



## Review

# Effects of Ethylene and 1-Methylcyclopropene on the Quality of Sweet Potato Roots during Storage: A Review

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**Abstract:** Sweet potato (*Ipomoea batatas* (L.) Lam.) is served as an important root crop worldwide due to its high yield, strong adaptability and nutrient richness. Sweet potato has played a significant role in ensuring food security and family income opportunities for local populations in China for years of experience. The storage roots, which provide abundant nutrition and health benefits to people, are the mainly harvested and consumed parts of sweet potato. However, after harvest, physiological disorders, such as sprouting, mechanical injury and infectious postharvest diseases, increase the magnitude of sweet potato root quality decline and nutritional compound losses. Ethylene and 1-methylcyclopropene (1-MCP) were considered to be effective commercial treatments in sweet potato postharvest. Exogenous ethylene and 1-MCP treatment could successfully inhibit root sprouts and reduce rot decay without affecting the storage quality of sweet potato. This review aims to summarize the latest available information on the effects of ethylene and 1-MCP with respect to enhancing or impairing sweet potato root quality. A better understanding of the influence of ethylene and 1-MCP on root quality parameters will be useful to further explore the role and mechanisms of action of ethylene in regulating the postharvest storage of sweet potato roots and contributions to technological development and innovation.

**Keywords:** *Ipomoea batatas*; postharvest; sprouting; curing; rot



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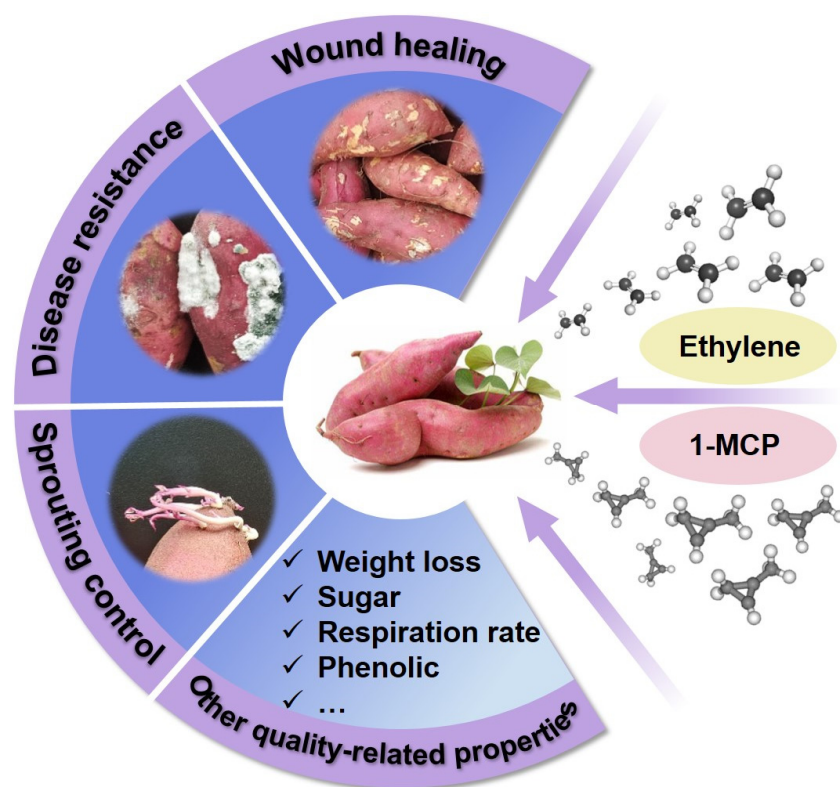
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## 1. Introduction

Sweet potato (*Ipomoea batatas* (L.) Lam.) is one of the most significant root crops, used worldwide as a traditional major food source, animal feed and industrial raw material, with numerous agronomic and nutritional advantages [1,2]. As a good source of carbohydrates, carotenoids, dietary fiber, anthocyanin and other nutrients for people, sweet potato is consumed in large quantities in China [3–5]. The nutrients with various antioxidants, anti-inflammatory, anti-diabetic, anti-hypotensive properties and specific anti-cancer bioactivities play an active role in promoting health and protecting the human body from diseases [6–8]. China is the leading producer of sweet potato at the global level, accounting for about 54.74% (FAOSTAT, 2020) of the world production [9]. Sweet potato production can be a source of income for most rural and peri-urban growers in most developing countries. Although numerous benefits can be obtained from the crop, postharvest losses make its production unprofitable in most parts of the world. On average, in China, 20 to 30% percent is lost in sweet potatoes during storage after harvest. These losses affect food security and nutritional health and have negative financial impacts on both consumers and farmers.

Long-term storage of sweet potato roots allows year-round availability of the crop but induces various physicochemical changes. During storage, the shelf-life of sweet potato

roots varies from a few days to months, depending on the cultivar and storage conditions. Deterioration in postharvest quality of sweet potato roots can be attributed to sprout growth, postharvest wounding, microbial attack and loss of nutritional properties (Figure 1) [10,11]. When offering the right conditions, sweet potato roots, which are dormant crops, tend to sprout after a short dormancy period. The appearance of sprouts promotes the wilting of sweet potato roots, leading to a decrease in nutritional value and causing pathogens to invade from the long germs. Freshly harvested sweet potato roots have a thin, delicate skin that is easily mechanically damaged by rough handling during harvest. The roots are particularly perishable during storage because of their high moisture content (50–80%), resulting in low mechanical strength, making damage occurrence likely during harvest and with high susceptibility to microbial decomposition. Root decay results from wound-induced fungal infections when the temperature and humidity are appropriate for fungal growth in storage. Root rot leads to a reduction in nutritional properties. The accumulation of toxins in the root caused by rot during storage should also be considered as it poses a serious threat to human health when consumed. On the other hand, a high respiratory rate produces heat and softens the textures, making them vulnerable to harm. A high rate of respiration also leads to weight loss and a reduction in nutritional quality, including sugar, phenolic, carotenoids and other nutrients [12]. Extending root dormancy, reducing root damage and decay and maintaining nutritional properties are the most important aspects for sweet potato utilization, storage, processing and marketing.



**Figure 1.** Main changes in the deterioration in postharvest quality of sweet potato roots under exogenous application of ethylene and 1-methylcyclopropene (1-MCP).

Maintaining the quality of sweet potato roots over a long period of storage is challenging, especially for large-volume growers. There are several options currently available for the management of postharvest in commercial sweet potato industries. Physical environmental regulation has generally been conducted through the manipulation of storage temperature and relative humidity [13]. The ideal storage conditions for sweet potato roots are at a temperature of 13–16 °C and a relative humidity of 80–95% [14,15]. However, sweet potato roots are much more sensitive to chilling injury, and cold storage facilities are

difficult to promote due to high energy consumption and high financial costs for growers. On the other hand, fungicides are usually applied in industrial operation after harvest to improve the root qualities. In general, fungicide may be applied by dipping the root in a chemical suspension tank, utilizing a waterfall application or spraying the fungicide alone or combined in a wax solution as the sweet potatoes pass over a brush roller conveyor. Although synthetic sprout inhibitors and fungicides (such as CIPC) are effective in maintaining quality during storage, the use of chemicals causes environmental pollution, and the chemical residues have a harmful influence on human health [16].

Ethylene ( $C_2H_4$ ) is the key endogenous plant hormone involved in plant development, maturation and rotting, which is closely related to postharvest quality maintenance in storage [17,18]. Crops produce ethylene while in storage, and pathogen attack, chilling and wounding also encourage the formation of ethylene in damaged crops. As an ethylene inhibitor, 1-MCP protects crops from both internal and external sources of ethylene and preserves the quality of fresh produce during storage [19]. In recent years, the important role of ethylene and 1-MCP has been noticed in sweet potato storage as secure, non-toxic green preservatives. Compared to the conventional technologies, ethylene and 1-MCP have the advantages of non-toxicity, good chemical stability, easy synthesis, negligible residue and low use concentration in postharvest of sweet potatoes. However, high exposures of ethylene or 1-MCP could cause root proximal disease, increased respiration rate, excessive weight loss and lower sugar content. These biological responses depend on the root sensitivity to ethylene. The responses of roots to different ethylene concentrations vary significantly with cultivars. Different treatment concentrations should be tested in advance between cultivars before use. Despite several disadvantages, since the correct application dosage is determined, using ethylene and 1-MCP is more effective, less expensive and safer than conventional technologies.

Several previous studies investigated the responses of sweet potato roots to ethylene using exogenous ethylene as well as ethylene-binding inhibitors such as 1-methylcyclopropene (1-MCP). Sweet potato has low ethylene sensitivity and produces very little ethylene during storage, which is typically considered as a non-respiratory, non-climacteric root [20,21]. However, according to another study, sweet potatoes were classified as climacteric roots due to their strong respiration after harvest [22]. The respiration type of sweet potato may vary depending on the cultivars, which needs further study and determination. Dipping in ethephon, continuous exposure to ethylene gas flow or 24 h exposure to 1-MCP effectively increased the commercial life of sweet potato roots. The effects of ethylene and 1-MCP on sweet potato postharvest are associated with respiratory rate variation, loss of water, sugar and phenolic accumulation, reactive oxygen species formation, phytoalexin protein production and interaction between phytohormones. Transcriptomic analysis has recently been employed to comprehend the mechanisms of ethylene-induced sprouting in onions [23]. The specific transcriptional responses to exogenous ethylene application in potatoes were revealed via RNA sequencing analysis [24]. Furthermore, the molecular changes associated with curing [25], carvone-treated sprouting [26], cold storage [27,28] and root development [29] in sweet potato roots were studied using RNA sequencing. The use of transcriptomic analysis may, thus, reveal molecular mechanisms involved in specific biological processes during ethylene and 1-MCP treatment.

Exogenous ethylene and 1-MCP treatment showed effective results in sprouting control, wound curing, disease resistance and maintenance of nutritional properties to maintain the postharvest storage quality of sweet potatoes (Figure 1). However, studies on the impacts of ethylene and 1-MCP on sweet potato root quality during storage are not available, and further studies are required to evaluate the parameters of sprout control, disease resistance and nutrition loss. In this review, we discuss the potential effects of ethylene and 1-MCP on the storage quality of sweet potato roots. A detailed overview of sprout growth, root decay, wound healing and other disorders, including weight loss, respiration rates and nutritional properties variation, is also provided in the review.

## 2. Effects of Ethylene and 1-Methylcyclopropene (1-MCP) on Sprouting Control of Sweet Potato Roots

Sprouting is nature's way of passing on the genome of the plant. Seeds begin to sprout and develop into the same plant as the seed through the process of sprouting. Under normal storage conditions, sweet potatoes are intended to sprout after a short dormancy period (about 2–4 weeks) [30]. Sprouting during storage depletes nutrients, which reduces the quality of the roots. Additionally, the longer sprouts and young leaves of sprouted sweet potato may carry bacteria or other pathogens. Although sprouted sweet potato is tender enough and generally safe to eat with no toxicity, people avoid eating them this way to prevent early sprouting.

Exogenous ethylene and 1-MCP have both been used for years in Western countries as green chemicals to suppress sprout growth of root crops, including potatoes, ginger, yams and onions, during storage. The application of ethylene and 1-MCP has been widely reported to control sprouting in stored potatoes [31,32]. Moreover,  $1 \mu\text{L L}^{-1}$  1-MCP significantly suppressed the sprouting of ginger rhizomes, reduced the accumulation of reactive oxygen species (ROS) and maintained quality at room temperature storage [33]. The sprouting inhibition of onion bulbs can be achieved when treated with  $10 \mu\text{L L}^{-1}$  ethylene or  $1 \mu\text{L L}^{-1}$  1-MCP, respectively, for as little as 24 h [34]. Just as in other root crops, 24 h exposure of sweet potato roots (cultivars 'Bushbuck' and 'Ibees') to  $625 \text{ nL L}^{-1}$  1-MCP or continuous  $10 \mu\text{L L}^{-1}$  ethylene inhibited sprout growth over 4 weeks of storage at  $25^\circ\text{C}$  [35]. In another study, continuous exogenous ethylene ( $10 \mu\text{L L}^{-1}$ ) or 24 h 1-MCP ( $1 \mu\text{L L}^{-1}$ ) treatment suppressed sprouting and the dark cooked color of 'Owairaka Red' sweet potato roots stored at  $25^\circ\text{C}$  and 85% RH for 4 weeks [36]. Similarly, control of sprouting was observed in sweet potato cultivar 'Covington' stored under continuous ethylene ( $10 \mu\text{L L}^{-1}$ ) during long-term storage at  $25^\circ\text{C}$  [37]. Application of 1-MCP ( $1 \mu\text{L L}^{-1}$ ) for 24 h also significantly inhibited sprout growth in 'Covington' roots [20]. However, sprouting of sweet potato cultivar 'Evangeline' decreased in response to 1-MCP ( $1\text{--}2 \mu\text{L L}^{-1}$ ) application in three of four experiments, while 'Beauregard' sprouting decreased in two of four experiments, which provides the first evidence of the variable effect of 1-MCP on different sweet potato cultivars [38]. The sprouting control abilities of 1-MCP may depend on cultivars.

According to previous studies,  $1 \mu\text{L L}^{-1}$  1-MCP applied for 24 h with continuous  $10 \mu\text{L L}^{-1}$  ethylene treatment is the most commonly used and most effective method to inhibit sprout growth in sweet potato roots. In general, continuous ethylene gas flow with air was applied, and 1-MCP solution was prepared using commercial tablets with fans to ensure even distribution. Sweet potato roots were exposed to the treatments in the sealed storage boxes at room temperature. Energy through sugar metabolism was used in sprouting control because the sugar concentration was reduced after 1-MCP and ethylene treatment [35]. Although ethylene increased root respiration, sprout growth was significantly suppressed. 1-MCP inhibited this increase in respiration rate and presumably counteracted the ethylene stimulation of this process. The observations that both ethylene on its own and 1-MCP inhibit sprout growth suggest that while continuous exogenous ethylene exposure inhibits sprout growth, ethylene is also essential for sprouting. Low concentrations of ethylene are necessary to break the dormancy in sweet potato roots, while high ethylene concentrations applied continuously inhibit sprouting. No sprout growth was observed when 1-MCP was applied, suggesting that ethylene production was inhibited by 1-MCP and remained dormant [35,39]. Dormancy of root crops is controlled by phytohormones, such as ethylene, ABA, cytokinins, gibberellins and auxin, in bud breaking and sprout growth. However, fewer studies were found on other phytohormones, except ethylene in sweet potato root. Reactive oxygen species (ROS) including hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) are also involved in breaking dormancy in root crops by affecting cellular balance or regulating the expression of genes involved in dormancy. The mechanism of ROS in the control of sprouting in sweet potato roots has been little explored.



### 3. Effects of Ethylene and 1-Methylcyclopropene (1-MCP) on Disease Resistance of Sweet Potato Roots

Sweet potato is susceptible to a variety of field and storage diseases. To date, postharvest diseases account for the majority of losses in stored sweet potato, severely restricting their production and commercialization. The high moisture content (50–80%) of sweet potato roots makes them highly perishable after harvest. Freshly harvested sweet potato roots generally have a thin, mechanically weak skin outside of the starchy flesh [40]. Pathogenic fungi are produced as a result of mechanical injuries and natural openings on the surface of the roots during harvest and handling. The infected roots begin to show discoloration, foul odor, textural changes or grow visible contaminations, which ultimately leads to decay [41].

Postharvest diseases of sweet potato roots can be attributed to several forms of pathogenic microorganism infections (fungi, bacteria or viruses), the majority of which are caused by fungi. The most important postharvest diseases caused by fungi mainly include soft rot (*Rhizopus stolonifer* [42], *Rhizopus oryzae* [41] and *Rhizopus nigricans* [41]), sclerotium rot (*Sclerotium rolfsii* [43]), foot rot (*Plenodomus destruens* [44]), black rot (*Ceratocystis fimbriata* [45,46]), white rot (*Globisporangium ultimum* [47]) and fusarium root rot (*Fusarium solani* [48,49]). These pathogens frequently infect sweet potato roots immediately after harvest or during storage and transport. They enter through natural plant openings and small wounds caused by insects or tools used in harvesting and transportation. Pathogens become more active, multiply rapidly and cause infections when the environment is favorable. Less air circulation, high relative humidity and warm temperature conditions combine to favor the growth of fungi [41].

Management of sweet potato postharvest diseases using synthetic fungicides is believed to increase environmental pollution and health hazards of worldwide concern. For this reason, the development of alternative methods, such as natural plant-derived products [45,46], GRAS (generally recognized as safe) compounds [48] and microbial antagonists [50], have been actively demonstrated to be most suitable to replace the synthetic fungicides. Ethylene, a naturally occurring plant hormone, increased the resistance of sweet potato against black rot in an earlier study [51]. However, in other studies, ethylene treatment promoted root proximal rot incidence in sweet potato cultivars 'Beauregard', 'Covington' and 'Chuanshanzi' during long-term storage [37,52,53]. Ethylene-induced decay predominantly initiates from the proximal region, where root splitting also occurred. End root splitting caused by ethylene treatment may increase the incidence of disease and lead to proximal rot in sweet potatoes. 1-MCP was normally evaluated in the context of its antagonistic response to ethylene. Previous work showed that 1-MCP effectively inhibited root decay in stored sweet potato roots. Application of  $1 \mu\text{L L}^{-1}$  1-MCP achieved a 10% lower incidence of rot symptoms compared to the control in 'Beauregard' and 'Evangeline' roots up to 133 days [54]. 'Bushbuck' and 'Ibees' treated with 1-MCP ( $625 \text{ nL L}^{-1}$ , 24 h) showed no disease when stored at  $25^\circ\text{C}$  for 4 weeks [35]. Root decay was also significantly reduced in 'Covington' roots by  $1 \mu\text{L L}^{-1}$  1-MCP for 24 h in 120 days [54].

Ethylene treatment usually increases disease development, simply through its acceleration of ripening or senescence. According to previous studies, ethylene increased disease in most sweet potato root cultivars. Several observations, however, indicate that when ethylene is applied before inoculation with a pathogen, it decreases or has no effect on disease development, but disease development is accelerated when plants are treated with ethylene after infection. The timing of ethylene exposure of root crops can influence whether resistance is promoted or suppressed. Ethylene can produce phytoalexins as pathogenesis-related proteins and rigidify cell walls in the induced systemic resistance of plants. Priming of defense-related genes ISR (induced systemic resistance) and pathogenesis related proteins SAR (systemic acquired resistance) requires the presence of a functional *NPR1* protein, triggered by ethylene receptor genes *etr1* and *ein2* in *Arabidopsis* [55]. 1-MCP treatment tended to maintain root quality and reduce disease development in most studies. The strongest effect of 1-MCP occurred when roots were harvested soon after treatment.

Application of 1-MCP immediately after harvest on the root crops is crucial for disease control [54,56]. The possible disease resistance mechanism after ethylene and 1-MCP treatment needs further study in sweet potato roots.

#### **4. Effects of Ethylene and 1-Methylcyclopropene (1-MCP) on Wound Healing of Sweet Potato Roots**

Some root, tuber and bulb vegetables, such as garlic, onions, potatoes and sweet potatoes, need to be cured prior to long-term storage. Following field drying, sorting and crating, within 1–2 h after harvest, sweet potato roots were cured in a controlled room in order to promote the healing of wounds acquired during harvest and handling. Curing, as a low-cost postharvest technique, allows skins to harden, wounds to heal and some of the starches to convert to sugars, which helps the tubers store for months [57]. The curing of sweet potato roots includes optimizing three conditions: temperature, relative humidity and ventilation. The optimal curing conditions are 85–95 °F (29–35 °C) and 80–90% relative humidity for 3–7 days [58].

Curing takes longer (up to 3 weeks) if conditions are less than perfect, and it can differ between sweet potato cultivars. It has been previously documented that dry matter content of sweet potato roots and wound healing efficiency are closely related. Cultivars with low dry matter content exhibited a longer shelf-life and more effective wound healing in earlier studies that investigated 34 cultivars [59]. Furthermore, the association was supported by the results of experiments conducted with 17 cultivars from different regions of the world, whose dry matter content ranged from 17.9% to 31.2% [60]. However, ‘Apomuden’ (19%) and ‘Nane’ (27%), two cultivars with low and high dry matter content, showed no significant difference in their wound healing ability [61].

Mass spectroscopic analysis of the curing process revealed that the sweet potato surface cells were desiccated, followed by the lignification of the underlying cell layers, finally covering the skin [59,62]. As a new epidermal tissue, this formative lignified layer performs as a barrier against pathogenic organisms and prevents excessive moisture loss [60,63]. Generally, no chemicals are required during the curing process. Unfortunately, although maintaining proper curing conditions is helpful for maintaining root quality, the rate of sprouting and decay during long-term storage is still very high. It is necessary to develop and combine safe and reliable chemicals in the curing process to extend the storage time of sweet potato roots. The amount of ethylene produced by sweet potato in response to wounding (2–4 days after wounding) varies among cultivars, and they respond differently to ethylene treatments [64–66]. Ethylene is involved in lignification and wound periderm formation during sweet potato wound healing [67]. Moreover, the storage protein of sweet potato sporamin, as a wound response promoter, was effectively activated by ethylene [68]. In addition, when 1-MCP was combined with curing, root sprouting was effectively inhibited during the subsequent storage and the healing of wounds [53]. Further investigation is required to evaluate the effects of ethylene and 1-MCP treatment, which are frequently used in the storage period after curing to control sprouting. Their effects on sweet potato quality also need to be examined when applied in conjunction with curing.

#### **5. Effects of Ethylene and 1-Methylcyclopropene (1-MCP) on Other Quality-Related Properties of Sweet Potato Roots**

After harvest, the sweet potato roots stay metabolically active and perform all functions of living tissues. The primary goal of storage is to maintain root quality and ensure adequate supply throughout the year by minimizing both physiological disorders and disease development [69]. According to previous research, the proper storage conditions for high-quality roots are 55 °F (13 °C) and 85–90% relative humidity, with adequate ventilation. Physiological disorders and nutritional losses are related to improper storage conditions, such as excessive light, extreme temperature, low oxygen and unsuitable moisture [70]. The following quality-related properties discussed were the other main characteristics of sweet potato roots that may be affected after harvest when ethylene and 1-MCP were applied during storage (Table 1).

**Table 1.** The effects of ethylene and 1-methylcyclopropene (1-MCP) on quality-related properties in different sweet potato cultivars.

Cultivars	Storage Conditions	Applications	Treatments	Quality-Related Properties	Reference
Organic ‘Covington’ and Portuguese-derived ‘Covington’	Cold storage at 15 °C	Sprouting control and disease resistance	1-MCP (1 $\mu\text{L L}^{-1}$ , 24 h)	Reduced sprouting and decay, phenolic compounds; no effect on respiration rate and sugar, maintained saleable weight	Amoah et al., 2012 [20]
‘Covington’	Cured (30 °C, 90% relative humidity, 7 days) then stored at 25 °C	Sprouting control	Ethylene (10 $\mu\text{L L}^{-1}$ , applied continuously)	Reduced sugar, phenolic compounds and phytohormones (abscisic acid and zeatin riboside); suppressed sprout growth, doubled root respiration; increased weight loss and incidence of proximal rots	Amoah et al., 2016 [37]
‘Covington’	Cold storage at 15 °C	Disease resistance	1-MCP (1 $\mu\text{L L}^{-1}$ , 24 h)	Reduced decay, weight loss; no effect on respiration rate and carbohydrates	Amoah et al., 2018 [54]
‘Bushbuck’	25 °C in incubators	Sprouting control	1-MCP (625 nL $\text{L}^{-1}$ , 24 h)	Inhibited sprouting; reduced respiration rate, weight loss, sugar content (sucrose, glucose and fructose)	Cheema et al., 2010 [71]; Cheema et al., 2013 [35],
			Ethylene (10 ppm, applied continuously)	Inhibited sprouting; increased respiration rate (3-fold), weight loss (slightly), sucrose; reduced glucose and fructose	
‘Beijing 553’ and ‘Chuanshanzi’	Curing at 29 °C for 4 days, then stored at (13 $\pm$ 0.5) °C, 90% relative humidity	Sprouting control and disease resistance	0.045% 1-MCP cyclodextrin powder, 1.6 g/case	Improved wound healing; inhibited sprouting and decay; increased sugar content; decreased starch content, no color change	Cao et al., 2021 [53]
‘BRS Rubissol’	Curing at 30 °C and 90% relative humidity for 7 days, stored in chambers at 25 °C and 90% relative humidity	Sprouting control	1-MCP 1 mg·L <sup>−1</sup> in 90 L chamber for 24 h	Reduced sprouting, weight loss; increased dry matter content; processed fried chips showed less browning	Lima et al., 2021 [72]
			Ethylene 10 $\mu\text{L L}^{-1}$ in 90 L chamber for 48 h	Reduced sprouting, weight loss; increased dry matter content	
‘Owairaka Red’	Curing at 30 °C and 90% relative humidity for 4 days then stored at 25 °C and 85% relative humidity	Sprouting control	1-MCP (1 $\mu\text{L L}^{-1}$ , 24 h) and continuous ethylene (10 $\mu\text{L L}^{-1}$ )	Inhibited sprout growth; increased root respiration rates and weight loss; no color change after cook	Pankomera et al., 2016 [36]
			1-MCP (1 $\mu\text{L L}^{-1}$ , 24 h)	No significantly differ from the control	
			Ethylene (10 $\mu\text{L L}^{-1}$ , applied continuously)	Inhibited sprout growth; increased root respiration rates and weight loss; darken cooked flesh color	
‘Belle Vue’	Curing for 4 days (25–30 °C) then stored at 20 °C	Sprouting control	Ethylene (0.001 kPa, applied continuously) with controlled atmosphere	Reduced sprouting; increased phenolics contents, sugars, weight loss and respiration rates	Sowe et al., 2018 [73]
‘Beauregard’	Curing at 85 °F and 85% relative humidity for 5 days then stored at 60 °F and 75–85% relative humidity	Wound healing	Dipping 1 h in 1-MCP (1 ppm) or ethephon (2.6 mM)	Breakdown-related features on skin appeared after ethephon treatment, not detected in 1-MCP treated roots	Villordon et al., 2012 [74]

### 5.1. Weight Loss

During storage, high moisture content (50–80%) evaporates from the surface of sweet potato roots, resulting in weight loss and possible shriveling of the delicate skin, particularly at the root ends. Although microbial decay is the main postharvest loss in sweet potato, weight loss is considered the second most important factor for economic losses in the marketing of sweet potatoes [41,74]. Weight loss has frequently been used as a stability indicator for postharvest and shelf-life quality control [54]. There are conflicting reports regarding the role of exogenous ethylene and 1-MCP on the weight loss of sweet potato roots. After harvest, in most cases, 1-MCP treatments achieved lower weight loss in root storage [37]. Several studies indicated that ethylene treatments promote weight loss in cultivars ‘Covington’ [37,54], ‘Owairaka Red’ [36] and ‘Belle Vue’ [73]. Ethylene plus 1-MCP treatments increased the weight loss of ‘Owairaka Red’ [36], while in ‘Bushbuck’ and ‘Ibees’, weight loss was decreased by all the treatments, including 1-MCP, ethylene and ethylene plus 1-MCP, respectively [35]. Excessive weight loss was proved to be associated with moisture loss, which was accelerated by an increased respiration rate and undesirable

environmental impacts during storage [37]. In general, ethylene treatment increased the respiration rate and induced weight loss, but 1-MCP inhibited ethylene release and reduced the respiration rate of the roots. This effect may differ depending on the treated cultivars' breathing patterns. Cultivars with low respiratory rates may not show significant changes in respiration rate after treatment. Weight loss varies due to different degrees of evaporation caused by different treatment methods, such as gas application or dipping. In addition, the curing process and sprouting control reduced the loss of weight due to the decreased evaporation and respiration [35,72]. Decay caused by pathogen infections leads to moisture loss and aggravated weight loss [54].

### 5.2. Respiration Rate

Sweet potato, as an underground storage root vegetable, typically has relatively low respiration rates. However, sweet potato continues to breathe highly in storage to release energy through the breakdown of stored carbohydrates in the roots. Exposure of sweet potato to ethylene significantly boosted the respiration rates in the roots of different cultivars, including 'Covington', 'Owairaka Red', 'Bushbuck' and 'Belle Vue' [35–37,73]. Additionally, 1-MCP showed negative impacts on changing this effect when ethylene was present in 'Owairaka Red' [36]. In general, the respiration data distinctly demonstrated the inhibitory effect of 1-MCP on ethylene. 1-MCP reduced the respiration rates of 'Bushbuck' [35] at room temperature (25 °C) stored in incubators, whereas no evident effects were observed on the respiration rates of 'Covington' and 'Owairaka Red' stored at low temperature (15 °C) and room temperature (25 °C), respectively. Genetic characteristics are the most important contributing aspect to the respiration rate of sweet potato [75]. Because of the differences in breathing patterns, various cultivars displayed low or high respiration rates after treatments. Harsh circumstances, such as mechanical damage, disease infection and sprout growth, also accelerated the rate of root respiration in storage. The differences observed above in the experiments could be attributed to the various states of the roots during storage. High respiration rates frequently coincide with active metabolic activity and lead to a short storage life that lowers dry matter content and causes weight loss.

### 5.3. Sugar Content

Sweet potato is known to be high in carbohydrates. Sweet potato with high sugar concentrations results in higher quality for processing. Consumer acceptability and preferences for sugar concentrations may vary regionally. Generally, people prefer low sugar concentrations when sweet potato is consumed as a staple food, whereas in the UK or US, sweet potato with high sugar concentrations is preferred. Carbohydrate macromolecules such as starch are converted into simple sugars, including sucrose, glucose and fructose, during sweet potato storage [71]. Transport and accumulation of these sugars are the sources of energy needed for root physiological metabolism and sprout growth. Conflicting data exist on the role of endogenous ethylene and 1-MCP in terms of maintaining sugar levels. In the roots of 'Covington' and 'Bushbuck', the concentration of monosaccharides was reduced by ethylene treatment [35,37]. 1-MCP decreased the amount of sucrose, glucose and fructose in 'Bushbuck' but had no effect on the sugars in 'Covington' [54,71]. Ethylene, on the other hand, increased the sugar content in 'Belle Vue' [73] and 'BRS Rubissol' [73]. 1-MCP improved the sugar content in 'Chuanshanzi' [53] and 'BRS Rubissol' [73]. In general, ethylene promotes respiration, evaporation and sugar hydrolysis, while 1-MCP inhibits ethylene production and increases sugar content. The difference in treatment results may also be related to the sugar content in various cultivars. Cultivars with high sugar content showed no significant changes following treatment. Differences in sugar determination methodologies could also potentially contribute to such variations.

### 5.4. Phenolic Compounds

Sweet potato roots contain high levels of phenolic compounds, especially chlorogenic acids. 1-MCP reduced phenolic levels in 'Covington' roots but increased the accumulation



of phenolic compounds in the proximal ends [38]. Phenolic compounds were unevenly distributed in sweet potato roots. Higher concentrations of phenolic compounds were observed in the proximal sections of the roots, while lower concentrations were in the middle sections [38,76]. The presence of phenolic compounds was related to protection against disease and is involved in anti-resistance responses in other crops. Higher phenolic compounds in the proximal ends after 1-MCP treatment may be one of the reasons for its reduction in pathogenic attack. Since root decay and sprout growth usually tend to occur at the proximal ends of sweet potato roots, it may be possible to explore how these processes relate to the content of enriched phenolic compounds after 1-MCP treatment. Ethylene was found to decrease phenolic compounds in 'Covington' roots [37] but increase the phenolic content in 'Belle Vue' roots [73]. The conflicting results may be related to differences between cultivars and measurement methods. The phenolic content in the proximal ends needs further observation in ethylene treatment experiments, which helps to reveal the relationship of sprouting, end rotting and phenolic compounds.

## 6. Conclusions and Future Perspectives

Sweet potato has a short maturity period (3–5 months), drought tolerance and wide ecological adaptation with nutritional and economic value for growers and consumers in different regions of the world. Traditionally, keeping the roots in long-term storage provides a continuous food supply in the diet season when the staple crops are exhausted. The difficulties in long-term storage of sweet potato, including sprouting control, disease resistance and nutritional properties loss, pose a major challenge for extending the shelf life and improving the quality of the roots. The potential of ethylene and 1-methylcyclopropene (1-MCP) to maintain the postharvest storage quality of sweet potato has been previously observed and studied by researchers. In this review, one of the focuses was to investigate the differences between various cultivars when applying ethylene and 1-MCP. Although ethylene and 1-MCP were effective in preventing sprouting, wounding and decay during storage, their effects varied significantly depending on the cultivars and application technologies. The influence of ethylene and 1-MCP on sweet potato postharvest quality needs to be discussed separately for each cultivar to elucidate the significance of ethylene. These differing effects might be related to the ethylene sensitivity variations of cultivars by themselves. In part, investigating the trend of respiration rate and the amount of ethylene released after harvest is a useful tool to observe ethylene sensitivity in each cultivar. Furthermore, application technologies, which lead to variable ethylene reactions in the same cultivar, might play a role. Sweet potato roots are highly perishable; technologies that are simple to use, consume less and maintain root quality are highly desirable.

Additionally, attention should also be paid to the molecular mechanisms underlying the effects of ethylene and 1-MCP in the storage roots of sweet potato roots. From previous studies trying to discuss the relationships between ethylene and some of the physiological indicators, such as respiration rate changes, weight loss and variations in sugar and phenolic content, the molecular mechanism behind them is still unclear. Physiological changes are regulated by gene expressions, and using molecular techniques to reveal the important role of ethylene in sweet potato postharvest is also critical. Low levels of ethylene are necessary for sprouting but, when applied at high levels, ethylene showed an inhibition effect on sprouting. 1-MCP suppressed sprouting and produced lower levels of ethylene in the root. This suggests that ethylene and 1-MCP regulated sprouting in different ways. Further studies are needed to understand the interactions between the multiple ethylene-related genes involved in sprouting. For disease resistance, ethylene induces resistance when applied before infection, whereas increased decay when applied during infection or after symptoms. The dual action of ethylene is that it sometimes acts as a pathogenic factor and sometimes as a virulence factor for pathogens. This implies that ethylene-regulated resistance responses depend on the spatial connections of numerous signals interacting in the network type. Previous evidence suggests that study of this network is becoming available through transcriptome analyses, indicating that the interaction of

various regulatory components controls numerous genes in complex ways. Future detailed analyses of the underlying molecular regulatory networks under the treatments should aid in further improving root quality in storage. As mentioned earlier, sweet potato is a good source of numerous balanced nutrients and health-promoting phytochemicals. Thus, more emphasis should be placed on studying the connections between storage characteristics and the internal nutritional compounds of the roots, which helps to illuminate the molecular mechanisms behind them. Furthermore, extensive research is also needed to develop green and ethylene-related preservatives in order to prolong the storage of sweet potato roots.

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