

Review

A Review on the Modified Atmosphere Preservation of Fruits and Vegetables with Cutting-Edge Technologies

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Abstract: Respiration and microbial infection are important causes of postharvest spoilage of fruits and vegetables (F&V). Atmosphere storage technology can significantly reduce postharvest losses. This comprehensive review aims to cover recent progress in the application of atmosphere storage to F&V preservation, not only focusing on the effect of gas conditions but also evaluating combination applications involving newer preservation technologies, including ethylene scavengers, high-pressure and decompression technology, ozone, ultraviolet radiation, active packaging, high-voltage electrostatic field, plasma treatment, and pulse-controlled atmosphere. Appropriate choice of storage conditions optimal for each F&V is essential since the physiological properties and sensory qualities are affected by them. The combination of atmosphere storage with these emerging technologies could contribute to significant reductions in food loss during storage.

Keywords: atmosphere storage technology; food loss; fruits and vegetables; shelf life



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1. Introduction

Fruits and vegetables (F&V) remain alive even after harvest. Subsequently, the process of transpiration is often the main cause of postharvest loss, although respiration can take precedence under conditions of high humidity when the transpiration rate is negligible [1]. An increase in respiration leads to excessive nutrient consumption, accelerating the aging of F&V and shortening their shelf life [2]. Almost all food categories, including F&V, roots and tubers, grains, oilseeds, milk, meat and fish, and seafood, are subject to wastage, though F&V constitute the single food category with the highest rate of loss (66%) despite their importance as a source of human nutrition and their contribution to health [3,4]. Therefore, control of respiration and microbial growth using atmosphere preservation technology is essential for F&V storage [5].

Respiration is a metabolic process that provides energy. There are two types of respiration in plants, depending on the involvement of O₂. Aerobic respiration consists of oxidative breakdown of organic reserves to simpler molecules, including CO₂ and water, with a release of energy [6,7]. Anaerobic respiration results in the production of ethanol by decarboxylation of pyruvate to CO₂ without O₂ consumption during fermentation metabolism [8,9]. Anaerobic respiration is undesirable during the storage of F&V because the large amounts of ethanol, acetaldehyde and other substances accumulated produce an unpleasant smell. Thus, respiration control in the postharvest ripening processes is a key strategy for reducing loss and maintaining quality [10,11]. In addition, food-borne diseases, such as bacterial food poisoning, are potentially serious and may affect health globally [12]. Consumption of raw F&V is recommended for a balanced diet, but sometimes raw F&V may carry pathogens in the form of harmful bacteria and viruses [13,14]. Modified atmosphere packaging (MAP) has been recognized as one of the solutions to secure the safety of F&V by protecting them from the negative effects of microbes [15,16].

Control of the atmosphere during storage can maintain the freshness of postharvest F&V and ensure a long shelf life without microbial pollution. Atmospheric control during storage has major advantages over other methods [17]. The storage atmosphere can maintain freshness and flavor without nutritional loss and operates under benign conditions compared to other preservation technologies, such as drying. Controlled atmosphere (CA) and MAP are two common postharvest technologies, both of which involve controlling the gas composition of the storage environment. The desired storage atmosphere is typically created by reducing O₂ concentration and increasing CO₂ concentration compared with that in ambient air [18]. However, extreme gas concentrations for storage have been reported in recent years, and they have shown good results [19,20]. Additionally, atmosphere control in combination with other technologies, such as ultraviolet radiation (UR) and ozone (O₃), are also gaining attention with the aim of obtaining better quality products.

There are two main parts to this review: (1) a comprehensive review of atmosphere storage for various F&V in recent years and (2) a review of the application of other emerging preservation technologies in relation to atmosphere storage. The potential for combining emerging technologies, including ethylene scavengers, high-pressure and decompression technology, O₃, UR, active packaging (AP), high-voltage electrostatic field (HVEF), plasma treatment (PT), and pulse-CA (pCA) with modified atmosphere preservation, is evaluated. A comprehensive summary of the effect of atmosphere preservation conditions on different types of F&V is provided for the first time. This review aims to provide guidance on the selection of appropriate atmosphere conditions for the preservation of various types of F&V to prolong shelf life and avoid food loss.

2. Comprehensive Review of Atmosphere Storage of Various F&V in Recent Years

Atmosphere storage is divided into CA storage and modified atmosphere (MA) storage. CA storage involves maintaining F&V in an atmosphere whose gas composition is artificially controlled, mainly to reduce O₂ concentration and increase CO₂ concentration. Strictly speaking, the levels of O₂ and CO₂ should be controlled within a narrow range. MA storage also belongs in the category of atmosphere storage, but in this case, there is allowance for wider ranges of O₂ and CO₂ concentrations, without any constant index [21]. Generally, the results from CA storage are superior because of the more strictly controlled gas (and temperature) conditions; in MA storage, gases in the packaging material are affected by respiration of F&V, and there may be interaction with surrounding air [22].

There are two types of gas conditioning employed, based on speed: rapid oxygen-reducing storage and natural oxygen-reducing storage. The latter takes more time because it relies on the respiration of F&V to consume and, therefore, reduce O₂ in the storage atmosphere. Generally, both a gas conditioner and a refrigeration unit need to be installed in an atmosphere storage warehouse to achieve optimum results [23].

Atmosphere storage keeps F&V in an under-ripe state (green) by delaying senescence. This effect is clearly observed with F&V rich in chlorophyll, such as cabbage and lettuce [24]. The hardness of fruits, especially persimmons and peaches, can be maintained well by atmosphere storage [25]. Certain physiological disorders, such as chilling injury, can be alleviated by atmosphere storage. For example, the symptoms of chilling injury to some vegetables can be alleviated by reducing the O₂ content and increasing the CO₂ content [26]. Chilling injury symptoms in peppers are significantly reduced under conditions of 8 ± 1 °C, 4.5% O₂, and 7.8% CO₂ [27]. Appropriate gas storage conditions can reduce the decay rate and the occurrence of pests in F&V [28]. Although atmosphere storage can prolong the storage life of F&V, if something goes wrong with the atmosphere, harmful effects may occur. For example, low O₂ levels can cause potato black heart symptoms [29]. When the temperature rises, the amount of O₂ required for respiration increases, and this imbalance is significant. An inappropriate increase in CO₂ concentration can cause red heart disease in apples and brown heart disease in apples and pears. Therefore, it is crucial for one to choose storage conditions that suit the characteristics of F&V concerned. Here, we summarize

the effects of atmosphere storage conditions (gas ratio, temperature, and relative humidity (RH)) and storage time on various F&V.

2.1. Effect of Atmosphere Storage on the Shelf Life of Various Fruits

The effects of atmosphere storage conditions on the shelf life of various fruits are summarized in Table 1. Pome fruits, such as apples, pears, and crabapples, mostly mature in autumn. Stored at 0–1 °C, they can be kept fresh for a long time. In recent reports, “double-low gases” were applied for the atmosphere storage of pome fruits. For apples and pears, 1–3% O₂ and 1–3% CO₂ were applied, and the storage period was extended to 3 months [30]. In addition to intact fruits, efforts to increase storage times of fresh-cut fruits have gradually increased. Inhibition of browning and extension of shelf life of fresh-cut pear fruit can be effectively achieved at 5–7 °C, 10% ± 5% O₂ and CO₂ [31]. Drupe fruits, such as peaches, apricots, and dates, are generally stored at 0–5 °C (though they should not be stored for too long in a freezer as this reduces the flavor). Double-low gases, with O₂ and CO₂ concentrations ranging from 3% to 15%, have been applied (these concentrations are higher than those applied for pome fruits). Berries such as grapes, strawberries, lychees, and cherries are small, and the pulp becomes serous after maturation. Generally, it is difficult to keep these fresh in cold storage. They can be frozen, but during the thawing process, the juice may be lost and the tissues loosened; this seriously damages the sensory quality and flavor. This is the reason why atmosphere storage is of great interest for the preservation of berry fruits. In most cases, berry fruits are stored at around 5 °C, and a few are stored at 0 °C. Double-high gases have been attempted for atmosphere storage. Although maintaining quality, the storage period of grapes can be extended to approximately 1 month, and that of strawberries and blueberries can be extended to 15 days [32–35]. Citrus fruits, such as tangerines, sweet oranges, grapefruits, and lemons, grow in the tropics and subtropics. They have a hard peel that is good protection and affords a longer shelf life. These fruits can be stored around 5 °C, which is convenient for the cold supply chain. Compound fruits include tropical pineapple, dragon fruit, and others. For these, cold storage time should not be too long, and, generally, a higher temperature of 2–7 °C is selected for refrigeration to maintain the nutrition and flavor quality of the pulp. The storage time of dragon fruit under double-low gases is extended by 29 days compared with single-gas conditions [36].

Table 1. Comparison of atmosphere storage of fruits.

Fruits	E.g.	Temp/°C	RH	Gas Ratio		Method	Storage Time	Source
				O ₂	CO ₂			
Pome	Apples	0 ± 0.1 °C	92–95%	2–3%	1%	pCA + MAP	90 d	2020 [30]
		1.5 ± 0.1 °C	94 ± 2%	1.2 kPa	2.0 kPa	CA	240 d	2020 [37]
		1 °C	-	1–3 kPa	3 kPa	CA	-	2016 [38]
		1.5–2.0 °C	99%	<2%	<1%	CA	>150 d	2020 [39]
	Pears	4 ± 2 °C	-	7%	2.5%	MA	14 d	2017 [40]
		1.1 °C	-	1–2%	<1%	1-MCP + CA	240 d	2020 [41]
Drupe	Plums	5 °C	-	6–16%,	10%	MA	5 d	2021 [31]
		0 °C	-	20%	0%	H-O ₂ + 1-MCP	210 d	2018 [42]
	Peaches	0 °C	90–95%	10%	4%	PVC + MAP	56 d	2021 [43]
		4 °C	-	10 kPa	0 kPa	MAP	90 d	2015 [25]
	Jujube fruits	0 °C	92%	3 kPa	10 kPa	1-MCP + CA	>21 d	2010 [44]
		5 °C	90%	14.50 kPa	3.86 kPa	MAP	49 d	2019 [45]
Berries	Apricots	4 °C	75%	5%	10%	MAP	42 d	2012 [46]
		4 °C	95%	6%	10%	CA	42 d	2020 [47]
	Grapes	4 ± 1 °C	-	Air	20%	1-MCP+H-CO ₂	>32 d	2019 [32]
		0 ± 0.5 °C	90–95%	2%	5%	MAP	>45 d	2018 [48]
		5 °C	-	1%	>20%	H-CO ₂	>20 d	2017 [33]

Table 1. Cont.

Fruits	E.g.	Temp/°C	RH	Gas Ratio		Method	Storage Time	Source	
				O ₂	CO ₂				
Citrus	Strawberries	5 °C	-	Air	5%	MAP	3 d	2021 [34]	
		0 ± 0.5 °C	-	20%	20%	MAP	10 d	2020 [49]	
		4.0 ± 1.0 °C	90–95%	5–10%	10–15%	MAP	18 d	2019 [50]	
		10 °C	70%	10%	0%	MAP	4 d	2019 [51]	
	Blueberries	4 °C	-	10 kPa	40 kPa	MAP	15 d	2020 [52]	
		Cherries	5 °C	-	16%	20%	MAP	21 d	2019 [53]
	Persimmons	0 ± 1 °C	90–95%	5%	10%	MAP-Ar	63 d	2019 [54]	
		5 °C	-	20 kPa	2 kPa	MAP	30 d	2018 [35]	
		Oranges	4 °C	0%	15 kPa	5 kPa	MAP + ZnO	20 d	2021 [55]
		Citrus unshiu Marc	4 °C	99.9%	9.9 ± 0.2%	2.1 ± 0.1%	MAP + ACP	45 d	2021 [56]
Compound-Fs	Dragon fruits	6 ± 0.5 °C	-	2 kPa	5 kPa	CA	50 d	2021 [36]	
		2–5 °C	-	5–21%	0%	MAP	21 d	2020 [22]	
	Pineapples	7 °C	-	50%	50%	MA	12 d	2013 [57]	

2.2. Effect of Atmosphere Storage on the Shelf Life of Various Vegetables

The effects of atmosphere storage conditions on the shelf life of various vegetables are summarized in Table 2. The edible parts of leafy vegetables are the leaves and the tender petioles, which contain large amounts of chlorophyll, vitamin C, and inorganic salts. Leafy vegetables are generally stored at 0–7 °C. However, vegetables of this type (e.g., cabbage and spinach) are difficult to keep in cold storage because of their high water content, which makes them subject to damage and rot. Atmosphere storage of leafy vegetables using low temperature and double-low gases can greatly extend storage time. Cabbage can be stored for 3–5 months at 0–2 °C, 2–5% O₂, and CO₂ atmosphere storage conditions [24,58]. By contrast, the storage period of leafy vegetables is only 8–21 days under double-high gas conditions at 4–7 °C [59]. Stem vegetables, such as lettuce, potatoes, onions, and garlic, are rich in starch, sugar, and protein and have low water content. They are suitable for long-term cold storage, but temperature and humidity must be controlled; otherwise, germination occurs. There are few reports on stem vegetables being stored below 4 °C and with double-low gases [60,61]. In fact, according to the characteristics of stem vegetables, the storage temperature and RH need to be reduced accordingly to prolong the storage period. The edible part of root vegetables is the root, which is rich in sugar and protein, similar to stem vegetables. Root vegetables such as radishes and carrots grow underground and are cold-resistant but not heat-resistant; these can be stored at room temperature or at low temperature [62,63]. The edible parts of fruit vegetables are their fruits and young seeds, which are rich in sugar, protein, vitamin C, and other nutrients. Fruit vegetables, such as tomatoes, peas, and melon, are actually similar to fruits and can be stored only for a short time in cold storage. In recent years, there have been many reports on the atmosphere storage of fruit vegetables since they have higher moisture content and require strictly controlled storage conditions. Fruit vegetables stored at 4–10 °C and double-low gases have an extended shelf life of approximately 1 month while maintaining quality, but under double-high gases or single-gas conditions, quality is inferior [24]. The storage period for beans has reached 6 months under atmosphere storage at a RH of 60–70% [64]. Beans have a lower moisture content than those of other fruit vegetables. Proper atmosphere storage conditions, appropriate to the physiological characteristics of fruit vegetables, can enhance the fresh-keeping effect. The edible parts of flower vegetables such as cauliflower, day lily, and leek flowers are the floral organs. Cauliflowers can be stored for around 30 days in cold storage at 4–10 °C. Mushrooms, whose fruiting bodies constitute the edible part, can be stored for a long time at room temperature when dried. When fresh, atmosphere storage of edible mushrooms at 4–10 °C and double-low gas conditions can be effective in prolonging the storage period [65,66].

Table 2. Comparison of atmosphere storage of various vegetables.

Vegetables	E.g.	Temp/°C	RH	Gas Ratio		Method	Storage Time	Source
				O ₂	CO ₂			
Leaf	Cabbage	4 °C	90%	0.7–1%	1%	MAP + HVEF	60 d	2021 [24]
		0 °C	93%	2%	5%	CA	150 d	2019 [58]
		2 °C	95%	2%	2%	CA	100 d	2019 [67]
	Spinach Celery Lettuce (Leaves)	4 ± 0.5 °C	90–95%	7%	7%	MAP	21 d	2018 [59]
		7 °C	97%	10%	9%	MAP	7 d	2012 [68]
		4 °C	-	18 kPa	3 kPa	MAP	>10 d	2005 [69]
Stem	Lettuce (Stems) Potatos	4 °C	90–95%	3%	10%	MAP	6 d	2019 [60]
		4 °C	90%	4%	2%	MAP	12 d	2019 [61]
Root	Carrots	4 (±1) °C	-	14.0 ± 1.0%	6.7 ± 0.6%	MAP	14 d	2021 [62]
		4 °C	-	80%	10%	UR + MAP	15 d	2021 [63]
Fruit	Tomatoes	10 °C	-	-	-	MAP	35 d	2021 [71]
		7 °C	-	14–19 kPa	2–3 kPa	MAP	21 d	2019 [72]
	Corns Beans	4 °C	90%	0.8–1%	2%	MAP + HVEF	48 d	2021 [24]
		20 °C	40–60%	1.5 KPa	9.0 KPa	CA	180 d	2020 [64]
	Eggplants	5 °C	-	80 kPa	0 kPa	MA	9 d	2014 [20]
	Cucumbers	4 °C	-	5%	5%	MAP	15 d	2019 [73]
Flower	Cauliflower	4 ± 1 °C	90 ± 5%	3%	5%	MAP	30 d	2019 [74]
		5 °C	96%	5%	10%	MAP	12 d	2018 [75]
	Broccoli	10 ± 1 °C	90–95%	30%	70%	MAP	24 d	2020 [76]
		1 °C	90%	2.0%	8.2%	MAP	25 d	2018 [77]
	Chive	4 °C	-	20 kPa	0 kPa	MAP	21 d	2018 [78]
Mushrooms	Shiitake	20 ± 0.5 °C	-	Air	10–30%	MAP	7 d	2007 [79]
		10 °C	-	20%	0%	MAP	5 d	2017 [66]
	Mushrooms	10 °C	90%	50%/100%	0%	H-O ₂ -MAP	7 d	2014 [80]
		5 ± 0.5 °C	90%	0%	Air	L-O ₂ -MAP	15 d	2021 [81]
		4 ± 1 °C	-	3%	7%	MAP	27 d	2020 [65]
4 °C	75 ± 2%	15%	5%	MA	10 d	2017 [82]		

Atmosphere storage is not necessarily appropriate for every F&V, and it is dependent upon their different physiological characteristics. As a guideline for atmosphere storage, F&V with high moisture content may be stored at 90–99% RH at 0–5 °C, whereas F&V with lower moisture content may be stored at lower RH (60–70%) at a temperature of 4–9 °C. As for gas conditions, double-low gases are most beneficial with O₂ and CO₂ content of 1–4%. Under double-high gas conditions of 5–15% O₂ and CO₂, F&V quality is inferior to that under double-low gases. However, the former conditions are good for some types of F&V that would otherwise become diseased at low levels of O₂ or CO₂.

3. Effect of Gas Control during Atmosphere Preservation

3.1. Atmosphere Preservation with Ethylene Scavenger

Ethylene is a key regulator of fruit ripening and plant senescence. It is important to control the synthesis of endogenous ethylene in the product and to ensure its removal from the environment during storage [83]. There are two regulating systems for the production of ethylene in climacteric fruit: System I is responsible for the low-rate synthesis of ethylene before the climacteric, and the basic System II is responsible for the self-catalyzed production of ethylene during the climacteric. Some fruits can synthesize ethylene in a short time; the ethylene level can be raised by several orders of magnitude compared to System I levels. Ethylene synthesis in both systems follows the methionine pathway [84,85].

Ethylene scavengers are used to preserve F&V by inhibition, absorption, or oxidation. The inhibitor 1-methylcyclopropene (1-MCP), the absorbent zeolite, and catalytic oxidants

KMnO_4 , ozone, and TiO_2 are examples of each type, respectively. 1-MCP is commonly used as an endogenous ethylene inhibitor, blocking the hormonal effects of ethylene by competing with ethylene receptors [86]. Olives exposed to high concentrations of ethylene experience a change in firmness from hard to soft; ethylene inhibitors (such as 1-MCP or silver nitrate) alleviate this effect well [87]. Zeolite has been widely reported as a promising energy-saving and environment-friendly treatment [88]. Excellent visible light catalytic degradation of ethylene by TiO_2 has also been demonstrated. Ethylene scavenger coupling, employing zeolite with a photocatalytic oxidant, extends the shelf life of fruits.

In recent years, there have been many reports on the combining of ethylene inhibitors with other methods, for example, the use of 1-MCP with atmosphere storage for fruits. The storage time of Yali pears can be extended to 210 days with a combination of 1-MCP and MAP [42]. The quality of pears can be maintained well after 1-MCP treatment followed by CA storage [41]. A study demonstrated that 1-MCP treatment and elevated O_2/CO_2 significantly inhibited browning and reduced the rotting rate of grape berries [32]. In addition, ethylene scavengers/inhibitors with catalysts such as zeolite, TiO_2 , and transition metals have been widely applied and have proved practical, as they promote in situ oxidation of ethylene without causing further pollution [89]. In summary, combining atmosphere storage with ethylene inhibitors can maintain fruit quality and holds promise for packaging during transportation.

Although 1-MCP is an effective, low-cost option and is designed to be harmless and free of residual problems, it may still cause some trouble during fruit storage [90]. Ethylene inhibitors block the signal transduction induced by ethylene by inhibiting the formation of ethylene–receptor complexes. Provided that the ethylene inhibitor is applied prior to endogenous ethylene production in the plant, it will preemptively bind to the ethylene receptors and, therefore, have a significant effect on the control of ripening and senescence of the climacteric fruit, greatly prolonging the fruit storage period and shelf life [85]. However, ethylene inhibitor treatment has little or no effect on the ripening of fruits that have entered the transition period. In addition, ethylene inhibitor treatment has no significant effect on the postharvest physiological changes that occur during the storage of non-climacteric fruits and sometimes even promotes ethylene production, leading to rotting. Ethylene absorbents such as activated carbon or zeolite need to be replaced once their absorbent capacity is reached (saturation) [84]. Durability, efficiency, and waste disposal are the remaining challenges for ethylene scavengers. Fortunately, emerging effective and environmentally friendly technologies based on the catalytic oxidation of ethylene (for example, photocatalysis induced by metal catalysts) provide solutions for these problems. Atmosphere preservation with ethylene scavengers shows promise for commercial application to most horticultural and fresh-cut products compared to traditional chemical preservatives.

3.2. Atmosphere Preservation with O_3 Treatment

Application of non-thermal technologies, such as ozone gas (O_3), for atmosphere storage is attracting much attention in the food processing industry. O_3 is a trioxigen inorganic molecule with a pungent smell and is formed from atmospheric O_2 by the action of electrical discharge. O_3 is a strong oxidant and, hence, possesses good disinfection and sterilization properties. The main functions of O_3 for atmosphere storage are (a) to block ethylene production, thereby inhibiting postharvest changes in F&V; (b) to act as a bactericide and prevent mildew and rot; and (c) to reduce transpiration and dehydration weight loss by causing stomata to close [91,92].

Owing to its high stability in air, gaseous O_3 is widely used in F&V storage [93]. As European regulatory agencies have classified O_3 as “Generally Recognized as Safe (GRAS)”, there is a wide scope for its applications. O_3 is generally combined with cold storage or atmosphere preservation [94]. The effects of combining MAP with a gaseous O_3 pre-treatment for strawberries, raspberries, and blueberries during cold storage have been investigated [52]. Significant reductions in yeasts and other fungi were confirmed

compared to samples stored in the air or with MAP without any pre-treatment, and berry quality was not affected by the O₃ pre-treatment.

Advantages of O₃ treatment are that it leaves no residues and is easy to handle in operation. O₃ can be added to the storage atmosphere continuously or intermittently. For example, O₃ treatment is now common for citrus fruit storage in California to prevent the production of conidia on decaying fruits infected by *Penicillium digitatum* or *Penicillium italicum* and has been shown to greatly reduce gray mold spread in grapes and other berries [93]. O₃ is effective in killing many harmful microorganisms on grapes and other fruits without leaving chemical residues. As O₃ is a low-cost antibacterial ingredient, fumigation with it can control postharvest pathogenic fungi on commodities that tolerate this gas, and O₃ can also be used to disinfect gas storage processing equipment and storage rooms during cleaning.

The O₃ concentration is critical to the gas's effectiveness. Low concentrations of O₃ were shown not to prevent virulence of the conidia of *Botrytis cinerea* [95]. Reports on other microorganisms indicate that very high doses of O₃ may be required to kill spore-forming microorganisms. To produce relatively pure O₃, it is important to use very dry air, preferably oxygen, as the raw material gas entering the corona discharge generator because other oxides (especially nitrogen oxide) may form and cause contamination [91]. In addition, RH is related to the bactericidal effect of O₃. When RH is <45% the disinfection activity of low-concentration O₃ is negligible. O₃ can kill microorganisms more quickly in a humid atmosphere [95].

O₃ can greatly extend the storage time of F&V and improve opportunities for their export. In addition, O₃ can also be used for sterilization in clean vegetable processing [96]. Low-concentration ozone water sterilizes quickly and efficiently without secondary pollution compared to the hypochlorite method currently used for vegetable sterilization.

3.3. Atmosphere Preservation at Extremely Modified Gas Concentration (H-CO₂ and H-O₂)

The aging of F&V is essentially related to high levels of respiration and low energy status. High concentrations of CO₂ and O₂ were believed to be unfavorable for the storage of F&V, so they are rarely applied for atmosphere preservation. However, some reports have shown unexpectedly good results. Normally, the combined percentage of the two gases in double-high gases is not more than 21% of the total gas composition, whereas in atmospheres with extremely high levels of CO₂ or O₂ (H-CO₂ and H-O₂, respectively), this value is often far exceeded. In a single-gas atmosphere, only one of these two gases is used, and the content of the other is zero. Reported values in H-CO₂ and H-O₂ atmospheres were 80 kPa O₂ + 20 kPa CO₂ or 50% O₂ + 50% CO₂. Compared with storage in air, a combination of H-CO₂ and H-O₂ levels (80 kPa O₂ + 20 kPa CO₂ and 90 kPa O₂ + 10 kPa CO₂) effectively inhibits microbial growth and maintains nutrients in blackberries [97]. Exposure to 50% or 90% O₂ significantly reduces the browning of fresh-cut lettuce and the odor caused by hypoxia [98]. H-O₂ effectively reduces weight loss in fresh-cut fruits during storage, reduces loss of hardness and total soluble solids, alleviates the decline of ascorbic acid and flavor, inhibits peroxidase activity, and delays the fluidity of water [31,63,99]. Moreover, H-CO₂ and H-O₂ gas concentrations have even been applied for atmosphere storage of animal products because of their antibacterial effect. [100,101] Application of H-CO₂ and H-O₂ in atmosphere storage is worth consideration for a variety of products.

H-CO₂ and H-O₂ inhibit respiration in F&V through high concentrations of gases (leading to extension of the shelf life) and concurrently ensure quality through their antibacterial effect. In MA preservation, adjusting the gas ratio to increase the preservation effect does not require an additional cost. However, the aid of other technologies, such as pulse-CA (pCA) technology, might be necessary for accurate control of the gas concentration. However, the use of high-concentration gases does not always have positive effects. When stored in CA, especially when the CO₂ level is higher than 25 kPa, mangoes typically suffer from physiological disorders [99]. The mango variety "Tommy Atkins" produced more ethanol when stored in CA containing 50 kPa and 70 kPa CO₂, and the respiration

rate increased when the CO₂ level was higher than 45 kPa [102]. The production of volatile compounds that produce the mangoes' aroma is also affected by CO₂ levels (>6 kPa). The effects of pure oxygen (100% O₂) on quality and microbial growth in fresh-cut pineapples have also been investigated. Even though microbial growth was inhibited, the numbers of aerobic bacteria, yeasts, and molds in pineapple slices packaged with pure O₂ were higher than the numbers in those packaged in low O₂ during long-term storage; the use of low-O₂ MAP (4% O₂ + 5% CO₂) can maintain the quality of fresh-cut pineapple better than pure O₂ packaging [103]. Therefore, further research is required to determine the range of high-concentration gas that achieves the desired result.

3.4. Atmosphere Storage with High Pressure or Decompression Technology

High-pressure at low temperatures inhibit microbial growth and enzyme activity, thereby greatly extending the shelf life of fresh foods such as fish or meat [104]. In addition, the increased pressure lowers the freezing point of water, permitting storage below 0 °C without freezing. Consequently, damage to the product due to ice crystal formation can be avoided, and there is a significant saving in energy because there is no need to remove latent heat. However, there are very few applications of F&V under high pressure. Strawberry juice was kept for 15 days at different pressure levels (0.1, 25, 100, and 220 MPa) at 20 °C and was compared with an original sample stored at atmospheric pressure at 5 °C. High-pressure storage reduced the initial microbial load of the juice by more than two logarithmic units, and viscosity and color were better maintained [105].

Decompression is also known as low-pressure storage. In this method of preservation, part of the gas in the storage room is removed by a vacuum pump so that the O₂ content is reduced below the minimum necessary for respiration. Ethylene production is also inhibited, resulting in good conditions for preservation [106]. In contrast to the gas adjustment methods mentioned above, decompression cannot change the gas composition, only the volume or density. Therefore, decompression techniques create a low O₂ (L-O₂) environment not by reducing the O₂ concentration but by reducing the gas density. Different L-O₂ environments can be obtained by controlling the vacuum level of the storage chamber. During fresh-keeping experiments on iceberg lettuce, a calibrated air release valve was used to carefully adjust the chamber pressure to reach its final value of 600 Pa [107]. During reduced pressure storage, the continuous pumping and input of fresh air ventilates ethylene and other volatile metabolites produced by the physiological metabolism, avoiding the physiological damage caused by these substances.

A decompression atmosphere also has the effect of vacuum cooling, which helps not only to reduce the respiratory heat but also to maintain low-temperature conditions for storage. A "MA vacuum cooling" (MAVC) process has been developed by integrating vacuum cooling and air conditioning technology. By using MAVC, flowering cabbage is vacuum cooled to a preset temperature at 4 °C, and the final pressure is set to 600 Pa in the pressure recovery stage, after which a specific mixture of oxygen, carbon dioxide, and nitrogen is used to replace the air in the vacuum chamber to achieve cooling and atmosphere adjustment simultaneously in the same equipment [59] (Table 2). Reduced pressure storage allows better heat dissipation and water exchange between the leaves, thereby improving the quality of the product and extending shelf life [106].

Zucchini (*Cucurbita pepo* var. *cylindrica*) were stored at low pressure (4 kPa) at 10 °C and 100% RH for 11 days, resulting in a 50% reduction in stem-end browning compared with fruit stored at atmospheric pressure (101 kPa) at 10 °C [108]. Normally, high or low pressure or decompression would be regarded as abnormal or adverse conditions for fruits, which may give rise to physical damage. The application of these techniques has been limited because of the abovementioned economic, technical, and structural integrity problems.

3.5. Atmosphere Preservation with Active Packaging (AP)

Atmospheric film bag packaging exploits the respiration of the packaged F&V, by which the concentration of CO₂ increases and the concentration of O₂ decreases. When

the gas mixture in the bag meets or is close to the gas composition suitable for storage, the MA can be realized spontaneously. The desired conditions can be achieved by taking advantage of the low air and moisture permeability of the packaging film. A polyethylene film is mainly used for the packaging material [109]. In recent years, some new large air bags made of special breathable materials and active ingredients have appeared. Active ingredient packaging refers to adding various gas absorbents and release agents to the packaging bag to remove excessive CO₂, ethylene, and moisture and to allowing timely replenishment of O₂, so that the packaging bag maintains a suitable gas environment for the preservation of fresh-cut vegetables [110]. To ensure food safety and prevent consumers from accidentally eating spoiled food, new packaging food spoilage indicators have been developed. Collectively, these technologies are referred to as “AP” [111].

AP has no significant effect on the chemical properties of F&V, such as pH, antioxidant activity, and total carotenoid content. In CA or MA packaging with a biaxially oriented polypropylene or cast polypropylene film, apricots can be stored for 28 days while their original quality is retained [46]. AP combined with the detection of microorganisms inside and outside of the packaging with the aid of electrical sensors, recording, and signalization (e.g., radiofrequency ID (RFID) and other methods) has been proposed [112]. In general, AP is an effective packaging method that reduces food safety risks and maintains food quality. AP can include the use of various chemicals to ensure food safety during storage. Common deoxidizers and antibacterial agents such as nisin, chitosan, and other active substances have been used in AP. Although AP offers many benefits, there is a risk that the packaging chemicals may contaminate the food during long-term storage, thereby endangering people’s health. The main technical challenge is to maintain the stability of packaging materials with their original mechanical and barrier properties, even after the addition of active materials. Therefore, the development of new AP materials is necessary for solving current problems.

4. Application of Emerging Technologies to Atmosphere Preservation

4.1. Application of Ultraviolet Radiation (UR) to Atmosphere Preservation

UR is irradiation in the range 100–400 nm. Wavelengths between 250 and 260 nm are easily absorbed by the nucleic acids in microorganisms, and after such UR exposure, the resultant changes in nucleoprotein molecular structure and metabolic disturbance lead to death [113]. UR is sometimes misunderstood by consumers as “radioactivity,” a misconception that needs addressing [114]. However, the importance of the role of UR in the sterilization of milk is undeniable [115]. UR can also inhibit the browning of dates [114]. It was found that UR + MAP showed a synergistic effect in maintaining physiological quality [63,116]. The effect of ultraviolet light (UR: 2 kJ m⁻²) and H-O₂ (MAP: 80% O₂, 10% CO₂, and 10% N₂) on the quality of fresh-cut carrots was investigated, and these conditions were confirmed to inhibit the growth of microorganisms [114]. UR is an alternative to heat treatment, and, in combination with MAP, has been shown to result in better sensory quality of the final product and improved safety through suppression of microorganisms. Heat treatment techniques (such as pasteurization) are commonly used in the food industry to extend shelf life. Pasteurization effectively kills most microorganisms, but it is not applicable for F&V because of physical damage to the product. Considering the characteristics of F&V, UR can be a better option to achieve good sterilization while maintaining product quality.

4.2. Application of High-Voltage Electrostatic Field (HVEF) to Atmosphere Preservation

HVEF is a non-thermal processing technology that does not leave residual chemicals and that has been applied to extend the shelf life of fresh-cut vegetables [117,118]. Electric fields generate ozone and affect cell membrane permeability and enzyme activity, thereby inhibiting the growth of microorganisms and extending the shelf life of agricultural products [118]. A combination of HVEF and MAP extended the shelf life of fresh-cut cabbage (HVEF intensity of 6000) to 60 days and extended the shelf life of small corn (HVEF in-

tensity of 4500) to 48 days [24]. Since the current needed to create the electric field is very small, the high voltage necessary for the technique can be maintained for a long time while low energy is consumed. In addition, HVEF is a simple physical process that does not leave chemical residues or result in secondary environmental pollution [118]. However, HVEF technology has a certain degree of risk in operation. Operators need knowledge of physics and electricity and know how to protect themselves. HVEF also requires a high humidity environment, but if the humidity is too high, the electric field may discharge through the air, causing a short circuit of the electric field and bringing the operation to a stop. Therefore, environmental humidity (usually > 70%) must be controlled [119]. In general, this method can provide better F&V preservation strategies for industrial applications.

Although HVEF technology is expensive, it has been used in developed countries to treat meat and juice that require refrigeration. The effect of HVEF combined with MAP for F&V has not yet been well investigated, but further research on the properties and sensory quality of the product is expected.

4.3. Application of Plasma Treatment (PT) to Atmosphere Preservation

Plasma is an ionized gas composed of charged particles, electric fields, ultraviolet photons, and active substances, all of which are considered effective for inactivating microorganisms and, hence, ensuring food safety [120]. PT induces two basic reactions that lead to cell death: (1) the active substances formed during plasma generation induce cell surface etching, and (2) the volatilization of compounds and the intrinsic desorption of ultraviolet (UV) photons induce gene damage. PT has been used in the sterilization of medical devices and for the surface treatment of materials. Plasma can be divided into two categories, namely low-temperature plasma (LTP) and thermal plasma [121]. Various terms have been used by different researchers for LTP, including atmospheric cold plasma (ACP), non-thermal plasma, atmospheric pressure plasma, or simply cold plasma (CP). PT has generally been carried out in a vacuum environment, but recently, atmospheric plasma systems for industrial application are emerging that reduce costs and increase processing speed [120].

ACP refers to a non-equilibrium plasma generated at or near ambient temperature and pressure. ACP involves reactive oxygen species, including free electrons, free radicals, and positive and negative ions, but the collision frequency of gas discharge is lower than in equilibrium plasma [121]. CP substances damage cell membranes, thereby inactivating microorganisms [56,122]. PT is a relatively new technology compared to conventional thermal treatment in the food industry. PT can effectively inactivate microorganisms, including biofilms, bacteria, and their spores and fungi [123]. Therefore, ACP can be applied to sterilize heat-sensitive fresh food to extend its shelf life. A combination of ACP and MAP can effectively inhibit the growth of microorganisms on citrus fruit to extend its shelf life [56] (Table 1). Losses in weight and total soluble solids during storage of cherry tomatoes can be effectively prevented by a combination of MAP and ACP. ACP greatly enhanced the antibacterial effect during atmosphere preservation [71] (Table 2).

PT exhibits many advantages for the food industry; it has a strong antimicrobial effect, results in little damage to food, does not require water or solvents, and leaves no residues. By contrast, owing to the limited penetration of plasma substances, sterilization is not complete, which hinders the applicability of PT at the laboratory scale. There have been few studies on the sensory acceptance of PT-treated products or on the production of undesirable flavors [120]. Further research is necessary to evaluate the feasibility of practical applications for the use of PT, especially ACP, in MA preservation.

4.4. Atmosphere Preservation with Dynamic Controlled Atmosphere (DCA) Technology

Dynamic controlled atmosphere (DCA) technology, in which storage conditions change over time, attracts great attention because F&V are susceptible to gas injury during long-term storage in a static controlled atmosphere. The storage gas composition is regularly adjusted by biosensors, namely chlorophyll fluorescence (DCA-CF), respira-

tion quotient (DCA-RQ), and ethanol (DCA-ET) [124,125]. Pulsed controlled atmosphere (pCA) storage is a semi-dynamic controlled atmosphere mode in which the proportion of gas in the storage environment is intermittently reset and calibrated at intervals of every seven days. pCA technology applied for MAP extended the storage period of apples to 90 days [30] (Table 1). Since the proportion of gas in the storage room atmosphere can be controlled and adjusted in real-time, damage to F&V that are sensitive to extremely high or low O₂ and CO₂ can be avoided [30]. Although the expected performance of DCA is promising, but its wide application is still limited because of problems such as high cost and difficulties of control to adjust the changing fruit physiology in real-time.

4.5. Application of Multiple Emerging Technology to Atmosphere Preservation

Traditional preservation methods typically adopt a single physical or chemical treatment at a relatively high intensity resulting in significant changes in the sensory quality of preserved food. Combinations of treatments at lower intensity could avoid food damage [24]. A combination of ethylene inhibitors (1-MCP) with H-CO₂ for CA storage of berries has been studied with the aim of improving quality. Pears can be stored with 1-MCP combined with H-O₂ for 210 days with high quality maintained [42]. These findings prove the practicality of combinations of technologies, such as an ethylene inhibitor with a high gas concentration, for atmosphere preservation. There is a vast space to be explored for the application of combinations of fresh-keeping technologies for atmospheric preservation.

It is important to understand the specific characteristics of the F&V being treated to choose the appropriate atmosphere preservation technology and thus maintain high quality in the form of shape, color, freshness, and nutritional value. The evaluation of emerging technologies has been limited to relatively few products, such as cabbages, mushrooms, and apples. Therefore, further research on combinations of emerging technologies and atmosphere preservation is required to find potential application value. To date, ethylene inhibitors, O₃ sterilization, UR, and high- and low-pressure technologies have been widely used in the MA preservation of F&V. Combinations involving other emerging technologies, such as extreme gas concentrations, AP, PT, pCA, and HVEF, require further feasibility studies to realize their potential in the field of atmosphere preservation.

5. Conclusions

This comprehensive review covers recent progress in the application of atmosphere storage to F&V, focusing on the effect of gas conditions. Emerging preservation technologies are also evaluated, including ethylene scavengers, high-pressure and decompression technology, ozone (O₃), UR, AP, HVEF, PT, and pulse-CA (pCA), for their potential combined use in the process of MA preservation and storage.

MA storage conditions may strongly affect product quality, such as color, flavor, and taste. Thus, proper selection of storage conditions suitable for each F&V is essential. There are limitations to the ability of conventional generally milder methods to extend shelf life and to scaling up. To further avoid losses in the supply chain of F&V, it is crucial for one to pay attention to combinations of innovative new technologies for atmosphere preservation. The mechanisms underlying the physiological changes in F&V and pathogen inactivation by these applications need to be elucidated. Furthermore, the feasibility of these technologies for commercial application should also be evaluated because each technology has its pros and cons. Some technologies, such as HVEF, PT, and pCA, need a scale-up for proof of concept. Even the current commercially available technologies, such as high-pressure and decompression technologies, ozone (O₃), and UR, still face challenges in the cost of installation and safety in operation.

MA preservation offers optimal storage conditions for F&V to reduce losses and maximize shelf life and the prospect of further maintaining quality with the aid of emerging technologies. This will meet the demands of producers and suppliers to increase income and give consumers access to nutritious F&V for good health.

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