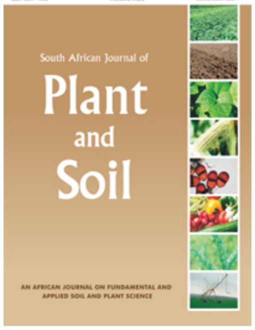

South African Journal of Plant and Soil

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjps20

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To cite this article: Bongolwethu P Mabusela, Zinash A Belay, Buntu Godongwana, Namrata Pathak, Pramod V Mahajan, Patricia M K Mathabe & Oluwafemi J Caleb (2021) Trends in ethylene management strategies: towards mitigating postharvest losses along the South African value chain of fresh produce – a review, South African Journal of Plant and Soil, 38:5, 347-360, DOI: 10.1080/02571862.2021.1938260

To link to this article: https://doi.org/10.1080/02571862.2021.1938260

Published online: 17 Dec 2021.

South African Journal of Plant and Soil 2021, 38(5): 347–360
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SOUTH AFRICAN JOURNAL OF PLANT AND SOIL
ISSN 0257-1862 EISSN 2167-034X
https://doi.org/10.1080/02571862.2021.1938260

Review

Trends in ethylene management strategies: towards mitigating postharvest losses along the South African value chain of fresh produce – a review

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The management of ethylene during postharvest storage is of critical importance to fresh produce wholesalers and retailers. The management of ethylene is an important determinant of the quality and shelf life of fresh fruit and vegetables. Ethylene blocking action and ethylene removal via potassium permanganate, photocatalytic oxidation and ozonation have been extensively researched and applied on a commercial scale to manage the impacts of ethylene postharvest. However, these techniques have certain inherent limitations that make them ineffective for long-term postharvest applications. This review therefore focuses on ethylene removal strategies during postharvest handling, and characterisation of the merits and demerits of such strategies. In addition, it provides an overview of emerging techniques such as photolysis, photocatalytic oxidation and ozone-assisted catalytic oxidation, as alternatives for ethylene management along the postharvest value chains. The intent of this review was to guide the development of more effective ethylene management technologies for long-term application in the South African fruit industry.

Keywords: ozone-assisted catalytic oxidation, photolysis, storage, vacuum ultraviolet

Introduction

In South Africa, 44% of fruit and vegetables are wasted, or lost before they reach the retail market shelves (WWF 2017). These losses severely influence livelihoods and the potential of the industry to meet market needs. Exposing harvested fruit and vegetables to ethylene has been found to have a beneficial or detrimental impact on fresh produce, depending on its functional role, initial concentration, and the extent of exposure (Saltveit 1999). If exposure of fresh produce to ethylene is not well managed it can induce various physiological processes, including senescence, discolouration and softening, and increased susceptibility to decay (Saltveit 1999; Pathak et al. 2017a). According to Wills et al. (1999), a reduction in the ethylene concentration from 0.1 $\mu L\ L^{-1}$ to > 0.005 $\mu L\ L^{-1}$ can increase the shelf life of fruit and vegetables by up to 60%. Hence, reducing ethylene concentrations during postharvest can have a beneficial impact via the reduction in the deleterious effects associated with accelerated ripening.

Nsumpi et al. (2019) conducted a routine mapping of ethylene hotspots within selected South African fruit packhouses with a questionnaire to survey ethylene management practices. The authors demonstrated from their survey that none of the packhouses use effective ethylene management strategies. Similarly, numerous ethylene hotspots were identified within the packhouses without any removal strategy besides ventilation. Furthermore, Nsumpi et al. (2020) established that mixed-fruit loading without effective ethylene management can have a negative impact on fruit quality and storage life.

Table 1 summarises the scope of existing review articles on ethylene management strategies published over the last two decades. None of these reviews offered an integrated postharvest ethylene management approach for South Africa's horticultural industry, packhouses or retail outlets. The aim of this review is therefore to provide a critical evaluation of the current techniques used for ethylene removal, taking into consideration their merits and limitations, in order to facilitate further research. We have highlighted the potential for integrating emerging techniques for ethylene management, such as vacuum ultraviolet (VUV) light photolysis and photocatalytic oxidation (PCO), along the South African postharvest value chains.

South African Journal of Plant and Soil is co-published by Informa UK Limited (trading as Taylor & Francis Group) and NISC (Pty) Ltd

Table 1: List of review articles on ethylene management published within the last two decades

Review focus/scope	Horticultural commodity	Technology limitations for long-term storage	Reference
Adsorbers combined with catalyst	Fruit and vegetable	Rapid saturation on frequent replenishment	Martínez-Romero et al. (2007)
Photocatalysis oxidation (PCO)	Fresh produce	Catalyst surface saturates over time	Keller et al. (2013)
Ozone-based	Fruit and vegetable	Harmful to human	Miller et al. (2013)
Ethylene control technologies (1-MCP)	Climacteric fruit	Not effective against exogenous ethylene	Zhang et al. (2017)
Absorbent materials	Fruit and vegetables	Rapid saturation on frequent replenishment	Álvarez-Hernández et al. (2017)
Potassium permanganate-based ethylene scavengers	Blueberries	Produces waste residues and toxic by-products	Álvarez-Hernández et al. (2019)
PCO and photolysis	Fresh produce	Electron-hole recombination and ozone production	Pathak et al. (2019)
Ethylene scavengers for active packaging (Absorbent)	Fresh produce	Suffer from adsorption capacity and requires frequent replenishment	Gaikwad et al. (2019)
Ethylene scavenging systems in packaging	Fresh produce	Not effective against exogenous ethylene Electron-hole recombination Produces waste residues	Sadeghi et al. (2019)
Ethylene-removing packaging	Food packaging	Challenges of integration technique: type of ethylene removers and packaging materials compatibility	Awalgaonkar et al. (2020)

Trends in ethylene management strategies

Table 2 summarises studies over the last ten years that assessed the beneficial impacts of ethylene removal on fruit and vegetables during storage. Commercial strategies and postharvest best practices for the handling of fruit and vegetables are based on various principles. These include: (i) inhibiting ethylene biosynthesis or production, and limitation or elimination of ethylene action during fruit ripening and harvest; (ii) avoidance of fresh product exposure to ethylene (control); and, (iii) active removal or scrubbing off of ethylene during storage and distribution (Watkins 2002; Pathak et al. 2017b,c). There are various technologies linked to these strategies as summarised in Table 3. However, most are not suitable for long-term storage, where it is necessary to continuously remove ethylene, during transportation over long distances or in closed storage facilities. Therefore, the development of new technologies that will ensure continuous ethylene removal is imperative.

Ethylene inhibitors

Hydrogen sulphide

Hydrogen sulphide (H_2S) has recently been identified as a gaseous plant growth regulator that can also inhibit fruit ripening and senescence in numerous fruit (Al Ubeed et al. 2018; Li et al. 2016; Li et al. 2017a). The application of H_2S has been shown to prevent ethylene-induced stomatal closure; however, the signalling pathways of H_2S and interaction with ethylene are still unclear (Jia et al. 2018). Al Ubeed et al. (2018) showed that both H_2S and 1-Methylcyclopropene (1-MCP) were effective in inhibiting chlorophyll degradation, preventing ion leakage, and slowing respiration, as well as endogenous ethylene production, for pak choy under ethylene-free air conditions. The effects of fumigation with H_2S on horticultural commodities are summarised in Table 3.

The extension of postharvest storage life due to H_2S has been attributed to the inhibition of various processes associated with senescence (Fotopoulos et al. 2015). H_2S is believed to be involved in the inhibition of endogenous ethylene production and the actions of ethylene (Al Ubeed et al. 2018). The possible role of H_2S in extending the storage life and conservation of fruit and vegetable quality have been recently reviewed by Ziogas et al. (2018) and Ali et al. (2019). However, in-depth research is still needed to determine the optimal application of H_2S for fresh produce. In addition, the commercial use of H_2S as a fumigant for fresh produce poses logistical and safety issues, while regulatory approval will also need to be obtained in the jurisdictions in which it is used. An alternative approach would be to use precursors of H_2S, such as cysteine (Ziogas et al. 2018; Ali et al. (2019).

Nitric oxide

Nitric oxide (NO), is a highly reactive free radical gas, that acts as a multifunctional signalling molecule in various plant physiological processes, such as fruit ripening and senescence (Aghdam et al. 2019; Wang et al. 2017; Wendehenne et al. 2004). Optimum NO concentrations have been reported to delay the climacteric phase of many tropical fruit and to prolong the postharvest storage life, by impeding ripening and senescence, and by suppressing the biosynthesis

Table 2: The benefits of ethylene removal for the quality of fruit and vegetables

Commodity	Beneficial impact	Reference
Strawberry	Maintained fruit quality for 15 d	Abdollahi et al. (2013)
Apple	Delayed ripening	Deyman et al. (2014)
Tomato	Decreased firmness,	Li et al. (2014a)
Papaya	Suppressed respiration, reduced mass loss, maintained firmness and delayed changes in peel colour	Li et al. (2014b)
Banana	Delayed ripening process	Zhu et al. (2015)
Mango	Delayed softening, decreased citric acid level and total sugars	Razzaq et al. (2016)
Green leafy vegetable	Delayed senescence	Al Ubeed et al. (2017)
Nectarine	Delayed ripening, reduced respiration and retained higher firmness	Bal (2018)
Mango	Reduced mass loss and delayed ripening	Elzubeir et al. (2017)
Kiwifruit	Reduced softening and development of skin darkening	Gabioud et al. (2018)
Broccoli	Reduced loss of chlorophyll and maintained texture and chemical composition	He and Xiao (2018)
Strawberry	Improved shelf life	Matar et al. (2018)
Mangoes	Delayed skin degreening and suppressed respiration	Pristijono et al. (2018)
Pineapple	Reduced peduncle mould	Sabater-Vilar et al. (2018)

of ethylene (Table 3). The successful application of NO is well documented in the literature for horticultural commodities (Manjunatha et al. 2012; Singh et al. 2013; Wang et al. 2016).

Zaharah and Sing (2011) investigated the effect of NO at a concentrations from 0–40 µL L^{-1} for 'Kensington' mangoes stored for 4 weeks at 5 °C. The results of this study indicated that NO treatments significantly alleviated chilling injury, ethylene production and respiration during storage. Selecting the optimum concentration of NO for fresh produce should be based on factors such as their ethylene sensitivity, which can have a significant impact on quality and shelf life. The application of NO during postharvest is limited by the need for an ultralow O_2 concentration during application of NO, in order to minimise its oxidation.

1-methylcyclopropene

1-methylcyclopropene (1-MCP) is an ethylene action inhibitor. It acts directly on the endogenous capacity for ripening by fixing the ethylene receptor and thus prevents it from coupling (Velardo-Micharet et al. 2017). It is used to delay the ripening process and to extend the shelf life of climacteric fruit (Watkins 2006; Luo et al. 2008). Han et al. (2014) demonstrated that the application of a 1-MCP treatment inhibited ethylene production and hence helped maintain the ascorbic acid, soluble protein content, and antioxidant enzyme activities of bitter melon cv. 'Duobaol' stored at 20 °C and 85–90% relative humidity (RH). Sun et al. (2012) reported that a 1-MCP treatment effectively extended the shelf life of Chinese kale cv. 'Bailey' by delaying the mass loss, chlorophyll degradation and colour change, in addition to minimising the rate of softening.

Various studies have demonstrated the positive impact of postharvest 1-MCP treatment on fresh produce (Table 3). However, its effectiveness varies depending on factors such as cultivar, ripening stage, fruit dry matter content, time and temperature of application, and harvesting season (Pan et al. 2016; Villalobos-Acuna et al. 2011). For instance, Bower et al. (2003) reported accelerated rot development in 1-MCP treated strawberry fruit. Similarly, Jiang et al. (2001) demonstrated the onset of disease in fruit treated with 1.0 µL L^{-1} 1-MCP and stored at 5 °C. As these results indicate that the effect of 1-MCP treatment to block ethylene could have a negative influence on fruit disease resistance, further studies should be carried out to investigate this issue.

Minimising exposure to ethylene

Storage temperature

Storage of fruit at cold temperatures is probably the simplest and most effective approach for the control of ethylene production and reduction of overall metabolism (Watkins 2002). Low temperature storage is associated with the delayed onset of ripening, by reducing the rate of deterioration, rate of ethylene production and rate of respiration (Wills et al. 2007a). The respiration of fresh produce is often regarded as the main parameter for monitoring metabolic activity (Wills et al. 2007b). In order to maintain postharvest quality it is important that fruit and vegetables are stored at low temperatures, to decrease all metabolic activity and biochemical reactions.

However, storage at low nonfreezing temperatures (> 2 °C) could induce physiological disorders and chilling injuries in some tropical and subtropical fruits (Aghdam et al. 2020). For example, banana fruit previously stored at temperatures below a threshold of 13 °C showed pronounced symptoms of chilling injury during shelf life (Jiang et al. 2004). In this case, appropriate temperature management is crucial to avoid chilling injuries and to maintain fruit quality. The management of the shelf life of produce via cold storage is dependent on the type of produce and other storage conditions, such as RH, hence the approach needs to be carefully considered.

Controlled/Modified atmosphere systems

Controlled atmosphere (CA) storage involves adjusting and maintaining an atmospheric composition, normally of low O_2 and high CO_2 concentrations, typically an O_2 concentration below 8% and a CO_2 concentration above 1%, depending on the type of commodity (Kader 2004). The suppression of ethylene production in CA storage is due to the low O_2, which retards the activation of 1-aminocyclopropane-1-carboxylate oxygenase (ACC oxidase), thus inhibiting ethylene biosynthesis. Although CA storage has been used

Table 3: Ethylene management strategies applied along the postharvest value chain of horticultural commodities within the last two decades

Strategies	Type of produce	Major outcomes	References
		Principle: Inhibition	
H_2S fumigation	Mulberry fruit (*Morus indica* L. 'Dianmian-1')	Fumigation was able to slow down decreases in soluble protein, titratable acidity and ascorbate contents	Hu et al. (2014a)
	Fresh-cut pears (*Pyrus pyrifolia* 'Dangshan')	Extended the shelf life of fresh-cut pears (dose-dependent) Maintained higher levels of reducing sugar and soluble protein Minimised the accumulation of hydrogen peroxide (H_2O_2), superoxide radicals and malondialdehyde (MDA)	Hu et al. (2014b)
	Broccoli florets (*Brassica oleracea* var. *italica*)	Maintained higher levels of carotenoids, anthocyanin, and ascorbate Reduces the accumulation of MDA, H_2O_2, and superoxide anion Down-regulated chlorophyll degradation related genes	Li et al. (2014b)
	Strawberry (*Fragaria ananassa* L. 'Fengxiang')	Inhibited respiration rate Maintained crust colour and minimised fruit decay	Zhang et al. (2014)
	Fresh-cut apples (*Malus ×pumila* 'Fuji')	Maintained higher levels of ascorbic acid, flavonoids, total phenolics, reducing sugars and soluble proteins Lower levels of free amino acids Down-regulated genes associated with senescence	Zheng et al. (2016)
	Kiwifruit (*Actinidia deliciosa* 'Qinmei')	Effectively alleviated ethylene-induced fruit softening and oxidative stress Attenuated the activity of polygalacturonase (PG), lipoxygenase (LOX), polyphenol oxidase (PPO) and amylase	Li et al. (2017c)
	Pak choy plants (*B. rapa subsp. chinensis* 'Shanghai'), Italian basil (*Ocimum basilicum*), and green curly kale (*B. oleracea* var. *sabellica*)	Inhibited ethylene production, respiration, mass and chlorophyll loss Reduced various antioxidant factors, total phenols and ion leakage Increased market life of green leafy vegetables	Al Ubeed et al. (2017)
	Strawberry (*F.* × *ananassa* Duch. 'Sweet Charlie')	Fruit maintained higher fruit firmness and titratable acidity Had lower decay compared to the control fruit Inhibited the loss in extractable juice via the modification of water mobility and cell wall metabolism	Zhi et al. (2018)
	Oranges (*Citrus sinensis* 'Valencia' 'Navel') and mandarins (*C. reticulata* Blanco 'Afourer')	Reduction in incidence of calyx drop, calyx browning and fungal decay Production of ethylene and ethanol for all three citrus species were reduced	Alhassan et al. (2020)
Nitric oxide (NO)	Strawberry (*F.* × *ananassa* Duch 'Selva')	Maintained fruit quality for 15 d Delayed postharvest decay	Abdollahi et al. (2013)
	Litchi (*Litchi chinensis* Sonn 'China')	Significantly reduce the pericarp browning Effectively reduced mass loss, and MDA content Delayed loss of total soluble solids, titratable acidity, and ascorbic acid	Barman et al. (2014)
	Papaya (*Carica papayas* 'Sui you 2')	Suppressed ethylene production and respiration Reduced mass loss Maintained firmness and delayed changes in peel colour	Li et al. (2014c)
	Banana (*Musa* spp., AAA group 'Brazil')	Had increased chilling tolerance due to improved antioxidant enzyme Induced expression of antioxidant related genes Decreased the accumulation of reactive oxygen species (ROS)	Wu et al. (2014)
	Mango (*Mangifera indica* 'Tainong')	Suppressed respiration Enhanced firmness, and decrease rot index and mass loss Enhanced the antioxidant activities and reduced accumulation of MDA, superoxide anion radical and H_2O_2	Ren et al. (2017)

Table 3: (cont.)

Strategies	Type of produce	Major outcomes	References
		Principle: Inhibition	
	Oranges (*C. sinensis* 'Navel')	Reduced the incidence of chilling injury in orange fruit Reduced the lipid peroxidation levels and H_2O_2 contents of the peel and pulp during storage Induced the activity of several antioxidant enzymes	Ghorbani et al. (2018)
	Oranges (*C. sinensis* 'Midknight Valencia' and 'Lane Late Sweet')	Reduced the concentrations of glucose, fructose, sucrose and total sugars in 'Midknight Valencia' only Reduced mass loss compared to control	Rehman et al. (2019)
1-MCP	Pears (*Pyrus communis* L. 'Bartlett' and 'd'Anjou')	Suppressed respiration Substantially decreased superficial scald	Bai et al. (2006)
	Pears (*P. communis* L. 'Bartlett')	Decreased rate of ethylene production, softening, respiration, yellow colour development, and Reduced incidence of scald and internal browning during 180 day of storage duration.	Villalobos-Acuna et al. (2011)
	Broccoli (*Brassica oleracea* var. *italica* 'Cicco')	Delayed degreening and chlorophyll degradation Induced a higher expression of *BoCLH2* Selectively inhibit some of the genes encoding enzymes related chlorophyll catabolism	Gómez-Lobato et al. (2012)
	Jujube fruit (*Zizyphus jujube* 'Huping')	Reduced the growth of blue mould rot and incidence of natural decay Activities of phenylalanine ammonia-lyase (PAL), PPO, catalase (CAT) and superoxide dismutase (SOD) were significantly induced	Zhang et al. (2012)
	Apple (*Malus domestica* Borkh. 'Empire')	Delayed ripening Total spermine and spermidine levels tended to be lower with 1-MCP	Deyman et al. (2014)
	Tomato (*Solanum lycopersicum* 'Ailsa Craig')	Delayed ethylene production Polygalacturonase activity was strongly inhibited	Li et al. (2014a)
	Banana (*Musa* spp., AAA group 'Brazil')	Effectively delayed and decreased respiration rate and ethylene production, Inhibited the activity of pectin lyase (PL), pectin methylesterase (PME), cellulase (CX) and polygalacturonase (PG), and Delayed the peak activity of ACC synthase (ACS) and ACC oxidase (ACO).	Zhu et al. (2015)
	Nectarines (*Prunus persica* 'Maria Aurelia')	Reduced the ethylene production during cold storage (0 °C) and shelf life (20 °C) Reduced the incidence of chilling injury Significantly reduced the activities of PPO, PG, and PEM Enzyme activities, colour and respiration rate	Özkaya et al. (2016)
	Mango (*M. indica* L. 'Kenington Pride')	Activities of softening enzymes significantly inhibited and ripening delayed Decreased citric acid, malic acid, succinic acid and total organic acids level and total sugars	Razzaq et al. (2016)
	Plum (*Prunus salicina* Lindl. 'Songold')	Reduced firmness loss and colour changes Maintained fruit acidity and Reduced the impact of chilling injury	Velardo-Micharet et al. (2017)
	Plum (*P. salicina* Lindl. 'Younai')	Retarded softening development Lower activities of cell wall degradation enzyme and content of water soluble pectin Higher contents of cell wall polysaccharides maintained	Lin et al. (2018)

Table 3: (cont.)

Strategies	Type of produce	Major outcomes	References
		Principle: Control / Minimising exposure	
Cold temperature	Green vegetables (pak choi, broccoli, mint, and green bean)	Chilling injury for green bean, increased as the storage temperature increased even with decline in ethylene concentration	Li et al. (2017c)
	Banana (*Musa acuminata colla* 'Raja Sere')	The shelf life of banana stored at 13 °C was increased by 12 d compared to 6 d for the banana stored at room temperature (28 °C)	Crismas et al. (2018)
MAP	Broccoli (*B. oleracea* var. *italica*)	Reduced loss of green colour and maintained texture and chemical composition Acceptable sensory score was maintained for 25 d, compared with only ~ 15 d for control samples	He and Xiao (2018)
	Strawberry (*F.* × *ananassa* Duch. 'Charlotte')	Extended shelf life Increase of CO_2 concentration in the headspace was able to significantly decrease the deterioration percentage of the fruit	Matar et al. (2018)
MA/CA storage	Mangoes (*M. indica* L. 'Haden' and 'Tommy Atkins')	Ethylene production was reduced slightly by low O_2 'Haden' fruit also showed a residual inhibitory effect on ethylene production after 2 or 3 kPa O_2 storage 'Tommy Atkins' fruit stored in 2 kPa O_2 produced a burst of ethylene upon transfer to air at 20 °C	Bender et al. (2000)
	Mango (*M. indica* L. 'Delta R2E2')	CA storage (6% CO_2 and 3% O_2) extended the shelf-life for 38 d Allowed the fruit to ripen normally with a yellow skin colour, good taste, high TSS and TSS/acid ratio, and a high total sugars content.	Lalel et al. (2005)
	Bananas plantain (*Musa paradisiacal* L. 'French')	Reduce ethylene production Enhanced the shelf life of the plantain	Agoreyo et al. (2007)
	Pear (*Pyrus bretschneideri* Rehd. 'Zaosuli')	Reduce ethylene production Thirteen volatile compounds were found to differentiate CA treatment from control	Goliáš et al. (2016)
	Avocado (*Persea americana* Mill. 'Hass') and Strawberry (*F. x ananassa* Duch. 'Sonata')	Reduce ethylene production Irrespective of timing, respiration of avocados stored at 20 °C was reduced under CA storage while regular atmosphere had higher ethylene production Avocado skin colour and internal discolouration were positively affected by the mid CA treatment Strawberry were firmer and maintained a more vibrant colour despite bursts of increased respiration rate	Alamar et al. (2017)
	Apple (*M. domestica* 'Jonagold') and Pear (*P. bretschneideri* Rehd. 'Conference')	CA condition of 0.5 kPa O_2 + 6.0 kPa CO_2 was most effective in suppressing ethylene production, respiration rate and gave higher respiratory quotient	Saquet and Streif (2017)
		Principle: Removal (scrubbing)	
Biofilter	Bananas (*Musa acuminata colla*)	Column packed with active sludge, peat wood chips, and humus with organic soil had higher ethylene removal rates	Moghadam et al. (2015)

Table 3: (cont.)

Strategies	Type of produce	Major outcomes	References
		Principle: Ethylene scrubbers	
Zeolite or $KMNO_2$ or $KMNO_2$- or zeolite-based matrix	Papaya (*Carica papaya*)	Reduced ethylene production by a factor of two Reduced the autocatalytic process of ethylene	Corrêa (2005)
	Kiwifruit (*A. deliciosa* 'Hayward')	Delayed reduction firmness Significantly extended shelf-life of the fruit	Ramin et al. (2010)
	Apple (*M. domestica* 'Golden Delicious')	Delayed degreening and maintained firmness	Sardabi et al. (2014)
	Tomato (*S. lycopersicum* L. 'Chonto')	Delayed mass loss and slowed firmness loss Retarded the ripening process	Salamanca et al. (2014)
	Nectarine (*P. persica* 'Bayramiç Beyazı')	Delayed ripening, retained higher firmness, Reduced respiration rate	Bal (2018)
	Tomato (*S. lycopersicum* L. 'Valouro')	Delayed fruit softening, and extended shelf life	Mansourbahmani et al. (2018)
	Tomato (*S. lycopersicum* L. 'Medano')	Effectively removed ethylene and delayed ripening	De Bruijn et al. (2020)
Ozone	Fresh-cut celery (*Apium graveolens* L.)	Reduced respiration rate	Zhang et al. (2005)
	Tomato (*S. lycopersicum* L. 'Carousel')	Maintained soluble sugars, increased β-carotene, lutein, and lycopene contents, maintained fruit firmness	Tzortzakis et al. (2007)
	Papaya fruit (*Carica papaya* L. 'Sekaki')	The fruit treated with ozone had lower respiration rate and delayed ripening compared to the control	Ong et al. (2014)
	Mango (*M. indica* L. 'Nam Dok Mai No. 4')	Significantly decreased the respiration rate Initially decreased ethylene production	Tran et al. (2015)
	Black mulberry (*Morus nigra* 'Dashi')	Higher levels of titratable acidity and total soluble solids Better retained colour and firmness Retarded respiratory intensity and decay rate	Han et al. (2017)
UV-C	Mangoes (*M. indica* L. 'Kensington Pride')	Delayed mango skin degreening Reduced endogenous ethylene production Suppressed respiration and lowered chlorophyll content	Pristijono et al. (2018)
	Tahitian limes (*C. latifolia*)	Maintained lime peel green colour Retained calyx attachment after 28 days storage Maintained low ethylene production and low respiration rates	Pristijono et al. (2019a)
	Sweet cherry (*P. avium* L. 'Sweetheart' and 'Lapin')	Significantly lower levels of postharvest rot 'Lapin' showed greater firmness retention relative to control	Pristijono et al. (2019b)

in many studies, critically low O_2 and high CO_2 concentrations may result in physiological CO_2 injury and the occurrence of anaerobic respiration (Abdalnoor 2015).

The studies summarised in Table 3 clearly demonstrated that the control and maintenance of the storage or packaging atmosphere that surrounds fresh fruit or vegetables could impact ethylene production or inhibition. It is important to mention that CA storage needs a special infrastructure, which is often expensive to set up in South Africa, whereas a modified atmosphere (MA) can be easily implemented in a standard storage room.

Active ethylene removal

Biofiltration

Biofiltration is a technique of ethylene removal that requires low energy consumption, as shown in Table 3. It utilises biologically active filters, such as layers of compost, peat or soil, that contain ethylene degrading microorganisms (Devinny et al. 1999; Kim 2003). The use of biological catalysts for the removal of ethylene in horticulture has been proposed since the early 1980s (Sherman 1985). However, very few articles have been published on its potential, and its application in real storage and transport conditions for fresh produce is scarce (Keller et al. 2013). The use of a biofilter for ethylene removal was explored by Elsgaard (1998). Isolated ethylene-oxidising bacteria were immobilised on peat soil and subjected to atmospheric gas flow (73.3 mL min^{-1}) containing defined ethylene concentrations (2 or 117 µL L^{-1}). The biofilter was successful in reducing ethylene to concentrations of 0.017 µL L^{-1} and < 0.04 µL L^{-1}, from those of 2.05 µL L^{-1} and 117 µL L^{-1} respectively.

Elsgaard (2000) showed that the removal efficiencies of a biofilter declined to 83% when temperature was lowered from 5 °C to 2 °C, which was attributed to the low activity of the bacteria at low temperature. A bench-scale zeolite-based ethylene biofilter was developed by Fu et al. (2011). The biofilter successfully removed 100% of ethylene at loading rates of 0.26–3.76 g m^{-3} h^{-1} when enriched with ethylene-degrading bacteria.

Ethylene removal by biofilters is more advantageous economically and environmentally, compared to chemical and physical methods. However, the biological systems are often slow. In addition, due to the large area required, the biofilter system may be subject to a drop in pressure, which may limit commercialisation of biofilters. Another major drawback of biofiltration is the necessity of finding a readily accessible and cheap substrate. These shortcomings associated with the application of biofilters for ethylene management could be the cause of its limited commercialisation. Thus, further research concerning conditions affecting the efficacy of biofilters is still needed.

Ethylene scrubbers

Potassium permanganate ($KMnO_4$) is an active compound that oxidises ethylene. Application of potassium permanganate is generally considered a low-cost technology, easy to apply and relatively eco-friendly, which effectively oxidises ethylene to CO_2 and H_2O. The use of oxidative agents such as $KMnO_4$ to manage ethylene removal during the postharvest handling of fruit and vegetables has been extensively reported (Table 3).

The use of $KMnO_4$ to reduce ethylene concentration in the atmosphere around horticultural produce was first reported by Forsyth et al. (1967). However, exposure of $KMnO_4$ under long-term storage with high ethylene-producing commodities could result in rapid saturation of the salt, thereby necessitating frequent replacement. Additionally, the oxidation reaction leads to the formation of by-products that themselves require disposal. In a complete reaction, $KMnO_4$ oxidises ethylene into CO_2 and water, while $KMnO_4$ itself is converted into MnO_2 and KOH. An incomplete oxidation reaction produces intermediates, such as potassium acetate, which may remain bound to the residue (Keller et al. 2013).

However, since ethylene is a gas and natural convection and diffusion are the only driving forces involved, $KMnO_4$ is not recommended for direct application without support material (Aprilliani et al. 2018). For this reason, $KMnO_4$ is usually supported on a porous inert solid material with a large surface area to facilitate and improve the oxidation process. The commonly used adsorbent materials are vermiculite, activated alumina, zeolite, silica gel, activated carbon and clays, but zeolites and carbon based adsorbents are the most commonly used substrates (Keller et al. 2013; De Bruijn et al. 2019). The postharvest application of $KMnO_4$ and support materials was extensively reviewed by ÁlvarezHernández et al. (2017), while Álvarez-Hernández et al. (2019) provided an extensive review of $KMnO_4$-based ethylene scavengers as an active packaging system for fresh horticultural produce.

Table 4 compares the properties of different ethylene adsorbents. Most support materials for $KMnO_4$ adsorb ethylene and, thus create an adsorption–oxidation system. This system generates a chemical residue, which is a potential concern with regard to waste management. This is a drawback of most ethylene scrubbers. In addition, the application of ethylene scrubbers is unsuitable for typical storage conditions (with high RH and low temperatures). Their efficiency has been shown to decline under such conditions.

Ozone is formed through high energy input, which splits available oxygen to form an unstable triatomic oxygen molecule (O_3) (Karaca and Velioglu 2007). Extensive reviews of the application of ozone for fruit and vegetable preservation were published by Miller et al. (2013) and Karaca and Velioglu (2007), thus it will not be covered in this review. Crisosto et al. (2000) investigated the capability of ozone to remove ethylene from an empty 60 m^3 refrigerated container. The authors found that the rate of ethylene reduction was proportional to the rate of ozone production. High ozone concentrations have been shown to have a critical influence on respiration and ethylene production during postharvest storage (Table 3). Some additional disadvantages of ozone use include irreversible plant/fruit tissue damage caused by exposure to ozone, and human health and safety concerns. In addition, the monitoring of the ozone concentration during a postharvest application would incur extremely high costs. These drawbacks limit the introduction of such technologies.

Advanced oxidation process

Photocatalysis

Photocatalytic oxidation (PCO) is an emerging technique that has been studied mostly for the removal of volatile organic compounds and other gaseous pollutants (Zhong and

Haghighat 2015). The advantages of this technology include implementation at ambient temperature and environmentally friendly end products (viz. CO_2 and H_2O). These benefits attracted the interest of researchers to evaluate the potential of the approach for the postharvest removal of ethylene (Pathak et al. 2019). Photocatalytic reactions occur via semiconductors, which are irradiated at a wavelength capable of activating the transfer of electrons from the valence band to the conduction band (Li et al. 2017b). This reaction produces an electron–hole (e–h+) pair (Basso et al. 2018). The generated electron-hole pairs at the surface of the catalyst react with adsorbed oxygen and water to produce reactive species (such as hydroxyl radicals, $OH^\bullet$ and superoxide ions, namely O_2^-), that ultimately oxidise ethylene to carbon dioxide and water (Pathak et al. 2017b). In most cases, TiO_2 is the commonly used photocatalyst, as it is chemically inert, highly stable, environmentally friendly and inexpensive (Chiara et al. 2015). Another interesting feature is its low band gap energy, which makes it a suitable semiconductor.

Even though the potential application of PCO to degrade ethylene for use in postharvest storage of fruit and vegetables may be promising (Chiara et al. 2015; Pathak et al. 2019), commercial application is very limited. The photocatalytic degradation of ethylene by TiO_2 at 3 °C was investigated by Hussain et al. (2011). Although the study was not done on a selected item of fresh produce, an ethylene removal efficiency > 80% was achieved. Chiara et al. (2015) showed that photocatalytic removal of ethylene by TiO_2 (using an 80Ti – 20Si nanocomposite) retarded ripening of tomatoes. Similarly, Basso et al. (2018) found that a continuous flow reactor using TiO_2 under UVA light was able to maintain an ethylene concentration close to zero, considering an ethylene production rate of 0.3182 μmol kg^{-1} h^{-1} during the ripening of cherry tomatoes.

Considerable work on parameter optimisation for ethylene removal efficiency by PCO has been conducted. This work included assessment of catalyst thickness (Basso et al. 2018), oxygen, RH, and light intensity (Lin et al. 2014), and initial ethylene flow rate, light wavelength and temperature (Pathak et al. 2019). High RH (> 90%) is the variable with the most significant negative effect on ethylene removal efficiency. However, high humidity is essential in the storage of fresh produce to minimise mass loss (Pathak et al. 2017a; Bovi et al. 2016). For PCO systems, unfavourable phenomena, such as the recombination of hole and electron that occurs on the surface of the catalyst could impact performance, due to a reduction in the number of oxidised species (Malayeri et al. 2019). To address these issues, different modification methods, such as surface sensitisation, precious metal deposition, non-metal ion loading and semiconductor composites are required. In addition, the deactivation of the catalyst, caused by accumulation of water vapour and intermediate compounds on the surface catalyst, further limits the attractiveness of this technology for the management of ethylene. However, this can be solved if hydrophobic catalysts are used (Kuwahara et al. 2009). The dominant degradation mechanism in PCO is adsorption on the catalyst surface. Unfortunately, like another technology discussed above, the disposal of used catalysts is an environmental concern. This concern could be addressed by recycling and regenerating the spent catalyst. In order to increase the efficiency of PCO,

Table 4: Examples of adsorbents and their ethylene adsorption capacity

Adsorbent	BET (m^2 g^{-1})	Temp. (°C)	Ethylene adsorption capacity (mmol kg^{-1})	Ethylene content (ppm)	Water content	Hydrophobicity index (HI)
Mordenite Na	320	30	19.6	50		2.4×10^{-4}
Mordenite Na	320	30	1.3	50	4200 ppm	2.4×10^{-4}
Chabazite		25	~0.15	~3.5		
$KMnO_4$ based adsorbents		25	34–41			
Saponite-TiO_2	368	20	~10	120	20–30% RH	11
Montmorillonite-TiO_2	301	20	~15	120	20–30% RH	21
Fluorine mica-TiO_2	402	20	~10	120	20–30% RH	33
TiO_2-P-25	49	20	~10	120	20–30% RH	20
Activated carbon (AC)	1120	30	~11–78	64–1000		
Carbon nanoballs (CNB)	1431	30	~7–11	64–400		
Pd/AC	1109	30	~7–71	64–1000		
Pd/CNB	827		~14–71	64–1000		

Note: Adapted from Keller et al. (2013)

multiple PCO reactors can be connected in series to other ethylene removal processes.

Vacuum ultraviolet (VUV) radiation
Photo-degradation employs VUV light sources, such as low-pressure and medium-pressure mercury lamps, with approximately 85% output at 254 nm and 15% output at 185 nm (Xu et al. 2019; Kang et al. 2018). Photolysis based on VUV light has better potential than PCO for removal of ethylene, due to the following characteristics: (i) the high-energy photons generated by 185 nm irradiation can degrade organic compounds; (ii) generation of oxidising agents such as hydroxyl radicals (•OH) from water molecules; and (iii) in the presence of O_2, the 185 nm irradiation can generate ozone (Yang et al. 2007). Vacuum ultraviolet light photolysis has been used for the removal of organics in the aqueous phase and air pollutants (Ollis et al. 1991; Cheng et al. 2011; Xu et al. 2014).

This potential of VUV has stimulated research into its postharvest application (Scott et al. 1971). In the study by Scott et al. (1971), a UV lamp successfully reduced ethylene produced by banana from 0.3 μg L^{-1} to 0.1 μg L^{-1} and < 0.03 μg L^{-1}, in 10 min and 2 h, respectively. Pathak et al. (2017b) and Pathak et al. (2017c) also highlighted the potential of VUV light photolysis for ethylene removal in fruit storage. Their results showed that flow rate exerted the most significant effect on the amount of ethylene removed, followed by initial ethylene concentration and lamp power. In another comparative study, Pathak et al. (20219) compared the removal efficiency of VUV light photolysis to PCO technology. The percentage ethylene removed in the VUV light photolysis reactor was 84.8%, whereas in the PCO reactor it was less than 14.86%. Although VUV light photolysis performed better than PCO technology, the low removal rates and generation of toxic ozone (O_3) still remained a major drawback and could delay the adoption of this technique. To improve the removal rate and reduce residual O_3, VUV light photolysis could be combined with downstream processes, such as ozoneassisted catalytic oxidation (OZCO) and/or PCO.

This novel combination (VUV-OZCO or VUV-PCO or VUV-OZCO-PCO) could generate additional reactive radicals for effective oxidation of ethylene, while the catalyst could eliminate the residual O_3. Huang et al. (2011) demonstrated that the efficiency of toluene removal was increased by 18.2% in a combined VUV-PCO process. In addition, the outlet concentration of O_3 was reduced from 30 μL L^{-1} to 1.8 μL L^{-1} in the VUV-PCO process, compared to the VUV light process alone. In another study, the VUV-PCO combination showed enhanced performance in relation to the degradation of ethylene and a high mineralisation rate, when compared to VUV light photolysis alone (Chang et al. 2013). The viability of combining VUV light photolysis with OZCO to eliminate O_3 and improve benzene degradation efficiency was studied by Huang et al. (2016a). The possible combinations of VUV-based processes, including VUV light combined with ozone-assisted oxidation and VUV-PCO for air purification, was reviewed by Huang et al. (2016b). Studies on ethylene removal by VUV-combined systems are still limited. Hence, further research is needed in South Africa on the optimisation of VUV light photolysis systems.

Conclusions

Ethylene inhibition using compounds such as 1-MCP and other inhibitors have been well adopted by the fruit industry in South Africa. However, strict international regulations on the chemical residues that are permitted on fresh horticultural commodities implies that other alternatives are needed. Technologies linked to cold storage and CA/MA systems are often capital intensive and far out of the reach of small and medium scale farmers. In addition, this approach does not prevent exposure of produce to exogenous ethylene. On the other hand, advanced oxidation technologies, such as photocatalytic oxidation, non-thermal plasma and vacuum ultraviolet light photolysis, could potentially be applied to ethylene removal under long-term storage and distant distribution. However, these emerging technologies require further improvement, or system optimisation, to be efficient. Overall, to mitigate postharvest losses due to endogenous or exogenous ethylene exposure, a concerted effort is required in South Africa to promote multidisciplinary collaboration between research institutions and the industry, to drive this innovation forward. Commercial upscaling of these technologies in order to ensure South Africa's food security would benefit from public–private partnerships.

Disclosure statement — No potential conflict of interest was reported by the authors.

Funding — This work is based on research supported wholly/in part by the National Research Foundation (NRF) of South Africa (Grant No. 116272), the NRF Incentive Funding for Rated Researchers (Grant No. 119192) awarded to Dr Caleb, and the co-funding received from HORTGRO Science and Post-Harvest Innovation (PHI) Programme (V-18-ARC-PH02 and 06/2019). The NRF Freestanding Post-Doctoral Fellowship (Grant No. 120729) awarded to Dr ZA Belay is gratefully acknowledged.

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Received 29 January 2021, revised 31 May 2021, accepted 01 June 2021
Guest Editor: John Bower