Food Engineering Reviews (2019) 11:159–183
https://doi.org/10.1007/s12393-019-09193-0

# Potassium Permanganate-Based Ethylene Scavengers for Fresh Horticultural Produce as an Active Packaging

Marianela Hazel Álvarez-Hernández[1] · Ginés Benito Martínez-Hernández[2] · Felipe Avalos-Belmontes[1] · Marco A. Castillo-Campohermoso[3] · Juan Carlos Contreras-Esquivel[1] · Francisco Artés-Hernández[2]

Received: 21 February 2019 / Accepted: 29 May 2019 / Published online: 29 July 2019


## Abstract
Potassium permanganate ($KMnO_4$) is a powerful ethylene ($C_2H_4$)-scavenging agent widely used in fresh horticultural commodities to delay the postharvest maturation. According to databases, it has been used for almost 50 years in food-packaging systems, and over 70 studies have evaluated its effects on fresh produce quality, mainly on climacteric fruit. However, the use of $KMnO_4$-based technology remains limited at a commercial scale, since there are still lots of doubts on its potential as an effective postharvest tool, as well as in relation with health, environmental and safety concerns. Depending on the commodity, and even the variety, these scavengers may have different effects, but overall, they can delay ripening/senescence-related processes such as chlorophyll degradation/colour changes, weight and firmness losses, disorders and diseases, acidity and sugar changes. This review comprises an updated overview of the current knowledge regarding the use of $KMnO_4$ as $C_2H_4$-scavenging agent, providing a concise appraisal on $KMnO_4$-based $C_2H_4$ removal application and its effect on the quality of fresh produce. $KMnO_4$ is commonly supported onto microporous mineral particles, which are placed into small sachets to avoid direct food contact within packages. Generally, $KMnO_4$-based $C_2H_4$ scavengers are jointly used with modified atmosphere packaging. Hence, $KMnO_4$-based $C_2H_4$-scavenging systems, as an active food-packaging technology, seem to be a relevant option to preserve the quality and safety of fresh horticultural produce. Nevertheless, although there are many $KMnO_4$-based products available in the market, which are presently reviewed, more research is required in order to obtain an optimal $C_2H_4$-scavenger performance.

**Keywords** Food packaging · Modified atmosphere · Ethylene removal · Shelf life · Fresh produce

## Introduction

In recent years, a growing interest of consumers in high-quality fresh fruit and vegetables has been observed [129]. This is mainly due to a better knowledge of the health benefits of produce consumption, as well as to the increased awareness of their nutritional content and functional traits [148]. Nevertheless, fruit and vegetables are perishable products whose safety, sensory and nutritional/functional qualities may be highly reduced if appropriate postharvest techniques are not applied, leading to a shortened shelf life [149, 174]. In addition, such reduced shelf life of fresh fruit and vegetables may result in postharvest losses with socioeconomic and environmental implications [100, 129]. For instance, in the year 2010, the United States Department of Agriculture reported a 10.5% loss of the total fruit and vegetables available at a retail level in the United States of America (USA) and 24.5% at the consumer level, leading to total economic losses of $34.8 billion [34]. Therefore, with the aim of improving the convenience and safety of horticultural products, without altering their sensory attributes, the world horticultural industry is constantly searching for innovative and sustainable processing, handling and storing techniques [10, 106].

Although it is well-known that temperature is the most important postharvest factor to be considered to preserve quality and safety in fresh horticultural products [86, 174], storing them in an improper atmosphere may result in some

✉ Francisco Artés-Hernández
fr.artes-hdez@upct.es

[1] Faculty of Chemical Sciences, Universidad Autónoma de Coahuila, 25280 Saltillo, COAH, Mexico

[2] Postharvest and Refrigeration Group, Department of Agricultural Engineering, Universidad Politécnica de Cartagena, 30203 Cartagena, Murcia, Spain

[3] Agricultural Plastics Department, Centro de Investigación en Química Aplicada, CIQA–CONACYT, 25294 Saltillo, COAH, Mexico

physiological disorders [171]. In this sense, ethylene ($C_2H_4$) is a plant hormone—physiologically active in trace amounts (even less than 0.001 μL $L^{-1}$)—whose postharvest actions are diverse and vary between produce [119, 133, 165]. Nonetheless, overall, the major effects are related to an accelerated ripening process in climacteric fruit and to an accelerated senescence of non-climacteric produce, affecting the quality and leading to a reduction in postharvest life [98, 169]. Furthermore, it has been found that exposure to $C_2H_4$ increases postharvest rotting (fungal development) in non-climacteric produce [131]. Therefore, $C_2H_4$ is a critical factor in postharvest management of fresh horticultural commodities, especially during long-term storage and long-distance transport [104, 179]. According to Kyriacou and Rouphael [99], prevention of detrimental $C_2H_4$ action may be achieved through the use of scavenging technologies. Meanwhile, Wills [165] point out that the use of $C_2H_4$ scavenging tools is a low-cost option for preserving fresh produce quality. In addition, $C_2H_4$ scavengers seem to be a promising tool to minimise the need for refrigeration and hence to reduce energy consumption [166].

$C_2H_4$-scavenging products may be used to remove $C_2H_4$ from storage facilities and transport vehicles, as well as from the in-package atmosphere [32]. Nevertheless, since packaging is a major critical factor in postharvest management for preserving quality and safety of perishable horticultural commodities [107, 172], the most common application of $C_2H_4$-scavenging technology is in food-packaging systems [25, 175]. In fact, at the time of data collection, it was found that most research deals with $C_2H_4$-scavenging tools as an extension of modified atmosphere packaging (MAP) technology for fresh produce (Table 1), although some trials have also been carried out on produce stored under controlled atmosphere (CA) conditions (Table 2).

Nevertheless, CA storage can be expensive since the facilities are usually fairly complex and the maintenance of the optimal gas levels demands a high surcharge [56]. Therefore, compared to CA technology, the active MAP technology is an attractive option to delay the rate of fresh fruit and vegetable physiological processes, extending their shelf life [75, 108].

Unlike traditional inert packaging, an active package is engineered to achieve an intentional and dynamic modification of the atmosphere within the package by means of scavenging or releasing technologies [75, 105]. Although the active MAP technology for fresh commodities is not new [176], it has gained popularity in recent years. Furthermore, in 2014, active packaging comprising $C_2H_4$-scavenger tools was described as an emerging technology [56]. Nowadays, one of the most commonly used $C_2H_4$-scavenging technology is based on potassium permanganate ($KMnO_4$) [4].

$KMnO_4$-based $C_2H_4$-scavenging systems for fresh fruit and vegetable packaging have been extensively studied [116, 170, 179]. Nonetheless, to the best of our knowledge, there is not a previous comprehensive review discussing applications of $KMnO_4$-based $C_2H_4$ scavengers in food packaging and their effects on quality aspects of fresh produce. In fact, there is a lack of attention on the influence of storage conditions and commodity physiology on the $C_2H_4$-scavenging performance of the said scavenging systems. Thus, the present review compiles studies concerning the $KMnO_4$ application as a postharvest tool to remove $C_2H_4$ from the surrounding atmosphere within the package. There, emphasis is made on reviewing $KMnO_4$-based $C_2H_4$-scavenger effects on quality attributes of both climacteric and non-climacteric produce. Furthermore, special attention is given to factors that may affect the scavenging performance of such $C_2H_4$ removal systems.

## State-of-the-Art of Potassium Permanganate-Based Ethylene Scavengers

$C_2H_4$ is a gaseous simple carbon–carbon double bond molecule that is commonly found in the environment. $C_2H_4$ is endogenously produced by plant tissues and some microorganism metabolism, but it can also occur as a result of combustion of hydrocarbons [91]. In fact, $C_2H_4$ is the most produced organic compound throughout the world [16]. Hence, because the postharvest life of many fresh fruit and vegetables is highly limited by means of their own metabolic processes and $C_2H_4$ exposure since they are still alive and respond to the environment factors, much effort has been devoted to protecting horticultural products from the negative effects of $C_2H_4$ exposure [91, 110, 178].

Among the available technologies for controlling $C_2H_4$, 1-methylcyclopropene (1-MCP) is an $C_2H_4$ action inhibitor that works by competitively blocking fruit $C_2H_4$ receptors [165]. As an effective $C_2H_4$ antagonist, 1-MCP has been globally recognised as a useful agro-food industry tool [161]. Nonetheless, it can only be conveniently used in certain horticultural products since pathological and physiological disorders (e.g. $CO_2$-related injuries and chilling-related disorders) may be increased in both non-climacteric and climacteric fruit after 1-MCP exposure [102, 162].

$C_2H_4$ action may also be avoided by removing $C_2H_4$ surrounding fresh commodities. It has been proven that $C_2H_4$ scavengers are effective in removing $C_2H_4$ from the in-package atmosphere of fresh fruit and vegetables [75, 116]. $C_2H_4$-scavenging technology involves physical phenomena (overall, adsorption) and/or chemical reactions (usually, $C_2H_4$-oxidising agents are used) [45].

$C_2H_4$ adsorption may be performed by means of materials with active surfaces such as activated carbon, zeolites and some clays (e.g. pumice, cristobalite and clinoptilolite) [91, 97, 154]. Such materials can be contained into a $C_2H_4$-permeable sachet, or fine particles of those minerals can be dispersed

**Table 1** Overview of $KMnO_4$-based $C_2H_4$-scavenger trials and effects on fresh produce packaged in modified atmospheres

| Produce | Ethylene scrubber application | Produce packaging | Storage conditions | Inferences | Reference |
|---|---|---|---|---|---|
| Climacteric fruit | | | | | |
| Apple (*Malus* sp.) 'Granny Smith' | 108 g of $KMnO_4$ supported on aluminium oxide. 22 fruit per EU | Held in a sealed PE bag (40 µm thickness) | 0.5 °C<br>2 weeks | Reduced $C_2H_4$ and $CO_2$ levels as well as bitter pit severity and superficial scald | Shorter et al. [143] |
| Apple 'Gala' | One sachet of $KMnO_4$-based $C_2H_4$ scavenger per 18 kg of fruit. $KMnO_4$ amount NS | Wrapped with HDPE (30 µm thickness) and packed in a carton box | 0 °C<br>(90–95% RH)<br>2 months<br>+ 7 days (2 °C, 70–80% RH) | Delayed ripening and skin colour change, reduced fruit pulp firmness loss and slowed TA decrease. SSC was not affected | Amarante and Steffens [6] |
| Apple 'Gala' | Three scrubber sachets (9 g each of vermiculite impregnated with $KMnO_4$) per 18 kg of fruit | Packaged into a LDPE bag (20 µm thickness) and packed in a carton box | 4 °C<br>15 days<br>+ 3 days (20 °C) | Reduced in-package $C_2H_4$ levels. Pulp firmness, colour, TA and SSC were not significantly affected | Brackmann et al. [29] |
| Apple 'Golden Delicious' | 10 g of $KMnO_4$ coated zeolite sachets (they were replaced at the middle of the storage period). 30 fruit per EU | Placed in a carton box and wrapped with craft paper | 0 °C<br>(90% RH)<br>5 months | Reduced pH increase and TA decrease. Minimised SSC accumulation. Delayed de-greening process and flesh firmness loss | Sardabi et al. [137] |
| Apple 'Golden Delicious' 'Bramley's Seedling' | 200 g of expanded mica impregnated with $KMnO_4$. 96–120 fruit per EU | Placed in a steel vessel and sealed with a permeable silicone membrane | 4 °C<br>~ 250 days | Reduced $C_2H_4$ concentration. Retarded softening and reduced superficial scald incidence | Knee and Hatfield [95] |
| Apple 'Royal Gala' | One sachet (10 g each of $KMnO_4$-based scavenger) per 18 kg of fruit | Packed in a carton box and wrapped with HDPE (30 µm thickness) | 0 °C<br>(90–95% RH)<br>2 months<br>+ 7 days (20 °C, 70–80% RH) | Reduced $C_2H_4$ concentration. Delayed peel de-greening and pulp firmness loss. Slowed SSC increase. Iodine-starch index and TA were not affected | Amarante and Steffens [7] |
| Apricot (*Prunus armeniaca* L.) | $KMnO_4$ impregnated into sponge cubes. The fruit was previously coated with 3% $CaCl_2$. Fruit weight and $KMnO_4$ amount NS | Packaged in a PE bag | 28–30 °C<br>(60–63% RH)<br>10 days | Delayed both weight and vitamin C content loss. Reduced SSC and TA decrease. Retained sensory parameters | Ishaq et al. [81] |
| Apricot 'Patterson' 'Castlebrite' | One 9-g $KMnO_4$ sachet | Packed in a box | 5 °C<br>14 days | SSC, TA and brown rot development were not affected | Palou and Crisosto [117] |
| Avocado (*Persea americana* Mill.) | 0.03 g $KMnO_4$ incorporated into 0.14 g ANP-incorporated ANF membrane. 1 fruit weighing ~ 153 g per EU | Placed in an opening bag containing ~ 0.23 g of a 5% ANP-incorporated ANF membrane piece loaded with 0.06 g $KMnO_4$ | 6 days | Removed in-package $C_2H_4$ | Tirgar et al. [154] |
| Avocado 'Hass' | 9.5 g of $KMnO_4$-based scrubber per kg of fruit. 10 fruit per EU | Placed in a polythene box and wrapped with LDPE film (25 µm thickness) | 6 °C<br>60 days | Reduced $CO_2$ and $C_2H_4$ concentration. Delayed pulp softening and peel resistance decrease | Corrêa et al. [48] |
| Avocado 'Pollock' | Pouches containing $KMnO_4$ impregnated into clay bricks. Granular charcoal (2 g) wrapped with a muslin cloth. 3 fruit per EU. $KMnO_4$ amount NS | Packed in a perforated LDPE bag (50 µm thickness) | 12 °C<br>(94% RH)<br>21 days | Reduced in-package $CO_2$ and $C_2H_4$ concentrations. Kept good visual quality. Inhibited disease incidence and reduced chilling injury. Delayed both weight and | Illeperuma and Nikapitiya [77] |

**Table 1** (continued)

| Produce | Ethylene scrubber application | Produce packaging | Storage conditions | Inferences | Reference |
|---|---|---|---|---|---|
| | | | | firmness losses. SSC and pulp colour were not significantly affected | |
| Baby banana (*Musa* AA Simmonds) clon Orito | Sachets containing 5 g of $KMnO_4$ and vermiculite mix at a dose of 1.5 and 1% *w/w* based on fruit weight, respectively. 300 g fruit per EU | Packed in a LDPE bag | 18 °C (70–80% RH) 16 days | Delayed peel yellowing. Slowed SSC increase and TA decrease. Reduced firmness loss and weight loss. Minimised SSC/TA ratio increase | García et al. [69] |
| Banana (*Musa* sp.) | 0.03 g $KMnO_4$ incorporated into 0.14 g ANP-incorporated ANF membrane. Fruit weigh NS | Placed into a zip-lock bag containing 0.7 g of a 5% ANP-incorporated ANF membrane piece loaded with $KMnO_4$ | 14 days | Removed in-package $C_2H_4$. Significantly delayed the incidence of dark brown regions on the skin. Reduced flesh softening | Tirgar et al. [154] |
| Banana | 100 g of ground bricks impregnated with $KMnO_4$ per 6 fruit hands (15–17 fingers per hand). Container device NS | Stored in a perforated PE bag | 14–18 °C (33–58% RH) 24 days | Delayed yellowing of peel and minimised ascorbic acid degradation. Reduced weight loss and firmness loss. Slowed SSC, total sugars, reducing sugar and TA increases. Retained the marketability percentage | Zewter et al. [177] |
| Banana 'Kolikutu' | Wrapped bricks impregnated with $KMnO_4$. One hand with 12–14 fingers per EU. $KMnO_4$ amount NS | Packed in a LDPE bag (75 µm thickness) | 14 °C 94% RH 30 days | Decreased in-package $C_2H_4$ and $CO_2$ concentrations. Minimal changes in physicochemical properties (weight, firmness, SSC, pH and SSC/TA) were observed after storage. Extended storage life by 6 days | Chamara et al. [42] |
| Banana 'Pachbale' | One sachet (5 g each of $KMnO_4$-impregnated white cement and limestone powder) per kg of fruit; plus, $CO_2$ and moisture absorbents | Packed in a PE bag (25 µm thickness) | 13 °C 18 days | Reduced respiration rate and minimised $CO_2$ and $C_2H_4$ concentration. $O_2$ and pulp/peel ratio were slightly affected. Delayed yellowing. Reduced firmness loss. Reduced SSC/TA ratio increase. Ascorbic acid content and pH were not affected. Extended 3–4 days fruit shelf life | Chauhan et al. [43] |
| Banana 'Prata Aña' | One sachet (10 g each of $KMnO_4$-based scavenger) per 3–5 fruit (~457 g) | Packed in LDPE bag (10 µm thickness) | 12 °C 35 days | Delayed colour peel changes and starch degradation. Reduced $C_2H_4$ concentration and delayed climacteric peak. Slowed SSC and TA increase. Slightly affected weight loss | Prill et al. [121] |
| Banana (*Musa cavendishii* L.) 'Williams' | One pouch (20 g of $KMnO_4$) per 3 hands of fruit | Stored in a PE bag (40 µm thickness) and placed in a carton box | 20 °C (65–70% RH) 45 days | Reduced weight loss. Delayed yellowing of peel and firmness loss. Peeling condition was not affected. Minimised pulp/peel ratio increase. Slowed increase of SSC and TA. Induced SSC/TA ratio increase and pulp pH decrease. Delayed ripening | Tourky et al. [155] |
| Banana 'Williams' | 25 g of vermiculite impregnated with $KMnO_4$. 3 half hands per EU | Placed into a sealed PE bag (40 µm) | 20 °C 38 days | Minimised $C_2H_4$ concentration. Reduced firmness loss. Delayed fruit deterioration | Scott et al. [139] |
| Banana (*Musa paradisiaca* L.) | One sachet (30 g each of clay impregnated with $KMnO_4$ (at a | | 27–30 °C 18 days | | Santosa et al. [136] |

**Table 1** (continued)

| Produce | Ethylene scrubber application | Produce packaging | Storage conditions | Inferences | Reference |
|---|---|---|---|---|---|
| 'Raja Bulu' | rate of 7.5% *w/w*) per 6 fingers (0.42–0.67 kg) of fruit | Stored in a plastic bag and packed in a carton filled with paper | | Delayed yellowing of peel and firmness loss. Reduced weight loss. Slowed TA increase. SSC and pulp/peel ratio were not affected | |
| Bitter gourd (*Momordica charantia* L.) 'Meghna-2' | 8 g of $KMnO_4$–celite mixture (containing 133% (*w/w*) $KMnO_4$) of per kg of fruit | Packaged in a PP bag (50 µm thickness) | 27–31 °C (69–72% RH) 6 days | Delayed weight loss as well as chlorophyll content degradation. Reduced disease index and spoilage. Preserved sensory quality | Bhattacharjee and Dhua [18] |
| Blueberry (*Vaccinium* spp.) 'Lanfeng' | One sachet (10 g each of $KMnO_4$-based scavenger at $KMnO_4$ concentration≥ 10%) per 200 g of fruit | Packaged into a PE bag (20 µm thickness) | 0 °C (85% RH) 60 days + 8 days (20 °C, 85% RH) | Delayed weight loss and fruit softening. Reduced decay incidence and prevented total phenolic content. Minimised SSC changes and $C_2H_4$ production | Wang et al. [160] |
| Blueberry (*Vaccinium corymbosum*) 'Duke' | One sachet containing 0.7 g of $KMnO_4$-modified montmorillonite (at a rate of 9.5% *w/w* $KMnO_4$) per 120 g of fruit | Placed in a PP tray and covered with a bioriented PP film (35 µm thickness) | 2 °C 46 days | Removed $C_2H_4$ without affect in-package $CO_2$ atmosphere. Reduced fungi-caused decay incidence and preserved weight, firmness, TA and SSC/TA for longer | Álvarez-Hernández et al. [5] |
| Date fruit (*Phoenix dactylifera* L.) 'Barhee' | One sachet (10 g each of sodium polyacrylate powder soaked in 5% $KMnO_4$ solution) per 20 fruit | Packaged into PVC-PE bags (670 µm thickness) | 5 °C 75% RH 27 days | Weight loss was not affected. Lowered firmness loss. Reduced soft brown spots incidence. Slowed SSC increase rate and TA decrease. Retarded skin colour changes | Mortazavi et al. [113] |
| (*Ficus carica* L.) 'Brown Turkey' | $KMnO_4$ incorporated into the film packaging. 10 fruit per EU | Wrapped with PE containing additive $KMnO_4$ | 2 °C 21 days | Highly delayed both weight and firmness losses. SSC and pH were not significantly affected. Reduced $C_2H_4$ concentration. Volatile compounds production was not affected | Bouzo et al. [26] |
| Guava (*Psidium guajava* L.) 'Baruipur' | One sachet containing 3 g of $KMnO_4$ plus one sachet containing 46 g of silica gel per 2 fruit (~ 200 g each fruit) | Packed with a PVC film (40 µm thickness) | 4 °C (85% RH) 30 days + 2 days (30 °C, 90% RH) | Delayed ripening rate and the greenness loss of peel. Reduced mould growth severity. Prevented chilling injury symptoms. Increased weight loss and reduced SSC increase. Reduced both phenol content and ascorbic acid content decrease rate. No significant effect was observed for reducing sugar and TA | Murmu and Mishra [115] |
| Guava | Sachets containing $KMnO_4$ impregnated into silica crystal | Packed with LDPE film (76.2 µm thickness) | 8 °C 49 days | Reduced fruit firmness SSC, TA and colour changes | Singh and Giri [146] |
| Guava | Sachets containing $KMnO_4$ at a rate of 10 g per kg of fruit. 30 fruit per EU. Sachet quantity NS | Packed in a foam plate and wrapped with PE film (10 µm thickness) | 8 °C (90% RH) 20 days | Increased weight loss and spoilage incidence. Slightly slowed colour changes. TA, SSC and vitamin C content were slightly affected. Firmness was not significantly affected | El-Anany and Hassan [58] |
| Kiwifruit (*Actinidia deliciosa*) 'Hayward' | Sachets containing a mixture of natural clay and $KMnO_4$ granules (at a rate of 9 g per kg of fruit). 8 fruit per EU. Sachet quantity NS | Placed in LDPE (13 µm thickness) | 0 °C (85–95% RH) 200 days | Delayed firmness. Reduced SSC increase and TA decrease. Slowed total chlorophyll and ascorbic acid degradation | Bal and Celik [12] |
| Kiwifruit 'Hayward' | 12 g of $KMnO_4$ per kg of fruit. Container device NS | Packed in a HDPE bag (40 µm thickness) | 20 °C 28 days | Delayed firmness loss and vitamin C content loss. Slowed TA and SSC decrease. | Ramin et al. [126] |

**Table 1** (continued)

| Produce | Ethylene scrubber application | Produce packaging | Storage conditions | Inferences | Reference |
|---|---|---|---|---|---|
| | | | | Reduced decay. Slowed pH increase tendency | |
| Mango (*Mangifera indica* L.) 'Dashehari' | $KMnO_4$-based $C_2H_4$ scavenger at a rate of 6% | Packed in a 200-mm gauge PE bag | 12 days | Reduced weight loss and rotting incidence. Delayed SSC decrease and vitamin C degradation. Retained soluble sugar and reducing sugar changes | Yadav et al. [173] |
| Mango 'Haden 2H' | One sachet (5 g each of $KMnO_4$) per 3.2 kg of fruit | Placed in a LDPE bag (28 µm thickness) | 12 °C (90% RH) 26 days | SSC, pH, TA, weight loss, colour, firmness and disease incidence were not affected | Castro et al. [37] |
| Mango 'Hindi Besennara' 'Alphonse' | One sachet containing $KMnO_4$ (at a rate of 2.5 g per kg of fruit). 24 fruit per EU | Packed in a card box and wrapped with LDPE film (28 µm thickness) | 8 °C (85–90% RH) 30 days | Firmness loss was not affected. Delayed weight loss. Slowed SSC increase and ascorbic acid degradation. Minimised TA decrease and increased shelf life | Ezz and Awad [65] |
| Mango 'Karuthacolomban' | Pouches containing $KMnO_4$-bricks. Plus activated granular (2 g) charcoal wrapped with muslin. 3 fruit per EU. $KMnO_4$ amount NS | Packed in a perforated LDPE bag (50 µm thickness) | 13 °C (94% RH) 21 days | Reduced in-package $O_2$, $CO_2$ and $C_2H_4$ concentrations. Slowed both weight and firmness loss. Delayed pH and SSC increase, as well as TA decrease | Illeperuma and Jayasuriya [76] |
| Mango 'Madu' | $KMnO_4$ at a rate of 450 g per litre | Packed in a PE bag and placed in a corrugated fibre board | 25–28 °C 21 days | Decreased respiration rate and ethylene production. Weight loss and decay percentage were not significantly affected | Basuki and Prarudiyanto [13] |
| Mango 'Tommy Atkins' | One sachet containing vermiculite impregnated with $KMnO_4$ at a rate of 10 g $KMnO_4$ per 0.5 kg fruit | Packed in a plastic tray and covered with a PVC film (14 µm thickness) | 13 °C (85–90% RH) 20 days + 6 days (14 °C, 70% RH) | Weight loss and pulp firmness were not significantly affected. Delayed TA decrease. Ascorbic acid degradation, SSC rate and SSC/TA were affected | Jeronimo et al. [84] |
| Mango 'Tommy Atkins' | $KMnO_4$-based $C_2H_4$ scavenger | Packed in a LDPE bag | 12 °C (90% RH) 21 days | Inhibited decay incidence. Delay firmness loss. Peel colour development and disease incidence were not affected | Castro et al. [36] |
| Melon, cantaloupe (*Cucumis melo* L.) 'Vera Cruz' | 12 sachets (2.5 g each of vermiculite impregnated with 0.25 g of $KMnO_4$) per kg of fruit. 4 fruit per EU | Placed in a box and wrapped with a LDPE film | 3 °C (85% RH) 14 days + 8 days (23 °C, 90% RH) | Weight loss, pulp/peel firmness, SSC, TA, pH, colour and decay incidence were not affected | Sá et al. [130] |
| Papaya (*Carica papaya* L.) 'Sunrise Golden' | Sachets of vermiculite impregnated with $KMnO_4$ at 1.5 g per bag. 3 fruit (~ 289.9 g each fruit) per bag. Sachet quantity NS | Packed in a hermetic LDPE bag (28 µm thickness) | 10.4 °C (90% RH) 25 days + 6 days (21 °C, 90% RH) | Delayed weight loss. Reduced pulp consistency loss and SSC increase. Maintained peel colour index. Reduced $CO_2$ production | Silva et al. [144] |
| Papaya | 20 g of KMnO4. Fruit weight and device container NS | Stored into a sampling chamber | 25 °C (60% RH) 8 days | Reduced $C_2H_4$ production | Corrêa et al. [47] |
| Pear 'Williams' | $KMnO_4$-based $C_2H_4$ scavenger | Packed in a sealed polyethylene bag | 1 °C 126 days | Reduced $C_2H_4$ level. Minimised brown heart | Scott and Wills [138] |
| Pear, Japanese 'Nijisseiki' | 20 g of $KMnO_4$ supported on aluminium oxide placed in | Packed into a LDPE bag (50 µm thickness) | 0 °C 252 days | | Giraldo et al. [70] |

**Table 1** (continued)

| Produce | Ethylene scrubber application | Produce packaging | Storage conditions | Inferences | Reference |
|---|---|---|---|---|---|
| | small dishes among the fruit. 20 fruit per EU | | | Delayed yellowing. Decreased $C_2H_4$ levels and respiration rate. Reduced disorders severity (flesh and core browning) | |
| Persimmon (*Diospyros kaki* L.) 'Fuyu' | Two sachets containing 8.5 g of alumina-$KMnO_4$ per box. 4 samples of 20 fruit (previously 1-MCP treated) per box | Packed in a plastic box internally coated with a PE bag (40 μm thickness) | − 0.1 °C 80 days | $KMnO_4$-based scavenger did not show an effect on fruit quality aspects when it was previously treated with 1-MCP | Argenta et al. [9] |
| Quince (*Cydonia oblonga* Mill.) 'Isfahan' | One sachet containing $KMnO_4$ at a rate of 5 g per kg of fruit. 10 fruit per EU | Stored in a sealed PE bag (60 μm thickness) | 0 °C (85–95% RH) 75 days + 7 days (20 °C) | Delayed colour changes, flesh firmness loss and β-carotene accumulation. Slowed astringent taste decrease. SSC was not affected | Akbari and Ebrahimpour [3] |
| Sapodilla (*Manilkara zapota* (L.) P. Royen) 'Itapirema-31' | Vermiculite impregnated with $KMnO_4$ sachets (at a rate of 0.375 g of $KMnO_4$ per kg of fruit), 4 fruit (120 g each fruit) per EU. Sachet quantity NS | Placed in a styrofoam tray with PVC film coating | 25 °C (54% RH) 10 days | Delayed firmness loss and vitamin C degradation. External and internal appearance, pulp colour, TA, pH, SSC, SSC/TA ratio and weight loss were no significant affected | de Souza et al. [53] |
| Sapota (*Manilkara achras* Mill.) 'Kallipatti' | 4 sachets $KMnO_4$-based scrubber (weight NS) per 10 kg of fruit | Packed in a corrugated fibre board box | 27–32 °C (70% RH) 13 days | Reduced weight loss. Firmness loss and TA were not affected. Slowed SSC increase and TA decrease. Delayed $C_2H_4$ and $CO_2$ production, as well as decay incidence | Bhutia et al. [19] |
| Sugar apple (*Annona squamosa* L.) | One $KMnO_4$-based scrubber sachet (at a rate of 9% $KMnO_4$, based on fruit weight). 4 fruit per EU | Placed in an expanded PS tray and wrapped with a PVC film (100 μm thickness) | 16 °C (90–100% RH) 12 days | Reduced weight loss. Delayed SSC and TA increase. Slowed pH decrease. Delayed fruit ripening | Chaves et al. [44] |
| Tomato (*Lycopersicon esculentum* Mill) 'Rio Grandi' | One sachet (containing a sponge cube impregnated with 800 ppm $KMnO_4$) per 70 fruit | Placed in a PE bag | 27 °C (80–90% RH) 60 days | Slowed pH and ascorbic acid increases. Delayed TA decrease, as well as phenolic content increase. Delayed lycopene biosynthesis. SSC was not significantly affected. Increased β-carotene increase rate | Mujtaba et al. [114] |
| Tomato (*Solanum* sp.) | 7.5 ppm $KMnO_4$ impregnated in cotton wool into aerated pouches, per 50 g of fruit. Pouch quantity NS | Placed into a plastic container | 14–18 °C 21 days | Retarded colour and textural changes | Wabali et al. [159] |
| Tomato (*Solanum lycopersicum* L.) 'Valouro' | 20% of $KMnO_4$ supported on zeolite and bentonite (2:1 *w/w*), 5 fruit per EU. Container device NS | Placed into a hermetically sealed container | 7 °C (90% RH) 35 days | Reduced $C_2H_4$ content of containers. Delayed fruit softening. Minimised both phenol content and antioxidant activity decrease rate. Slowed vitamin C content decrease and lycopene content increase. Delayed water weight loss and reduced decay severity | Mansourbahmani et al. [109] |
| Tomato 'Chonto' | 1.5% zeolite and 1.5% $KMnO_4$ sachets, based on fruit fresh weight. 3 fruit per EU. Sachet quantity NS | Stored in TPT packaging | 18 °C (85% RH) 28 days | Delayed weight loss. Slowed firmness loss and SSC increase. TA was not affected | Salamanca et al. [132] |
| Non-climacteric fruit | | | | | |
| Longkong fruit (*Lansium domesticum* Corr.) | $KMnO_4$-based scrubber. Fruit previously treated with 1-MCP | Wrapped with foam-net | 18 °C 14 days | Maintained pericarp colour, flesh colour and taste in good quality | Suvanjinda et al. [151] |

**Table 1** (continued)

| Produce | Ethylene scrubber application | Produce packaging | Storage conditions | Inferences | Reference |
|---|---|---|---|---|---|
| Loquat (*Eryobotria japonica* Lindl.) 'Precoce de Itaquera' | One $KMnO_4$-based scrubber sachet (weight NS), per 5 fruit | Stored in a PET tray and wrapped with a PVC film (10 μm thickness) | 6 °C (90% RH) 18 days | Delayed $C_2H_4$ production. $CO_2$ production and weight loss were not affected. Increased shelf life | Campos et al. [35] |
| Maxixe (*Cucumis anguria*) | One sachet (6.5 g vermiculite impregnated with 4 g $KMnO_4$) per 4 fruit | Placed into a styrofoam tray and wrapped with PVC film | 10 °C (90% RH) 10 days | Maintained good appearance. Reduced vitamin C content decrease. Delayed chlorophyll degradation and colour changes. Accelerated non-reducing sugars increase. Weight loss, reducing sugars, soluble sugars and starch content and morphological aspects were not affected | Silva et al. [145] |
| Pineapple (*Ananas comosus* (L.) Merr.) 'Gold Extra Sweet' | $KMnO_4$-based $C_2H_4$ scavenger | NS | 7.5 °C (85–90% RH) 25 days + 3 days (18 °C, 85–90% RH) | Decreased peduncle rot incidence | Sabater-Vilar et al. [131] |
| Pointed gourd (*Trichosanthes dioica* Roxb.) 'Kaijli' | 8 g of celite impregnated with $KMnO_4$ (in a rate of 133% $KMnO_4$ *w/w*) per kg of fruit | Packed in PP bags (50 μm thickness) | 29–33 °C (68–73% RH) 8 days | Inhibited spoilage and disease incidence. Delayed chlorophyll content loss. Reduced weight loss at the beginning of the storage period | Bhattacharjee and Dhua [17] |
| Strawberry (*Fragaria* sp.) 'Torrey' | One sachet (10 g each of $KMnO_4$ supported on alumina) per 18–22 (250 g) fruit | Held in a punnet overwrapped with 5 layers of PE film (9 μm thickness) | 20 °C 4 days | Reduced $C_2H_4$ concentration as well as the deterioration rate. Slightly reduced $CO_2$ concentration. $O_2$ levels were not affected | Kim and Wills [94] |
| Strawberry 'Torrey' | Sachets containing 10 g of $KMnO_4$ impregnated onto activated alumina and vermiculite beads. 18–22 (250 g) fruit per EU. Sachets quantity NS | Packed into a punnet overwrapped with PE film (50 μm thickness) | 0 °C 8 days | Reduced $C_2H_4$ level. Delayed firmness loss. Minimised the deterioration rate. Decreased susceptibility to fungus. Increased storage life | Wills and Kim [167] |
| Vegetables | | | | | |
| Broccoli (*Brassica oleracea* L., Italica group) 'Marathon' | One sachet (20 g each of $KMnO_4$ supported on an inert carrier) per 5 broccoli heads | Stored in a bag (PD-961EZ) | 0–1 °C 29 days | Weight loss and overall appearance were not affected. Slightly delayed softening. Reduced acetaldehyde concentration | DeEll et al. [54] |
| Lettuce (*Lactuca sativa*) | Sachets of $KMnO_4$ supported into activated alumina beads. 6 lettuce heads (1–1.2 kg each head) per EU. $KMnO_4$ amount NS | Packaged into an unsealed PE bag (50 μm thickness) | 0 or 20 °C 35 days | Reduced $C_2H_4$ and $CO_2$ levels. Delayed leaf browning. Kept good quality. Increased storage life | Kim and Wills [93] |

*SSC*. soluble solid content; *TA*, titratable acidity; *PE*, polyethylene; *HDPE*, high-density PE; *LDPE*, low-density PE; *PS*, polystyrene; *PET*, polystyrene terephthalate; *PVC*, polyvinyl chloride; *TPT*, thermoformed PE terephthalate; ~, approximately; *ANP*, alumina nanoparticle; *ANF*, alumina nanofibre; *EU*, experimental unit; *NS*, not specified

**Table 2** Overview of $KMnO_4$-based $C_2H_4$-scavenger trials and effects on fresh produce stored under controlled atmosphere conditions

| Produce | Ethylene scrubber application | Produce packaging | Storage conditions | Inferences | Reference |
|---|---|---|---|---|---|
| Climacteric fruit | | | | | |
| Apple (*Malus domestica* Borkh) 'Brookfield' | $KMnO_4$ sachets (sachets quantity and $KMnO_4$ weight NS). 25 fruit per EU | Stored in a storage chamber under controlled atmosphere | 1 °C (94% RH) 8 months + 7 days (20 °C) | Decreased $C_2H_4$ production and respiration rate. Delayed flesh firmness loss and reduced TA decrease | Brackmann et al. [31] |
| Apple 'Brookfield' | Sachets containing $KMnO_4$ (sachets quantity and $KMnO_4$ weight NS). 25 fruit per EU | Placed in a hermetically closed chamber under controlled atmosphere | 1.5 °C (94% RH) 8 months + 6 days (20 °C) | Decreased $C_2H_4$ production and respiration rate. Both internal $C_2H_4$ and $CO_2$ concentrations were decreased | Brackmann et al. [30] |
| Apple 'Gala' | $KMnO_4$-based scavenger | Stored under controlled atmosphere conditions | 1 °C 8 months + 7 days | Reduced $C_2H_4$ concentration. Delayed firmness loss. Maintained green colour and good appearance and taste | Brackmann and Saquet [27] |
| Vegetables | | | | | |
| Cauliflower (*Brassica oleracea*) 'Teresópolis Gigante' | 10 sachets (8 g each of $KMnO_4$) per 3 heads | Stored in a chamber | 0.5 °C (97% RH) 2 months + 5 days (20 °C) | Delayed de-greening of head and leaf. TA, SSC, firmness and weight loss were not affected | Brackmann et al. [28] |

*SSC*, soluble solid content; *TA*, titratable acidity; *PE*, polyethylene; *HDPE*, high-density PE; *LDPE*, low-density PE; *PS*, polystyrene; *PET*, polystyrene terephthalate; *PVC*, polyvinyl chloride; *TPT*, thermoformed PE terephthalate; ~, approximately; *EU*, experimental unit; *NS*, not specified

into the packaging film (e.g. polyethylene films) [158, 172]. Nevertheless, active films incorporating mineral powders have shown low $C_2H_4$ removal efficacy because of low amount of mineral that can be incorporated without affecting the mechanical properties of the package [83]. In addition, they are opaque and grainy materials and incorporated mineral powders affect film permeability letting carbon dioxide ($CO_2$) gas out more rapidly and letting oxygen ($O_2$) enter more readily than regular plastic films [97].

Another scavenging approach is based on chemical processes [99], although in some cases such an approach is not profitable. For instance, palladium (Pd) and titanium dioxide ($TiO_2$) are catalytic materials that can efficiently remove $C_2H_4$ [87, 153], but Pd is expensive and the reaction between $TiO_2$ and $C_2H_4$ is ultraviolet light dependent [154, 175].

Over the years, the most well-known, inexpensive and commonly used $C_2H_4$-scavenging technologies have been those based on $KMnO_4$, a strong agent that chemically scavenges $C_2H_4$ by an oxidation process [116, 142].

$KMnO_4$-based $C_2H_4$-scavenging technology has been widely used for almost 50 years. The first report on the $KMnO_4$ application in $C_2H_4$-scavenging systems for fresh fruit preservation dates from 1967 [67]. Early studies were on the storage of apples and bananas, where Forsyth et al. [67] and Scott et al. [139], respectively, found that $KMnO_4$ can be useful to delay the ripening process. Since then, large research on the effects of $KMnO_4$ on fresh horticultural products has been developed (Tables 1 and 2). Research results for 19 climacteric fruit and 5 non-climacteric fruit and 3 vegetable products were identified through searching in the Scopus and Web of Science search engines.

Most research has been largely centred on climacteric fruit, particularly in cultivars of apple and banana species, which in addition to produce a high $C_2H_4$ rate, they are highly $C_2H_4$ sensitive [24]. Moreover, $KMnO_4$-based $C_2H_4$-scavenging products can be also used to protect floral products from the $C_2H_4$ detrimental damage (e.g. flower abscission or wilting, epinasty of buds and flowers and leaf shedding), maintaining their good appearance and extending their shelf life [8, 92].

Nowadays, several $KMnO_4$-based products engineered for $C_2H_4$-scavenging applications are commercially available. As presented in Table 3, commercial $C_2H_4$ scavengers have been developed in different shapes (beads, cylindrical and irregular pellets and powder) containing 3.5–12% *w*/*w* $KMnO_4$.

According to the available information, currently available products in the market have a $C_2H_4$-scavenging capacity ranging from 3 to 6.5 L $kg^{-1}$. Furthermore, there are some commercial $KMnO_4$-based products such as Bi-On® SORB (Bioconservacion S.A., Barcelona, Spain), Chemisorbant (Purafil, Inc., Doraville GA, USA), MM-1000 MULTI-MIX® MEDIA (Circul-Aire Inc., Montreal, Canada) and Sofnofil™ (Molecular Products Limited, Essex, UK) that are not specifically intended for the removal of $C_2H_4$ but are marketed as broad-spectrum contamination control materials for air purification in industrial applications.

**Table 3** $KMnO_4$-based $C_2H_4$ scavengers currently available in the market

| Trade name (manufacturer) | General description | $C_2H_4$-scavenging capacity (L/kg) | General characteristics | Commercially available presentations | Application guidelines | Reference |
|---|---|---|---|---|---|---|
| Air Repair™ (DeltaTrack Inc., Pleasanton, CA, USA) | Activated aluminium impregnated with $KMnO_4$ | NS | Shape: spherical pellets | Bulk beads/sachet/tube/blanket | NS | DeltaTrak Inc. [55] |
| Befresh (Befresh Technology, S.L., Barcelona, Spain) | Natural clays impregnated with $KMnO_4$ | 4.5 | Shape: cylindrical pellets | Sachet/tube/module | NS | Befresh Technology [14]; Befresh Technology [15] |
| Befresh+ (Befresh Technology, S.L., Barcelona, Spain) | Natural clays impregnated with $KMnO_4$ | 6.5 | Shape: cylindrical pellets | Sachet/tube/module | NS | Befresh Technology [14]; Befresh Technology [15] |
| Bi-On® R8 (Bioconservacion S.A., Barcelona, Spain) | Natural clays impregnated with 8% $KMnO_4$ | 3.5 | Shape: cylindrical pellets<br>Bulk density 0.84 g/mL<br>Pellet diameter 2.3–4 mm<br>Moisture content 15–20% | Bulk granules/sachet/tube/machine/module | Temp. − 20–50 °C<br>RH 10–95% | Bioconservacion [20] |
| Bi-On® R12 (Bioconservacion S.A., Barcelona, Spain) | Natural clays impregnated with 12% $KMnO_4$ | 4.5 | Shape: cylindrical pellets<br>Bulk density 0.84 g/mL<br>Pellet diameter 2.3–4 mm<br>Moisture content 15–20% | Bulk granules/sachet/tube/machine/module | Temp. − 20–50 °C<br>RH 10–95% | Bioconservacion [21] |
| BIOPAC (BIOPAC Pty Ltd., West Burleigh, Australia) | Porous material mixed with $KMnO_4$ | 2.8–4.2 | Shape: spherical pellets | Tube/sachet/module | NS | Biopac [22] |
| BioX® 4.0 (BioXTEND Co., Fort Myers, FL, USA) | Alumina mixed with 4.0–4.5% $KMnO_4$ | 2.8–3.0 | Shape: spherical pellets<br>Pellet diameter 3.0 mm<br>Moisture content 15–20% | Bulk granules/tube/sachet/module | NS | BIOXTEND [23] |
| BioX® 8.0 (BioXTEND Co., Fort Myers, FL, USA) | Alumina mixed with 8.0–8.5% $KMnO_4$ | 3.4 | Shape: spherical pellets<br>Pellet diameter 3.0 mm<br>Moisture content 15–20% | Bulk granules/tube/sachet/module | NS | BIOXTEND [23] |
| BRYSORB™ 508 (Bry-Air (Asia) Pvt. Ltd., Gurugram, India) | Activated alumina impregnated with $KMnO_4$ | NS | Shape: spherical beads<br>Pellet diameter 2.5–3.5 mm<br>Bulk density 0.85–0.90 g/mL<br>Moisture content 20–25% | Bulk granules | Temp. − 20–50 °C<br>RH 10–95% | Bry-Air (Asia) Pvt. Ltd. [33] |
| Eris filter (Miatech, Inc., Clackamas OR, USA) | $KMnO_4$ pellets | NS | Shape: spherical pellets | Blanket | NS | Miatech Inc. [111] |
| Ethysorb® (Molecular Products Limited, Essex, UK) | Activated alumina impregnated with 3.5–5% $KMnO_4$ | NS | Shape: spherical pellets<br>Bulk density 1 g/mL<br>Particle size 2.5–5.0 mm<br>Relative density 3.3 g/mL | Bulk beads/tube/blanket | Temp. − 10–40 °C<br>RH 10–95% | Molecular Products Limited [112] |
| Extend-A-Life™ (AgraCo Technologies International, LLC, Dillsburg PA, USA) | Zeolite coated with 8% $KMnO_4$ | NS | NS | Sachet/filter | NS | AgraCo Technologies International LLC [1]; AgraCo Technologies International LLC [2] |
| GK3 (GREENKEEPER IBERIA, S.L., Madrid, Spain) | Phyllosilicate and aluminosilicate loaded with 8% $KMnO_4$ | 3.4 | Shape: cylindrical pellets<br>Particle diameter 2.0, 3.0 and 4.0 mm<br>Moisture content 15% | Tube/machine/module | NS | Flink [66]; GreenKeeper [71]; GreenKeeper Iberia SL. [72] |
| GK4 (GREENKEEPER IBERIA, S.L., Madrid, Spain) | Phyllosilicate and aluminosilicate loaded with 12% $KMnO_4$ | 4.2 | Shape: cylindrical pellets<br>Particle diameter 2.0, 3.0 and 4.0 mm<br>Moisture content 15% | Tube/machine/module | NS | Flink [66]; GreenKeeper [71]; GreenKeeper Iberia SL. [72] |
| | Phyllosilicate and aluminosilicate loaded with $KMnO_4$ | NS | Shape: powder | Sachet/blanket | NS | Flink [66]; GreenKeeper [71] |

**Table 3** (continued)

| Trade name (manufacturer) | General description | $C_2H_4$-scavenging capacity (L/kg) | General characteristics | Commercially available presentations | Application guidelines | Reference |
|---|---|---|---|---|---|---|
| GK/P (GREENKEEPER IBERIA, S.L., Madrid, Spain) | | | | | | |
| GKZ4 (GREENKEEPER IBERIA, S.L., Madrid, Spain) | Zeolite loaded with $KMnO_4$ | 2* | Shape: irregular granules<br>Particle diameter 0.6–1.5 mm | Sachet/blanket | NS | Flink [66]; GreenKeeper [71] |
| Prodew (Prodew, Marietta, GA, USA) | $KMnO_4$ granules | NS | Shape: cylindrical pellets | Sachet/machine/tube | NS | Prodew [122]; Prodew [123] |
| PURETHYL (ISOLCELL S.p.A., Laives, Italy) | Activated alumina granules impregnated with $KMnO_4$ | NS | NS | Machine | NS | ISOLCELL S.p.A. [82] |
| Retarder® (RETARDER SRL, Verzuolo, Italy) | Mix of clays and oxidising agents (such as $KMnO_4$) | NS | Shape: cylindrical pellets | Sachet/tube | NS | RETARDER SRL. [128] |
| Ryan® (Sensitech Inc., Beverly MA, USA) | Mixture of natural clays and 6% $KMnO_4$ | 3.0 | Shape: cylindrical pellets<br>Pellet diameter 3.0 mm | Sachet/tube | NS | Sensitech Inc. [140] |
| Select (Purafil, Inc., Doraville GA, USA) | Activated alumina impregnated with 8% $KMnO_4$ | NS | Shape: spherical pellets<br>Bulk density 0.8 g/mL<br>Pellet diameter 3.2 mm<br>Moisture content ≤ 35% | NS | Temp. − 20–51 °C<br>RH 10–95% | Purafil Inc. [124]; Purafil Inc. [125] |
| KEEPCOOL (KEEPCOOL, Molina de Segura, Spain) | Sepiolite mixed with $KMnO_4$ and activated carbon | NS | Shape: irregular granules<br>Particle size 0.6–0.3 mm | Sachet/filter/machine | NS | Climent [46]; KEEPCOOL [88]; KEEPCOOL [89] |
| KEEPFRESH (BLUE TECK SYSTEMS, S.L., Madrid, Spain) | Natural zeolite impregnated with 6% $KMnO_4$ | NS | NS | Sachet/sheets/tube/machine | NS | KEEPFRESH [90]; Köstekli et al. [96] |
| Super Fresh Media (Ethylene Control, Inc., Selma CA, USA) | Natural zeolite impregnated with 4–6% $KMnO_4$ | NS | Shape: irregular granules | Bulk beads/sachet/blanket | NS | Ethylene Control Inc. [62] |

*NS*, not specified; *RH*, relative humidity

*Data supplied by the manufacturer company

## Ethylene Removal Reaction and Application Form of the Potassium Permanganate-Based Ethylene Scavengers

As presented in Tables 1, 2, 3, $KMnO_4$ is usually supported on a porous $C_2H_4$ adsorber substrate with a large surface area, typically alumina, to facilitate the redox reaction [120, 154]. These $C_2H_4$-scavenger products work through an adsorption–oxidation mechanism, where $C_2H_4$ is physically adsorbed by the porous medium and then oxidised by $KMnO_4$ [4]. $KMnO_4$ oxidises $C_2H_4$ by attacking its double bond [101]. The $C_2H_4$ stoichiometric oxidation reaction (Eqs. 1–4) was previously described by Keller et al. [91]:

$$3CH_2CH_2 + 2KMnO_4 + H_2O \rightarrow 2MnO + 3CH_3CHO + 2KOH \quad (1)$$

$$3CH_3CHO + 2KMnO_4 + H_2O \rightarrow 3CH_3COOH + 2MnO_2 + 2KOH \quad (2)$$

$$3CH_3COOH + 8KMnO_4 + \rightarrow 6CO_2 + 8MnO_2 + 8KOH + 2H_2O \quad (3)$$

Thus, the overall stoichiometric oxidation reaction is

$$3CH_2CH_2 + 12KMnO_4 \rightarrow 12MnO_2 + 12KOH + 6CO_2 \quad (4)$$

As the reaction proceeds, a gradual colour change from purple to dark brown occurs because the permanganate anion ($MnO_4^-$) is reduced into manganese dioxide ($MnO_2$) [110, 168]. This phenomenon can be clearly noted in Figs. 1 and 2. These figures show the $C_2H_4$ breakthrough measurement on a $KMnO_4$-based $C_2H_4$ scavenger (Bi-On® R12, Bioconservacion S.A., Barcelona, Spain) held under a continuous $C_2H_4$-enriched air flow (5000 ppm at 120 mL min$^{-1}$) at room temperature (22 °C) and the changes in $KMnO_4$ concentration (%) and colour that occur in the material over time.

$KMnO_4$-based $C_2H_4$ scavengers are mainly used in sachet form for food-packaging application but can also be found in different presentation forms such as blankets, filter tubes or filter machines that can be placed in warehouses or transport chambers, incorporated into household refrigerators systems, or directly incorporated into the packaging material [83, 110, 120]. For instance, Taboada-Rodríguez et al. [152] reported that barrier properties of the cardboard material usually used in food packaging could be improved by applying a coating made of polylactic acid and $KMnO_4$ supported onto sepiolite. However, $KMnO_4$ is not typically integrated into food contact surfaces of food packaging because of its toxicity and colour [25, 68].

In a commonly individual $C_2H_4$-scavenging packaging system (Fig. 3), a sachet containing the $C_2H_4$-scavenger product is placed within the produce package [83], at the upper part of the package [113, 142]. At this point, it should be clarified that the most suitable position to attach a scavenger—or a release—sachet will depend on the density of the gaseous compound to be scrubbed or released, respectively. The density of a gas can be deduced from the ideal gas law (Eqs. 5–8):

$$P \times V = n \times R \times T \quad (5)$$

$$P \times V = \frac{m}{M} \times R \times T \quad (6)$$

$$\frac{P \times V}{R \times T} = \frac{m}{M} \quad (7)$$

$$d = \frac{P \times M}{R \times T} \quad (8)$$

where $P$ is the atmosphere (atm), $M$ is the gas molar mass (g mol$^{-1}$), $R$ is the gas constant (0.082 atm L (K mol)$^{-1}$), and $T$ is the temperature (K).

Therefore, since $C_2H_4$ tends to rise to the top of the package because it is slightly less dense than air (for instance, the $C_2H_4$ and air density are 1.16 and 1.20 g mol$^{-1}$, respectively, at 22 °C and 1 atm), the upper part of the package seems to be the most suitable position to attach an $C_2H_4$-scavenger sachet. Then, the sachet material must be highly permeable to the $C_2H_4$ gas molecule, allowing $C_2H_4$ uptake from the in-package atmosphere through a convection and diffusion mechanism [97, 175]. Some typically used sachet materials reported in the literature are polyethylene (PE), muslin cloth or cellulose [58, 114]. In general, the commercially available active packaging agents such as $KMnO_4$-based products are typically packed into heat-sealed Tyvek® film sachets [172]. DuPont™ Tyvek® is a high-density PE film (Fig. 4) that meets the US and European Union regulations for food contact applications [57].

## Human Health and Environmental Concerns

Although there are already several registered commercial $KMnO_4$-based products (Table 3), the active packaging use in the European market is just beginning to increase [158]. Gaikwad and Lee [68] and Vilela et al. [158] attribute such behaviour to low consumer acceptance and to a strict legislation. Despite the fact that $KMnO_4$-based $C_2H_4$ scavengers are commonly placed into individual devices to keep products free from contamination and avoid human health risks associated with $KMnO_4$ poisoning, there is still concern about possible $KMnO_4$ migration. In this sense, it is highly recommended to avoid direct exposure to $KMnO_4$, particularly, at concentrated solutions and to undiluted $KMnO_4$ [78]. Besides that, $KMnO_4$ can be harmful if it is swallowed, being classified by the Globally Harmonized System of Classification and Labelling of Chemicals as harmful if swallowed under the code H302 [156]. Therefore, it is true that $KMnO_4$-based products must be carefully handled. Nonetheless, it is well documented that the risk of $KMnO_4$ intoxication is not

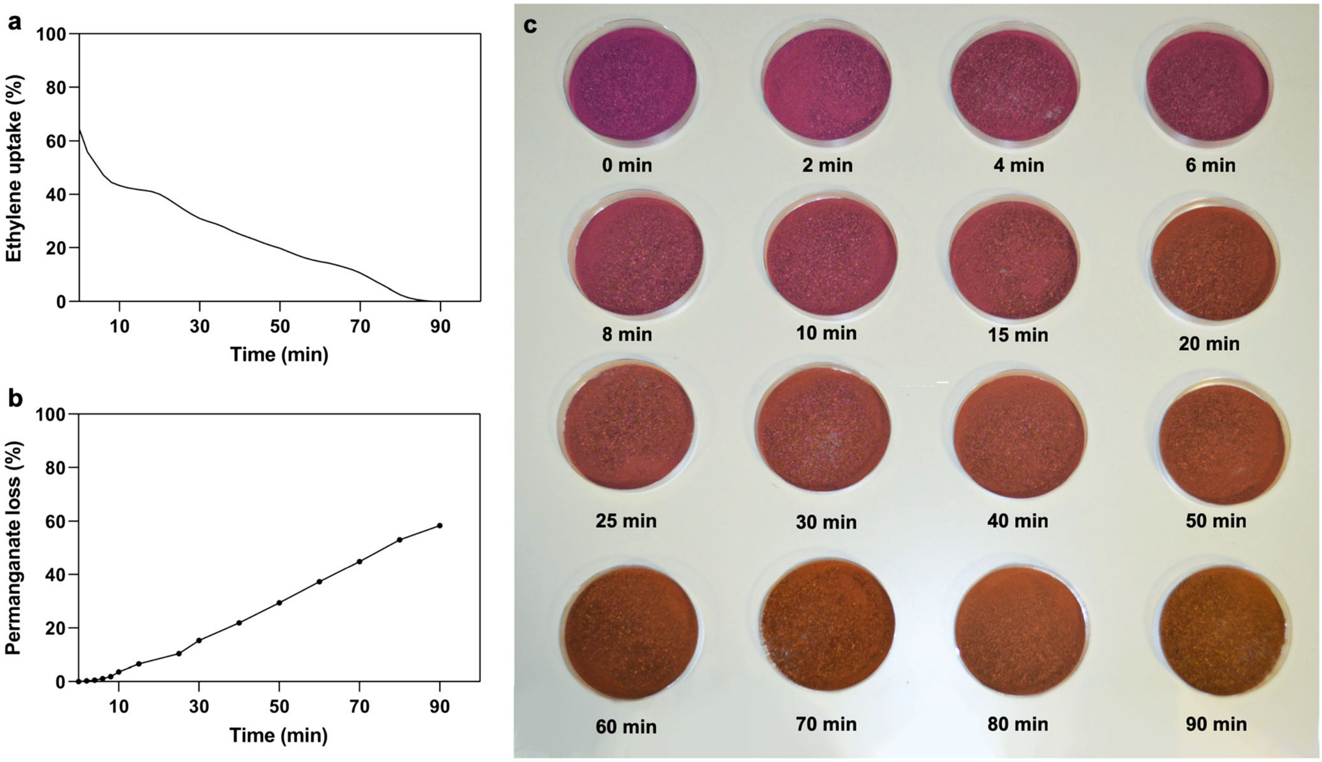


**Fig. 1** Changes in $C_2H_4$ uptake capacity (**a**) and $KMnO_4$ concentration (**b**) and visual colour change image (**c**) of a $KMnO_4$-based $C_2H_4$ scavenger (Bi-On® R12, Bioconservacion S.A.) material over time

common, being approximately 142.9 mg $kg^{-1}$ (10 g of $KMnO_4$ per person weighing 70 kg) the lethal adult dose and 750 mg $kg^{-1}$ the oral $LD_{50}$ rat dose [38, 79]. In addition, $KMnO_4$ is not listed on the World Health Organization (WHO) Acute Hazard Rankings [80]. Furthermore, $KMnO_4$ is commonly used at low concentrations in highly diluted solutions as antiseptic and antifungal drug and it is included in the WHO Essential Medicines List [163]. $KMnO_4$ as an

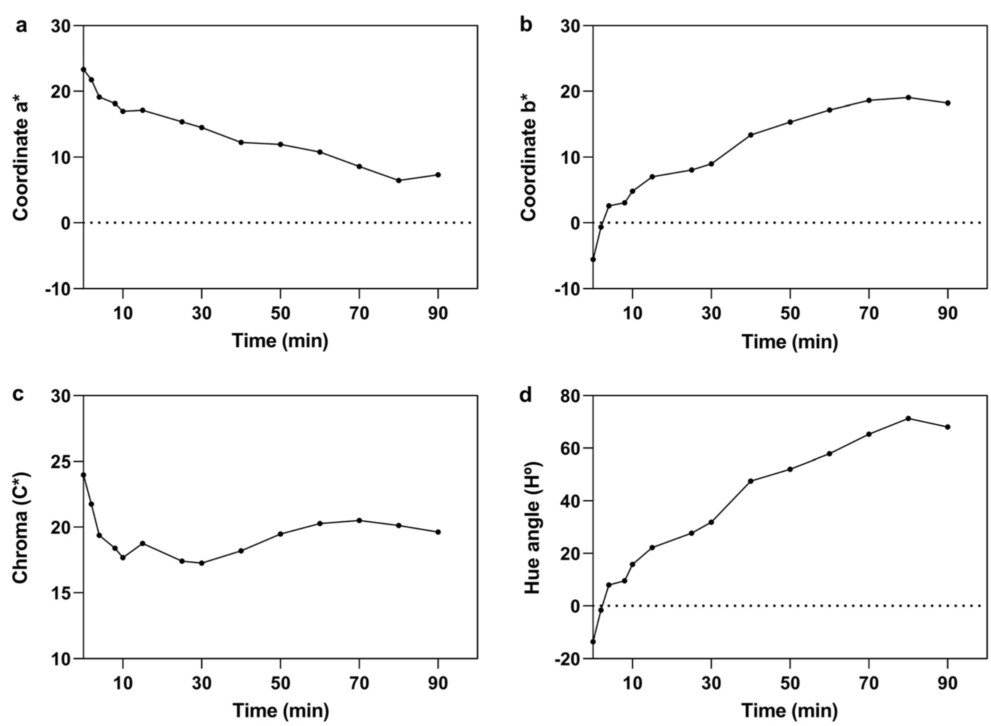


**Fig. 2** Evolution of colour parameters *a**, *b**, *C** and *H*° over time for a $KMnO_4$-based $C_2H_4$ scavenger (Bi-On® R12, Bioconservacion S.A.) held under a continuous $C_2H_4$-enriched air flow

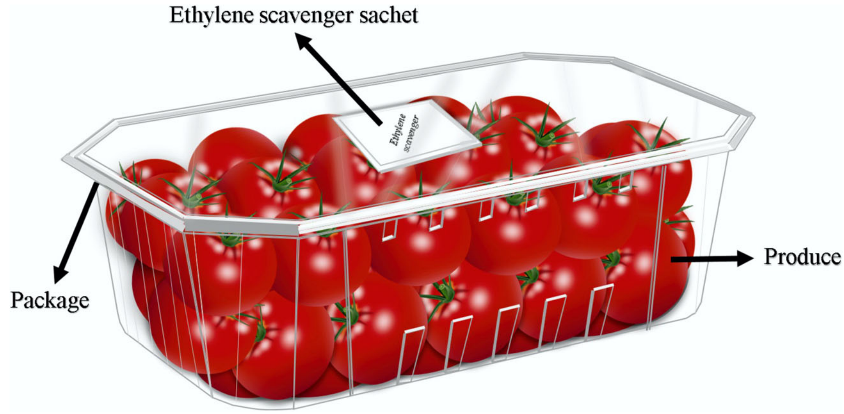

**Fig. 3** Schematic representation of an $C_2H_4$-scavenger sachet used in horticultural produce packaging

indirect food additive is regulated by the Food and Drug Administration (FDA) under the Code of Federal Regulations (21 CFR §175.105 2018) [39]. General US FDA requirements for food contact applications are also established through the Code of Federal Regulations (21 CFR §177.1520 2018 and 21 CFR §177.2010 2018) [40, 41], while the European Union has specific requirements related to active packaging and its non-active parts that are regulated by the Regulation 1935/2004/EC and Regulation 450/2009/EC [63, 64]. Particularly, Regulation 450/2009/EC establishes a legal basis for active packaging safety and marketing [83]. The European Union and US regulation aspects concerning active and intelligent food packaging have been extensively discussed by Dainelli et al. [50] and Restuccia et al. [127].

On the other hand, the high oxidising power, either in heterogeneous conditions or without solvents, makes permanganate and its compounds of particular environmental concern. However, the permanganate oxidation process is considered to be eco-friendly [51]. In fact, permanganate (specifically, $KMnO_4$) has been defined as a green oxidant in organic chemistry since the inorganic coproducts (particularly, $MnO_2$) can be re-oxidised to permanganate, providing a sustainable approach [141, 147]. Therefore, as a green oxidant, $KMnO_4$ has been widely used in industrial and agricultural processes, including air purification (by removing $C_2H_4$, pollutants such as sulphur dioxide ($SO_2$), hydrogen sulphide ($H_2S$), aldehydes and other volatile organic compounds), water treatment to remove pollutants such as algal toxins and pharmaceuticals, as a bleaching agent in textile industry and as an antimicrobial agent in pesticide products [51, 147, 154].

$KMnO_4$ is not listened on the WHO Environmental Health Criteria Documents [164]. However, since $KMnO_4$ is typically used at full scale for water treatment applications [61, 73], it is regulated by the United States Environmental Protection Agency under the chemical code number 068501 because high doses can be harmful to aquatic life [60]. $KMnO_4$ is classified by the Globally Harmonized System as a very toxic agent to aquatic organisms under code numbers H400 and H410 [156]. Hence, $KMnO_4$-based products should not be released into the environment (prevent from reaching water bodies such as lakes and rivers, soil and sewage systems). In addition, since $KMnO_4$ is a strong oxidant agent, it can enhance combustion of other substances and can also release irritating or toxic fumes in a fire; thus, $KMnO_4$-based products should be stored, disposed and separated from reducing, flammable and combustible substances [78]. Nevertheless, when $KMnO_4$ is supported onto a solid material, the aforementioned $MnO_2$ re-oxidation process is interfered [141]. The above gives rise to non-toxic and chemically inert by-products (Eq. 4) that do not represent an environmental concern and can be disposed of as normal waste [91, 135]. Therefore, $KMnO_4$-based $C_2H_4$ scavengers can be considered an environmental-friendly tool that can be used in active packaging technology for horticultural products, with proper handling and relevant safety measures.

## Effects of Potassium Permanganate-Based Ethylene Scavengers on Postharvest Quality of Fresh Produce

As earlier mentioned, significant effort has been made to elucidate $KMnO_4$ effects on quality attributes of both climacteric fruit and non-climacteric produce. Tables 1 and 2 show how $KMnO_4$-based products may be used to delay some physicochemical changes associated with produce ripening and senescence. However, cultivar, maturity stage, storage period and storage conditions, as well as the presence of exogenous $C_2H_4$ during storage or transportation, are some factors that may counteract the effect of these $KMnO_4$-based tools [117]. For instance, in climacteric fruit, the rate and intensity of $C_2H_4$ production are higher at the ripe stage, regarding mature and half ripe stages [118]. The latter fact can be observed in the studies carried out by Bhutia et al. [19] and Amarante and Steffens [6, 7], where the effect of $KMnO_4$-based $C_2H_4$ scavengers on 'Kallipati' sapote, 'Gala' apple and 'Royal Gala' apple was evaluated at different ripening stages. The results indicated that the $C_2H_4$ scavengers may retard the physiological and physicochemical processes in sapote and 'Gala' apple

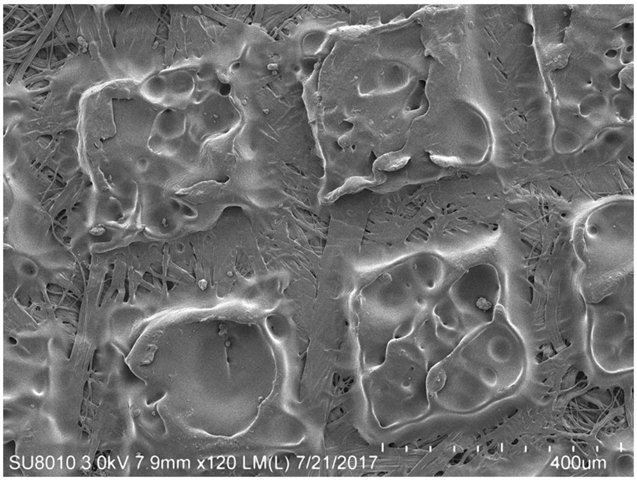


**Fig. 4** Scanning electron microscope image of DuPont™ Tyvek®

independently of the maturity stage, although the effects were more pronounced in fruit harvested and stored at a mature stage [6, 19]. Meanwhile, the influence of the maturity stage on the efficiency of $C_2H_4$ scavengers was found to be more marked in 'Royal Gala' apple [7]. Amarante and Steffens [7] reported that, despite having removed the total amount of $C_2H_4$ inside the apple package at each maturation stage, it was only possible to delay the ripening process in fruit harvested at less advanced maturation stage, while in fruit with a higher maturity stage, no significant effect was observed. The authors attributed such results to the fact that the $C_2H_4$ production rate increases along with the ripening process, causing a higher accumulation of $C_2H_4$ inside the package and hindering the $C_2H_4$ removal efficiency. Thus, the effect of $C_2H_4$ scavengers to delay the ripening process and extend the fruit and vegetable shelf life is more evident when they are harvested at the mature green stage. Therefore, it is recommended to harvest fruit and vegetables at the latter maturation stage or before the autocatalytic production of $C_2H_4$ in order to obtain the maximum benefit from the $C_2H_4$ scavengers.

In addition, because the responses to $KMnO_4$-based $C_2H_4$ scavengers may vary between cultivars and species, in the following subsections, apple, banana, mango and tomato are used to illustrate the range of responses to $KMnO_4$-based $C_2H_4$ scavengers since most of the literature available focuses on the study of such products. Nonetheless, an outline of the general responses of other climacteric fruit and non-climacteric produce to $KMnO_4$-based $C_2H_4$ scavengers is provided to illustrate the potential for use and both benefits and limitations that may be reached by using $KMnO_4$-based technology.

## Apple

$KMnO_4$-based $C_2H_4$ scavengers within apple packages at low storage temperature (0–4 °C) have shown positive effects on quality parameters, being effective to delay maturation process and then prolonging its shelf life up to 8 months [31]. Particularly, in 'Gala', 'Royal Gala', 'Golden Delicious' and 'Brookfield' cultivars, the incorporation of a $KMnO_4$-based $C_2H_4$ scavenger into the storage container has been shown to decrease pulp firmness loss and to delay shell yellowing (Tables 1 and 2). Shorter et al. [143] and Knee and Hatfield [95] reported that bitter pit and superficial scald was reduced in 'Granny Smith' and 'Golden Delicious' apple, respectively, by scavenging $C_2H_4$ with $KMnO_4$-based tools.

On the other hand, the titratable acidity (TA) and soluble solid content (SSC) behaviours throughout the ripening process depend on the variety in question. Therefore, $KMnO_4$ effects on TA and SSC parameters are different in each variety. The latter fact may be explained since each variety has its unique characteristics. For example, the storage of 'Golden Delicious' apple under MAP conditions together with a $KMnO_4$-based $C_2H_4$ scavenger at low temperature led to a lower TA decrease and a lower SSC accumulation [137]. Meanwhile, the TA decrease in 'Gala' variety was delayed, and SSC was not affected [6, 29]. The opposite effect was observed in 'Royal Gala' apple with the SSC increase minimised while the TA behaviour was unaffected [7].

In general, it can be concluded that $KMnO_4$-based $C_2H_4$ scavengers are a useful tool to delay the de-greening process and pulp firmness loss in apple fruit, as well as to reduce flavour changes or variations in sugars and free organic acid contents throughout storage at low temperatures. Furthermore, physiological disorders may also be decreased in refrigerated apples by using $KMnO_4$-based $C_2H_4$ scavengers.

## Banana

Very good results can be obtained by removing $C_2H_4$ from the surrounding fruit atmosphere, especially for long-distance transportation. In this sense, Wills et al. [170] reported that the green life of 'Cavendish' banana can be increased of about 27 days at 15 °C, 17 days at 20 °C and 11 days at 25 °C by reducing the $C_2H_4$ concentration from 1.0 to 0.01 $\mu L\ L^{-1}$.

From different research studies, the incorporation of $KMnO_4$-based tools inside packages, storage rooms or banana reefers has shown to be effective in delaying the chlorophyll degradation process—and then, the shell yellowing process—reducing weight loss and slowing down the softening process during storage [69, 136, 155, 177].

On the other hand, as mentioned above, the TA and SSC changes are different depending on the characteristics of the product. In this sense, several authors pointed out that both TA and SSC factors tended to increase throughout the storage period of banana fruit [136, 155, 177]. Meanwhile, García et al. [69] found that SSC increased while TA tended to decrease during the baby banana storage period. In agreement with the authors, a similar SSC and TA behaviour was observed in 'Prata Aña' banana by Prill et al. [121]. However, in general, it has been observed that changes in TA and SSC can be delayed by incorporating $KMnO_4$-based materials into banana packages regardless of whether the TA and SSC tend to increase or decrease [69, 136, 155, 177]. Moreover, the SSC/TA ratio tends to increase in banana fruit throughout storage, but García et al. [69] and Tourky et al. [155] reported that the said increasing trend was reduced in baby banana and 'Williams' cultivar, respectively, by packaging fruit with $KMnO_4$-based tools.

The banana pulp/peel ratio is a quality parameter that indicates differential changes in the moisture content of skin and pulp. This parameter tends to increase throughout the maturation process due to a differential change in osmotic pressure driven by the sugars increase in the pulp [155]. Nevertheless, Chauhan et al. [43] reported that the pulp/peel ratio changes in 'Pachbale' bananas can be delayed if the fruit is packaged into a PE bag together with a $KMnO_4$-based $C_2H_4$ scavenger (5 g of scavenger per kg of fruit) and stored 18 days at 13 ± 1 °C. Similarly, 'Williams' banana stored in PE bags together with a $KMnO_4$-based $C_2H_4$ scavenger (20 g of $KMnO_4$ per 3 hands) showed a slight delay in the increase of pulp/peel ratio during 45 days at 20 ± 2 °C [177]. Nevertheless, the incorporation of a similar $C_2H_4$-scavenger tool inside a 'Raja Bulu' banana package (approximately 60 g of scavenger per kg of fruit) did not affect the pulp/peel ratio during 18 days at 27–30 °C [136].

Based on the above, $KMnO_4$-based $C_2H_4$-scavenger sachets are a useful tool in conjunction with the passive MAP technique to preserve the green life of banana fruit during transportation. Nonetheless, the search for innovative and promising packaging technologies continues. In this sense, a new kind of technology consisting of membranes made of alumina nanoparticle (ANP)-incorporated alumina nanofibres (ANF) loaded with $KMnO_4$ was recently developed by Tirgar et al. [154]. In order to evaluate the effectiveness of the developed membranes, the authors performed a shelf life study by packing banana fruit into bags containing the developed membrane. Results showed that $KMnO_4$ incorporated into ANP-incorporated ANF membranes has the potential to remove a great amount of $C_2H_4$ in the package and to delay the incidence of dark brown regions on the skin and flesh softening of banana fruit. However, it must be taken into account that every food contact material must comply with a strict series of requirements before considering their commercial application [50, 127].

## Mango

The $KMnO_4$-based $C_2H_4$-scavenger effects have been also studied on mangoes. Ezz and Awad [65] studied its effects on 'Hindi Basennara' and 'Alphonse' mangoes packaged under MAP conditions and stored at 8 °C. The results showed fewer weight losses in both mango varieties, but no effect on firmness loss was observed. Similarly, Jeronimo et al. [84] studied the effect of $KMnO_4$-based $C_2H_4$ scavengers on 'Tommy Atkins' mangoes at 13 ± 1 °C. However, no significant effect was observed on fruit firmness loss nor on weight loss. At the end of the aforementioned studies, higher TA/ascorbic acid values and lower SSC were observed in the three studied mango cultivars regarding that fruit packed without an $C_2H_4$-scavenger tool. Furthermore, Jeronimo et al. [84] noted that $C_2H_4$ removal from the package slowed fruit metabolism resulting in lower SSC and TA changes. Hence, $C_2H_4$ scavengers are an effective tool to complement the MAP for maintaining the quality of the mango fruit.

## Tomato

The use of $KMnO_4$-based $C_2H_4$ scavengers has also shown good results in tomatoes, regarding quality maintenance during storage. Mujtaba et al. [114] found that packaging 'Rio Grandi' tomato into PE bags together with a $KMnO_4$-based $C_2H_4$ scavenger can decrease SSC/ascorbic acid increment, induce TA to increase and retard lycopene biosynthesis, without effects on fruit pH. Moreover, the use of a $KMnO_4$-based $C_2H_4$ scavenger in 'Chonto' tomato packaging can help to achieve lower weight and firmness losses and to slow SSC increment while TA is not affected [132].

## Other Climacteric Fruit

The effect of $KMnO_4$-based $C_2H_4$ scavenger has been also evaluated on other climacteric fruits such as papaya, quince fruit, fig, kiwi, sapote and sugar apple (Table 1). Particularly, the incorporation of a $KMnO_4$-based $C_2H_4$ scavenger inside the 'Sunrise Golden' papaya package can help to reduce pulp consistency loss and the SSC increment, in addition to minimising peel colour changes [144]. Based on similar observations, Bal and Celik [12] reported that 'Hayward' kiwi maturity process can be delayed by fruit packaging in conjunction with a $KMnO_4$-based $C_2H_4$ scavenger, which showed to be helpful to decrease firmness loss and TA changes, delay SSC increment and delay chlorophyll degradation.

Although a lower β-carotene content was observed by incorporating a $KMnO_4$-based $C_2H_4$ scavenger into the packaging of 'Isfahan' quince fruit, less firmness loss was observed [3]. Meanwhile, SSC increment, TA decrease, weight losses and firmness losses can be delayed during the storage of 'Kallipati' sapote by using $KMnO_4$-based $C_2H_4$ scavengers [19]. In sugar apple fruit, lower weight loss, lower SSC and TA increase and a mild pH decrease were found after the incorporation of $KMnO_4$-based $C_2H_4$ scavengers [44].

As can be seen from previously reported studies, the application of $KMnO_4$-based $C_2H_4$ scavengers in climacteric fruit packaging has mainly resulted in positive effects regarding quality maintenance. Nevertheless, some studies have not reported significant effects after incorporation of a $KMnO_4$-based scavenger into the packaging. Sá et al. [130] did not find significant $C_2H_4$ removal effects on melon. In addition, only a slight decrease in colour changes and a reduction of ascorbic acid biosynthesis were observed in guava fruit after the incorporation of $KMnO_4$-based $C_2H_4$ scavenger into the package [58]. Therefore, these studies suggest that this postharvest technique is not completely justified in guava and melon, although more research is needed to elucidate these issues.

### Non-climacteric Produce

Few significant information concerning $KMnO_4$-based $C_2H_4$-scavenger effects on non-climacteric products is available (Tables 1 and 2). Nonetheless, good results have been found. For instance, cherry storage in conjunction with a $KMnO_4$-based $C_2H_4$ scavenger resulted in fewer weight and firmness losses, while a delay in both SSC and TA changes was also observed [59]. The 'Precoce de Itaquera' loquat shelf life was extended with the incorporation of a $KMnO_4$-based $C_2H_4$ scavenger into the package [35]. In another study on 'Teresópolis Gigante' cauliflower, it was possible to delay the chlorophyll degradation process by using an $C_2H_4$ scavenger [28]. Furthermore, 'Marathon' broccoli softening process was delayed when it was stored together with a sachet containing $KMnO_4$ [54]. As can be noted, $KMnO_4$-based $C_2H_4$ scavengers seem to be a useful tool to delay senescence processes of non-climacteric produce, but there is an insufficient body of trials to speculate on the potential of the technology on such produce.

## Factors Affecting Potassium Permanganate-Based Ethylene Scavenger Efficiency/Performance in Packaging Technology

The $C_2H_4$ removal efficiency of $KMnO_4$-based $C_2H_4$-scavenger materials mainly depends on temperature, humidity and the amount of material used [25, 168]. Furthermore, the success of a postharvest technology to ensure good quality maintenance without compromising the safety and nutritional value of produce depends on the good understanding of the produce biology and physiology [105, 157]. Then, it is important to consider the latter factors in order to achieve an optimal performance of the $C_2H_4$-scavenger material.

### Ethylene Scavenger Dose

Martínez-Romero et al. [110] pointed out that the cost–benefit could be optimised by adjusting the appropriate scavenger dose to remove $C_2H_4$ during the storage period of the shelf life of the target produce. Particularly, the application of $KMnO_4$-based $C_2H_4$-scavenger materials in sachet form is well suited for short storage periods. The use of such sachets is not recommended during long-term storage of high $C_2H_4$-producing commodities since the $C_2H_4$ scavenger may be rapidly saturated, requiring frequent sachet replacement [165].

In this sense, some authors have evaluated the effect of $KMnO_4$-based $C_2H_4$ scavengers by using different doses in order to determine the amount of scavenger material needed to remove as much $C_2H_4$ as possible from the in-package atmosphere. Brackmann et al. [29] needed to incorporate three sachets (each one containing 9 g of $KMnO_4$-impregnated material per 18 kg of fruit) inside the package of 'Gala' apples in order to reach an $C_2H_4$ concentration of 1.4 $\mu L\ L^{-1}$ after 15 days of storage at 4 °C. Meanwhile, an $C_2H_4$ concentration of 51.3 $\mu L\ L^{-1}$ was found inside the apple packages without $C_2H_4$ scavengers, and an $C_2H_4$ concentration of 3.78 $\mu L\ L^{-1}$ was reached by using just one $C_2H_4$-scavenger sachet. Amarante and Steffens [7] found no significant differences concerning the $C_2H_4$ in-package concentration nor on the 'Royal Gala' apple quality (shell colour, pulp firmness and SSC) after 2 months of storage at $0 \pm 0.5$ °C and 90–95% relative humidity (RH) using either one or two $C_2H_4$-scavenger sachets (10 g of $KMnO_4$-impregnated material each one per 18 kg fruit).

On the other hand, Santosa et al. [136] studied the effectiveness of three different doses of a $KMnO_4$-based $C_2H_4$ scavenger (10, 30 and 50 g of scavenger material containing 7.5% $KMnO_4$, per 6 fruit units) during storage of 'Raja Bulu' banana fruit up to 18 days at 27–30 °C. They found no significant differences in physical quality attributes (such as shell colour and weight loss) by using either 30 or 50 g of $C_2H_4$ scavenger. Therefore, they concluded that 30 g of $C_2H_4$ scavenger per 6 fruit is enough to delay the ripening process 'Raja Bulu' banana. In another study, García et al. [69] evaluated the baby banana response to different concentrations of support material and $KMnO_4$. They reported 1% *w*/*w* vermiculite and 1.5% *w*/*w* $KMnO_4$ (percentages based on fresh fruit weight) as the most favourable combination to maintain the baby banana quality at 18 °C and 70–80% RH for 16 days. The above percentages are similar to those reported by Salamanca et al. [132] for 'Chonto' tomato. The authors reported that the lowest weight loss and SSC, as well as the highest firmness, can be achieved by storing 'Chonto' tomato together with 5% zeolite and 1.5% $KMnO_4$ (percentages based on fresh fruit weight) during 28 days at 18 °C (85% RH).

Furthermore, Akbari and Ebrahimpour [3] reported that it is possible to delay the pulp firmness loss of quince fruit, colour change and accumulation of β-carotene by using 2.5 g of $KMnO_4$ per kg of fruit during 150 days at 0 °C (85–95% RH). Nevertheless, it was possible to retain a higher quince fruit firmness when 5 g of $KMnO_4$ per kg was used. In addition, Silva et al. [144] reported that 'Sunrise Golden' papaya can be preserved in good condition up to 25 days at

10 °C (85–95% RH) by incorporating a $KMnO_4$-impregnated vermiculite sachet (containing approximately 1.7 g of $KMnO_4$ per kg of fruit) inside the packaging.

As observed, suitable doses of $C_2H_4$ scavenger vary depending on the horticultural product. Accordingly, the $C_2H_4$-scavenger dose required to achieve a calibrated decrease in $C_2H_4$ concentration together with an increase in the commodity shelf life depends mainly on the $C_2H_4$ production of the packaged produce, as well as on the $C_2H_4$ uptake capacity of the $C_2H_4$-scavenger material [91, 110]. On the other hand, both the $C_2H_4$ production and the $C_2H_4$ sensitivity of produce are mainly influenced by maturity stage, packaging characteristics (including $O_2/CO_2/C_2H_4$ in-package concentrations) and storage conditions [19, 35, 149]. Thus, further studies are still needed to determine the minimum required $C_2H_4$-scavenger concentration for a specific product bearing in mind all of the above factors.

## Ethylene Removal Capacity of the Scavenger Material

As mentioned above, the $C_2H_4$ removal capacity of the scavenger material must be known in order to set the most appropriate $C_2H_4$-scavenger dose. However, the $C_2H_4$ removal capacity of the products is not always indicated by the manufacturers (Table 3). Nonetheless, it can be assayed by passing a continuous $C_2H_4$-enriched air flow through a cylindrical reactor containing the $C_2H_4$-scavenger material sample, in a similar way as is described by Terry et al. [153] and de Chiara et al. [52]. The assay is conducted until the reactor outlet $C_2H_4$ concentration reaches the inlet $C_2H_4$ concentration (breakthrough measurement). Finally, the $C_2H_4$ uptake capacity is usually estimated based on the ASTM D6646-03 standard (Standard Test Method for Determination of the Accelerated Hydrogen Sulfide Breakthrough Capacity of Granular and Pelletized Activated Carbon) by the American Society for Testing and Materials [11], which was developed for hydrogen sulphide, with some adaptations as follows:

$$\frac{\mathrm{g\ C_2H_4}}{\mathrm{cm^3\ C_2H_4\ scavenger\ product}} = \frac{\left(\frac{c}{100}\right) \times F \times t \times \left(\frac{1\,\mathrm{L}}{1000\,\mathrm{cm^3}}\right) \times \left(\frac{1\,\mathrm{mol}}{22.4\,\mathrm{L}}\right) \times \left(\frac{28.05\,\mathrm{g\ C_2H_4}}{\mathrm{mol}}\right)}{V} \quad (9)$$

The equation can be simplified to:

$$\frac{\mathrm{g\,C_2H_4}}{\mathrm{cm^3\ C_2H_4\ scavenger\ product}} = \frac{\left(1.25 \times 10^{-3}\mathrm{g\,cm^3}\right) \times C \times F \times t}{V} \quad (10)$$

where $C$ is the inlet $C_2H_4$ concentration in the air stream (volume %), $F$ is the total $C_2H_4$/air flow rate ($cm^3\ min^{-1}$), $t$ is the time to breakthrough (min), and $V$ is the volume of the $C_2H_4$-scavenger product contained in the reactor ($cm^3$).

Nonetheless, since the $C_2H_4$ uptake capacity is usually expressed in L $kg^{-1}$ units, the following equation can be obtained by replacing the volume variable ($V$) per weight ($W$) in Eq. 10, and then multiplying by the $C_2H_4$ density in order to change grams units per litre:

$$\frac{\mathrm{L\,C_2H_4}}{\mathrm{kg\ C_2H_4\ scavenger\ product}} = \frac{\left(1.25{*}10^{-3}\,\mathrm{g\,cm^3}\right){*}C{*}F{*}t}{W{*}\left(1.261\,\mathrm{g\,L\ C_2H_4}\right)} \quad (11)$$

where $W$ is the weight of the $C_2H_4$-scavenger product sample.

At this point, it is important to clarify that although the $C_2H_4$-scavenging capacity is an important feature to consider, it does not determine if one product is better than the other is. The most suitable product to remove $C_2H_4$ surrounding a commodity should be chosen based on the specific fruit or vegetable to be protected, the storage conditions and the desired market period since each produce has its own biological and physiological features [157].

## Packaging Material

The interaction between the product and the packaging material is very important since the atmospheric composition in the package depends on the produce type, packaging material and storage temperature [49]. MAP is characterised by retarding the maturation and senescence in fresh produce by slowing down their respiration and $C_2H_4$ production rates [108, 174]. According to Janjarasskul and Suppakul [83], the common approaches to decrease $C_2H_4$ production are reducing storage temperature and balancing $O_2$:$CO_2$ concentrations in MAP. Although, in turn, with the aim of reaching the optimum $O_2$:$CO_2$ ratio in the shortest period of time, the respiration rate and the $C_2H_4$ production of the produce will define the best suitable film according to its permeability characteristics [49, 108, 118].

In most studies regarding the use of the $KMnO_4$ effect on the quality of fresh commodities, the produce is packaged into commercially available polymer films (PE; polyvinyl chloride (PVC); polystyrene terephthalate (PET)) of 10–60 μm thicknesses (Table 1).

The effect of $KMnO_4$-based $C_2H_4$ scavengers on packaged products under different films has been evaluated by some authors, who have obtained interesting results. Akbari and Ebrahimpour [3] evaluated the effect of non-perforated PE bags and perforated PE bags as 'Isfahan' quince fruit packaging in conjunction with a $KMnO_4$-based tool during postharvest storage at 0 °C and 85–90% RH. They found that the overall quality was better maintained when quince fruit samples were stored in non-perforated PE bags for 75 days. Nevertheless, the fruit firmness was well maintained up to 150 days by using perforated bags. In contrast, Zewter et al. [177] reported that the chemical quality of bananas packaged in perforated bags together with $KMnO_4$ sachets and maintained at 14–18 °C (33–58% RH) was longer maintained (24 days) compared to samples stored in non-perforated bags (20 days). Such different results can be explained since the banana fruit has a high respiration rate and a high $C_2H_4$ production leading to higher gas permeability requirements of the film [177].

Furthermore, the activity of enzymes responsible for cell wall degradation, colour changes and $C_2H_4$ production may be slowed down by reducing the $O_2$ and $C_2H_4$ levels [119]. Moreover, $CO_2$ acts as an antagonist of the $C_2H_4$ action, while high $CO_2$ concentrations inhibit the activity of the enzymes 1-aminocyclopropane-carboxylate synthase and 1-aminocyclopropane-carboxylate oxidase, which catalyse the $C_2H_4$ synthesis pathway [96, 119, 166]. Therefore, $C_2H_4$ removal combined with the incremented $CO_2$/reduced $O_2$ reached by using MAP results in a synergistic system that causes a lower metabolic rate of the fruit or vegetable [83, 177].

## Storage Temperature

$KMnO_4$-based $C_2H_4$ scavengers may delay ripening under different storage temperatures as observed in Tables 1 and 2. It is well known that adsorption of any molecule depends on several parameters, including temperature, adsorbate (molecule to be adsorbed) concentration, pressure and RH [68]. Nevertheless, there is a lack of studies concerning temperature impact on the efficiency of $KMnO_4$-based $C_2H_4$ scavengers. Lidster et al. [103] reported that high temperature increases the $C_2H_4$ removal efficiency of both $KMnO_4$ crystals and $KMnO_4$ supported on aluminium oxide. However, Campos et al. [35] achieved the total removal of $C_2H_4$ by using $KMnO_4$-based $C_2H_4$ scavengers during loquat fruit storage at both 6 and 18 °C. Nevertheless, it should be noted that the $C_2H_4$ production of loquat fruit was lower at 6 °C than at 18 °C. Therefore, since the fruit $C_2H_4$ production is also reduced at low temperatures, the $C_2H_4$ removal efficiency reduction under low temperatures is not a big problem to deal with.

On the other hand, since the $C_2H_4$ production and the product $C_2H_4$ sensitivity is influenced by temperature, the optimum storage temperature depends on the commodity to be packaged [165]. Campos et al. [35] and Ezz and Awad [65] stated that better results could be obtained when the produce is stored under MAP at low temperatures. Such observation may be explained since low temperatures help to decrease the produce metabolism leading to less $C_2H_4$ production, which facilitates a complete $C_2H_4$ removal from the packaging [6, 65]. Conversely, although low-temperature storage is the most common tool for delaying ripening, some produce (i.e. some varieties of peach, grapefruit, lemon and lime, cucumbers, summer squash, eggplants and green beans) are susceptible to chilling injury under cold storage [74, 85]. Therefore, the appropriate storage temperature must be selected depending on the produce characteristics since some fruit and vegetables may show physiological disorders at unappropriated storage temperatures for them [119].

Additionally, temperature plays an important role in the permeability of polymeric films. Specifically, the exposure of the film to high temperatures decreases $O_2$ permeability and increases $CO_2$ permeability [134].

## Relative Humidity

High RH is needed to prevent the dehydration and weight loss in fruit and vegetables because transpiration significantly affects the physical and chemical properties of horticultural crops [85]. In addition, RH is another extrinsic factor that may affect the $C_2H_4$ adsorption efficiency, as previously stated. According to Chopra et al. [45], $H_2O$ molecules can compete for adsorption sites with $C_2H_4$. However, the $H_2O$ presence is required to carry out the $C_2H_4$ oxidation process [91]. In this sense, Janjarasskul and Suppakul [83] suggested that the moisture released from the transpiration and respiration of the produce helps in the activation of $KMnO_4$.

In a recent study, Spricigo et al. [150] evaluated the $C_2H_4$ removal capacity of silica and alumina particles impregnated with $KMnO_4$ at different RH levels (45, 60, 75 and 90%) for 1 h. They found that the $C_2H_4$ removal capacity of $KMnO_4$-impregnated alumina particles tend to increase as the RH increase. On the other hand, they also observed that the $C_2H_4$ removal capacity of $KMnO_4$–silica particles increased as the RH increased from 45 to 75% RH, while at 90% RH, a removal capacity decrease was observed. The $C_2H_4$ adsorption reduction of the $KMnO_4$–silica particles at high RH may be due to the competition between $C_2H_4$ and $H_2O$ molecules for binding sites since silica is a high $H_2O$ adsorber material and $H_2O$ molecules are adsorbed faster than those of $C_2H_4$ [45].

## Other Considerations

The scavenging capacity and efficiency/performance of $KMnO_4$-based $C_2H_4$ scavengers strongly depends on the support material properties and on the $KMnO_4$ concentration [68, 97]. In fact, a wide range of properties determine the ability of a material to act as an appropriate $KMnO_4$ support, such as pore structure, surface area, bulk density, surface chemistry and $KMnO_4$ uptake capacity [4]. Several studies have demonstrated that support materials with higher surface areas, lower bulk densities and higher $KMnO_4$ uptake capacity are more efficient in reducing $C_2H_4$ levels [150, 154]. In addition, it should be considered that the support material could be able to absorb $C_2H_4$ from the atmosphere, but also it could absorb other organic compounds, negatively altering the fresh commodity characteristics [68, 83, 116]. However, we will not delve into this issue since a comprehensive review, specifically dedicated to supporting materials commonly used for $KMnO_4$-based $C_2H_4$ scavengers, has recently been published [4].

## Conclusions and Future Perspectives

The physicochemical parameters, sensory quality and nutritional properties of fresh fruit and vegetables can be preserved for a longer time by combining modified atmosphere packaging and $C_2H_4$-scavenging systems such as those based on $KMnO_4$. Furthermore, reducing $C_2H_4$ action could help to reduce postharvest losses, improve food safety and help economic sustainability. Therefore, an increasing interest in $C_2H_4$ scavengers has been paid in the last years. Related companies have invested intense research on this issue in order to develop new materials and technologies to improve the efficiency of the current $C_2H_4$ scavengers. At this point, special attention has been given to the application of nanotechnology. In addition, it is possible to chemically, or physically, modify the support material structure to improve the $KMnO_4$ incorporation. Nevertheless, although the $C_2H_4$-scavenging technology has been widely used during the last decades, and some commercial products are already available, an important research effort at both laboratory and industrial scales is still needed. More specific technical data concerning application conditions of the different $C_2H_4$ scavengers is required. It is necessary to study the optimal use conditions of each material, such as the recommended temperature and RH to obtain the maximum benefit from the scavenger. Additionally, it is necessary to demonstrate the $C_2H_4$-scavenger performance under other critical storage parameters taking into account the metabolic rate of the packaged produce, which depends on the kind of commodity, variety and maturity stage and also on the packaging material. Especially, efforts at understanding and modelling the $C_2H_4$-scavenging dynamic processes of $KMnO_4$-based products are needed. On the other hand, consumers have a lower level of awareness on the $KMnO_4$-based $C_2H_4$-scavenging technology efficacy and safety, resulting in lower acceptance, and then affecting its commercialisation. Therefore, the continuous improvement of consumer awareness is needed.

**Acknowledgements** The authors express their gratitude to all companies which gave their information about their products and especially to those that have worked with us in this area. Finally, the authors would like to thank Dr. Jorge A. Cañas-Montoya (Universidad Autónoma de Coahuila, México) for the SEM image.

**Funding Information** The authors are grateful to CONACYT (National Council of Science and Technology of Mexico) for the postgraduate grant (No. 291212) provided to Marianela Hazel Álvarez-Hernández.



## References

1. AgraCo Technologies International LLC (2014) Frequently asked questions of our ethylene removal products. AgraCo Technologies International, LLC http://www.agraconew.com. Accessed 06 Jan 2019
2. AgraCo Technologies International LLC (n.d.) Extend-a-life ethylene removal systems. All about ethylene and the solution for removal. http://www.pottersmix.com. Accessed 06 Jan 2019
3. Akbari H, Ebrahimpour H (2014) Potassium permanganate and packing types impacts on postharvest quality and storage period of quince fruit (*Cydonia oblonga* Mill). Int J Adv Life Sci 7:267–275
4. Álvarez-Hernández M, Artés-Hernández F, Ávalos-Belmontes F, Castillo-Campohermoso M, Contreras-Esquivel J, Ventura-Sobrevilla J, Martínez-Hernández G (2018) Current scenario of adsorbent materials used in ethylene scavenging systems to extend fruit and vegetable postharvest life. Food Bioprocess Technol 11:511–525. https://doi.org/10.1007/s11947-018-2076-7
5. Álvarez-Hernández M, Martínez-Hernández G, Avalos-Belmontes F, Rodríguez-Hernández A, Castillo-Campohermoso M, Artés-Hernández F (2019) An innovative ethylene scrubber made of potassium permanganate loaded on a protonated montmorillonite: a case study on blueberries. Food Bioprocess Technol 12:524–538. https://doi.org/10.1007/s11947-018-2224-0
6. Amarante C, Steffens C (2009a) O tratamento pré-colheita com AVG, aliado à absorção do etileno durante o armazenamento refrigerado, preserva a qualidade de maçãs 'Gala'. Rev Bras Frutic 31:334–342. https://doi.org/10.1590/S0100-29452009000200007
7. Amarante C, Steffens C (2009b) Sachês absorvedores de etileno na pós-colheita de maçãs 'Royal Gala'. Rev Bras Frutic 31:71–77. https://doi.org/10.1590/S0100-29452009000100011
8. Araújo F, Silva T, Ramos P, Guimaraes A, Silva F, Finger F (2015) Longevity of *Epidendrum ibaguense* flowers affected by an ethylene absorber. Acta Hortic 1071:281–285. https://doi.org/10.17660/ActaHortic.2015.1071.35
9. Argenta L, Vieira M, Scolaro A (2009) Conservação da qualidade de caqui 'Fuyu' em ambiente refrigerado pela combinação de 1-MCP e atmosfera modificada. Rev Bras Frutic 31:323–333. https://doi.org/10.1590/S0100-29452009000200006
10. Artés F, Gómez P, Aguayo E, Escalona V, Artés-Hernández F (2009) Sustainable sanitation techniques for keeping quality and safety of fresh-cut plant commodities. Postharvest Biol Technol 51:287–296. https://doi.org/10.1016/j.postharvbio.2008.10.003
11. ASTM (2014) ASTM D6646-03 (2014), standard test method for determination of the accelerated hydrogen sulfide breakthrough capacity of granular and pelletized activated carbon. ASTM International, West Conshohocken. https://doi.org/10.1520/D6646-03R14
12. Bal E, Celik S (2010) The effects of postharvest treatments of salicylic acid and potassium permanganate on the storage of kiwifruit. Bulgarian J Agric Sci 16:576–584
13. Basuki E, Prarudiyanto A (2017) Inactivation of ACC oxidase (Acco) during modified atmosphere storage (MAS) of mango. Int J Sci Technol Res 6:167–172
14. Befresh Technology (2018a) ¿Qué es BEfresh? Befresh Technology, S.L. http://www.befreshtech.com. Accessed 06 Jan 2019
15. Befresh Technology (2018b) Soluciones para la purificación del aire. Befresh Technology, S.L. http://www.befreshtech.com. Accessed 06 Jan 2019
16. Berezkin K, Fomchenko A, Aslapovskaya Y, Gromova O, Bekhtereva E, Maul K (2017) High-resolution spectroscopy of the $CH_2 = CD_2$ molecule: analysis of the hot $\nu_7 + \nu_{10} - \nu_{10}$ band. Russ Phys J 60:557–561. https://doi.org/10.1007/s11182-017-1108-5

17. Bhattacharjee D, Dhua R (2017a) Ethylene absorbents improve the shelf life of pointed gourd (*Trichosanthes dioica* Roxb.) fruits. Int J Pure Appl Biosci 5:64–71. https://doi.org/10.18782/2320-7051.2450
18. Bhattacharjee D, Dhua R (2017b) Influence of ethylene absorbents on shelf life of bitter gourd (*Momordica charantia* L.) fruits during storage. Int J Curr Microbiol App Sci 6:1553–1563. https://doi.org/10.20546/ijcmas.2017.605.169
19. Bhutia W, Pal R, Sen S, Jha S (2011) Response of different maturity stages of sapota (*Manilkara achras* Mill.) cv. Kallipatti to in-package ethylene absorbent. J Food Sci Technol 48:763–768. https://doi.org/10.1007/s13197-011-0360-x
20. Bioconservacion (2015a) Bi-On® R8 technical datasheet. http://www.subsoleservicios.cl. Accessed 06 Jan 2019
21. Bioconservacion (2015b) Bi-On® R12 technical datasheet. http://www.subsoleservicios.cl. Accessed 06 Jan 2019
22. Biopac (n.d.) Ethylene control. BIOPAC Pty ltd. http://www.biopac.com.au. Accessed 06 Jan 2019
23. BIOXTEND (2012) BioX® granule. BioXTEND Co. http://www.bioxtend.com. Accessed 06 Jan 2019
24. Blanke M (2014) Reducing ethylene levels along the food supply chain: a key to reducing food waste? J Sci Food Agric 94:2357–2361. https://doi.org/10.1002/jsfa.6660
25. Bodbodak S, Rafiee Z (2016) Recent trends in active packaging in fruits and vegetables. In: Siddiqui MW (ed) Eco-friendly technology for postharvest produce quality. Academic, London, pp 77–125. https://doi.org/10.1016/B978-0-12-804313-4.00003-7
26. Bouzo C, Travadelo M, Gariglio N (2012) Effect of different packaging materials on postharvest quality of fresh fig fruit. Int J Agric Biol 14:821–825
27. Brackmann A, Saquet A (1999) Low ethylene and rapid CA storage of 'Gala' apples. Acta Hortic (485):79–84. https://doi.org/10.17660/ActaHortic.1999.485.9
28. Brackmann A, Trevisan J, Martins G, Freitas S, Mello A (2005) Qualidade pós-colheita de couve-flor 'Teresópolis gigante' tratada com etileno, absorvedor de etileno e 1-metilciclopropeno. Ciênc Rural 35:1444–1447. https://doi.org/10.1590/S0103-84782005000600035
29. Brackmann A, Hettwer R, Tonetto S, Eisermann A, Machado A (2006) Uso de filmes de polietileno e absorção de etileno para o transporte refrigerado de maçã 'Gala'. Semina: Ciências Agrárias 27:423–428
30. Brackmann A, Thewes F, Anese R, Both V (2014) Effect of growth regulators on 'Brookfield' apple gas diffusion and metabolism under controlled atmosphere storage. Pesq Agrop Brasileira 49:323–329. https://doi.org/10.1590/S0100-204X2014000500001
31. Brackmann A, Thewes F, Santos L, Machado E, Ludwig V, Artmann L (2015) Effect of growth regulators application on the quality maintenance of 'Brookfield' apples. Bragantia 74:453–456. https://doi.org/10.1590/1678-4499.0050
32. Brody A, Strupinsky E, Kline L (2001) Ethylene control. In: Brody A, Strupinsky E, Kline L (eds) Active packaging for food applications. CRC, Boca Raton
33. Bry-Air (Asia) Pvt. Ltd (2017) Granular media BRYSORBTM series for gas phase filtration systems product brochures. Bry-Air (Asia) Pvt. Ltd. https://bryair.com. Accessed 06 Jan 2019
34. Buzby JC, Farah-Wells H, Hyman J (2014) The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States. USDA-ERS Economic Information Bulletin Number 121 https://doi.org/10.2139/ssrn.2501659
35. Campos J, Hasegawa P, Purgatto E, Lajolo F, Cordenunsi B (2007) Qualidade pós-colheita de nêsperas submetidas ao armazenamento sob baixa temperatura e atmosfera modificada. Food Sci Technol 27:401–407. https://doi.org/10.1590/S0101-20612007000200033
36. Castro J, Pfaffenbach L, Carvalho C, Rossetto C (2005) Effects of film packaging and cold storage on postharvest quality of 'Tommy Atkins' mangoes. Acta Hortic 682:1683–1688. https://doi.org/10.17660/ActaHortic.2005.682.224
37. Castro J, Conte R, Carvalho C, Rossetto C (2010) Effects of postharvest treatments and film packaging on quality of 'Haden 2H' mangoes. Acta Hortic 864:295–298. https://doi.org/10.17660/ActaHortic.2010.864.39
38. Cevik S, Yesil O, Ozturk T, Guneysel O (2012) Potassium permanganate ingestion as a suicide attempt. Clin Pract 2:e32–e32. https://doi.org/10.4081/cp.2012.e32
39. CFR (2018a) Adhesives, 21 CFR §175.105 2018. Electronic Code of Federal Regulations e-CFR. https://www.ecfr.gov
40. CFR (2018b) Ethylene polymer, chlorosulfonated, 21 CFR §177.2210 2018. Electronic Code of Federal Regulations e-CFR. https://www.ecfr.gov
41. CFR (2018c) Olefin polymers, 21 CFR §177.1520 2018. Electronic Code of Federal Regulations e-CFR. https://www.ecfr.gov
42. Chamara D, Illeperuma K, Galappatty T, Sarananda K (2000) Modified atmosphere packaging of 'Kolikuttu' bananas at low temperature. J Hortic Sci Biotechnol 75:92–96. https://doi.org/10.1080/14620316.2000.11511206
43. Chauhan O, Raju P, Dasgupta D, Bawa A (2006) Modified atmosphere packaging of banana (cv. Pachbale) with ethylene, carbon dioxide and moisture scrubbers and effect on its ripening behaviour. Am J Food Technol 1:179–189. https://doi.org/10.3923/ajft.2006.179.189
44. Chaves M et al (2007) Use of potassium permanganate in the sugar apple post-harvest preservation. Cienc Tecnol Aliment 5:346–351. https://doi.org/10.1080/11358120709487711
45. Chopra S, Dhumal S, Abeli P, Beaudry R, Almenar E (2017) Metal-organic frameworks have utility in adsorption and release of ethylene and 1-methylcyclopropene in fresh produce packaging. Postharvest Biol Technol 130:48–55. https://doi.org/10.1016/j.postharvbio.2017.04.001
46. Climent M (2015) El filtro que conserva las frutas y verduras frescas más tiempo. Unidad Editorial Información General S.L.U., El Mundo http://www.elmundo.es. Accessed 06 Jan 2019
47. Corrêa S et al (2005) Effect of the potassium permanganate during papaya fruit ripening: ethylene production. J Phys IV France 125:869–871. https://doi.org/10.1051/jp4:2005125201
48. Corrêa P, Resende O, Menezes D (2010) Ethylene absorption analysis in the modified atmosphere composition during the 'Hass' avocado conservation under different temperatures. Acta Hortic 864:317–322. https://doi.org/10.17660/ActaHortic.2010.864.42
49. Cortellino G, Gobbi S, Bianchi G, Rizzolo A (2015) Modified atmosphere packaging for shelf life extension of fresh-cut apples. Trends Food Sci Technol 46:320–330. https://doi.org/10.1016/j.tifs.2015.06.002
50. Dainelli D, Gontard N, Spyropoulos D, Zondervan-van E, Tobback P (2008) Active and intelligent food packaging: legal aspects and safety concerns. Trends Food Sci Technol 19:S103–S112. https://doi.org/10.1016/j.tifs.2008.09.011
51. Dash S, Patel S, Mishra B (2009) Oxidation by permanganate: synthetic and mechanistic aspects. Tetrahedron 65:707–739. https://doi.org/10.1016/j.tet.2008.10.038
52. de Chiara M, Pal S, Licciulli A, Amodio M, Colelli G (2015) Photocatalytic degradation of ethylene on mesoporous $TiO_2$/$SiO_2$ nanocomposites: effects on the ripening of mature green tomatoes. Biosyst Eng 132:61–70. https://doi.org/10.1016/j.biosystemseng.2015.02.008
53. de Souza W, Bezerra M, Dantas P, da Curnha A, Sales R (2017) Potassium permanganate effects on the quality and post-harvest conservation of sapodilla ( *Manilkara zapota* (L.) P.Royen) fruits

under modified atmosphere. Acta Agron 66:331–337. https://doi.org/10.15446/acag.v66n3.54579
54. DeEll J, Toivonen P, Cornut F, Roger C, Vigneault C (2006) Addition of sorbitol with $KMnO_4$ improves broccoli quality retention in modified atmosphere packages. J Food Qual 29:65–75. https://doi.org/10.1111/j.1745-4557.2006.00056.x
55. DeltaTrak Inc (2018) Air repair ethylene absorbers, 2018. DeltaTrak Inc. https://www.deltatrak.com. Accessed 06 Jan 2019
56. Dodd M, Bouwer J (2014) The supply value chain of fresh produce from field to home: refrigeration and other supporting technologies. In: Florkowski WJ, Shewfelt RL, Brueckner B, Prussia SE (eds) Postharvest handling, 3rd edn. Academic, San Diego, pp 449–483. https://doi.org/10.1016/B978-0-12-408137-6.00016-8
57. DuPont (2019) Tyvek® for food active packaging. DuPont. http://www.dupont.com. Accessed 12 May 2019
58. El-Anany A, Hassan G (2013) Impact of activated carbon from date pits, potassium permanganate and their combination on extending the postharvest quality of three maturity stages of guava during cold storage. Int J Postharvest Technol Innov 3:403–425. https://doi.org/10.1504/IJPTI.2013.060272
59. Emadpour M, Ghareyazie B, Rezai K, Omrani A, Mohammadi G (2009) Effect of potassium permanganate-coated nano-zeolites on cherry quality and shelf life. J Agric Eng Res 10:11–26
60. EPA (2018) Active ingredient listing. Office of Pesticide Programs. United States Environmental Protection Agency. https://ofmpub.epa.gov. Accessed 21 Nov 2018
61. EPA (n.d.) Permanganate. Drinking Water Treatability Database. United States of Environmental Protection Agency. https://iaspub.epa.gov. Accessed 21 Nov 2018
62. Ethylene Control Inc. (2015) Safety datasheet. Technical data sheet supplied by the manufacturer company
63. European Commission (2009) Commission Regulation (EC) No 450/2009 of 29 May 2009 on active and intelligent materials and articles intended to come into contact with food. *OJ L 135, 30.5.*2009. Official Journal of the European Union, Strasbourg
64. European Parliament and Council of the European Union (2004) Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC. *OJ L 338, 13.11.2004*
65. Ezz T, Awad R (2011) Effect of some post harvest treatments under different low temperature on two mango cultivars. Aust J Basic Appl Sci 5:1164–1174
66. Flink (n.d.) Filtro Easyfit technical datasheet. Flink. http://flink.pe. Accessed 06 Jan 2019
67. Forsyth F, Eaves C, Lockhart C (1967) Controlling ethylene levels in the atmosphere of small containers of apples. Can J Plant Sci 47: 717–718. https://doi.org/10.4141/cjps67-126
68. Gaikwad K, Lee Y (2017) Current scenario of gas scavenging systems used in active packaging—a review. Korean J Pack Sci Technol 23:109–117. https://doi.org/10.20909/kopast.2017.23.2.109
69. García J, Balaguera-López H, Herrera A (2013) Conservación del fruto de banano bocadillo (Musa AA Simmonds) con la aplicación de permanganato de potasio ($KMnO_4$). Rev Colomb Cienc Hortíc 6:161–171. https://doi.org/10.17584/rcch.2012v6i2.1974
70. Giraldo E, Szczerbanik M, Scottpez K, Paton J, Best D (2005) Effects of polyethylene bags, ethylene absorbent and 1-methylcyclopropene on the storage of Japanese pears. J Hortic Sci Biotechnol 80:162–166. https://doi.org/10.1080/14620316.2005.11511910
71. GreenKeeper (n.d.) Tipos de granulados. GREENKEEPER IBERIA, S.L. http://greenkeeperiberia.es. Accessed 06 Jan 2019
72. GreenKeeper Iberia SL (n.d.) Gama de granulado GK de Alta capacidad. Technical data sheet supplied by the manufacturer company. Madrid
73. Guan X, He D, Ma J, Chen G (2010) Application of permanganate in the oxidation of micropollutants: a mini review. Front Environ Sci Eng China 4:405–413. https://doi.org/10.1007/s11783-010-0252-8
74. Gudenschwager O, Defilippi B (2016) Fresh fruit aroma: an integrative overview for a complex flavor trait. In: Pareek S (ed) Postharvest ripening physiology of crops. CRC, Boca Raton, pp 513–552
75. Guo P, Fu Y, Liu X, Li D, Xu W (2018) Research and application progress on food active MAP packaging. In: Zhao P, Ouyang Y, Xu M, Yang L, Ren Y (eds) Applied sciences in graphic communication and packaging, vol 477. Lecture Notes in Electrical Engineering. Springer, Singapore, pp 495–501. https://doi.org/10.1007/978-981-10-7629-9_61
76. Illeperuma C, Jayasuriya P (2002) Prolonged storage of 'Karuthacolomban' mango by modified atmosphere packaging at low temperature. J Hortic Sci Biotechnol 77:153–157. https://doi.org/10.1080/14620316.2002.11511472
77. Illeperuma C, Nikapitiya C (2002) Extension of the postharvest life of 'Pollock' avocado using modified atmosphere packaging. Fruits 57:287–295. https://doi.org/10.1051/fruits:2002025
78. ILO (2015) 0672_Potassium permanganate. ICSC database. International Chemical Safety Cards (ICSCs). https://www.ilo.org. Accessed 11 May 2019
79. IPCS (1981) Manganese. Environmental health criteria 17. World Health Organization http://www.inchem.org/
80. IPCS (2010) The WHO recommended classification of pesticides by hazard and guidelines to classification 2009. World Health Organization & International Programme on Chemical Safety. World Health Organization. http://www.who.int
81. Ishaq S, Ahmed H, Masud T, Ali S (2009) Influence of post harvest calcium chloride application, ethylene absorbent and modified atmosphere on quality characteristics and shelf life of apricot (*Prunus armeniaca* L.) fruit during storage. Pak J Nutr 8:861–865. https://doi.org/10.3923/pjn.2009.861.865
82. ISOLCELL S.p.A (n.d.) PURETHYL. Assorbitore Purethyl. ISOLCELL S.p.A. https://storage.isolcell.com. Accessed 06 Jan 2019
83. Janjarasskul T, Suppakul P (2018) Active and intelligent packaging: the indication of quality and safety. Crit Rev Food Sci Nutr 58:808–831. https://doi.org/10.1080/10408398.2016.1225278
84. Jeronimo E, Brunini M, Arruda M, Cruz J, Gava G, Silva M (2007) Qualidade de mangas 'Tommy Atkins' armazenadas sob atmosfera modificada. Ciênc Agrotecnol 31:1122–1130. https://doi.org/10.1590/S1413-70542007000400027
85. Kader A (2002) Postharvest technology of horticultural crops, 3rd edn. UCANR Publications, Richmond
86. Kader A (2013) Postharvest technology of horticultural crops—an overview from farm to fork. Ethiop J Appl Sci Technol:1–8
87. Kaewklin P, Siripatrawan U, Suwanagul A, Lee YS (2018) Active packaging from chitosan-titanium dioxide nanocomposite film for prolonging storage life of tomato fruit. Int J Biol Macromol 112: 523–529. https://doi.org/10.1016/j.ijbiomac.2018.01.124
88. KEEPCOOL (2018a) Filtros de etileno. KEEPCOOL. http://keep-cool.es. Accessed 06 Jan 2019
89. KEEPCOOL (2018b) Filtros KEEPCOOL KF para almacenamiento refrigerado. KEEPCOOL. http://keep-cool.es. Accessed 06 Jan 2019
90. KEEPFRESH (2018) Products. BLUE TECK SYSTEMS, S.L. https://www.keepfresh.eu. Accessed 06 Jan 2019
91. Keller N, Ducamp M-N, Robert D, Keller V (2013) Ethylene removal and fresh product storage: a challenge at the frontiers of chemistry. Toward an approach by photocatalytic oxidation. Chem Rev 113:5029–5070. https://doi.org/10.1021/cr900398v
92. Ketsa S, Imsabai W, van Doorn W (2005) Effect of precooling and ethylene absorbent on the quality of dendrobium 'Pompadour'

flowers. Acta Hortic 669:367–372. https://doi.org/10.17660/ActaHortic.2005.669.48
93. Kim G-H, Wills R (1995) Effect of ethylene on storage life of lettuce. J Sci Food Agric 69:197–201. https://doi.org/10.1002/jsfa.2740690209
94. Kim G-H, Wills R (1998) Interaction of enhanced carbon dioxide and reduced ethylene on the storage life of strawberries. J Hortic Sci Biotechnol 73:181–184. https://doi.org/10.1080/14620316.1998.11510962
95. Knee M, Hatfield S (1981) Benefits of ethylene removal during apple storage. Ann Appl Biol 98:157–165. https://doi.org/10.1111/j.1744-7348.1981.tb00433.x
96. Köstekli M, Özdzikicierlev O, Cortés C, Zulueta A, Esteve M, Frígola A (2016) Role of potassium permanganate ethylene on physicochemical properties, during storage of five different tomato cultivars. MOJ Food Process Technol 3:281–289. https://doi.org/10.15406/mojfpt.2016.03.00069
97. Kruijf N, Beest M, Rijk R, Sipiläinen-Malm T, Losada P, Meulenaer B (2002) Active and intelligent packaging: applications and regulatory aspects. Food Addit Contam 19:144–162. https://doi.org/10.1080/02652030110072722
98. Ku V, Shohet D, Wills R, Kim G (1999) Importance of low ethylene levels to delay senescence of non-climacteric fruit and vegetables. Aust J Exp Agric 39:221–224. https://doi.org/10.1071/EA98123
99. Kyriacou M, Rouphael Y (2018) Towards a new definition of quality for fresh fruits and vegetables. Sci Hortic 234:463–469. https://doi.org/10.1016/j.scienta.2017.09.046
100. Lebersorger S, Schneider F (2014) Food loss rates at the food retail, influencing factors and reasons as a basis for waste prevention measures. Waste Manag 34:1911–1919. https://doi.org/10.1016/j.wasman.2014.06.013
101. Lee SY, Lee SJ, Choi DS, Hur SJ (2015) Current topics in active and intelligent food packaging for preservation of fresh foods. J Sci Food Agric 95:2799–2810. https://doi.org/10.1002/jsfa.7218
102. Li L, Lichter A, Chalupowicz D, Gamrasni D, Goldberg T, Nerya O, Ben-Arie R, Porat R (2016) Effects of the ethylene-action inhibitor 1-methylcyclopropene on postharvest quality of non-climacteric fruit crops. Postharvest Biol Technol 111:322–329. https://doi.org/10.1016/j.postharvbio.2015.09.031
103. Lidster P, Lawrence R, Blanpied G, McRae K (1985) Laboratory evaluation of potassium permanganate for ethylene removal from CA apple storages. Trans ASAE 28:331–0334. https://doi.org/10.13031/2013.32252
104. Liu M, Chervin C (2017) Ethylene and fruit ripening. In: Reference module in food science. Elsevier, pp 1–9. https://doi.org/10.1016/B978-0-08-100596-5.21256-0
105. López-Gómez A, Fernández P, Palop A, Periago P, Martinez-López A, Marin-Iniesta F, Barbosa-Cánovas G (2009) Food safety engineering: an emergent perspective. Food Eng Rev 1:84–104. https://doi.org/10.1007/s12393-009-9005-5
106. Mahajan P, Caleb O, Singh Z, Watkins C, Geyer M (2014) Postharvest treatments of fresh produce. Philos Trans R Soc A Math Phys Eng Sci 372:20130309. https://doi.org/10.1098/rsta.2013.0309
107. Manalili N, Dorado M, van Otterdijk R (2014) Appropriate food packaging solutions for developing countries. Food and Agriculture Organization of the United Nations (FAO), Rome
108. Mangaraj S, Goswami T, Mahajan P (2009) Applications of plastic films for modified atmosphere packaging of fruits and vegetables: a review. Food Eng Rev 1:133–158. https://doi.org/10.1007/s12393-009-9007-3
109. Mansourbahmani S, Ghareyazie B, Zarinnia V (2018) Study on the efficiency of ethylene scavengers on the maintenance of postharvest quality of tomato fruit. J Food Meas Charact 12:691–701. https://doi.org/10.1007/s11694-017-9682-3
110. Martínez-Romero D, Bailén G, Serrano M, Guillén F, Valverde JM, Zapata P, Castillo S, Valero D (2007) Tools to maintain postharvest fruit and vegetable quality through the inhibition of ethylene action: a review. Crit Rev Food Sci Nutr 47:543–560. https://doi.org/10.1080/10408390600846390
111. Miatech Inc. (2019) Erisfilter. Miatech, Inc. https://eris-filter.com. Accessed 06 Jan 2019
112. Molecular Products_Limited (2009) Ethysorb®. Molecular Products Limited. http://www.molecularproducts.com. Accessed 06 Jan 2019
113. Mortazavi S, Karami Z, Mostaan A (2015) Use of ethylene scavenger sachet in modified atmosphere packaging to maintain storage stability of khalal date fruit. Int J Postharvest Technol Innov 5:52–63. https://doi.org/10.1504/IJPTI.2015.072447
114. Mujtaba A, Masud T, Butt S, Qazalbash M, Fareed W, Shahid A (2014) Potential role of calcium chloride, potassium permanganate and boric acid on quality maintenance of tomato cv. Rio grandi at ambient temperature. Int J Biosci 5:9–20. https://doi.org/10.12692/ijb/5.9.9-20
115. Murmu SB, Mishra HN (2018) Selection of the best active modified atmosphere packaging with ethylene and moisture scavengers to maintain quality of guava during low-temperature storage. Food Chem 253:55–62. https://doi.org/10.1016/j.foodchem.2018.01.134
116. Ozdemir M, Floros JD (2004) Active food packaging technologies. Crit Rev Food Sci Nutr 44:185–193. https://doi.org/10.1080/10408690490441578
117. Palou L, Crisosto C (2003) Postharvest treatments to reduce the harmful effects of ethylene on apricots. Acta Hortic (599):31–38. https://doi.org/10.17660/ActaHortic.2003.599.1
118. Paul V, Pandey R, Srivastava G (2012) The fading distinctions between classical patterns of ripening in climacteric and non-climacteric fruit and the ubiquity of ethylene—an overview. J Food Sci Technol 49:1–21. https://doi.org/10.1007/s13197-011-0293-4
119. Pech JC, Purgatto E, Bouzayen M, Latché A (2012) Ethylene and fruit ripening. In: McManus MT (ed) Annual plant reviews volume 44. Wiley-Blackwell, West Sussex, pp 275–304. https://doi.org/10.1002/9781118223086.ch11
120. Pereira D, Cruz J, Paseiro P (2012) Active and intelligent packaging for the food industry. Food Rev Int 28:146–187. https://doi.org/10.1080/87559129.2011.595022
121. Prill M, Neves LC, Tosin JM, Chagas EA (2012) Atmosfera modificada e controle de etileno para bananas 'Prata-Anã' cultivadas na Amazônia Setentrional Brasileira. Rev Bras Frutic 34:990–1003. https://doi.org/10.1590/S0100-29452012000400005
122. Prodew (2012) Maintaining freshness from harvest to retail. Prodew. http://www.prodew.com. Accessed 06 Jan 2019
123. Prodew (2018) Ethylene control. Prodew. http://www.prodew.com. Accessed 06 Jan 2019
124. Purafil Inc. (2015) Product bulletin for purafil select media. Purafil, Inc https://www.purafil.com. Accessed 06 Jan 2019
125. Purafil Inc. (2019) Select. Purafil, Inc. https://www.purafil.com. Accessed 06 Jan 2019
126. Ramin A, Rezaei A, Shams M (2010) Potassium permanganates and short term hypobaric enhances shelf-life of kiwifruits. Acta Hortic (877):849–852. https://doi.org/10.17660/ActaHortic.2010.877.113
127. Restuccia D, Spizzirri UG, Parisi OI, Cirillo G, Curcio M, Iemma F, Puoci F, Vinci G, Picci N (2010) New EU regulation aspects and global market of active and intelligent packaging for food industry applications. Food Control 21:1425–1435. https://doi.org/10.1016/j.foodcont.2010.04.028
128. RETARDER SRL (n.d.) Conservazione. Assorbitori di Etilene. RETARDER SRL. http://www.retarder.it. Accessed 06 Jan 2019

129. Rouphael Y, Kyriacou MC (2018) Quality and safety of fresh fruits and vegetables at harvest. Sci Hortic 239:78–79. https://doi.org/10.1016/j.scienta.2018.05.006
130. Sá C, Oliveira E, Terao D, Hansen A (2008) Efeito do $KMnO_4$ e 1-MCP com atmosfera modificada na conservação pós-colheita de melão. Cantaloupe Revista Ciência Agronômica 39:60–69
131. Sabater-Vilar M, Suñé-Colell E, Castro-Chinchilla J, Sáenz-Murillo M (2018) Reduction of postharvest rotting with an ethylene absorbent: a case study with pineapple. Acta Hortic 1194: 721–728. https://doi.org/10.17660/ActaHortic.2018.1194.103
132. Salamanca F, Balaguera-López H, Herrera A (2014) Effect of potassium permanganate on some postharvest characteristics of tomato 'Chonto' fruits (*Solanum lycopersicum* L.). Acta Hortic 1016:171–176. https://doi.org/10.17660/ActaHortic.2014.1016.24
133. Saltveit ME (1999) Effect of ethylene on quality of fresh fruits and vegetables. Postharvest Biol Technol 15:279–292. https://doi.org/10.1016/S0925-5214(98)00091-X
134. Sandhya (2010) Modified atmosphere packaging of fresh produce: current status and future needs. LWT Food Sci Technol 43:381–392. https://doi.org/10.1016/j.lwt.2009.05.018
135. Santos A, Rosas J (2016) *In situ* chemical oxidation (ISCO). In: Albergaria J, Nouws H (eds) Soil remediation: applications and new technologies, 1st edn. CRC, Boca Raton
136. Santosa E, Widodo WD, Kholidi (2010) The use of clay as potassium permanganate carrier to delay the ripening of Raja Bulu banana. Jurnal Hortikultura Indonesia 1:88–95. https://doi.org/10.29244/jhi.1.2.88-95
137. Sardabi F, Mohtadinia J, Shavakhi F, Jafari AA (2014) The effects of 1-methylcyclopropen (1-MCP) and potassium permanganate coated zeolite nanoparticles on shelf life extension and quality loss of golden delicious apples. J Food Process Preserv 38:2176–2182. https://doi.org/10.1111/jfpp.12197
138. Scott K, Wills R (1974) Reduction of brown heart in pears by absorption of ethylene from the storage atmosphere. Aust J Exp Agric 14:266–268. https://doi.org/10.1071/EA9740266
139. Scott K, McGlasson W, Roberts E (1970) Potassium permanganate as an ethylene absorbent in polyethylene bags to delay ripening of bananas during storage. Aust J Exp Agric 10:237–240. https://doi.org/10.1071/EA9700237
140. Sensitech Inc. (2013) Ryan® ethylene absorption products from sensitech. Sensitech Inc. https://files.sensitech.com. Accessed 06 Jan 2019
141. Shaabani A, Rahmati A, Sharifi M, Rad J, Aghaaliakbari B, Farhangi E, Lee D (2007) Green oxidations. Manganese(II) sulfate aided oxidations of organic compounds by potassium permanganate. Monatsh Chem Chem Month 138:649–651. https://doi.org/10.1007/s00706-007-0667-5
142. Sharma R, Ghoshal G (2018) Emerging trends in food packaging. Nutr Food Sci 48:764–779. https://doi.org/10.1108/NFS-02-2018-0051
143. Shorter A, Scott K, Ward G, Best D (1992) Effect of ethylene absorption on the storage of Granny Smith apples held in polyethylene bags. Postharvest Biol Technol 1:189–194. https://doi.org/10.1016/0925-5214(92)90001-6
144. Silva D, Salomão L, Siqueira D, Cecon P, Rocha A (2009) Potassium permanganate effects in postharvest conservation of the papaya cultivar Sunrise Golden. Pesq Agrop Brasileira 44: 669–675. https://doi.org/10.1590/S0100-204X2009000700003
145. Silva F, Ribeiro W, França C, Araújo F, Finger F (2015) Action of potassium permanganate on the shelf-life of *Cucumis anguria* fruit. Acta Hortic 1071:105–111. https://doi.org/10.17660/ActaHortic.2015.1071.9
146. Singh R, Giri S (2014) Shelf-life study of guava (*Psidium guajava* L.) under active packaging: an experiment with potassium permanganate salt as ethylene absorbent. J Food Saf Food Qual 65:32–39. https://doi.org/10.2376/0003-925X-65-32
147. Singh N, Lee D (2001) Permanganate: a green and versatile industrial oxidant. Org Process Res Dev 5:599–603. https://doi.org/10.1021/op010015x
148. Slavin JL, Lloyd B (2012) Health benefits of fruits and vegetables. Adv Nutr 3:506–516. https://doi.org/10.3945/an.112.002154
149. Sousa-Gallagher M, Tank A, Sousa R (2016) Emerging technologies to extend the shelf life and stability of fruits and vegetables. In: Subramaniam P (ed) The stability and shelf life of food, 2nd edn. Woodhead Publishing, Duxford, pp 399–430. https://doi.org/10.1016/B978-0-08-100435-7.00014-9
150. Spricigo P, Foschini M, Ribeiro C, Corrêa D, Ferreira M (2017) Nanoscaled platforms based on $SiO_2$ and $Al_2O_3$ impregnated with potassium permanganate use color changes to indicate ethylene removal. Food Bioprocess Technol 10:1622–1630. https://doi.org/10.1007/s11947-017-1929-9
151. Suvanjinda P, Kangkhamanee S, Surawoot A, Suphatthra L, Chootummatat S, Charoensang U (2014) The development of technology to increase production efficiency for good quality longkong in the lower southern area. Acta Hortic 1024:133–140. https://doi.org/10.17660/ActaHortic.2014.1024.14
152. Taboada-Rodríguez A, García-García I, Cava-Roda R, López-Gómez A, Marín-Iniesta F (2013) Hydrophobic properties of cardboard coated with polylactic acid and ethylene scavengers. J Coat Technol Res 10:749–755. https://doi.org/10.1007/s11998-013-9493-3
153. Terry L, Ilkenhans T, Poulston S, Rowsell L, Smith A (2007) Development of new palladium-promoted ethylene scavenger. Postharvest Biol Technol 45:214–220. https://doi.org/10.1016/j.postharvbio.2006.11.020
154. Tirgar A, Han D, Steckl AJ (2018) Absorption of ethylene on membranes containing potassium permanganate loaded into alumina-nanoparticle-incorporated alumina/carbon nanofibers. J Agric Food Chem 66:5635–5643. https://doi.org/10.1021/acs.jafc.7b05037
155. Tourky M, Tarabih M, El-Eryan E (2014) Physiological studies on the marketability of Williams banana fruits. Am J Plant Physiol 9: 1–15. https://doi.org/10.3923/ajpp.2014.1.15
156. UNECE UNECfE (2009) Globally harmonized system of classification and labelling of chemicals (GHS), 3rd edn. United Nations, New York and Geneva
157. Valero D, Serrano M (2010) Postharvest biology and technology for preserving fruit quality, 1st edn. CRC, Boca Raton. https://doi.org/10.1201/9781439802670
158. Vilela C, Kurek M, Hayouka Z, Röcker B, Yildirim S, Antunes MDC, Nilsen-Nygaard J, Pettersen MK, Freire CSR (2018) A concise guide to active agents for active food packaging. Trends Food Sci Technol 80:212–222. https://doi.org/10.1016/j.tifs.2018.08.006
159. Wabali VC, Esiri A, Zitte L (2017) A sensory assessment of color and textural quality of refrigerated tomatoes preserved with different concentrations of potassium permanganate. Food Sci Nutr 5: 434–438. https://doi.org/10.1002/fsn3.410
160. Wang S, Zhou Q, Zhou X, Wei B, Ji S (2018) The effect of ethylene absorbent treatment on the softening of blueberry fruit. Food Chem 246:286–294. https://doi.org/10.1016/j.foodchem.2017.11.004
161. Watkins CB (2006) The use of 1-methylcyclopropene (1-MCP) on fruits and vegetables. Biotechnol Adv 24:389–409. https://doi.org/10.1016/j.biotechadv.2006.01.005
162. Watkins C (2007) The effect of 1-MCP on the development of physiological storage disorders in horticultural crops. Stewart Postharvest Rev 3:1–6. https://doi.org/10.2212/spr.2007.2.11
163. WHO (2017) WHO model list of essential medicines, 20th list (March 2017, amended August 2017). World Health Organization http://www.who.int

164. WHO (2018) Environmental health criteria. International Programme on Chemical Safety. World Health Organization https://www.who.int. Accessed 21 Nov 2018
165. Wills R (2015) Low ethylene technology in non-optimal storage temperatures. In: Wills R, Golding J (eds) Advances in postharvest fruit and vegetable technology, 1st edn. CRC, Boca Raton, pp 167–190. https://doi.org/10.1201/b18489
166. Wills R, Golding JB (2015) Reduction of energy usage in postharvest horticulture through management of ethylene. J Sci Food Agric 95:1379–1384. https://doi.org/10.1002/jsfa.6930
167. Wills R, Kim G (1995) Effect of ethylene on postharvest life of strawberries. Postharvest Biol Technol 6:249–255. https://doi.org/10.1016/0925-5214(95)00005-Q
168. Wills R, Warton M (2004) Efficacy of potassium permanganate impregnated into alumina beads to reduce atmospheric ethylene. J Am Soc Hortic Sci 129:433–438. https://doi.org/10.21273/JASHS.129.3.0433
169. Wills R, Warton M, Mussa D, Chew L (2001) Ripening of climacteric fruits initiated at low ethylene levels. Aust J Exp Agric 41:89–92. https://doi.org/10.1071/EA00206
170. Wills R, Harris D, Spohr L, Golding J (2014) Reduction of energy usage during storage and transport of bananas by management of exogenous ethylene levels. Postharvest Biol Technol 89:7–10. https://doi.org/10.1016/j.postharvbio.2013.11.002
171. Wongs-Aree C, Noichinda S (2011) Sugar apple (*Annona squamosa* L.) and atemoya (*A. cherimol*a Mill. × *A. squamosa* L.). In: Yahia EM (ed) Postharvest biology and technology of tropical and subtropical fruits. Mangosteen to white sapote. Woodhead Publishing, Cambridge, pp 399–427e. https://doi.org/10.1533/9780857092618.399
172. Wyrwa J, Barska A (2017) Innovations in the food packaging market: active packaging. Eur Food Res Technol 243:1681–1692. https://doi.org/10.1007/s00217-017-2878-2
173. Yadav M, Singh S, Singh D, Singh G (2010) Effect of ethylene absorbent on quality and shelf-life of mango (*Mangifera indica*). Indian J Agric Sci 80:832–834
174. Yahia E, Serrano M, Valero D, González-Aguilar G (2017) Influence of postharvest technologies and handling practices on phytochemicals in fruits and vegetables. In: Yahia EM (ed) Fruit and vegetable phytochemicals: chemistry and human health, 2nd edn. Wiley-Blackwell, West Sussex. https://doi.org/10.1002/9781119158042.ch27
175. Yildirim S, Röcker B, Pettersen MK, Nilsen-Nygaard J, Ayhan Z, Rutkaite R, Radusin T, Suminska P, Marcos B, Coma V (2018) Active packaging applications for food. Compr Rev Food Sci Food Saf 17:165–199. https://doi.org/10.1111/1541-4337.12322
176. Zagory D, Kader A (1988) Modified atmosphere packaging of fresh produce. Food Technol 42:70–77 76-77
177. Zewter A, Woldetsadik K, Workneh T (2012) Effect of 1-methylcyclopropene, potassium permanganate and packaging on quality of banana. Afr J Agric Res 7:2425–2437. https://doi.org/10.5897/AJAR11.1203
178. Zhang J, Cheng D, Wang B, Khan I, Ni Y (2017) Ethylene control technologies in extending postharvest shelf life of climacteric fruit. J Agric Food Chem 65:7308–7319. https://doi.org/10.1021/acs.jafc.7b02616
179. Zhang Y, Liu Q, Rempel C (2018) Processing and characteristics of canola protein-based biodegradable packaging: a review. Crit Rev Food Sci Nutr 58:475–485. https://doi.org/10.1080/10408398.2016.1193463