is more effective than a one-time treatment, but this was not true in pak choy (*Brassica rapa*) (Able *et al.* 2002). Ripening is delayed in bananas by 12-20 days (Saeed and Abu-Goukh 2013), in tomatoes by 5-10 days (Hoeberichts *et al*. 2002; Wills and Ku 2002) and in mangoes by 4-7 days (Elzubeir 2012) with one application of 1-MCP, but fruit must be retreated for continued effect.



Molecules of 1-MCP also bind to the ethylene receptors.	However, 1-MCP does not ‘unlock’ the ethylene receptor so no message is sent.	The 1-MCP is not released, so molecules of ethylene are unable to bind to the receptor.	Eventually, new ethylene receptors may be formed, and the cell regain sensitivity to ethylene.

Figure 2: When 1-methylcyclopropene (1-MCP) binds to the ethylene receptor, it does not ‘unlock’ the receptor and remains locked to the receptor preventing the binding of ethylene and the chemical reaction does not occur (Blankenship 2001).

With bananas, factors such as cultivar, maturity of fruit, prior exposure to ethylene, or growing conditions appear to greatly influence the results of using 1-MCP and the ability of the fruit to eventually ripen. Bananas treated with 1-MCP and kept in polyethylene bags eventually ripen, indicating that bananas might make new receptors in this situation (Jiang *et al.* 1999a; Saeed and Abu-Goukh 2013). However, bananas treated with 1-MCP may also stay green or ripen with an uneven colour (Harris *et al.*, 2000). Lack of ripening probably indicates that receptors were not regenerated. Jiang *et al.* (2001a) reported that, although banana fruits held at 30-40 °C did not de-green, their increased softening at elevated temperatures and inhibition of this response by 1-MCP, suggest that heat enhances synthesis of new ethylene sites which mediated banana fruit softening. Bananas attached to the plant and treated with 1-MCP eventually ripened normally, while harvested treated fruit did not ripen properly (Blankenship and Dole 2003). The role of abscisic acid (ABA) in ripening bananas appears to be mediated through ethylene, as 1-MCP-treated bananas do not show the stimulation of ripening caused by ABA (Jiang *et al.* 2000). Jiang *et al.* (1999b) suggested that 1-MCP exhibits non-competitive binding with the receptor in banana.

Partial responses in some apple cultivars either seem to suggest these cultivars are able to regenerate sites or that binding is incomplete. 'McIntosh' apples, for instance, may need higher 1-MCP concentrations, perhaps because this cultivar produces large amounts of ethylene (Watkins *et al.* 2000).

4. Physiological responses to 1-MCP

1-methylcyclopropene delays fruit ripening, maintains quality and extends shelf-life of apple (Beaudry 2001), avocado (Woolf *et al.* 2005), banana (Golding *et al.* 1998; Pelayo *et al.* 2003; Saeed and Abu-Goukh 2013), mango (Hofman *et al.* 2001; Elzubeir 2012), Plum (Candan *et al.* 2006; Manganaris *et al.* 2008) and tomato (Moretti *et al.* 2002). These fruits responded well to 1-MCP, showing inhibition of ethylene production, reduction of respiration rates, maintenance of firmness and other quality aspects both during and after storage (Watkins *et al.* 2000).

The ability of 1-MCP to delay ripening of mature-green, pre-climacteric bananas has been widely demonstrated (Sisler and Serek 1997; Golding *et al*. 1998; Joyce *et al.* 1999) as well as the time-concentration-temperature dependence of this response (Macnish *et al.* 2000). A single exposure to 1-MCP can inhibit apple fruit sensitivity to ethylene fruit sensitivity to ethylene. 1-methylcyclopropene delays the onset of the rise in ethylene production and similarly delays the rise in respiration, aroma production and softening. It can prevent ripening for an extended period (>30 days) even at ambient temperature (25°C) and reduces the incidence of the storage disorder, superficial scald (Beaudry 2001). Commercialization of 1-MCP has mostly occurred for apple and banana fruits. These fruits responded extremely well to 1-MCP (Watkins *et al*. 2000).

Post-harvest application of 1-MCP was an efficient method to delay tomato fruit ripening. As 1-MCP concentration increased, ripening was further delayed. Tomatoes treated with 250, 500 and 1000 ml/l of 1-MCP were delayed by 8-11, 11-13 and 15-17 days, respectively (Moretti *et al*. 2002). Fruits treated with 1-MCP took almost twice as long as untreated fruits and time to ripen is increased with increasing 1-MCP concentration in banana (Saeed and Abu-Goukh 2013), avocado (Woolf *et al*. 2005) and mango (Elzubeir 2012).

A post-harvest application, by immersion, of 1-MCP formulation delayed fruit ripening, reduced firmness loss, skin colour changes, respiration rate and fruit weight loss and extended the shelf-life of plum fruit, harvested at an advanced maturity stage when ripened immediately after harvest or after cold storage (Manganaris *et al*. 2008). A pronounced suppression of ethylene production in fruits treated with 1000 and 10,000 ng/kg 1-MCP was detected. Furthermore, all fruits ripened normally and did not show any chilling injury symptoms when ripe fruits were evaluated after cold storage (Manganaris *et al*. 2008).

4.1. Respiration and ethylene production

1-methylcyclopropene reduces or delays the increase in respiration rates. Mature-green bananas treated with 1-MCP significantly delayed the peaks of respiration and ethylene production, but did not significantly reduce the peak height (Jiang *et al*. 2004; Saeed and Abu-Goukh 2013). Respiration was suppressed in propylene-treated banana subsequently gassed with 1-MCP (Golding *et al*. 1998). Respiration was inhibited in 'Fuji', 'Grany Smith' and 'Red Delicious' apples (Fan *et al*. 1999a, Fan *et al*. 1999b). Respiration increase was delayed in avocado by about 6 days and the magnitude was reduced by about 40% with 1-MCP treatment (Hofman *et al*. 2001). Similar results were reported in plum (Dong *et al*. 2002), apricot (Fan *et al*. 2000), guava (Bassetto *et al*. 2005) and mango (Elzubeir 2012).

Respiration rate was reduced by 1-MCP in lime (Jomori *et al*. 2003), broccoli (Fan and Mattheis 2000a) and carrot (Fan and Mattheis 2000b).The stimulation of respiration in sweet cherry by exogenous ethylene occurred regardless of 1-MCP treatment (Gong *et al*. 2002). 1-methylcyclopropene treatment had no effect on nectarine (Dong *et al*. 2001a) and apricot (Dong *et al*. 2002).

1-methylcyclopropene treatment effectively decreased ethylene production during storage and increased shelf-life in plum fruits kept 15 and 30 days at 0˚C. Changes in ethylene production by 1-MCP were associated with a decrease of firmness loss and maintenance of titratable acidity, but not with development of red flesh colour (Candan *et al*. 2006). SmartFresh® (1-MCP) treatment also significantly reduced the level of internal ethylene in apple varieties in air and CA stored fruits at all removal times for up to 10 months storage. The lowering of ethylene production and action in the treated fruits reduced or lowered subsequent effects during storage (Golding *et al*. 2004).

4.2. Fruit weight loss

Fruit weight loss was significantly lower in 'Kichner' and 'Abu-Samaka' mangoes treated with 1-MCP at 250 and 500 ppb, compared with the control (Elzubeir 2012). Similar results were reported in plums (Martinez-Romero *et al*. 2003), avocado (Jeong *et al.* 2001) and bananas (Saeed and Abu-Goukh 2013). On the other hand, 1-MCP did not affect weight loss in oranges (Porat *et al*. 1999) and mangoes (Hofman *et al.* 2001).

4.3. Chlorophyll degradation and colour changes

1-methylcyclopropene prevents or delays chlorophyll degradation and various types of colour changes in a wide range of crop species. 1-methylcyclopropene significantly delayed the development of peel colour in bananas. Fruits treated with 1-MCP at 62.5 125 and 250 ppb reached the full yellow colour (colour score 7) after 13, 17 and 20 days later, compared with the untreated fruits, respectively (Saeed and Abu-Goukh 2013). Similar delay in peel colour development was reported in mangoes (Elzubeir 2012). Degreening of 'Fuji' apples was inhibited by 1-MCP (Fan and Mattheis 1999), while 1-MCP-treated 'Red Chief' apples had a greener background colour than untreated fruits. Chlorophyll fluorescence measurements indicated that loss of chloroplast function was largely independent of ethylene (Mir *et al*. 2001). In apricots 1-MCP-treated fruits were greener and exhibited less colour change than untreated controls (Fan *et al*. 2000). This was also found to be true in peaches (Kluge and Jacomino 2002). Other researchers found that apricot and plum colour changes were not affected by 1-MCP (Dong *et al*. 2002).

Degreening of orange (*Citrus sinensis*) was blocked by 1-MCP and stimulated by exogenous ethylene (Porat *et al*. 1999). In lime (*Citrus auratifolia*) application of 1-MCP conserved the colour of stored fruits at 10ºC (Jomori *et al*. 2003). However, degreening was not affected by 1-MCP in 'Oroblanco', a pummelo-grapefruit hybrid (Porat *et al*. 2001).
1-methylcyclopropene delayed green colour loss in guava fruits (Bassetto *et al*. 2005) and skin colour change in avocado (Feng *et al.* 2000; Jeong *et al*. 2001). After 4 weeks storage, avocado fruits treated with 1-MCP were greener (as rated by eye) than untreated fruits. In addition, there was less fruit to fruit variability in colour. 1-methylcyclopropene treated fruits tend to be lighter, more vivid and greener than untreated fruits when measured by Minolta chromameter (Woolf *et al*. 2005).

1-methylcyclopropene has been shown to greatly delay red colour development of tomato fruits (Huber *et al*. 2003). Fruits treated with 250, 500 and 1000 ml/l of 1-MCP showed degradation of chlorophyll and expression of carotenoids after 6-7, 8-9 and 10-11 days, respectively, of 1-MCP application. At the end of the storage period, control fruits contained 190% more total carotenoids than fruits treated with 1000 ml/l of 1-MCP (Moretti *et al*. 2002). 1-methylcyclopropene has been reported to cause a reduction of anthocyanine content and phenylalanine ammonia-lyase (PAL) activity, which catalyzes the first step of anthocyanine biosynthesis in strawberries (Jiang *et al*. 2001b). When bananas treated with 1-MCP were subsequently treated with propylene, degreening was delayed and fruit had a patchy, uneven colour (Golding *et al*. 1998). Harris *et al.* (2000) also found that bananas treated with 1-MCP did not have commercially acceptable colour development.

1-methylcyclopropene delayed chlorophyll degradation in coriander, when ethylene was present (Jiang *et al*. 2002) and prevented broccoli yellowing, both with and without exogenous ethylene (Fan and Mattheis 2000a).

4.4. Flesh firmness and softening

1-methylcyclopropene delayed fruit softening in most fruits, while some crop species were not affected. 1-methylcyclopropene application retarded softening in banana fruit (Jiang *et al*. 1999a; Saeed and Abu-Goukh 2013), 'Ginger Gold' apple (Fan *et al*. 1999a), peach (Kluge and

Jacomino 2002), nectarine (Dong *et al*. 2001a), apricot (Fan *et al*. 2000), plum (Dong *et al*. 2001b), mango (Hofman *et al*. 2001: Elzubeir 2012), papaya and custard apple (Hofman *et al*. 2001), guava (Bassetto *et al*. 2005) and tomato (Moretti *et al*. 2002). Firmness of tomato fruits treatment with 1000 ml/l 1-MCP was about 88% higher than control fruits after 17 days at 20±1°C and 85-95% relative humidity (Moretti *et al*. 2002). Apples maintained firmness after 1-MCP treatment (Fan *et al*. 1999a; Watkins *et al*. 2000; Mir *et al*. 2001). 1-methylcyclopropene treatment maintained apple firmness better than controlled atmosphere (CA) storage (Mir *et al*. 2001). Watkins *et al*. (2000) found that the combination of 1-MCP and CA was better than either alone.

Avocado fruits treated with 500 nL/L 1-MCP were firmer than fruits treated with 100 nL/L 1-MCP and all 1-MCP treated fruits were firmer than untreated controls (Woolf *et al*. 2005). Flesh firmness was delayed without negative impacts on the qualitative or quantitative aroma composition of the fruits (Pelayo *et al*. 2003; Saeed and Abu-Goukh 2012). After cold storage, 1-MCP did not allow nectarines to ripen normally, compared with ethylene-treated fruits, which softened normally (Dong *et al*. 2001a).

Orange softening was not affected by 1-MCP or ethylene (Porat *et al.* 1999). No firmness difference was detected between fruits treated with ethylene alone or 1-MCP with ethylene-treatment in strawberry fruits (Tian *et a*l. 2000). Jiang *et al*. (2001b) found that 1-MCP maintained strawberry fruit firmness.

More detailed examinations of fruit softening showed that polygalacturonase (PG) and cellulase activities were lowered by 1-MCP, but the activities of both enzymes were still present and avocado fruit ripened and softened normally (Feng *et al*. 2000). Jeong *et al*. (2001) found that PG activity was completely suppressed for up to 10 days, indicating that softening can occur without PG activity in avocado. Pectinesterase (PE) activity was delayed in 1-MCP-treated avocado fruits, compared with the control, but followed a similar pattern (Jeong *et al*. 2001). In plums exo-PG and endo-glucanase were lower in 1-MCP-treated fruits when compared with the untreated fruits, while pectin-esterase and endo-PG were similar (Dong *et al.* 2001b).

4.5. Total soluble solids

The effects of 1-MCP on soluble solids content have been studied in different fruit crops. Soluble solids were higher in 1-MCP-treated papaya (Hofman *et al*. 2001) and apple (Fan *et al.* 1999a). However, soluble solids were reduced in 1-MCP-treated strawberries (Tian *et al*. 2000), bananas (Saeed and Abu-Goukh 2013) and mangoes (Elzubeir 2012). Fan *et al.* (1999a) showed that soluble solids were higher in 1-MCP treated 'Delicious' and 'Fuji' apples, but were not affected in 'Ginger Gold', 'Gala' and 'Jonagold' apples. Soluble solids were also unaffected by 1-MCP in oranges (Porat *et al.* 1999), apricots, plums (Dong *et al*. 2002) and custard apples (Hofman *et al*. 2001). Control and 1-MCP treated tomato fruits had similar total soluble solids content during the entire experiment, but between 8 and 11 days after 1-MCP application, control fruits had a significant increase in total soluble solids (> than 4.0°Brix). Fruits treated with 1-MCP had average total soluble solids content of 3.80, but by the end of the storage period, there were no significant differences in soluble solids for all treatments (Moretti *et al*. 2002).

4.6. Titratable acidity

Titratable acidity was higher in 1-MCP-treated plum fruits stored at 20°C or 0°C for 10 days and subsequently transferred to 20°C (Manganaris *et al*. 2007). Similar results were reported in 1-MCP treated apples (Fan *et al*. 1999a), mango (Elzubeir 2012) and lettuce (Fan and Mattheis 2000b). On the other hand, titratable acidity was found not to be affected by 1-MCP treatment in tomato (Moretti *et al*. 2002) and citrus fruits (Porat *et al*. 1999).

4.7. Ascorbic acid content

1-methylcyclopropene treatment decreases or delays the loss in ascorbic acid content in banana (Saeed and Abu-Goukh 2013), mango (Elzubeir 2012), and broccoli (Fan and Mattheis 2000a). Ascorbic acid concentration was not influenced by 1-MCP in guava fruits (Bassetto *et al*. 2005).

5. Conditions for 1-MCP treatment

The response of the fruit to 1-MCP depends upon a number of variables. These include: cultivar, maturity, concentration, temperature, duration of exposure, application technique, and storage environment (Beaudry 2001; Pelayo *et al.* 2003).

5.1. Temperature

In most studies, 1-MCP has been applied at temperatures ranging from (20° to 25°C). Lower temperatures have been used, but a relationship exists between concentration, application time and temperature. Applications at low temperatures are not effective on some crops. In coriander (*Coriandrum sativum*), 1-MCP was not effective at low temperatures (5-10°C), presumably due to low sensitivity to ethylene (Jiang *et al.* 2002). In broccoli (*Brassica oleracea*), 1-MCP application produced better results in preventing yellowing and rotting at 20°C than at 5°C, but an effect occurred at both temperatures (Able *et al.* 2002). In apples, a given concentration of 1-MCP had less effect on firmness as storage temperature was lowered (Mir *et al.* 2001) and it was hypothesized that lower temperatures might lower the affinity of the binding site for 1-MCP. A relationship was noted between treatment time and temperature, apples at 3°C required 9 hours treatment, whereas only 6 hours treatment was needed at higher temperatures to delay ripening (DeEll *et al.* 2002).

5.2. Concentration

Effective concentrations of 1-MCP vary widely with commodity, and with respect to time of treatment, temperature and method of application. Inconsistencies in EthylBloc® powder that occurred during the early years of production may account for some discrepancies. The minimum concentration required was 2.5 nL/L (ppb) on carnation, while in apples some studies showed 1µL/L (ppm) was required to block ethylene action (Sisler *et al.* 1996a; Fan *et al*. 1999a). Concentrations between 1and 12 µL/L were effective in blocking ethylene action in broccoli (Fan and Mattheis 2000a; Able *et al*. 2002). In tomato 7 nL/L of 1-MCP blocked the green to red colour change for 8 days (Sisler *et al.* 1996b). Higher concentrations of 1-MCP (0.1-100 µL/L) for short durations (2 h) were effective on green tomatoes (Wills and Ku 2002), with at least 20 µl/l required to increase post-harvest life of ripe tomatoes. While 5 and 50 nl/l had no effect on unripe bananas, 500 nL/L delayed ripening (Harris *et al.* 2000), which is in contrast to Sisler *et al.* (1996b), who reported that only 0.7 nL/L was effective. Saeed and Abu-Goukh (2013) reported that 1-

MCP at 62.5, 125 and 250 ppb delayed banana fruit ripening by 12, 16 and 20 days, respectively, compared with the untreated fruits. Avocado fruits treated with 500 nL/L 1-MCP were firmer than fruits treated with 100 nl/l and all 1-MCP treated fruits were firmer than untreated control fruits (Woolf *et al*. 2005). Similar results were reported in mango (Elzubeir 2012). Sisler *et al.* (1996a) noted that 250-300 nL/L of 1-MCP for 5 min were as effective on carnation as 0.5 nL/L for 24 hours. Two applications of 100 nL/L were found to be more beneficial in reducing ethylene-induced mesocarp discolouration in avocado than just one application (Pesis *et al.* 2002). Multiple applications of 1-MCP during storage of 'Red Chief' apples were more effective at higher temperatures than at 0°C (Mir *et al.* 2001). However, multiple applications of 1-MCP to broccoli had no more experimental effect than one application (Able *et al.* 2002).

5.3. Treatment duration

In most studies, treatment duration ranged from 12 to 24 h achieve a full response. An exposure of 6 h at 0.45 µL/L was not enough to induce respiratory or ethylene production changes in avocado (Jeong *et al.* 2001). A time/temperature relationship was noted with banana (Jiang *et al.* 1999b), such that higher concentrations of 1-MCP were required for shorter treatment times. Cultivar should also be considered. ‘Empire’ apples required less treatment time than ‘Cortland’ to achieve the same effect at the same 1-MCP concentration (DeEll *et al.* 2002). Avocado fruits treated with 100 nL/L for 6 hours ripened more quickly than fruits treated for 12 and 24 hours (6.4, 7.2 and 7.1 days, respectively). Duration of treatment did not influence ripening rate of fruits treated with 500 nL/L (Woolf *et al*. 2005).

5.4. Developmental Stage and Plant Maturity

Plant developmental stage must be considered when applying 1-MCP as effects vary with plant maturity. 1-methylcyclopropene effects in apricot decreased with advanced fruit development (Fan *et al.* 2000). A leafy brassica was found to respond less to 1-MCP than a floral brassica, possibly due to different ages of leaves and inherent differences between flowers and leaves (Able *et al*. 2002). Banana maturity was a major factor in the response of the fruit to 1-MCP (Harris *et al*. 2000). Because commercial lots of bananas can have a range of maturity, 1-MCP treatment would likely result in ‘mixed’ lots of fruit. In the 'Red Chief' strain of ‘Delicious’ apples advanced maturity slightly decreased the effect of 1-MCP (Mir *et al*. 2001).

The time from harvest to 1-MCP treatment varies with the crop species, generally the more perishable the crop, the more quickly after harvest 1-MCP should be applied. 1-methylcyclopropene must be applied as soon as possible after harvest to broccoli and pak choy (*Brassica rapa*) (Able *et al*. 2002). In bananas treated with ethylene, fruit had to be treated with 1-MCP within 24 h to delay ripening (Jiang *et al.* 1999b). Ethylene production, softening, and internal browning in ripening apricots and plums were inhibited when fruits were treated with 1-MCP after storage, but not before storage (Dong *et al.* 2002).

6. Future research

As the effects of 1-MCP are not readily reversible by exposure of ethylene, treatments must be applied in such a way that the fruit ripen normally after a period of transit or storage. The rate at which the fruit regains ethylene sensitivity is dependent on many variables. These include: commodity, cultivar, maturity, concentration of 1-MCP, temperature, duration of exposure, application technique and storage environment. 1-methylcyclopropene had been used only very recently in Sudan, and only two studies were carried out, one on ‘Grand Nain’ bananas (Saeed and Abu-Goukh 2013) and the other on ‘Kitchner’ and ‘Abu-Samaka’ mango cultivars (Elzubeir 2012). All the variables that affect the rate at which the fruit regains ethylene sensitivity should be investigated on the major exportable fruits that require effective delay in fruit ripening.

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