climate

Review

Potential for More Sustainable Energy Usage in the Postharvest Handling of Horticultural Produce through Management of Ethylene

Ron Baden Howe Wills

School of Environmental and Life Sciences, University of Newcastle, Ourimbah, NSW 2258, Australia; ron.wills@newcastle.edu.au

Abstract: The perishable nature of fruit and vegetables requires some technological intervention to maintain quality during handling and marketing. The technology of choice for many years has been use of low temperatures as it is effective in reducing metabolism and hence extend postharvest life. However, refrigerated storage is energy intensive and the growing urgency to reduce international greenhouse gas emissions has created a need for technologies that are more environmentally sustainable but still acceptable to consumers. Ethylene is well known to promote ripening and senescence of fruit and vegetables. This presentation will review the existing data that support the potential for managing the concentration of ethylene in the atmosphere around produce in postharvest situations to allow a reduced reliance on refrigeration and thus reduce energy consumption. Methods for managing ethylene levels around produce, and barriers that need to be overcome in order to move from a temperature-based mindset are discussed.

Keywords: ethylene; storage temperature; energy reduction; postharvest horticulture

check for updates

Citation: Wills, R.B.H. Potential for More Sustainable Energy Usage in the Postharvest Handling of Horticultural Produce through Management of Ethylene. *Climate* **2021**, *9*, 147. https://doi.org/10.3390/cli9100147

Academic Editor: Pedro Dinis Gaspar

Received: 25 August 2021
Accepted: 27 September 2021
Published: 28 September 2021

1. Introduction

Fresh fruit and vegetables are unique in being the only food group that remain living entities during postharvest handling and marketing. It is readily accepted that produce are living, when attached to the parent plant, but after harvest they still need to continue all the same metabolic systems in order to maintain cellular function and integrity. These systems require energy that is generated through respiration involving the oxidation of sugars and other substrates with the loss of carbon as CO_2 and water by transpiration. However, the act of harvesting prevents the replenishment of nutrients from the parent plant or by photosynthesis. Thus, over time, the ability of all produce to sustain normal metabolism declines which leads to increasing cellular dysfunction. From a marketing perspective, this results in loss of quality due to changes in appearance, texture or taste and enhanced susceptibility to microbial infection. Fresh fruit and vegetables are thus classified as perishables.

The need for some innovation to slow the rate of metabolism and thus extend the postharvest life of fruit and vegetables arises when produce are marketed some distance from the production area or where an economic advantage can be gained by extending to marketing period. Indeed, the current situation in many countries is for a wide range of produce to be traded internationally and consumers demanding year-round availability for seasonal commodities, situations that have exacerbated the requirement for postharvest technology.

The primary technological intervention to extend the marketing period of fruit and vegetables is to reduce the temperature of produce. The benefit of storage at reduced temperature has long been known in countries with a cold winter. For example, storage of Chinese cabbages in China and apples in North America and Europe in cellars or caves was practiced at village and farm level and provided a much needed food source during winter.

The advent of mechanical refrigeration in the 1850s transformed the use of low-temperature storage into a reliable technology. Low temperature refrigerated storage of food was well established at the beginning of the twentieth century, with apples and pears being the major stored horticultural crops [1,2].

Numerous research studies around the world have now identified the optimum low temperature at which individual fruit and vegetables achieve maximum postharvest life and comprehensive lists of recommended storage temperatures for individual produce have been published, for example by the USDA [3]. These recommendations are based on a reduction in metabolism being optimal just above the freezing temperature of about -1 °C, but the recommended temperature is higher for produce where abnormal metabolism leads to chilling-related injury, physiological disorders, or failure to fully ripen. The gold standard for the postharvest handling of fruit and vegetables is now considered to be cool-chain management where the optimum temperature is consistently maintained around produce at all stages from the farm to wholesale, retail and the consumer, and in the transport systems linking these destinations.

However, cool-chain management is energy-intensive. A review on energy usage in the postharvest horticultural industry by East [4] identified that it utilised a significant proportion of the total energy consumption. Cited examples included that cooling and storage of fresh horticultural produce in California consumed about 1 billion kWh of energy annually, and marketing of fruit and vegetables accounted for about 2.5% of total UK CO_2 emissions. Refrigerated storage became *de rigeur* when energy was cheap and concern about greenhouse gas emissions did not exist. The world has moved to an energy minimization mode and horticulture, in common with many other industries, needs to reduce its carbon footprint from an economic perspective, due to the increasing cost of energy, and to be seen by the community as a good corporate citizen.

In an energy-conscious world, it is appropriate to ask if there is an alternative methodology that can reduce the use of refrigeration across a wide range of produce. The option proposed in this paper is to reduce the impact of ethylene on postharvest metabolism by either reducing exposure to ethylene, or inhibiting ethylene action. It will review data available for a wide range of produce on the effect of ethylene concentration and its interaction with temperature in postharvest life with the aim of quantifying a reduced need for refrigeration. Technologies available to utilise reduced ethylene and barriers to implementation will also be discussed.

2. Function and Presence of Ethylene in Fruit and Vegetable Environments

Ethylene ($CH_2{=}CH_2$) is notable as the defining metabolic difference between plant and animal systems. It is synthesized by plants and is universally accepted as having a major regulatory role in germination, growth, development and senescence of all plants at quite low concentrations. Postharvest effects of ethylene on fruit and vegetables have been known for many centuries, even if its identity remained unknown due to inadequate analytical techniques. It was not until the 1930s that ethylene was identified with Gane [5] reporting ethylene synthesis by plants and Crocker et al. [6] proposing ethylene as the agent responsible for fruit ripening and senescence of vegetative tissues. The advent of gas chromatography in the 1960s provided the analytical sensitivity to below parts per million ($\mu L\ L^{-1}$) levels, which enabled expanded research efforts into the biosynthesis of ethylene and its presence in produce and postharvest situations.

Any intervention technology needs to recognize the differing role of ethylene in: (1) initiating ripening in climacteric fruit; and (2) accelerating senescence of non- climacteric fruit and vegetables [7,8]. Climacteric fruits have a distinct ripening pattern, with the defining characteristic being a pronounced increase in respiration to a peak value or climacteric. They are often harvested at a mature but unripe state, with the aim of preventing ripening during storage and transport to markets and then ripened close to consumer outlets. By contrast, non-climacteric produce, which can be fruits or non-seed-bearing vegetables, are harvested at or close to desirable eating quality with no dramatic changes occurring after harvest. The response of non-climacteric produce to increased ethylene is an acceleration of the rate of normal senescence. However, for both climacteric and non-climacteric produce, the presence of ethylene during marketing reduces the marketing life.

While all fruits and vegetables synthesise ethylene, albeit at different rates [9], in a commercial postharvest environment, the source of ethylene affecting a produce can also be from other produce held in the same chamber. In addition, ethylene in the ambient air can be generated from a range of industrial sources, such as motor vehicle exhaust, natural gas leakage, or from a range of industrial effluent sources [10]. The rapid diffusivity of ethylene into plant tissues means that all exogenous sources of ethylene are as effective as endogenous ethylene in modifying metabolic and physiological behaviour. In order to consider methods of ameliorating the effects of ethylene, it is therefore important to know the actual concentration of ethylene that produce are subject to during storage and marketing.

However, in the relatively few published case studies on ethylene concentrations throughout the postharvest chain have found measureable but widely varying level at all operational phases. Morris et al. [11] determined the ethylene concentration in cartons of lettuce at nine stages from the field through to domestic refrigerator and the range from 455 measurements was 0.01 to 2.95 $\mu L\ L^{-1}$ with a mean ethylene level during postharvest chain of 0.20 $\mu L\ L^{-1}$. Schouten [12] in a smaller trial surveyed the level of ethylene in a shipment of mixed vegetables at six times during a 58 h transport in a closed truck and a ventilated trailer and found mean ethylene values of 5.9 and 0.68 $\mu L\ L^{-1}$, respectively. A study by Wills et al. [13] conducted over a three-year period determined the ethylene concentration in 700 atmospheric samples collected from handling and storage areas in the Sydney fruit and vegetables wholesale markets, produce distribution centres, supermarket retail stores and domestic refrigerators. They found a measureable ethylene concentration, defined as >0.005 $\mu L\ L^{-1}$ which was the limit of detection of their gas chromatograph, in all samples. A concentration of 0.1 $\mu L\ L^{-1}$ was found to be common in many areas with levels of 0.2 to 1 $\mu L\ L^{-1}$ in fruit storage chambers. It is worth noting that an ethylene concentration of 0.1 $\mu L\ L^{-1}$ has long been cited as the threshold atmospheric level below which no physiological effects are induced [9,14] but the concept was developed at a time when this concentration was close to the prevailing analytical sensitivity.

A series of laboratory studies was conducted by Wills and colleagues [15,16] to determine the effect on postharvest quality of holding a wide range of produce in ethylene concentrations that ranged from 0.001 to 10 $\mu L\ L^{-1}$. They found a progressive increase in postharvest life across 30 types of produce as the ethylene concentration was reduced. The relationship for all produce was a linear increase in postharvest life with logarithmic decrease in ethylene. Examples of data from some of their produce are illustrated in Figure 1.

Pranamornkith et al. [17] conducted a similar study with kiwifruit stored at 1.5 °C and found fruit ripening was progressively delayed as the ethylene concentration was decreased in a logarithmic manner from 1 to 0.001 $\mu L\ L^{-1}$. These findings imply there is no "safe" level of ethylene that does not cause a deleterious effect on postharvest life. Hence, for any current postharvest situation, any reduction in ethylene concentration will result in an increase in postharvest life.

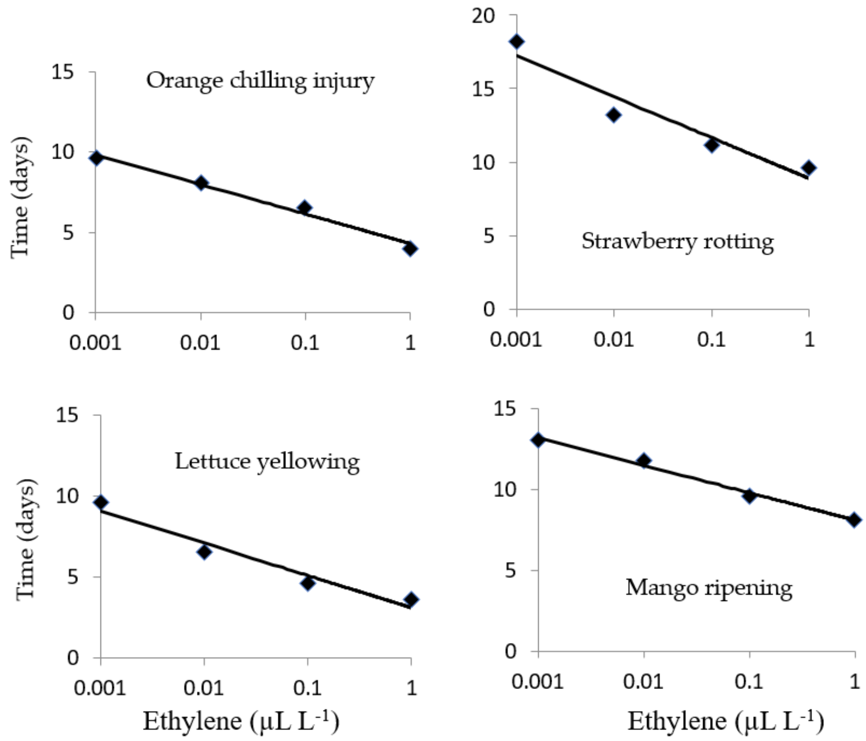

Figure 1. Relationship between ethylene concentration and time (days) for produce to senesce or ripen. Graphs were generated from data given in Wills et al. [15,16].

3. Interaction of Temperature and Ethylene Concentration on Postharvest Life

If ethylene management is to be a partial or complete substitute for low temperature refrigeration, it is necessary to know the relationship between temperature and ethylene concentration in ability to inhibit ripening of individual climacteric fruit and senescence of non-climacteric fruit and vegetables.

3.1. Ripening of Bananas

Banana is a climacteric fruit that is harvested in most countries when mature but unripe with marketing system geared to transporting the fruit in an unripe condition and ripened with ethylene on arrival at the target market. Bananas are among the most internationally traded fruit crops with 22 million tonnes exported in 2020 with substantial imports into temperate countries in Europe, USA and Japan from a range of tropical countries [18]. This long-distance transport of bananas is by sea under refrigeration at 13–15 °C in order to prevent ripening in transit [19]. In addition, in a large country such as Australia, banana production occurs a considerable distance from major urban centres and refrigerated road trucks at 14–16 °C is the standard mode of transport [20]. The energy used in such transportation is considerable and Lescot [21] has estimated that the refrigerated shipping of bananas by sea is the largest source of greenhouse gas emissions in the banana production chain. Similarly, with refrigerated trucking of bananas, where hiring of non-refrigerated trucks is 20–25% cheaper [22]. The extra charge for refrigerated trucks is primarily due to higher consumption of diesel. Allowing for the many fixed costs such as labour and trucking fees it is estimated that the energy savings with non-refrigerated trucks would be at least 50%.

Wills et al. [23] quantified the relationship between temperature, ethylene concentration and time to ripen of Cavendish bananas that were stored at 15, 20 and 25 °C in an atmosphere containing <0.001, 0.01, 0.1 and 1.0 μL L^{-1} ethylene (Figure 2). The equation they derived from the data showed a linear relationship for time to ripen and temperature but a logarithmic relationship with ethylene. Thus, there was greater benefit by reducing ethylene than by reducing temperature. The equation was applied to the shipping of

Cavendish bananas from Costa Rica to Italy, which is at 13°C with a voyage time of up to 16 days. Using international meteorological data, the maximum shipping temperature (July) is 24 °C, and it indicates that fruit could be shipped without ripening if ethylene was maintained at 0.01 μL L^{-1}. For the minimum shipping temperature (January) of 17 °C, fruit could be shipped if ethylene was maintained at 0.08 μL L^{-1}. While such ethylene concentrations can be achieved with a range of technologies, Wills et al. [24] found the ventilation of banana cartons with ambient air, (generally <0.01 μL L^{-1}) at a flow rate of 14 L hr^{-1} maintained ethylene around fruit at a concentration of 0.01 μL L^{-1}. Thus, it is possible to ship fruit for a 16-day voyage over the year without refrigeration. However, if it was deemed desirable to have a safety buffer of up to 4 days to allow for any delay in shipping or unloading, Figure 2 indicates a temperature of 20 °C would ensure fruit did not ripen in transit in an atmosphere of 0.01 μL L^{-1} ethylene. Such a shipping temperature is 7 °C higher than the current temperature and would give a considerable energy saving for the voyage.

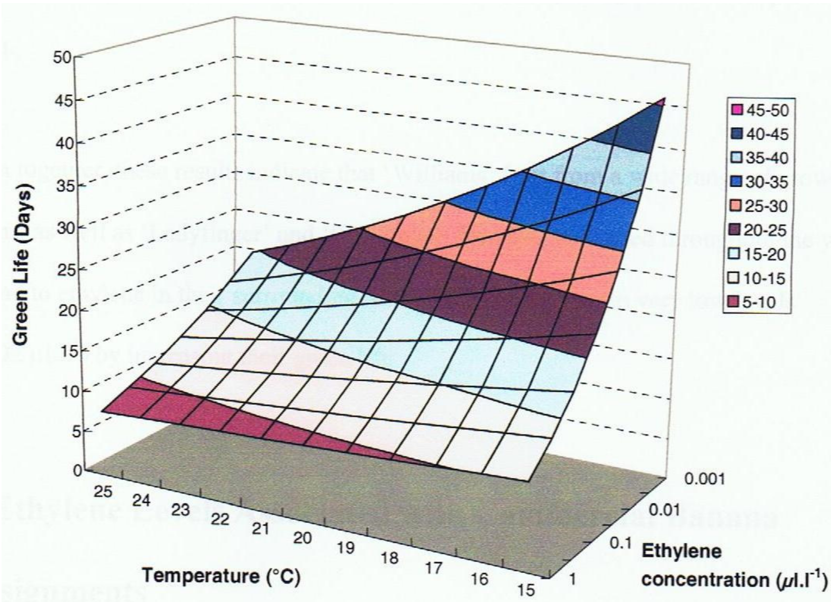

Figure 2. Interaction of temperature and ethylene concentration on the time to ripen of bananas. Graph was generated from data given in Wills et al. [23].

An innovation over the last decade in the transport of bananas from Central America to Europe by Dole and other shippers [25] is to pack fruit in modified atmosphere (MA) bags but to still use refrigeration. The ability of the low oxygen and high carbon dioxide atmospheres generated in such bags to retard ripening of bananas was first reported as long ago as 1966 [26]. Scott and Gandanegara [27] subsequently examined a range of storage temperatures and found that at 24 °C, use of an MA bag inhibited the ripening of bananas for 22 days compared to 14 days for bananas stored in air. They also found inclusion of potassium permanganate impregnated pellets to absorb ethylene into the MA bags further increased the time to ripen to 42 days. Since these times are well in excess of current shipping times and therefore it would seem feasible for sealed MA bag transport of bananas from the Central America to Europe to not require refrigeration.

Wills et al. [23] also applied the equation of temperature, ethylene concentration and green life of Cavendish bananas to the Australian trucking situation. They modelled a five-day 3000 km road transport route from the tropical production area to the Sydney urban market. Using meteorological data, they predicted that bananas transported in the prevailing mean summer temperature of 25 °C would not require refrigeration if the ethylene level did not exceed 0.58 μL L^{-1} while transport at the mean winter temperature of 14 °C fruit could withstand a level of about 0.90 μL L^{-1} without ripening *en route*.

These are quite high ethylene levels and considered unlikely to occur during the five-day transit. This contention is supported by Wills et al. [28], who in a survey over 12 months of 363 banana cartons on arrival at the Sydney wholesale markets found a mean ethylene concentration of 0.06 μL L^{-1} with the highest measurement being 0.28 μL L^{-1}, albeit that fruit were from refrigerated shipments.

3.2. Senescence of Leafy Vegetables

Li et al. [29] stored four non-climacteric green vegetables at a temperature range of 0 to 20 °C and ethylene range of 0.001 to 1.0 μL L^{-1}. They found that the postharvest life, as determined by consumer acceptance criteria of yellowing for pak choy and broccoli, leaf abscission for mint, and pod softening and chilling injury for green bean, increased as the temperature and ethylene concentration decreased.

The recommended storage temperature for pak choy, broccoli and mint is 0 °C ([30–32], respectively) but these recommendations are based on laboratory studies to find the maximum possible postharvest life. The study by Li et al., [29] found the postharvest life at 0 °C of these produce ranged from 40–60 days with the longer times at the lower concentrations of ethylene. However, it is questionable as to the amount of produce that requires a 40–60-day market life with many trading chains only requiring a postharvest life of $\leq$3 weeks. The regression equations Li et al. [29] generated for each produce allowed calculation of the temperature and ethylene levels required for any nominated postharvest life. Their data for broccoli to achieve a 7-, 14- or 21-day postharvest life are given in Table 1. This shows firstly, that for all storage periods, the temperature that broccoli need to be held increases by 4 C as the ethylene is reduced from 1 to 0.001 μL L^{-1}. They found a similar effect for pak choy and mint. Using a 14-day postharvest life as an example, maintaining ethylene at 0.001 μL L^{-1} would allow a storage temperature of about 10 °C. This is well above the current recommendation of 0 °C and would result in substantial energy savings. Indeed, in many temperate regions, 10 °C is close to the mean ambient temperature during cooler months so no refrigeration would be needed.

Table 1. The storage temperature of broccoli that allows specific postharvest life periods in the presence of specific ethylene concentrations.

Postharvest Life (Days)	Temperature (°C)			
	<0.001	0.01	0.1	1 μL L^{-1}
7	14	13	12	10
14	9	8	6	5
21	6	4	3	2

Generated from data in Li et al. [29].

For green beans the recommended storage temperature is 5.0–7.5 °C due to the development of chilling injury at lower temperatures [33]. Li et al. [29] found that beans were more sensitive to ethylene than pak choy, broccoli and mint. Table 2 shows that for a seven day postharvest life, the temperature that beans need to be held increases by 9 °C as the ethylene is reduced from 1 to 0.001 μL L^{-1}. For the longer storage periods of 14 and 21 days, it was not possible to maintain produce in an acceptable condition unless the ethylene level was maintained at $\leq$0.1 and $\leq$0.01 μL L^{-1}, respectively. However, if ethylene was maintained at 0.001 μL L^{-1} then storage temperatures of 18 and 13 °C, respectively, would allow marketing of beans after 14 and 21 days, respectively. The commercial relevance of maintaining a low ethylene level was shown by Wills and Kim [34] who reported hessian bags and polystyrene boxes of beans in retail and wholesale markets contained ethylene from 0.17 to 1.17 μL L^{-1} with a mean concentration of 0.45 μL L^{-1}.

Table 2. The storage temperature of green bean that allows specific postharvest life periods in the presence of specific ethylene concentrations.

Postharvest Life (Days)	Temperature (°C)			
	<0.001	0.01	0.1	1 μL L^{-1}
7	24	23	20	15
14	18	15	10	-
21	13	8	-	-

Generated from data in Li et al. [29].

An added benefit for all vegetables could be from a reduced respiration that occurs when the ethylene level is lower [29,35]. This was demonstrated by Becker and Fricker [36], who used the equation for rate of heat generated during respiration, and calculated that a decrease in ethylene from 0.1 to 0.001 μL L^{-1} around a 10 kg box of green bean stored at 10 °C would require 61 J less energy to be removed per hour, or 1460 J per day. This would thus further reduce the refrigeration needed to maintain the storage temperature.

3.3. Marketing Produce in Tropical Regions

Many countries in tropical regions are less developed but have a substantial horticulture industry with produce grown on small holdings and marketed soon after harvest to local or nearby villages. With the short market chain in terms of time and distance, there was little need for technology to limit postharvest change. However, with economic development there is growing interest in trucking produce to larger urban centres within the country or to neighbouring countries. In order to market to these more distant destinations and cope with unexpected delays there is a need for some technology to maintain produce quality during the longer transport and distribution time.

In developed countries, the technology of choice is to reduce the storage temperature of produce. However, in regional areas of most developing countries, refrigerated storage or transport facilities are either not available or are expensive to utilize by small traders. In addition, if refrigeration becomes more accessible its usage will add to the world energy consumption. The management of ethylene levels around produce is a possible alternate technology to maintain the required produce quality during marketing.

3.3.1. Tomato Ripening

The benefit of reducing the ethylene concentration around unripe tomatoes without temperature control was demonstrated by Ku et al. [37]. The marketing of tomatoes in Laos involves packing fruit into polystyrene boxes that are transported 750 km over about 24 h to the capital city, Vientiane. Traders report that substantial ripening occurs during the journey, which limits marketing options to withhold fruit from the market if the price is depressed or fruit is in oversupply. Ku et al. [37] added sachets of an ethylene absorbent into polystyrene boxes of green tomatoes and assessed the proportion of fruit remaining green during nine days at an ambient temperature of 26–32 °C in Vientiane. On the assumption that an acceptable market outcome is achieved if 75% of tomatoes remain green, they found boxes with ethylene absorbent sachets had a 7-day supply chain market life, which was double the 3.5 days for fruit in control containers. Thus, the market life doubled without any temperature management. The study, however, did not have the ability to measure the change in ethylene concentration in the boxes.

3.3.2. Senescence of Vegetables

A more detailed study under controlled conditions of temperature and ethylene concentration was carried out with a range of vegetables by Wills et al. [38]. Since they found no published data for levels of ethylene around produce during marketing at tropical ambient temperatures, they conducted a simulated commercial trial in the laboratory and found that after one day at 30 °C, ethylene accumulation around different produce ranged from 0.3 to 1.5 μL L^{-1} with a mean value across all produce of 0.8 μL L^{-1}. They then examined the effect of atmospheric ethylene at 0.001, 0.01, 0.1 and 1.0 μL L^{-1} on the retention of visual quality of cucumber, golden squash, bitter melon, green bean, pak choy, choy sum, parsley held at a typical tropical ambient temperature of 30 °C [39] at high humidity. Reducing atmospheric ethylene progressively increased the postharvest life of all produce. The extension in market life in 0.001 μL L^{-1} was about 13 days for cucumber, nine days for golden squash and three days for green bean. Market life extension was 1–2 days for bitter melon, coriander, parsley and pak choy but this represents an approximate doubling of the market life that occurred at 1 μL L^{-1} and is considered commercially worthwhile in many developing countries. The marked benefit of reduced ethylene for a 2–day increase in postharvest life is illustrated in Figure 3 where the appearance of bitter melon after three days at 30 °C shows melons held in 1.0 μL L^{-1} were unmarketable while those held in 0.001 μL L^{-1} were still of high quality. Thus, the higher ethylene levels used in this study can be considered likely around stack of produce held at tropical temperatures and the extension of market life found when ethylene was reduced from 1 to 0.001 μL L^{-1} could reflect expectations of actual commercial benefits at 30 °C.

Figure 3. Appearance of bitter melon after storage for three days at 30 °C in the presence of ethylene at 0.001 μL L^{-1} (left) and 1.0 μL L^{-1} (right). Photograph supplied by Li and Wills [40].

For comparison, Wills et al. [38] also stored produce at the commonly accepted ambient temperature in temperate regions of 20 °C in the same range of ethylene concentrations. All produce held at 30 °C in 0.001 μL L^{-1} were found to have a similar postharvest life to that stored at 20 °C in 0.1 μL L^{-1}, a common ethylene level around produce in temperate markets [13]. Thus, maintaining a low ethylene atmosphere at 30 °C was equivalent to reducing the storage temperature by 10 °C.

Cucumber is widely available in temperate and tropical countries with a recommended storage temperature of 10 °C [41]. Wills et al. [38] published data for cucumber stored at 30 and 20 °C, they also had unpublished data for cucumber stored at 10 °C [40] which is now included in Table 3. This shows firstly, that at 30 °C storage under current commercial conditions where cucumbers are exposed to 1 μL L^{-1}, they have a short postharvest life but this is increased to about 15 days if the ethylene level is reduced to ≤0.01 μL L^{-1}. It can also be seen that the postharvest life of about 15 days is similar to that of cucumbers stored at 20 and 10 °C in the common ethylene level of 0.1 μL L^{-1} experienced at these temperatures. Thus, reducing ethylene to ≤0.01 μL L^{-1} around cucumbers at 30 °C gives an equivalent postharvest life to 20 and 10 °C held under current marketing conditions.

Table 3. Postharvest life of cucumber stored at 10, 20 and 30 °C in a range of ethylene concentrations.

Ethylene (µL L^{-1})	Postharvest Life (Days)		
	30 °C	**20 °C**	**10 °C**
0.001	16	23	30
0.01	14	20	23
0.1	9	15	17
1	3	7	9

Data for 30 and 20 °C from Wills et al. [38] and for 10 °C from Li and Wills [40].

3.3.3. Green Colour Retention of Limes

Persian (Tahitian) limes are grown in tropical and sub-tropical regions and mature fruit are harvested when the skin is still green. The postharvest retention of a green colour is of major importance, as yellow fruit is of considerably lower value to consumers. The recommended storage temperature for limes to retain a green peel colour is 10 °C, which is the threshold temperature below which the fruit is susceptible to chilling injury [42]. Li et al. [43] examined the effect on green life of limes held in various ethylene concentrations at the recommended storage temperature (10 °C), and the ambient temperature in temperate regions (20 °C) and tropical regions (30 °C). The findings in Figure 4 show that the green life at 10 °C increased as the ethylene concentration decreased and was maximal in ≤0.01 µL L^{-1} ethylene at about 24 days. Increasing the temperature to 20 °C showed a similar pattern of change in green life with ethylene concentration but at every concentration the green life was lower than at 10 °C with a maximum green life of about 21 days in ≤0.01 µL L^{-1} ethylene. However, storing limes at 30 °C resulted in a longer green life at all concentrations than at 10 °C with the maximum green life of about 27 days achieved in ethylene concentrations of ≤0.1 µL L^{-1}. Thus, holding limes at 30 °C generated a longer green life than at the recommended temperature (10 °C) and it was achieved in the presence of a higher concentration of ethylene. There would therefore be a marketing advantage of not using refrigeration for limes grown and marketed in tropical regions.

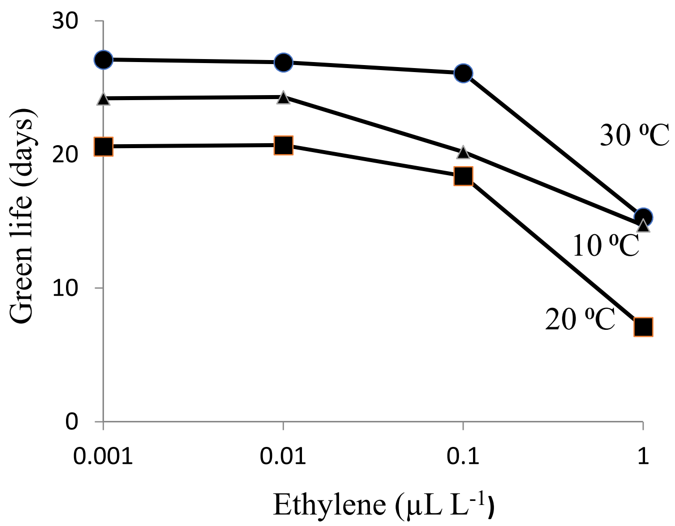

Figure 4. Green life of limes stored at different temperatures and ethylene concentration. Graph generated from data given in Li et al. [42].

3.4. Controlled Atmosphere Storage of Apples

Apples are grown widely around the world with global production of about 85 million tonnes [44]. Considerable volumes are stored for up to 12 months at low temperature, and distributed through extensive domestic and international marketing chains. The use of storage in a low oxygen-controlled atmosphere (CA) is widespread and is often supplemented by pre-storage treatment with 1-methylcyclopropene (1-MCP). 1-MCP acts by binding irreversibly to ethylene-binding sites, thereby preventing the action of ethylene on produce (see Section 4.3). For apples, this benefit is in the maintenance of firmness and acidity, and reduction in the number of various physiological disorders [45].

Kittemann et al. [46] examined the potential for apples treated with 1-MCP to be stored in CA at a higher temperature than untreated fruit. The aim was to evaluate the energy saving benefits against any potential loss in fruit quality at the higher temperature. Three cultivars of untreated apples were stored for seven months in a commonly used CA in Germany of 1% O_2 and 2.5% CO_2 at 1 °C. 1-MCP-treated fruit were stored in the same CA in a similar size commercial chamber but at 5 °C.

After seven months storage, the energy consumption for each room was calculated from the operating times of refrigeration compressor, ventilation fans, defrosting and CO_2 scrubber machinery. Total energy use was reduced by 70% in the 5 °C chamber with the 1-MCP-treated fruit compared to the 1 °C chamber with the untreated fruit.

Contrary to what might be expected, overall fruit quality of the 1-MCP-treated fruit stored at 5 °C was superior to that of the untreated fruit at 1 °C. This was reflected in:

- Weight loss of all three cultivars was lower for apples stored at 5 °C.
- Firmness of Jonagold apples was greater in the 1-MCP-treated fruit at 5 °C, with no significant difference for Golden Delicious and Pinova apples between the treatments.
- Incidence of fungal rots was reduced for Pinova fruit. It was ≤5% for both treatments of Jonagold and Golden Delicious.

Sensory analyses after storage plus seven days at 20 °C was conducted only on Jonagold and Pinova apples. The texture of Jonagold apples was rated higher for the 1-MCP-treated fruit and accordingly, its purchase preference was higher. There was no difference in the texture preferences of Pinova apples for each treatment.

Thus, for all quality attributes, storage of 1-MCP-treated fruit at 5 °C was either superior in quality to untreated fruit at 1 °C or was not significantly different. Hence, the use of an ethylene-inhibiting agent allowed substantial energy savings through storage at a higher temperature and better retention of fruit quality.

The findings are in agreement with a conference paper by McCormick et al. [47] who similarly compared storage of German Gala apples in CA (1% O_2 and 2% CO_2) with untreated fruit at 1.5 °C and 1-MCP-treated fruit at 4 °C. After 5.5 months storage there was a 35% reduction in energy usage for the room with 1-MCP treated fruit, which were firmer, contained higher acid and preferred by a sensory panel than fruit stored at 1.5 °C.

4. Methods to Manage Ethylene

In any commercial postharvest storage or transport situation, ethylene will accumulate to some extent as there will always be endogenous production by produce as well as exposure to exogenous sources. Hence, some technology is generally required to ensure ethylene is maintained at a desired low level throughout the marketing chain. Numerous methods have been proposed to limit the impact of ethylene on postharvest produce. The modes of action of such methods include oxidation or absorption of ethylene, physical removal of ethylene, inactivation of ethylene action and inhibition of ethylene synthesis. The following section highlights technologies that are considered more likely to be commercially relevant in the context of reducing the impact of ethylene on produce to allow a higher storage temperature to be utilized.

4.1. Potassium Permanganate

Ethylene is chemically quite reactive with a range of compounds able to react with the double bond. Potassium permanganate ($KMnO_4$) is a strong oxidizing agent that readily reacts with ethylene to generate carbon dioxide and water as the main end-products. Its first reported use to reduce the ethylene concentration around postharvest produce was by Forsyth et al. [48] and Scott et al. [49] on apples and bananas, respectively. Numerous subsequent studies, for example, on avocado [50], mango [51], kiwifruit [52], lemon [53] and strawberry [54], reported that inclusion into a package of potassium permanganate impregnated onto a porous inert material decreased the ethylene concentration and enhanced postharvest life. Indeed, an accepted practice in many laboratories wanting to generate an "ethylene-free" air stream is to pass ambient air through a column of potassium permanganate impregnated beads. Analysis of the effluent air stream shows that the ethylene concentration is below the limit of detection, which in our laboratory is 0.001 $\mu L\ L^{-1}$.

Potassium permanganate can be incorporated into a postharvest regime as it is now commercially available in pellet form from a diverse range of manufacturers in many countries that are highly competitive with each other for sales. Products are available in small sachets suitable for single packages up to larger tubes suitable for containers or storage chambers. Potassium permanganate products thus offer the ability to reduce ethylene in all size packages and chambers. The current commercial situation with potassium permanganate products has been recently reviewed by Álvarez-Hernández et al. [55] who point out that a major limitation to its wider usage is the availability of little objective published data on the relative effectiveness of individual products on individual produce at both laboratory and industrial scale. They indicate such studies also need to consider effects of temperature and humidity as well as different rates of ethylene production of produce including differences between cultivar and maturity. A potential marketing advantage for products with potassium permanganate is that the compound is an approved additive for use with organic produce [56].

4.2. Ventilation

The simplest technology to reduce ethylene around horticultural produce is to pass ambient air across the produce. Such ventilation could be particularly useful where produce is stored on-farm or on a nearby site as ambient air in rural areas contains a low level of ethylene at about 0.001 $\mu L\ L^{-1}$ [57]. It would also be suitable for long distance transport whether by truck, rail or ship where produce is moved mainly through non-urban areas. It may be less applicable to operations in large urban centres where the concentration of ambient ethylene is higher, commonly in the range of 0.01–0.1 $\mu L\ L^{-1}$ [57]. Ventilation has the added advantage of being chemical-free, and should be accepted by consumers who are increasingly wary of synthetic chemicals added to foods. From an economic perspective, ambient air is free to use, there is an unlimited supply and it is available at all sites.

An undesirable by-product of ventilation is an increase in transpiration from produce. This can be reduced by ventilating with air at high humidity. Wills et al. [24] found air needs to be maintained at $\geq$90% RH to ensure weight loss of bananas was below an acceptable level of 4 g 100 g^{-1} and suggested that transport vehicles be fitted with a small water tank coupled to inexpensive computer-controlled data loggers that will inject a mist into the incoming air stream when required. Ventilation of shipping containers would be with humid ocean air so an acceptable weight loss should be easier to maintain.

A form of passive ventilation is the recent development of a membrane that is claimed to be selectively porous to ethylene but resistant to the transfer of carbon dioxide, oxygen, water and other organic volatile compounds emitted by produce [58]. The addition of a small membrane patch to a container or other sealed storage chamber offers the prospect of maintaining a low concentration of ethylene inside a chamber with no energy expenditure and minimal increase in weight loss.

4.3. 1-Methylcylcopropene (1-MCP)

1-MCP is a competitive inhibitor for ethylene. It acts by attaching irreversibly to ethylene-binding sites, thus preventing ethylene from attaching and eliciting signal transduction. It was discovered and patented 25 years ago by Sisler and Blankenship [59]. Patent protection has supported the development of 1-MCP into an internationally approved postharvest additive for horticultural commodities by being readily availability to researchers around the world who have published many hundreds of papers on its effect on numerous produce and having a commercial sponsor to promote development. It is currently marketed as SmartFresh^{SM} Quality System by Dow Chemicals. Characteristics of 1-MCP that allowed approval by regulatory authorities around the world are it being a gaseous molecule that is easily applied by fumigation and is active at very low concentrations, normally at parts per billion (nL L^{-1}). By 2011, regulatory approval for use of 1-MCP had been obtained in over 40 countries for a wide variety of fruits and vegetables. The specific produce registered within each country varies greatly and relates to the importance of the commodity in that country.

However, Watkins [45] indicates that most use of SmartFresh^{SM} technology is for apples held under CA storage. This is mainly due to the large volumes of fruit kept in CA storage for up to 12 months and that apple is an ideal fruit for 1-MCP because, although it is a climacteric fruit, it is harvested close to optimum eating quality so permanent inhibition of ethylene is acceptable. Many other climacteric fruits such as avocado and banana only require a delay in ripening during storage and transport but then need to be ripened to ensure the consumer receives the expected quality characteristics of ripe fruit. Reversing the effect of 1-MCP on demand, and in full, remains an on-going challenge. A permanent inhibition of ethylene action is acceptable for non-climacteric fruit and vegetables and despite research showing many such produce react favourably to 1-MCP, there has been relatively little commercial use on such produce.

Apart from problems in abnormal ripening of some fruit, 1-MCP poses some logistical issues as it is applied by a pre-storage fumigation that requires batch treatment in a sealed chamber. This presents particular problems in treating smaller volumes of a produce. Aqueous application of 1-MCP would provide flexibility as a dip or line spray while fruit are being sorted. However, aqueous treatment raises issues of interaction of 1-MCP with other co-treatments such as antimicrobial agents. Other possibilities are the use of sachets [60] or polymer films [61] containing material that allows slow release of 1-MCP into the atmosphere around produce by the high relative humidity conditions in a package. Commercialisation of such technologies is dependent on support from the 1-MCP patent holder, Dow Chemicals.

4.4. Ozone and Active Oxygen

Ozone is well known to the food industry as a strong oxidizing agent that can remove pathogens and its oxidation of ethylene is also well documented [62]. However, the level of ozone in the atmosphere must be carefully controlled, as it is toxic to produce and humans and a level of 0.1 L^{-1} is a common permitted limit of exposure in the workplace. Ozone generating systems are commercially available in a range of sizes and prices, and would need to be assessed for individual situations for cost and technical efficacy. They are, however, suitable only for large storage chambers. Skog and Chu [63] evaluated one such unit and found that ozone at 0.04 L L^{-1} prevented the accumulation of ethylene in apple and pear storage rooms and a range of vegetables could tolerate this ozone level without damage. It was thus deemed suitable for use in wholesale storage rooms where are a range of ethylene-producing produce are co-stored with ethylene-sensitive produce.

A variation introduced by Scott et al. [64] used a UV lamp that emitted mainly at 254 nm but with trace emissions at 185 nm to effect a rapid loss of ethylene in the atmosphere around bananas in a sealed chamber but without any fruit injury. They speculated that while ozone was generated at 185 nm, it was rapidly degraded to atomic oxygen, which was more effective in oxidizing ethylene than ozone. Scott and Wills [65] then developed a system in which the atmosphere from a chamber was circulated through a scrubber containing UV lamps emitting the required ratio of 185 and 254 nm where ethylene was degraded but ozone did not emerge from the scrubber. A range of commercially available ethylene scrubbing systems using UV lamps and photocatalytic oxidation are now available, for example, from Absoger [66]. Keller et al. [67] claimed the newer more efficient ethylene removal technologies can maintain levels of ethylene below 0.001 L L^{-1}.

4.5. Adsorbents

Early attempts to reduce ethylene levels were by adsorption onto activated charcoal and a range of diatomaceous earths, clays and minerals. However, Reid and Dodge [68] found most of these had insufficient ethylene adsorption capacity to maintain a low ethylene atmosphere for any prolonged period. There are, however, recently released commercial products that do not disclose the mode of action or the material used, but they appear to act by adsorption—their efficacy is yet to be determined independently of the manufacturer or marketing agents.

The efficiency of carbon-based adsorption has been improved in scrubber units that use metal catalysts. For example, Martínez-Romero et al. [69] improved reactivity by incorporating 1% palladium into activated carbon and regenerated its activity by heat pulsing. Such devices are suitable for storage rooms rather than individual packages.

5. Discussion

It has been shown reducing the concentration of ethylene around horticultural produce increases postharvest life and that reducing ethylene has a similar effect to reducing the storage temperature., There would seem to be general acceptance by the horticultural industry that a reduction in the use of refrigerated storage and transport of fruit and vegetables and the commensurate reduction in energy use leading to reduced greenhouse gas emissions would be of benefit for the industry and the environment. However, it is noteworthy that it in the 10+ years since East [4] highlighted the need to reduce energy in storage and handling, only a few research groups have published studies on how energy reduction can be achieved. This paper has shown that management of ethylene levels around produce can be at least a partial substitute for refrigeration and in some instances a replacement for refrigeration.

However, industry remains reluctant to change current practices. A major impediment is considered to be overcoming risk aversion in the upending of accepted wisdom over many years that cool chain management is the gold standard for postharvest handling of fresh fruit and vegetables. This risk aversion is illustrated by the example noted in Section 3.1 of some international banana traders who place a polyethylene bag around bananas in a carton but still maintain the container at a low temperature. Research shows either technology will deliver the desired outcome, so why are both systems used concurrently?

Change in industry practice would be assisted if there was greater interest in ethylene metabolism by postharvest researchers. For this to occur, there firstly, needs to be greater understanding by researchers that 0.1 L L^{-1} is not the threshold concentration for activity of ethylene and that ethylene above 0.001 L L^{-1} is detrimental to postharvest quality. It is telling that while numerous published papers evaluate the effectiveness of some technology or compound on a wide range of quality factors, the vast majority do not even measure ethylene. Thus, conclusions in these papers on the mode of action of the applied treatment may be erroneous. Indeed, in one of the few papers to include ethylene measurement, a time course study by Al Ubeed et al. [70] of the beneficial effect of hydrogen sulphide fumigation on the green leafy vegetable, pak choy, found that the first quality factor to be affected by hydrogen sulphide was a reduction in ethylene synthesis. They concluded that reducing ethylene metabolism was the key action of hydrogen sulphide that led to inhibition of other senescence attributes.

The paucity of studies on ethylene is considered to be in large part due to the relative difficulty in measuring ethylene at the low physiologically effective concentrations important for fruit and vegetables. The standard method for measuring ethylene is with flame ionisation gas chromatography (FIDC). With a good instrument held in a controlled temperature environment, it is possible to attain a sensitivity of 0.001 L L^{-1} but many FIDC systems struggle to measure 0.01 L L^{-1}. However, the cost and expertise needed to sustain a FIDC system is beyond the capability of many small research laboratories especially in less developed countries, and it is impractical to locate instrumentation at most cool stores or packing sheds. While many types of ethylene sensor devices are commercially available [71] our experience has been that most are not able to accurately measure levels of $\leq$0.01 µL L^{-1} ethylene.

The inability to rapidly measure low levels of ethylene is a major hurdle in demonstrating to an industry participant that there is a need to reduce ethylene in their storage situation. In addition, how does someone implementing an ethylene-reducing technology know if the intervention is effective? This is in contrast to measurement of temperature, which is cheap, generates a continuous measurement and no training is needed to take a measurement. Thus, a critical development is the availability of a low-cost, portable, digital readout instrument that gives real time assessment of the ethylene concentration. It would seem that companies marketing ethylene-reduction technologies should be more proactive in supporting development of such an instrument, as they would be a major beneficiary of the technology.

A marketing advantage of reduced energy usage could be through increasing community concerns about climate change with the horticultural industry being seen as a good corporate citizen. In the 1990s, the United Kingdom developed an energy rating for foods based on the concept of food miles that measures the distance the food has travelled from the farm gate to the consumer. Such a measure is flawed as postharvest transport is only a small fraction of the energy used to produce food and is poorly correlated to the total energy usage during production and marketing. However, it is a simple concept that consumers can relate to and there would be marketing value in a trader who can advertise that its produce was less energy intensive than those of competitors.

The greatest benefit accruing to industry participants would be in reducing costs by holding produce at a higher temperature. Of course, this needs to be balanced by any cost to introduce some new technology to reduce ethylene. It can be a daunting process to contemplate how to capture the cost benefit of less refrigeration usage and is best tackled in a systematic manner. The first step should be to know the maximum time required for a particular marketing chain for a specific produce and then determine the temperature required to maintain quality for this period. Where a relatively short market life is required, it may be possible to hold produce at ambient temperature without having any ethylene reduction intervention. For longer marketing periods, an investigation should be made of the level of ethylene in the current storage and transport system and then determine the increase in temperature that accompanies a reduction in ethylene around produce. While it is not commercially practical to modify the storage temperature by small increments, it could be feasible to replace storage at 0 °C with storage at 5 °C or 10 °C, temperatures that are in commercial usage. If the required temperature is 15 °C or some other sub-ambient temperature, especially in tropical regions, use of standard air conditioning may be cost effective.

Selection of an ethylene reduction technology obviously needs to be effective, reliable, manageable and cost-effective. The most universal technology currently available is potassium permanganate-based products as they are commercially available from a wide range of manufacturers as small sachets suitable for single packages up to tubes suitable for storage rooms or containers. However, they do have a limited life and without regular measurement of ethylene levels it is currently it is not easy to decide when to replace the product. 1-MCP is highly effective in inhibiting ethylene action but only in a limited range of produce and the technology currently requires batch fumigation which tends to make it suitable only for higher volume produce. Ventilation with ambient air is worthy of consideration as it is an endless free resource and is chemical-free both in usage and post-usage supply. The issues that need to be managed are to maintain the air stream at a sufficient high humidity to prevent excessive weight loss from produce, and where the incoming air is at a higher temperature than that of the storage chamber a heat exchange unit may be required. The technology is only suitable for storage rooms and transport vehicles and containers. As mentioned in Section 4.2, if the ethylene-porous membrane proves to be highly selective for ethylene, it could make ventilation of storage chambers a viable option as the membrane should last many seasons and requires no energy input.

6. Conclusions

Decreasing ethylene levels in the atmosphere around horticultural produce inhibits ripening and senescence with continuous increase in postharvest life obtained down to very low concentrations of 0.001 $\mu L\ L^{-1}$. Reducing ethylene around produce has a similar beneficial effect as reducing the storage temperature. Managing ethylene levels in storage situations can then be a partial or total replacement for refrigeration with the subsequent reduction in energy usage.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Ryall, A.L.; Pentzer, W.T. *Handling, Transportation and Storage of Fruits and Vegetables*; AVI Publishing: Westport, CT, USA, 1974.
2. Farrer, K.T.H. *A Settlement Amply Supplied: Food Technology in Nineteenth Century Australia*; Melbourne University Press: Carlton, VIC, Australia, 1980.
3. USDA. *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66*; Gross, K.C., Chien, Y.W., Saltveit, M., Eds.; U.S. Department of Agriculture, Agricultural Research Service: Washington, DC, USA, 2016.
4. East, A.R. Energy efficient postharvest storage and handling. *CAB Rev. Perspect. Agric. Veterin. Sci. Nutr. Nat. Resour.* **2010**, *5*, 1–9.
5. Gane, R. Production of ethylene by some fruits. *Nature* **1934**, *134*, 1008. [CrossRef]
6. Crocker, W.; Hitchcock, A.E.; Zimmerman, P.W. Similarities in the effects of ethylene and the plant auxins. *Contrib. Boyce Thompson Inst.* **1935**, *7*, 1–248.
7. Abeles, F.B.; Morgan, P.W.; Saltveit, M.E. *Ethylene in Plant Biology*, 2nd ed.; Academic Press: New York, NY, USA, 1992.
8. Wills, R.B.H.; Golding, J.B. *Postharvest: An Introduction to the Physiology and Handling of Fruit and Vegetables*, 6th ed.; UNSW Press: Sydney, Australia, 2016.
9. Burg, S.P.; Burg, E.A. The role of ethylene in fruit ripening. *Plant Physiol.* **1962**, *37*, 179–189. [CrossRef]
10. Kader, A.A. Ethylene-induced senescence and physiological disorders in harvested horticultural crops. *HortScience* **1985**, *20*, 54–57.
11. Morris, L.L.; Kader, A.A.; Klaustermeyer, J.A.; Cheney, C.C. Avoiding ethylene concentrations in harvested lettuce. *Calif. Agric.* **1978**, *32*, 14–15.
12. Schouten, S.P. Significance of ethylene in postharvest handling of vegetables. In *Ethylene and Plant Development*; Roberts, J.A., Tucker, G.A., Eds.; Butterworths: London, UK, 1985; pp. 353–362.
13. Wills, R.B.H.; Warton, M.A.; Ku, V.V.V. Ethylene levels associated with fruit and vegetables during marketing. *Aust. J. Expt. Agric.* **2000**, *40*, 485–490.
14. Knee, M.; Proctor, F.J.; Dover, C.J. The technology of ethylene control: Use and removal in post-harvest handling of horticultural commodities. *Ann. Appl. Biol.* **1985**, *107*, 581–595. [CrossRef]
15. Wills, R.B.H.; Ku, V.V.V.; Shohet, D.; Kim, G.H. Importance of low ethylene levels to delay senescence of non-climacteric fruit and vegetables. *Aust. J. Expt. Agric.* **1999**, *39*, 221–224.
16. Wills, R.B.H.; Warton, M.A.; Mussa, D.M.D.N.; Chew, L.P. Ripening of climacteric fruits initiated at low ethylene levels. *Aust. J. Expt. Agric.* **2001**, *41*, 89–92. [CrossRef]
17. Pranamornkith, T.; East, A.; Heyes, J. Influence of exogenous ethylene during refrigerated storage on storability and quality of *Actinidia chinensis* (cv. Hort16A). *Postharvest Biol. Technol.* **2012**, *64*, 1–8. [CrossRef]
18. FAO. *Banana Market Review–Preliminary Results 2020*; FAO: Rome, Italy, 2021.
19. John, P.; Marchal, J. Ripening and biochemistry of the fruit. In *Bananas and Plantains*; Gowen, S., Ed.; Chapman and Hall: London, UK, 1995; pp. 434–467.
20. Australian Bananas. Production. Available online: www.Australianbananas.com.au/Pages/all-about-bananas/production (accessed on 20 July 2021).
21. Lescot, T. Carbon footprint analysis in banana production. In Proceedings of the Second Conference of the World Banana Forum, Guayaquil, Ecuador, 28–29 February 2012.
22. Spennigal, D.; Harker Transport, Brisbane, Australia. Personal communication, 2014.
23. Wills, R.B.H.; Harris, D.R.; Spohr, L.J.; Golding, J.B. Reduction of energy usage during storage and transport of bananas by management of exogenous ethylene levels. *Postharvest Biol. Technol.* **2014**, *89*, 7–10. [CrossRef]
24. Wills, R.B.H.; Harris, D.R.; Seberry, J.A. Use of ventilation with ambient air to inhibit ripening of banana during long distance transport. *Food Aust.* **2012**, *64*, 38–44.
25. De Martino, D.; Dole Italy. Personal communication, 2014.

26. Scott, K.J.; Roberts, E.A. Polyethylene bags to delay ripening of bananas during storage. *Aust. J. Expt. Agric. Anim. Husb.* **1966**, *6*, 197–224. [CrossRef]
27. Scott, K.J.; Gandanegara, S. Effect of temperature on the storage life of banana in polyethylene bags with ethylene absorbent. *Tropic. Agric.* **1974**, *51*, 23–26.
28. Wills, R.B.H.; Harris, D.R.; Seberry, J.A. Delayed ripening of bananas through minimisation of ethylene. *Tropic. Agric.* **1999**, *76*, 279–8223.
29. Li, Y.; Wills, R.B.H.; Golding, J.B. Interaction of ethylene concentration and storage temperature on postharvest life of the green vegetables, pak choi, broccoli, mint and green bean. *J. Hortic. Sci. Biotech.* **2017**, *92*, 288–293. [CrossRef]
30. Luo, Y. Bok choy. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, USDA Handbook 66*; Gross, K.C., Chien, Y.W., Saltveit, M., Eds.; U.S. Department of Agriculture, Agricultural Research Service: Washington, DC, USA, 2016; p. 243.
31. Toivonen, P.M.A.; Forney, C. Broccoli. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, USDA Handbook 66*; Gross, K.C., Chien, Y.W., Saltveit, M., Eds.; U.S. Department of Agriculture, Agricultural Research Service: Washington, DC, USA, 2016; p. 248.
32. Cantwell, M.; Reid, M. Herbs (Fresh Culinary): Recommendations for Maintaining Postharvest Quality. 2001. Available online: http://postharvest.ucdavis.edu/Commodity_Resources/Fact_Sheets (accessed on 15 July 2021).
33. Cantwell, M. Bean. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, USDA Handbook 66*; Gross, K.C., Chien, Y.W., Saltveit, M., Eds.; U.S. Department of Agriculture, Agricultural Research Service: Washington, DC, USA, 2016; p. 230.
34. Wills, R.B.H.; Kim, G.H. Effect of ethylene on postharvest quality of green beans. *Aust. J. Expt. Agric.* **1996**, *36*, 335–337. [CrossRef]
35. Li, Y.; Golding, J.B.; Arcot, J.; Wills, R.B.H. Continuous exposure to ethylene in the storage environment adversely affects 'Afourer' mandarin fruit quality. *Food Chem.* **2018**, *242*, 585–590. [CrossRef]
36. Becker, B.R.; Fricke, B.A. Transpiration and respiration of fruits and vegetables. In Proceedings of the International Refrigeration Meeting, Commissions C2 with B2, D1 and D2-3, New Developments in Refrigeration for Food Safety and Quality, Lexington KY, USA, 2–4 October 1996; pp. 110–121.
37. Ku, V.V.V.; Inthalangsee, B.; Wills, R.B.H. Use of maturity sorting and reducing ethylene with potassium permanganate to enhance marketing of tomatoes in Laos at ambient tropical temperatures. *J. Hortic. Postharvest Res.* **2019**, *2*, 61–68.
38. Wills, R.B.H.; Li, Y.; Golding, J.B. Maintaining the market life of vegetables held at an ambient tropical temperature by reducing exogenous ethylene. *Trop. Agric.* **2018**, *95*, 31–37.
39. Youryon, P.; Supapvanich, S. Effect of storage temperatures on physical quality and bioactive compounds in 'Leb Mu Nang' banana (*Musa* A9A) fruit. *Trop. Agric.* **2017**, *94*, 1–8.
40. Li, Y.; Wills, R.B.H.; (University of Newcastle, Newcastle, Australia). Unpublished data. 2014.
41. Saltveit, M.E. Cucumber. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, USDA Handbook 66*; Gross, K.C., Chien, Y.W., Saltveit, M., Eds.; U.S. Department of Agriculture, Agricultural Research Service: Washington, DC, USA, 2016; p. 303.
42. Burns, J.K. Lime. In *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, USDA Handbook 66*; Gross, K.C., Chien, Y.W., Saltveit, M., Eds.; U.S. Department of Agriculture, Agricultural Research Service: Washington, DC, USA, 2016; p. 390.
43. Li, Y.; Wills, R.B.H.; Golding, J.B. Storage at elevated ambient temperature and reduced ethylene delays degreening of Persian limes. *Fruits* **2017**, *72*, 288–291. [CrossRef]
44. FAO. *Food and Agriculture Data*; FAO: Rome, Italy, 2021; Available online: www.fao.org/faostat (accessed on 30 July 2021).
45. Watkins, C.B. Low ethylene technology in non-optimal storage temperatures. In *Advances in Postharvest Fruit and Vegetable Technology*; Wills, R.B.H., Golding, J., Eds.; CRC Press: Boca Raton, FL, USA, 2015; pp. 117–145, Chapter 6.
46. Kittemann, D.; McCormick, R.; Neuwald, D.A. Effect of high temperature and 1-MCP application or dynamic controlled atmosphere on energy savings during apple storage. *Europ. J. Hortic. Sci.* **2015**, *80*, 33–38. [CrossRef]
47. McCormick, R.; Neuwald, D.; Streif, J. A case study: Potential energy savings using 1-MCP with 'Gala' apples in commercial CA storage. In *Acta Horticulturae 877: VI International Postharvest Symposium*; Erkan, M., Aksoy, U., Eds.; ISHS: Leuven, Belgium, 2010; pp. 323–326.
48. Forsyth, F.R.; Eaves, C.A.; Lockhard, C.L. Controlling ethylene levels in the atmosphere of small containers of apples. *Canad. J. Plant Sci.* **1967**, *47*, 717–718. [CrossRef]
49. Scott, K.J.; McGlasson, W.B.; Roberts, E.A. Potassium permanganate as an ethylene absorbent in polyethylene bags to delay the ripening of bananas during storage. *Aust. J. Expt. Agric. Anim. Husb.* **1970**, *10*, 237–240. [CrossRef]
50. Hatton, T.T.; Reeder, W.F. Quality of "Lula" avocados stored in controlled atmospheres with or without ethylene. *J. Am. Soc. Hortic. Sci.* **1972**, *97*, 339–343.
51. Esguerra, E.B.; Mendoza, J.R.; Pantastico, E.B. Regulation of fruit ripening II use of perlite $KMnO_4$ insert as an ethylene absorbent. *Philipp. J. Sci.* **1978**, *107*, 23–31.
52. Scott, K.J.; Guigni, J.; Bailey, W. The use of polyethylene bags and ethylene absorbent to extend the life of kiwifruit (*Actinidia chinensis* Planch) during cool storage. *J. Hortic. Sci.* **1984**, *50*, 563–566. [CrossRef]
53. Wild, B.L.; McGlasson, W.B.; Lee, T.H. Effect of reduced ethylene levels in storage atmospheres on lemon keeping quality. *HortScience* **1976**, *11*, 114–115.

54. Kim, G.H.; Wills, R.B.H. Interaction of enhanced carbon dioxide and reduced ethylene on the storage life of strawberries. *J. Hortic. Sci. Biotech.* **1998**, *73*, 181–184. [CrossRef]
55. Alvarez-Hernandez, M.H.; Martínez-Hernández, G.B.; Avalos-Belmontes, F.; Castillo-Campohermoso, M.A.; Contreras-Esquivel1, J.C.; Artés-Hernández, F. Potassium permanganate-based ethylene scavengers for fresh horticultural produce as an active packaging. *Food Eng. Rev.* **2019**, *11*, 159–183. [CrossRef]
56. Australian Certified Organic Standard 2019 Version 1. Available online: https://austorganic.com (accessed on 23 August 2021).
57. Alberta Environment. *Assessment Report on Ethylene for Developing Ambient Air Quality Objectives*; Alberta Environment: Edmonton, AB, Canada, 2003.
58. Nemser, S.; Compact Membrane Systems, Newport, DE, USA. Personal communication, 2021.
59. Sisler, E.C.; Blankenship, S.M. Method of Counteracting an Ethylene Response in Plants. U.S. Patent 5518988, 21 May 1996.
60. Lee, Y.S.; Beaudry, R.; Kim, J.N.; Harte, B.R. Development of a 1-methylcyclopropene (1-MCP) sachet release system. *J. Food Sci.* **2006**, *71*, C1–C6. [CrossRef]
61. Hotchkiss, J.H.; Watkins, C.B.; Sanchez, D.G. Release of 1-methylcyclopropene from heat-pressed polymer films. *J. Food Sci.* **2007**, *72*, E330–E334. [CrossRef] [PubMed]
62. Dickson, R.G.; Law, S.E.; Kays, S.J.; Eiteman, M.A. Abatement of ethylene by ozone treatment in controlled atmosphere storage of fruits and vegetables. In Proceedings of the 1992 International Winter Meeting, Nashville, TN, USA, 15–18 December 1992; pp. 1–9.
63. Skog, J.; Chu, C.L. Effect of ozone on qualities of fruits and vegetables in cold storage. *Canad. J. Plant Sci.* **2001**, *81*, 773–778. [CrossRef]
64. Scott, K.J.; Wills, R.B.H.; Patterson, B.D. Removal by ultra-violet lamp of ethylene and other hydrocarbons produced by bananas. *J. Sci. Food Agric.* **1971**, *22*, 496–497. [CrossRef]
65. Scott, K.J.; Wills, R.B.H. Atmospheric pollutants destroyed in an ultra-violet scrubber. *Lab. Pract.* **1973**, *22*, 103–106. [PubMed]
66. Absoger Controlled Atmosphere. Available online: www.absoger.fr/equipement/catalyseur-dethylene (accessed on 16 August 2021).
67. Keller, N.; Ducamp, M.N.; Robert, D.; Keller, V. Ethylene removal and fresh product storage: A challenge at the frontiers of chemistry. Toward an approach by photocatalytic oxidation. *Chem. Rev.* **2013**, *113*, 5029–5070. [CrossRef]
68. Reid, M.; Dodge, L. New ethylene absorbents: No miracle cure. *Perish. Handl. Newsl. UC Davis* **1995**, *83*, 8.
69. Martínez-Romero, D.; Guillen, F.; Castillo, S.; Zapata, P.J.; Valero, D. Development of a carbon-heat hybrid ethylene scrubber for fresh horticultural produce storage purposes. *Postharvest Biol. Technol.* **2009**, *51*, 200–205. [CrossRef]
70. Al Ubeed, H.M.S.; Wills, R.B.H.; Bowyer, M.C.; Golding, J.B. Interaction of the hydrogen sulphide inhibitor, propargylglycine (PAG), with hydrogen sulphide on postharvest changes of the green leafy vegetable, pak choy. *Postharvest Biol. Technol.* **2019**, *147*, 54–58. [CrossRef]
71. Xing, Y.; Zhu, H.; Chang, G.; Yu, K.; Yue, F. Metal Oxide Nanostructures-Based Gas Sensor for Ethylene Detection: A Review. *Mater. Sci. Eng.* **2019**, *677*, 022082. [CrossRef]