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Characteristics and Main Points of the Theory and Technology of Hypobaric Storage and Preservation of Fresh Agricultural Products: Insights Gained from Two Monographs by Stanley P. Burg

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Abstract In 2004 and 2014, two monographs on hypobaric storage (LP) were published by Stanley P. Burg. Based on his theoretical framework and technological advancements, as well as the research and development of equipment conducted under his guidance, alongside customer practices and reflections on various scientific literature both domestically and internationally, it is posited that, as articulated in the monograph, misconceptions regarding his theory and technology in Western scientific literature prior to 1985 continue to persist. This ongoing dissemination of misunderstandings has resulted in a near stagnation of research and has adversely impacted the Chinese academic community as well. Consequently, it is essential to delineate the characteristics and main points of its theory and technology, with the aim of offering guidance to individuals seeking to comprehend its foundational purpose. LP technology is a dynamic physical technology that continuously and uninterruptedly extracts air from a closed container and simultaneously introduces fresh, low-pressure moist air from the external environment, while maintaining specific levels of humidity and/or temperature within the container and upholding a predetermined pressure value. Preservation technology is the collective term for the set of various technical parameters associated with preservation, including pressure, relative humidity, and other relevant factors, to which LP equipment is specifically designed. The theory of LP is characterized by the enhanced diffusion of gases and vapors that enter and exit the commodity in a dynamic manner under low pressure conditions. The theoretical points involve equipment performance, low pressure, the impact of trace concentrations of gases such as O_2, CO_2 and C_2H_4 that naturally occur at low pressure, diffusive mass transfer, heat transfer, and impacts on the activity of enzymes associated with maturation and senescence. The technology is characterized by dynamic low pressure, and the range of commodities preserved is comparable to that of refrigeration. However, certain commodities exiting the hypobaric environment possess subsequent preservation advantages that are not available through refrigeration. The main points of the technology encompass an extended sotrage life, a postponement of quality degradation, minimized water loss, the suppression of pathogen growth, and the killing of both internal and external insects of the commodity under dynamic low pressure conditions. The core advantage of LP technology lies in its ability to significantly reduce water loss, inhibit respiration and C_2H_4 action, and pathogen growth, killing insects and modulate the activity of enzymes associated with maturation and senescence in post-harvest fresh horticultural products. Consequently, this technology plays a crucial role in prolonging the post-harvest lifespan of these commodities and mitigating quality degradation. Over the past decade, researchers in China have developed a hypobaric short period treatment technology, grounded in LP theory and technical practice, which is commonly referred to as hypobaric treatment. This method has garnered significant attention, leading to an increase in both domestic and international research. A growing body of literature categorizes LP as hypobaric treatment, while some studies also consider vacuum packaging and modified atmosphere packaging (MAP) as LP or hypobaric treatment. Misunderstandings are exacerbated by confusion surrounding nomenclature, which, in conjunction with pre-existing misconceptions, represents a significant barrier to both the research and practical application of the technology. The successful commercial implementation of a vacuum cold fresh chain, centered on LP or hypobaric treatment technology, may be the sole solution to the prevailing misunderstandings associated with LP.

Key words Hypobaric storage, Stanley P. Burg, Hypobaric treatment preservation, Theory, Technology, Characteristics and main points, Vacuum cold fresh chain

0 Introduction

In 2004 and 2014, Stanley P. Burg[1-2] published two monographs on hypobaric storage (LP) that provide a comprehensive, systematic, and in-depth examination of the fundamental theories and technologies associated with LP. These works include a substantial number of experimental results and some of commercial examples, which are presented across various chapters. Additionally, many erroneous results derived from the use of inappropriate hypobaric devices and methods in the international scientific literature, including instances of hasty generalizations, are dispersed across multiple chapters. A comprehensive and systematic reading of Burg's monograph is essential for accurately grasping its original meaning. If taken out of context, it is likely to generate new misunderstandings and potentially lead to the dissemination of misinformation. The studies conducted by Burg[2] and Zheng Xianzhang[3] suggest that the claims made in Western academic literature concerning the shortcomings of LP technology are fundamentally based on experimental errors (see page 2 of reference[2]). Burg further elucidates that the skepticism surrounding LP in academic circles is largely attributable to these experimental inaccuracies found in Western studies published prior to 1985. The literatures had significantly reduced public interest in LP studies, resulting in a marked decline in hypobaric research during that period. Notably, no erroneous reports have been retracted, and these

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studies continue to be frequently cited (see page 13 of reference[2], and reference[3]). In March 2005, the author received a Burg's monograph, published in 2004[1]. Under his guidance, the author was encouraged to establish a company in 2008. With his direct guidance, the technical equipment was developed, and the products successfully penetrated both military and civilian markets. The research continued to focus on experiments related to the preservation of fresh agricultural products, as well as antibacterial and insecticidal studies, encompassing over 100 varieties of fresh agricultural products and cooked foods, in addition to more than 50 types of fresh-cut fruits and vegetables. In 2014, the author received the electronic version of the monograph[2], which was also published in that year. Since February 2005, over 300 emails have been exchanged regarding this work. For more than a decade, the author has engaged in a comprehensive study of the monographs[1-2], aiming to elucidate the theoretical and technological characteristics they present. This endeavor not only serves the author's personal academic growth but also seeks to assist those interested in grasping the original intent of the referenced works. It is hoped that this understanding will contribute to the advancement of the fresh food circulation industry.

The LP theory was initially developed by Mr. and Mrs. Burg[1]. The concept that plant commodities may be preserved in a continuously refreshed partial vacuum originated from research on gas exchange in fruits. This research demonstrated that the internal concentrations of carbon dioxide (CO_2) and ethylene (C_2H_4) in fruits are directly influenced by variations in atmospheric pressure (see page 9 of reference[2]). This finding implies that the LP theory is based on the premise that different ambient pressures impact the gas exchange between the interior and exterior of the fruit, resulting in alterations in internal gas concentrations. Burg's perspectives on the postharvest behavior of commodities under varying atmospheric pressures have been formulated in an effort to elucidate the documented benefits of hypobaric storage in comparison to air-conditioned storage, while not consistently aligning with the prevailing theories of postharvest physiology (see page xiv of reference[1]). This indicates that Burg developed the theory of LP by adopting an alternative perspective on postharvest physiology during that period and investigating postharvest LP physiology from a novel viewpoint. The theory is characterized by a discussion of the effects of increased diffusion of gases and vapors that permeate commodities under conditions of dynamic low pressure. The theoretical points involve equipment performance, low pressure, the impact of trace concentrations of gases such as O_2, CO_2 and C_2H_4 that naturally occur at low pressure, diffusive mass transfer, heat transfer, and impacts on the activity of enzymes associated with maturation and senescence. The LP technique was personally pioneered by Burg[4]. LP storage is a flow-through method that replenishes the O_2 concentration expended during respiration while simultaneously preventing the accumulation of metabolized C_2H_4, CO_2, and NH_3 both within and outside the commodity (see page 36 of reference[2]). Therefore, the technology is distinguished by its dynamic low-pressure characteristics, which markedly differ from those of vacuum cooling, controlled atmosphere (CA), modified atmosphere packaging (MAP), and vacuum packaging technologies. While the range of commodities preserved using this technology is comparable to that achieved through refrigeration, certain commodities exhibit preservation advantages post-exit from the hypobaric environment that refrigeration does not provide. The principal technical points are as follows: the implementation of dynamic low pressure contributes to an extended storage life, delays the deterioration of quality, minimizes water loss, inhibits the growth of pathogens, kills insects both within and outside the commodity, facilitates the natural maturation of certain tropical fruits upon exiting the hypobaric environment, and allows for the mixed storage and transportation of various goods. The core advantage of LP technology lies in its ability to significantly reduce water loss, inhibit respiration and C_2H_4 action, and pathogen proliferation. Additionally, it demonstrates efficacy in insect control and modulates the activity of enzymes associated with maturation and senescence in post-harvest fresh horticultural products. Consequently, LP technology plays a crucial role in prolonging the post-harvest lifespan of these commodities and mitigating quality degradation.

In 2011, Zheng Xianzhang *et al.* [5] conducted an experimental study utilizing LP technology to investigate the shelf-life of fresh-cut vegetables subjected to cold chain breakage, specifically in environments lacking temperature control or at normal temperature. Subsequently, in 2013, it was demonstrated that hypobaric short period treatment technology[6] could extend the shelf-life of leafy greens, beans, and mangoes at normal temperature. This treatment also delayed the onset of browning on the cut sections of freshly cut leafy greens. The authors proposed that both LP and hypobaric short period treatment technologies could serve as primary processing methods for fresh fruits and vegetables at the point of origin. Furthermore, they introduced the concept of a vacuum cold chain centered around these technologies, along with its fundamental operational model[7]. To date, there have been no international reports regarding the application of hypobaric short period treatment for fresh horticultural products, including freshly cut vegetables, aimed at preserving freshness, delaying quality deterioration, and maintaining a vacuum cold chain. Over the past decade, there has been a notable increase in research conducted in China on the utilization of hypobaric short period treatment for fresh horticultural commodities. This research focuses on extending the subsequent refrigeration freshness and shelf life at normal temperature, as well as mitigating the initial quality deterioration of these products[8-16]. Nevertheless, there exists a tendency within the scientific literature to characterize LP as hypobaric treatment[17-22]. Furthermore, the literature concerning MAP[23] as hypobaric treatment, as well as vacuum packaging[24] as a form of LP treatment, has been published in reputable academic journals. Misunderstandings are further intensified by confusion surrounding nomenclature, which, in conjunction with pre-existing

misconceptions, represents a significant barrier to both the research and application of the technology. Burg's LP technology is primarily designed for storage and transportation purposes. However, its effectiveness in commercial applications can be limited, as it is influenced by factors such as pre-cooling, packaging, and distribution at the initial stages of the commercial distribution chain. Consequently, the effective commercial implementation of vacuum cold chain technology[7] will serve as a definitive means for LP to dispel misconceptions. Simultaneously, it has the potential to establish a novel model for the circulation of fresh food.

1 Concept of LP

In 1963, Burg[4] submitted a patent application to the United States Patent Office for a method of fruit storage, which was subsequently granted in 1967. This document represents the inaugural patent concerning LP fruits. The LP method was first described by Burg in chapter 1 of storage in the food industry: advances in application and theory, in 1996 (see page 1 of reference[2]). In 2007, Burg *et al.*[25] proposed that Dr. Burg invented the LP technique and obtained a United States patent for it in 1966 – 1967. Burg's hypobaric storage method was initially called LPS or LP. Subsequently, Tolle (1969, 1972) suggested the term 'hypobaric'. Rynearson proposed the trade name 'Dormavac™' (dormant in a vacuum) to describe Grumman's intermodal hypobaric container and the original 'wet' LP method. More recently, the service mark 'VacuFresh℠' has become associated with the 'dry' LP method, while 'TransVac' refers to the newly designed 'square' LP container (see page xiv of reference[1]). The 'wet' LP method involves the application of a mechanical humidification system, whereas the 'dry' LP method utilizes a metabolic humidification system (see page 64 of reference[2]). The assertion made by Ding Zhansheng[26] regarding the development of a more comprehensive hypobaric storage theory and technology by Burg and others in 1962, including the hypobaric warehouse of 'TransVac' and the 'VacuFresh™' brand, is inconsistent with historical records. Similarly, Feng Shuangqing's claim[27] that Burg and others in the United States proposed a complete hypobaric storage theory and technology in 1966 also contradicts established historical facts.

Hypobaric and LP storage methods have been extensively utilized on an international scale since their introduction in the 1960s, owing to their distinct characteristics. This is in contrast to vacuum pre-cooling, vacuum packaging, and other preservation techniques that involve vacuum processes, such as MAP.

The concept of LP can be analyzed and summarized based on the monograph by Burg[1] (chapters 1 – 4, 6, 9, 12 – 13). LP denotes a specific type of dynamic hypobaric physical technology that continuously and uninterruptedly extracts air and simultaneously introduces fresh hypobaric humid air from the external environment while maintaining a specific level of humidity and/or temperature within a closed container and upholding a predetermined pressure value. Consequently, it encompasses four continuous and simultaneous operational technologies: continuous air extraction, continuous air exchange, continuous humidification, and low-temperature maintenance. In 2001, Wang Li *et al.*[28] categorized LP preservation techniques into two distinct types: periodic pumping (static) and continuous pumping (airflow). Subsequently, in 2010, Zheng Xianzhang *et al.*[29] classified these techniques into intermittent pumping and continuous pumping based on the hypobaric pumping method. Notably, the working pressure associated with continuous pumping was at least one order of magnitude[7] (original table 1) lower than that of intermittent pumping, resulting in a significantly enhanced preservation effect[7,13,25,30,35,39]. It should be pointed out that there were two sets of data in original Table 1 of reference[7] that need to be corrected: the positions of ($30 - 100^b$) and ($100 - 1\,000$) need to be swapped; swap the positions of ($10 - 30^b$) and ($100 - 800^c$). Burg's hypobaric technology is characterized by continuous pumping. Both forms of the product are classified as mechatronic equipment. In section II of the text, Zhang Xiuling[31] presents the concept of hypobaric preservation technology, particularly emphasizing that hypobaric storage represents a method that integrates vacuum cooling, air-conditioned storage, low-temperature preservation, and hypobaric technology. This concept, along with the structure of hypobaric warehouse originally illustrated in Fig. 7.2, markedly deviates from Burg's LP theory and its technical intentions.

2 Theory of LP

2.1 Preservation mechanism The development of LP theory and technology, similar to that of preservation theory and technologies such as refrigeration and CA, advances alongside the progress of science and technology. Burg asserted that during the 1960s, the extent to which pedicel-end scars, lenticels, stomates, and the presence of liquid and solid phases contributed to the process of gas exchange remained ambiguous. However, subsequent research has corroborated the conclusion that atmospheric pressure influences internal gas concentrations by affecting gas diffusion (see pages 10 and 11 of reference[1]). According to Burg[1], by the conclusion of the 20th century, the foundational theory of LP had reached a level of maturity, significantly influencing both research and commercial applications of LP technology. Furthermore, Burg[2] provided a comprehensive outline and made enhancements to specific theories and techniques related to LP. For example, the Fuller relation employed in the calculation of the diffusion coefficient (D) for a binary air/water vapor mixture is corrected by Burg[2] (see original equation 3.1 on page 28), addressing a clerical error identified in Burg[1] (see original equation 15.34 on page 538).

According to Burg[1-2], it can be concluded that the primary mechanism of hypobaric preservation is to continuously and uninterruptedly extract air from a closed container and introduce fresh, hypobaric, humid air from the external environment while maintaining a certain humidity and/or temperature within the container, as well as maintaining a consistent pressure value. In this dynamic hypobaric environment, the diffusion rates of gases and vapors into and out of the product are significantly enhanced. The O_2 con-

sumed during respiration is continuously replenished, while CO_2, NH_3, and C_2H_4 produced through metabolic processes are effectively expelled. This results in a storage environment that is virtually devoid of CO_2, NH_3, and C_2H_4, both inside and outside the stored product. By balancing the mass transfer resistance associated with fresh plant commodities, which arises from respiration, C_2H_4 production, and the epidermal and intercellular systems, a minimal gradient of O_2, CO_2, and C_2H_4 is established between the center and the surface of the commodity. Additionally, the reduction of water loss from the commodity is achieved through a combination of humidification techniques, heat transfer methods, and the inhibition of respiration. Low pressure, which can be less than 600 Pa, effectively inhibits respiration, slows decay of Vc, and suppresses pathogen growth. It also reduces gas concentrations both inside and outside the product, thereby maintaining quality attributes such as odor. Additionally, low pressure is effective in killing insects and demonstrates greater efficacy at low O_2 concentrations compared to atmospheric conditions. Low concentrations of O_2, which can be less than 0.1%, effectively inhibit respiration, inhibit decay of Vc, suppress pathogen growth, eliminate insect populations, delay maturation and senescence, and increase the threshold for chilling injury. Similarly, low concentrations of CO_2, which can be less than 0.000 2%, result in the opening of plant stomata in the darkness, thereby enhancing gas diffusion, inhibiting C_2H_4 production, and preventing the accumulation of succinate. Furthermore, low concentrations of C_2H_4, which can be less than 0.5% of the original concentration, can also delay the maturation and senescence of fresh horticultural products. The conditions of low pressure, low O_2, low CO_2, and low C_2H_4 are mutually compatible and synergistically advantageous for the preservation of commodities. The synthetic action of these factors constitutes the fundamental benefits of LP: they effectively inhibit water loss, respiration and C_2H_4 action, and pathogen proliferation, while also killing insects and modulating the activity of enzymes associated with maturity and senescence in post-harvest fresh horticultural products. Consequently, these conditions significantly extend the post-harvest lifespan and mitigate quality deterioration.

2.2 Theoretical characteristics The theory centers on the effects of improved diffusion of gases and vapors that enter and exit the commodity at dynamic low pressure. The theory is founded on a comprehensive and extensive basis. The theory is formed and developed through an iterative exploration based on the fundamentals of plant physiology, post-harvest physiology, pests, and food microbiology; the fundamentals of engineering mechanics, materials science, vacuum science, engineering thermodynamics, chemical thermodynamics, and even fluid dynamics; the fundamental of automated control theory; and the support of a large amount of information from both laboratory and commercial research on equipment and preservation process parameters (over 2 200 references in reference[1] and more than 500 in reference[2], covering the period from the early 20th century to the eve of the publication of the monograph).

2.3 Theoretical points The theoretical points involve equipment performance, low pressure, the impact of trace concentrations of gases such as O_2, CO_2 and C_2H_4 that naturally occur at low pressure, diffusive mass transfer, heat transfer, and impacts on the activity of enzymes associated with maturation and senescence.

2.3.1 Equipment performance. The equipment must employ three or four continuous pumping types that exhibit a sufficiently low leakage rate within the vacuum chamber. This requirement is fundamental for achieving the core advantages of LP.

2.3.2 Low pressure. The appropriate low pressure is a critical technical parameter for hypobaric preservation. For raw fresh horticultural commodities, the optimal pressure is 1.33 – 2.67 kPa, or potentially lower (see page 2 of reference[1] and page 2 of reference[17]). In contrast, for meat, poultry, and fish, the suitable pressure is 0.6 kPa or lower (see pages 448, 471 –474, 451, and 478 of reference[1] and page 2 of reference[25]). The primary effects of low pressure predominantly include a reduction in gas concentration, inhibition of respiratory heat, suppression of pathogen growth, killing of insects, retardation of Vc delay, and preservation of flavor and other quality attributes. Additionally, low pressure demonstrates greater efficacy at low O_2 concentrations compared to atmospheric conditions.

(i) Reduction in gas concentration. In general, the concentrations of O_2, CO_2, C_2H_4, NH_3, ethanol, acetaldehyde, and α-farnesene within a vacuum chamber exhibit a proportional decrease in relation to the reduction in pressure. However, the relationship between gas concentrations and pressure drop may not remain proportional, influenced by factors such as the temperature, relative humidity of the vacuum chamber, and the rate of leakage within the chamber. Consequently, the concentrations of these gases tend to remain consistently low. According to Table 1.1 in the *Standard Composition of Dry Air* (*Recommended*) for sea level altitude[32], the volume percentage of O_2 is 20.947 6%. This volume percentage is equivalent to the concentration of O_2. Consequently, the proportionally lower O_2 concentration can be calculated as $20.947\ 6 \times 1.33/101.325 = 0.275\%$, which exceeds 0.15%.

(ii) Inhibition of respiratory. Low pressure can reduce the respiration rate by approximately 90% (see original Fig. 4.2 on page 84 of reference[1]), which depicts the relationship between respiration rate and pressure across various commodities.

(iii) Suppression of pathogen growth. The term pathogen was translated as pathogenic organism or simply pathogen by Xu[56] and as pathogen by Bi Yang[57]. Experimental studies utilizing pure cultures of pathogenic fungi have demonstrated direct inhibition of microbial growth and spore germination under low pressure conditions (see page 309 of reference[1]). *A. tenuis*, *C. gloeosporioides*, and *E. carotovora* associated with pepper, as well as *A. tenuis* and *E. carotovora* associated with tomato, and *Colletotrichum* sp. associated with cucumber, are unable to grow under the low pressure of 2.67 kPa (see page 327 of reference[1]). The meat samples exhibited a predominance of lactic acid bacteria and were largely free from *Pseudomonads*, *Enterobacteria*, and *E. coli* when subjected

to a low pressure of 0.57 kPa (see page 450 of reference[1]). Twelve hours following hypobaric treatment at 0.5 atm, the activities of defense-related enzymes, including phenylalanine ammonia lyase and chitinase, reached their peak levels. Additionally, peroxidase activity exhibited an immediate increase. In contrast, polyphenol oxidase, which does not possess the capability to inhibit fungal infections, showed no significant changes. The application of a 10% O_2 concentration at 1 atm did not replicate the observed increase in defense-related enzyme activities or the decrease in rot incidence associated with natural infection or spore inoculation. This finding suggests that the inhibition of decay is attributable to changes in pressure rather than a reduction in O_2 concentration (see page 126 of reference[2]). The genus *Pseudomonas*[53] is known to cause spoilage in raw fruits and vegetables, as well as in frozen meat, poultry, and eggs (see original Table 10.2 on page 230 of reference[53]).

(iv) Killing of insects. Experiments conducted on *Aedes aegypti* adults and house-fly pupae have demonstrated that mortality in mosquitoes at extremely low pressures may be attributed to at least three factors: dehydration, hypoxia, and the low pressure itself (see page 95 of reference[2]). There are approximately 4 000 species of insects classified within the family Culicidae[59] globally, with around 370 species identified in China (see page 385 of reference[59]). Low pressure killed Caribbean fruit fly eggs and larvae[33].

(v) Retardation of Vc delay. LP consistently appears to enhance the ascorbic acid content by eliminating naturally occurring CO_2 from the interstitial spaces of plant cells while simultaneously reducing the partial pressure of O_2. Research has demonstrated that LP conditions effectively preserve ascorbic acid levels in various plant species, including apples (10.1), asparagus (Table 4.8), currants (10.12), cress (10.38), parsley (10.46 and Fig. 10.4), radishes (10.49), and spinach (10.50) (see page 108 of reference [1]). The impact of varying pressure levels on Vc content in asparagus is illustrated in the original Table 4.8 (see page 97 of reference[1]), which reports an initial Vc value of 65.8 mg/100 g fresh weight. Following a 14-day period under low pressure conditions of 101.3, 10.67, 5.33, and 2.67 kPa, the Vc content were measured at 26.3, 32.3, 35.5, and 45.2 mg/100 g fresh weight, respectively.

(vi) Preservation of flavor and aromatic volatiles. Initially, low pressure was suspected to potentially evacuate or out-gas flavor and aroma components. However, the underlying cause became evident when it was observed that the same symptoms manifested during prolonged CA storage and occurred more rapidly at reduced partial pressures of O_2. This phenomenon was attributed to the depletion of O_2 rather than to an increased diffusive escape of volatiles at lower pressures (see page 67 of reference[1]). Fresh matsutake mushrooms demonstrated superior performance compared to the refrigeration control regarding appearance, quality, weight loss, volatile components, and flavor retention when stored at a dynamic low pressure of 1.5 kPa for 20 d, or subjected to a treatment of 48 h followed by refrigeration for 18 d at the same dynamic low pressure of 1.5 kPa[34]. Metmyoglobin present in meat and fish facilitates lipid oxidation, resulting in the development of stale or rotten odors. LP inhibits lipid oxidation by swiftly removing all O_2 and does not rely on the capacity of the product to eliminate O_2 (see page 448 of reference[1]).

(vii) Better performance of LP at the same low O_2 concentrations compared to atmospheric conditions. LP is more effective than CA in prolonging the storage life of apples at comparable partial pressures of O_2. The reduction in firmness and chlorophyll breakdown is slower in LP, abscissic acid synthesis is prevented, the ascorbic acid content is increased, acid catabolism is reduced, sugar is maintained at a higher value, electrolyte leakage and physiological disorders such as internal breakdown are reduced or eliminated, shelf life after transfer to ambient conditions is greatly improved, and respiration, ethylene synthesis and ethylene content are remarkably lower, as well as very low weight loss (see page 373 of reference[1]). The data presented in the original Table 7.4 of reference[1] indicate that the growth rate of *Botrytis cinerea* under low pressure conditions was 61.7% of the growth rate observed at atmospheric pressure, specifically at a partial O_2 pressure of 0.008 atm. Furthermore, as illustrated in Table 7.5 of the same source, the spore germination rate of *Aspergillus niger* at low pressure was found to be 25% of that observed under CA conditions, at a consistent O_2 concentration of 2.3% (see page 310 of reference[1]).

2.3.3 Impact of low O_2 concentration. The effects of low O_2 concentration encompass six key aspects: the inhibition of respiration, the suppression of pathogen growth, the killing of insects, the inhibition of Vc attenuation, the delay of maturation and senescence, and the elevation of the threshold for chilling injury.

(i) Inhibition of respiratory heat. The inhibition of respiratory heat in raw fresh horticultural products is an unavoidable outcome of low O_2 concentrations.

(ii) Suppression of pathogen growth. The concentration of O_2 necessary to inhibit the growth of obligate aerobic and microaerobic bacteria, as well as the majority of fungi, varies significantly among species; however, it is typically less than 1% to exert a substantial effect (see page 302 of reference[1]). According to the original Table 7.2 in reference[1], the decay rate of strawberries stored for 5 d at 3 ℃ followed by 2 d at 15 ℃ was observed to be 10.3% at the O_2 concentration of 21%, 8.3% at 1%, and 4.5% at 0.25% (see page 305 of reference[1]). LP conditions typically yield commodities with an O_2 concentration ranging from 0.1% to 0.25%. This concentration exerts a significant inhibitory effect on the growth of molds and bacteria, as well as on the development of spores (see page 308 of reference[1]). It is essential to recognize that fungal growth and spore germination normally the effects of O_2 and moderate CO_2 concentration tend to be mutually offsetting, so that any benefit which low O_2 concentration might provide for decay control is likely to be counteracted by adding a tolerable CO_2 concentration. Specifically, the growth of *Pseudomonas fluorescens* was observed to be slightly enhanced by 3% CO_2 at a concentra-

tion of 0.25% O_2 (Fig. 5.2, top). Additionally, the development of several species of *Phytophthora* was stimulated by 5% CO_2 at a concentration of 1% O_2 (see page 307 of reference[1]).

(iii) Killing of insects. The tissue and gas exchange systems of insects and plants exhibit significant differences. Consequently, the same concentration of O_2 under hypobaric pressure can result in the mortality of insects while leaving plants unharmed (see page 339 – 344 of reference[1]). According to the specific insect species, relative humidity, life stage, and temperature, the O_2 content in the atmosphere must be maintained below 0.9% – 5.0% to effectively kill insects and their larvae present in stored grains (see page 337 of reference[1]). In both plants and insects, the Q_{10} value for O_2 consumption ranges from 2 to 3. However, the rate of O_2 consumption is typically greater in various types of dormant insects and their respective life stages at equivalent temperatures. The critical O_2 intensity utilized by insects, as presented in Table 8.2, is an order of magnitude higher than the optimal value for LP storage, as indicated in Table 4.7 (see page 336 of reference[1]). In both insects and plants, the primary limiting factor for respiratory exchange is the diffusion of O_2. This process is influenced by the O_2 diffusion coefficient, the partial pressure difference of O_2 between the atmosphere and the mitochondria, as well as the total resistance of the system to O_2 transport (see page 105 of reference [2]). Nevertheless, there are exceptions to the principle that lower O_2 concentrations are more advantageous. For instance, the pupae of *Sitophilus oryzae* exhibit a mortality period of 20 d at 0% O_2, whereas they only survive for more than 14 d at 1% O_2 (see page 349 of reference[1]).

(iv) Inhibition of Vc loss. Low O_2 concentrations have been shown to decrease the loss of Vc in various fruits and vegetables, including asparagus, mango, Chinese cabbage, and apple (see page 96 of reference[1]).

(v) Delay of maturation and senescence. The inhibition of respiration due to low O_2 concentration inevitably postpones both maturation and senescence.

(vi) Elevation of the threshold for chilling injury. Low O_2 concentrations may elevate the temperature threshold for chilling injury (see page 325 of reference[1]).

2.3.4 Impact of low CO_2 concentration. LP's ability to drastically decrease both the ambient and intercellular CO_2 concentration levels has proven to be an important advantage providing benefits that cannot be duplicated by elevating CO_2 concentration (see page 32 of reference[2]). Excessive concentrations of CO_2 can adversely affect the flavor of various fruits and vegetables, inhibit the natural discoloration of fruits, promote the breakdown of tissue in exposed vegetables, lead to internal discoloration and decomposition, and induce external discoloration, particularly in high humidity environments (see page 93 of reference[1]). High concentrations of CO_2 also contribute to the loss of ascorbic acid in various fruits and vegetables, including asparagus, bananas, mangoes, okra, strawberries, and other berries (see page 108 of reference[1]). Conversely, the primary effects of low CO_2 concentrations encompass the opening of stomata in the darkness, the inhibition of C_2H_4 production, and the prevention of succinate accumulation.

(i) Opening of plant stomata in the darkness. As the concentration of CO_2 increases from 0% to 0.035%, there is a gradual closure of the stomata (see page 32 of reference[2]). The alterations in the aperture size of stomatal slits (μm) resulting from an increase in CO_2 concentration from 0% to 0.035% are illustrated in the original Fig. 4.11 on page 110 of reference[1]. Additionally, these changes are depicted in the original Fig. 4.13 on page 112 of reference[1], which presents scanning electron micrographs of the stomata of *Hibiscus* cuttings.

(ii) Inhibition of C_2H_4 production. CO_2 removal has been shown to decrease C_2H_4 production in various plant tissues, including rice leaves, sweet potato, oat leaves, as well as pear and apple slices (see page 99 of reference[1]).

(iii) Prevention of succinate accumulation. The accumulation of succinic acid results in browning and subsequent necrosis of tissues. The mechanism of action is detailed in reference[1] on page 107.

2.3.5 Impact of low C_2H_4 concentration. Ethylene-induced ripening, flower fading, senescence, chlorophyll loss, abscission, physiological disorders, epinasty, and various tropistic and tortional responses contribute to the deterioration of horticultural commodities during transport and storage. In addition, a hypobaric pressure decreases a horticultural commodity's internal C_2H_4 concentration by opening stomates and enhancing diffusive gas exchange through air phases, and also by lowering the internal CO_2 concentration and internal O_2 concentration sufficiently to inhibit ethylene production (see page 132 of reference[1]). Ripening and senescence is hastened by ethylene produced either by an invading pathogen or by the host in response to disease, wounding and chilling, and during the normal course of ripening, flower fading and abscission (see page 313 of reference[1]).

2.3.6 Diffusive mass transfer. The pressure gradient generated by the dynamic low pressure facilitates a diffusive mass transfer of air and vapor between the surface of fresh horticultural products and the surrounding cells. This phenomenon represents a significant distinction from the mass transfer processes occurring at atmospheric pressure in the absence of a pressure gradient. Diffusion refers to the random thermal movement of molecules. In plant tissues, the diffusion of water vapor occurs unidirectionally through air-filled structures such as stomata, lenticels, and pedicel-end scars, a process known as transpiration. Transpiration enhances the net outward flux of CO_2, NH_3, and volatile organic compounds, including ethanol and acetaldehyde, from plant tissues, thereby constraining the net inward flux of O_2. The impact of pressure on the concentration of gases and vapors within plant tissue, as mediated by its effect on diffusion, has been confirmed by empirical research (see page 27 of reference[2]). The mass transfer process significantly influences the postharvest storage life by modulating water loss and the cellular concentrations of various volatile compounds, including O_2, CO_2, C_2H_4, and NH_3. The

impact of gas-phase mass transfer under LP conditions, along with the advantages it offers, differentiates LP from other storage methods (see page 18 of reference[1]). The diffusion pathway of goods from the interior to the exterior encompasses several components: the membrane of cellular inclusions, cytosol, plasmalemma, cell wall, air gap surrounding the cell, commodity skin (stomata or cuticle or pedicel-end scar), retained air layer, commodity, packaging, packing box, and storage atmosphere (see page 19 of reference[1]). The architecture of plant cells is illustrated in Fig. 2-5 of Zhai Zhonghe *et al.*[58], which presents a model of plant cells (see page 39 of reference[58]). In comparison to atmospheric pressure, the accelerated diffusion at a partial pressure of 1.33 kPa results in a reduction of the O_2 and CO_2 gradients by approximately 76-fold. Furthermore, when considering the inhibition of breathing due to LP, the gradient may be diminished by an additional 10-fold (Example 1, see page 127 of reference[1]).

2.3.7 Heat transfer. The mode of heat transfer significantly influences water loss. Jian Lingcheng *et al.*[49] pointed out that water is the most essential element for cellular life activity (see page 8 of reference[49]). In addition to mechanical damage and improper harvesting timing, water loss frequently represents a critical factor that diminishes the storage life and quality of horticultural crops (see page 240 of reference[1]). Water loss represents a multifaceted phenomenon resulting from mechanical, biological, and physical interactions. Historically, biologists have approached this issue by examining the vapor pressure gradient between the commodity and the surrounding air. A higher gradient correlates with an accelerated rate of water transfer. To mitigate water loss, it is necessary to either increase the relative humidity of the storage air or decrease the water conductivity of the stored commodities. This can be achieved, for instance, by applying a wax coating to the surface of the commodities or by utilizing water-retaining wraps for protection (see page 45 of reference[2]). Conduction, convection, radiation, and evaporation (or condensation) modulate the vapor-pressure and temperature gradients that develop in systems containing biological material, and heat transferred by evaporative cooling determines the rate of water loss. During hypobaric storage, most of the respiratory (equation 4.16) and fermentative (equation 4.17) heat is transferred by the major available heat transfer mode, evaporative cooling, and the commodity must be kept warmer than the storage air and chamber wall to prevent radiation and convection from providing it with environmental heat that would evaporate additional water and increase weight loss (see page 39 of reference [2]). The installation of a polyester film radiant reflective lining between the inner surface of the storage box and the stored commodities reduces water loss from the commodities (see page 159 of reference[2]).

2.3.8 Impact on the activity of enzymes associated with maturation and senescence. LP functions to modulate the activity of enzymes involved in maturation and senescence, thereby extending postharvest longevity and mitigating quality deterioration. The enzymes implicated in this process include phenylalanine ammonia lyase (PAL), superoxide dismutase (SOD), chitinase, peroxidase (POD), catalase (CAT), polyphenol oxidase (PPO), *etc.* Chen Wenxuan[35] conducted research on the LP storage of Cuiguan pears over a period of 60 d, examining the effects of different storage methods on SOD activity. The study investigated continuous pumping at a pressure of (0.5 ± 0.1) kPa, intermittent pumping at (50 ± 5) kPa, and refrigeration control. The results, as illustrated in Figs. 4-10 (see page 33 of reference[35]), indicated that the SOD activities were measured at 30, 20, and 16 U/g, respectively, with an initial value of approximately 42 U/g. Furthermore, the impact on PPO activity was found to be less pronounced in the continuous pumping method compared to the intermittent pumping method and the refrigeration control, resulting in the lowest level of browning observed (see page 34 of reference[35]). The enzymatic scavenging system[57] responsible for the removal of reactive oxygen species (ROS), which includes SOD, POD, and CAT, serves to protect plant tissues from the detrimental effects of ROS (see page 64 of reference[57]). Additionally, Li Rongqian *et al.*[48] have presented a discussion that closely parallels this topic (see page 147 of reference[48]).

Research has demonstrated that the activities of SOD, POD, PPO and PAL, which are associated with maturation and senescence, can still be influenced by the refrigeration or normal temperature after hypobaric treatment for fresh horticultural commodities[8,11,40,43].

3 LP technology

LP preservation technology encompasses LP equipment and a range of associated technical parameters, including pressure, relative humidity, and other preservation process. This concept can be likened to computer technology, which integrates both hardware and software components. In general, LP storage preservation technology may refer to either the equipment utilized or the technical parameters governing the preservation process. It is important to note, however, that techniques such as vacuum pre-cooling, vacuum packaging, and MAP, which also involve low pressure conditions, are not belong to LP preservation technology.

3.1 Technical characteristics Dynamic low pressure is fundamentally distinct from and unrelated to vacuum cooling, CA, MAP, and vacuum packaging techniques. However, the preservation effect may be enhanced when utilized in conjunction with them, such as hypobaric storage or hypobaric treatment combined with vacuum pre-cooling, as well as hypobaric treatment paired with MAP. Hypobaric storage technology possesses a diverse array of applications and is capable of preserving various commodities in a manner comparable to refrigeration, but with superior outcomes.

3.2 Technical points The optimal combination of CO_2 and O_2 for CA storage is significantly influenced by the type of fruits, vegetables, or flowers. This is largely due to the structural diversity present at atmospheric pressure, which affects the resistance of each commodity to gas exchange, as well as the extent of the gas gradient generated by the commodity's surface and intercellular

system. The variation in optimal LP conditions across different products should be minimal, as stomatal opening and increased diffusion at low pressures lead to gas concentrations near each cell that are comparable to those present in the atmosphere. While there are exceptions, including tomatoes, bananas, peaches, peppers, cucumbers, and numerous other fruits and vegetables for which the optimal LP conditions have yet to be established, two primary storage categories have typically been defined when the optimal LP pressure and temperature are known. These categories are as follows: for cold-tolerant commodities, the optimal conditions are 0 ℃ with a pressure of 1.3 – 2.0 kPa (10 – 15 mmHg); for tropical commodities, the conditions are 4.4 – 16.0 ℃ with a pressure of 2 – 4 kPa (15 – 30 mmHg). Additionally, it has been observed that lower O_2 concentrations can be satisfactory or even preferable, as evidenced by the finding that a concentration of 0.003% O_2 is optimal for lettuce (see page 371 of reference[1]).

3.2.1 Extended preservation period. The use of LP technology significantly prolongs the preservation period of products, extending it by a factor of 1 to 9 in comparison to traditional refrigeration methods. Additionally, LP technology prolongs the shelf life both refrigeration and normal temperature after leaving hypobaric environment. For instance, the maximum storage duration for bananas is reported to be 150 d under hypobaric conditions, 42 – 56 d in CA, and 14 – 21 d when stored in refrigeration (see page xv of reference[1]). The mean vase life of Laddie and Scania carnation fresh-cut flowers, as reported in reference[1], was evaluated under different storage conditions. After 42 d, the vase life was recorded as 7.2 and 8.5 d for hypobaric conditions, while it was 2.2 and 3 d for refrigeration. When stored for 58 d, the vase life under hypobaric conditions was consistently recorded at 7.9 d, whereas under refrigeration conditions, it was consistently recorded at 0 d. (original Table 10.6 on page 419 of reference[1]). After being stored in a 12.2 m Grumman/Dormaac intermodal hypobaric container for 42 d, two lamb carcasses were hung at ambient conditions (21.1 – 26.7 ℃, 50% – 60% RH) to simulate an outdoor market in the Middle East[1]. No objectionable odor or mucus was observed during the initial 24 h, indicating that the 42 d shipment of lambs successfully withstood the traditional Arab practice of hanging carcasses at ambient outdoor temperatures for 24 h prior to butchering and sale (see page 474 of reference[1]).

3.2.2 Good maintenance of original quality (appearance, texture, vitamin content, odor, flavor, *etc.*). Parsley demonstrated a significant reduction in the losses of protein, ascorbic acid, and chlorophyll over a period of 56 d at 3 ℃, 95% relative humidity, and 10 kPa in LP. In contrast, during refrigeration, the losses were substantial after 35 d (see page 413 of reference[1]). According to the data presented in Fig. 10.4 (see page 414 of reference[1]), the nutrient losses observed after 56 d of storage, in comparison to the initial values, were quantified as follows: protein loss was 19.4% under LP and 44.4% under refrigeration; ascorbic acid loss was 27.1% in LP and 64.5% in refrigeration; and chlorophyll loss was 10.5% in LP and 63.2% in refrigeration. Meat stored under LP offers the advantage of dry ageing and wet ages, as discussed on pages 460 – 462 of reference[1]. After 9 600 kg of fresh lamb carcasses were stored in a 12.2 m Grumman/Dormaac intermodal hypobaric container for 28 d, the selected cuts were prepared, cooked, and subsequently evaluated by an experienced tasting panel. The mutton stored under LP conditions was compared with fresh mutton purchased from a local supermarket. Of the judges, 28 out of 29 found the mutton stored under LP to be more tender, 23 judges deemed it juicier, and 21 preferred its flavor (see page 473 of reference[1]). Chen Wenxuan[35] conducted a study on the storage of Cuiguan pears under LP for 60 d, and compared three storage methods: continuous pumping at (0.5 ± 0.1) kPa, intermittent pumping at (50 ± 5) kPa, and a refrigeration control. The findings indicated that the titratable acidity decreased by 33.3%, 47.6%, and 66.7%, respectively, in comparison to the initial value. Additionally, the content of total soluble sugar, as illustrated in original Fig. 4.4 (see page 30 of reference[35]), was approximately 11.0%, 9.9%, and 8.2%. The Vc content, referenced in Fig. 4.5 (see page 30 of reference[35]), was about 5.6, 4.8, and 3.5 mg/100 g, respectively. Furthermore, the water loss, as depicted in original Fig. 4.2 (see page 29 of reference[35]), was approximately 3%, 4.2%, and 4.5%, respectively.

3.2.3 Low water loss rate. The latent heat generated during respiration contributes to a water loss rate that typically ranges from 10 (NA, refrigeration) to 5 (CA) to 1 (LP) (see pages 245 – 246 of reference[1]). Additionally, reference[3] presents findings from our researchers' LP tests, which demonstrated that the rate of water loss under these conditions was lower than that observed with atmospheric pressure refrigeration.

3.2.4 Effective inhibition of microbial growth such as fungi, bacteria, mold and yeast. The rate of growth inhibition of molds and bacteria at equivalent partial pressures or concentrations of O_2 was significantly greater under LP compared to CA (see original Tables 7.4 and 7.5 on page 310 of reference[1]). For instance, the growth rate of *Botrytis cinerea* at an O_2 partial pressure of 0.008 atm was recorded at 37% under LP, whereas it was 60% under CA (see original Table 7.4). Additionally, the effects of a 2.3% O_2 concentration on the mycelial transmission rate and average sporulation rate of *Aspergillus niger* were measured at 65 and 2, respectively, under LP, in contrast to 85 and 8 under CA (see original Table 7.5).

3.2.5 Killing of adults, larvae, pupae, and eggs both within and outside of goods. Exposure to low pressure at temperatures of 18 or 25 ℃ for 120 h resulted in 100% mortality rates among both adult and larval stages of several species, including *Ephestia cautella* (Wlk.), *Oryzaephilus surinamensis* (L.), *Tribolium castaneum* (Hbst.), *Callosobruchus maculatus* (F.), *Sitophilus oryzae* (L.), and *Trigoderma granarium* Everts, *etc.* Notably, adults of *E. cautella*, *O. surinamensis*, and *C. maculatus*, as well as both adults and larvae of *T. castaneum*, were killed within 7 h (see page 345 of reference[1]). The original Table 8.5 (see page 347 of reference[1]) indicated that the mortality rate of green aphids was correla-

ted with pressure and duration. Specifically, the mortality rate at 15 mm Hg was recorded as 98.3% for 24 h of exposure and 100% for 52 h of exposure.

3.2.6 Mitigation of chilling injury in tropical fruits and natural maturation after leaving hypobaric environments. Fruits and vegetables that have been injured by chilling are particularly susceptible to decay. Additionally, at a critical 'transition' temperature, chilling changes the state of membranes from liquid to gel or semi-crystalline, disrupting the integrity of the membrane channels, causing metabolic dysfunction, solute leakage, tissue degeneration and a loss of compartmentation (see page 321 of reference[1]). When bananas were subjected to LP conditions at a temperature of 14.4 ℃ and a pressure range of 5.33 – 6.67 kPa (40 – 50 mmHg = 0.8% – 1.0% O_2 concentration) for 4 months, their sensitivity to C_2H_4 did not diminish. Following the transfer of the banana fruits to ambient air, they continued to ripen, exhibiting normal characteristics in terms of color, texture, sweetness, flavor, and aroma. When exposed to atmospheric pressure at 18 ℃ with a 1% O_2 concentration for 11 d, the bananas exhibited a loss of the capacity for C_2H_4 production as well as the development of acceptable flavor and sweetness (see page 67 of reference[1]). Bananas began to ripen without ethylene treatment 1 – 2 d after removal from LP (see page 380 of reference[1]).

3.2.7 Mixed storage and transportation of goods. Different types of goods may be combined for the purposes of storage and transportation. Additionally, the vacuum-sealed door can be opened at any time to facilitate the entry and exit of these goods. In instances of mixed storage involving cabbage, carrots, bananas, tomatoes, and apples, it has been observed that when these items are stored at atmospheric pressure, the presence of C_2H_4-producing apples leads to the loss of green coloration in cabbage, the shedding of its leaves, and the development of a bitter taste in carrots. However, cabbage, carrots, and apples were successfully stored together under LP without any adverse effects (see page 438 of reference[1]). Certain commodities can be maintained at atmospheric pressure for 3 – 8 h per day without substantially diminishing their LP lifespan (see page 437 of reference[1]).

4 Hypobaric short period treatment and its preservation advantages

4.1 Concept of hypobaric short period treatment In contrast to LP periods, which typically span several days or months, hypobaric short period treatment refers to hypobaric short period treatability storage within few dozens of hours, then refrigeration, or place in a normal temperature, or carrying out processing. The treatment is categorized into two types: hypobaric refrigeration short period treatment[5-6,8-15,34,36,38-41] and hypobaric short period treatment[6,10,37,42-43]. Collectively, these approaches are referred to as hypobaric treatment. Both conventional LP equipment and specially designed apparatus can be utilized for this purpose.

Inspired by Burg's LP theory and technology, Zheng Xianzhang *et al.*[5] conducted a study in which they placed post-harvest broccoli, bell peppers, Huahuang vegetable (a type of green vegetable produced in Shanghai), scallions, and potatoes in a hypobaric refrigeration warehouse for 24 – 49 h. Following this treatment, the vegetables were cleaned, cut into fresh fresh-cut vegetables, and placed in plastic bags or plastic boxes. Subsequently, they were either refrigerated or stored in an uncontrolled environment. The results indicated that the preservation effect of the hypobaric treatment was superior to that of the refrigeration control. Conversely, the effectiveness was significantly diminished when fresh-cut vegetables were subjected to processing and subsequently stored under LP. Following extensive testing of numerous vegetables and edible mushrooms, the concept of hypobaric refrigeration short period treatment technology was introduced in 2013[6]. Subsequently, the hypobaric short period treatment is discussed in the monograph authored by Burg[2], which presents a case study conducted by Hou and Zheng from 2011 to 2013. In this study, 40 different types of fresh vegetables and fruits were subjected to hypobaric short period treatment for 16 – 48 h. The results indicated a significant reduction in fungal decay and an extended storage life compared to the control group. For instance, following a hypobaric treatment of cauliflower for 36 h and subsequent storage in MAP for 104 d, 95% of the cauliflower remained edible, retained its white color, exhibited a Vc content of 35.8 mg/100 g, and displayed only minimal black mold spots. In contrast, the refrigeration control group of cauliflower exhibited discoloration to black within a few weeks (see pages 126 – 127 of reference[2]).

4.2 Preservation advantages of hypobaric short period treatment A series of experimental studies have demonstrated that fresh horticultural commodities can have the advantage of '5 prolonging' subsequent preservation following hypobaric storage or transportation, or hypobaric treatment.

4.2.1 Prolonging the preservation period of refrigeration by 1 – 3 times or more[5-6,9-11,36,40,42]. For instance, blueberries[11] produced in the Northeast China, when subjected to treatment at a pressure of 1.45 – 1.55 kPa and a temperature of (4 ± 1) ℃ for 12 h prior to refrigeration, demonstrated a decay rate of 10% after approximately 12 d after the hypobaric refrigeration short period treatment, as indicated in the original Fig. 2 (see pages 15 of reference[11]). In contrast, the refrigeration control group reached a 10% decay rate in only 5 d. Furthermore, the weight loss observed after 21 d after the hypobaric refrigeration short period treatment was 8.14%, which was less than the weight loss exceeding 10% recorded in the refrigeration control group. Similar to the findings regarding Yunnan-produced morels[36], the application of treatment at a pressure of (800 ± 50) Pa and a temperature of (1 ± 0.5) ℃ for 2.5 h, followed by refrigeration, resulted in a 100% good rate of the mushrooms after approximately 11 d after hypobaric refrigeration treatment. In contrast, the refrigeration control group only has about 5 d, as illustrated in the original Fig. 1 (see page 320 of reference[36]).

4.2.2 Prolonging the shelf-life of products subjected to cold

chain breakage (commonly referred to as normal temperature) in both high and low temperature environments[6,10,13,37-39,41-42]. For example, the marketability of strawberries[37] subjected to a hypobaric treatment of 20 kPa for 2 h and 40 kPa for 4 h, followed by 12 d at a temperature of (22 ± 2) ℃, was found to be 14.7% and 17.3% higher than that of the control group, respectively (see page 14 of reference [37]). Similar to the findings reported for peaches[38], the weight loss observed after a 12 h treatment at pressures ranging from 1.45 – 1.55 kPa and a temperature of (3 ± 1) ℃ was recorded as 7.10% for the hypobaric refrigeration treatment and 9.48% for the refrigeration control. From the original Fig. 2 (see page 323 of reference[38]), it can be concluded that the initial soluble solids content was 10.5%, the initial Vc content was 9.5 mg/100 g, and the titratable acid content was 100%. After 25 d, the soluble solids content, Vc content, and titratable acid content after the hypobaric treatment were measured at 13.8%, 3.4 mg/100 g, and 46.9%, respectively, while the refrigeration control exhibited values of 12.8%, 2.38 mg/100 g, and 33.9%.

4.2.3 Slowing down the decline rate or even increasing the original qualities (appearance, texture, nutrient content, *etc.*)[5,6,9-16,34,36-41]. For instance, blueberries[11] sourced from Northeast China were subjected to treatment at a pressure of 1.45 – 1.55 kPa and a temperature of (4 ± 1) ℃ for 12 h, followed by refrigeration. According to the original Fig. 3 (see page 16 of reference[11]), the soluble solids content after 21 d increased from an initial value of 10.5% to approximately 11.6% after the hypobaric refrigeration treatment, whereas the control group maintained a stable level of around 10.5% over the same period. Furthermore, as illustrated in the original Fig. 7 (see page 16 of reference [11]), the anthocyanin content increased from an initial value of 1.5 to 3.6 mg/g after the hypobaric refrigeration treatment, while the control group exhibited an increase to 3.0 mg/g.

4.2.4 Delaying pathogen growth[40,42-43]. For instance, the logarithmic value lg (CFU/g) for the total colony counts of waxberry[40], which were subjected to hypobaric refrigeration treatment at pressures ranging from 1 450 – 1 550 Pa and a temperature of (3 ± 1) ℃ for 12 h, followed by refrigeration for 20 d, was approximately 7.8. In contrast, the refrigeration control exhibited a value of 9.8 (see original Fig. 7 on page 166). Strawberries[42] were subjected to hypobaric treatments of 25, 50, and 75 kPa for 4 h at a temperature of 20 ℃, followed by storage at either 20 d or 5 ℃. The treatment at 50 kPa consistently inhibited the progression of decay in samples stored at both temperatures, thereby affirming the efficacy of this technique as a non-chemical preservation method. An *in vitro* study investigating fungal growth demonstrated that the hypobaric treatment did not exert a direct influence on fungal growth rates. However, the hypobaric treatment resulted in an immediate increase in respiration rates, suggesting a physiological response to hormonal stress. The incidence of decay in strawberries[43] treated at 20 ℃ for 4 h under a pressure of 50 kPa, followed by storage at 20 ℃ for 4 d, was approximately 52% in the hypobaric treatment group compared to 78% in the control group. According to the original Fig. 1A (page 79), there was negligible difference in decay rates between storage at a 10% O_2 concentration and the control group maintained at atmospheric pressure. The findings of the study indicated that hypobaric treatments led to a reduced incidence of decay, attributed to the stimulation of pertinent defense enzymes. Notably, the activities of PAL and chitinase reached their peak at 12 h post-treatment, whereas POD activity exhibited an immediate increase following the treatment.

4.2.5 Delaying browning of surfaces and cut sections[5-6,9-10,39]. The raw materials of fresh-cut broccoli[39] were subjected to hypobaric refrigeration for 24 h, followed by processes including cutting, washing, MAP, and finally refrigerated for 49 d. The control samples exhibited a generally relatively green appearance, but were affected by grey mould on individual pieces, with some pieces displaying ulceration and a reduced Vc content of 34 mg/kg. In contrast, the samples treated with hypobaric refrigeration were predominantly greener than the control, exhibiting dry, mould-free, and rot-free characteristics, along with a significantly higher Vc content of 458 mg/kg. Fresh-cut sword beans[6] were stored under hypobaric conditions at pressures of 1 129 – 1 257 Pa and temperatures between 17.0 and 18.2 ℃ (without temperature control) for 23 h. Following this period, the beans were washed, cut, and placed into plastic containers. Notably, no browning was observed in the hypobaric treatments after 150 h of refrigeration and 54 h at ambient temperature. In contrast, significant browning occurred in the control group after 105 h of refrigeration and 23 h at ambient temperature (see original Figs. 10-13 of reference[6]).

The '5 prolonging' subsequent preservation advantages of hypobaric treatment represent one of the fundamental technologies for establishing the foundational model of the vacuum cold fresh chain (see original Fig. 1.1 on page 44 of reference[7]).

5 Discussion and conclusions

5.1 Discussion

5.1.1 LP research of laboratories does not sure yield the commercially anticipated results. The findings derived from laboratory studies do not invariably reflect the anticipated behavior under commercial conditions. The processes of heat and mass transfer, air circulation and distribution, gas gradients between the commodity and the surrounding atmosphere, as well as the uniformity of humidity and temperature, exhibit significant differences in commercial containers filled with commodities in dense cardboard boxes compared to small laboratory setups where commodities may be stored 'naked'. Each of these factors has a substantial impact on the results obtained (see page 372 of literature[1]). The anticipated behavior of fresh commodities under commercial conditions encompasses various links of fresh circulation chain, including post-harvest treatment, storage, packaging, transportation, temporary storage, and distribution. Burg's LP technologies are applicable solely to two links of the storage and transportation chain. Conse-

quently, it can be challenging for the LP technologies to function independently. The aforementioned benefits associated with the '5 prolonging' subsequent preservation advantages of hypobaric storage or treatment, along with the vacuum cold chain that integrates LP technology as its foundation[7], may represent the most viable approach to achieving the expected commercial behaviors.

5.1.2 The two monographs have a wide range of content, both theoretical and technical masterpieces, and require basic disciplinary support for learning and understanding. A thorough study and comprehension of these works necessitate a foundational understanding of the relevant underlying disciplines. The author faced constraints related to the professional background and proficiency in English, which resulted in significant challenges when studying the two monographs by Burg[1-2]. Fortunately, the author was able to expand knowledge by engaging with various Chinese university textbooks and monographs, including Plant Physiology[44-45], Postharvest Physiology of Fruits and Vegetables[46-47], Stress Plant Biology or Cytology[48-50], Fresh Cut Vegetables[51-52], as well as other relevant monographs[26-27,53-59]. Although the author's study of the monograph commenced in 2005, it was limited by the aggregation process, which inevitably resulted in certain omissions and incomplete coverage. Consequently, analysis, judgment, and general errors are inevitable, we would be grateful if knowledgeable people could question, correct, supplement, and guide us.

5.1.3 LP theory and technology have developed in response to the demands of social progress. Important advances in science occasionally are 'lost', only to be rediscovered many years later. Research on the plant hormone, ethylene, carried out prior to 1935, demonstrated that this gas is the fruit-ripening hormone. However, by 1955, there was little interest in ethylene and the early literature drifted into obscurity. The gas was considered an oddity, a by-product of plants rather than a ripening hormone, and ethylene research practically ceased. It was only when the early findings were 'rediscovered' using the newly available technology of gas chromatography that plant physiologists again became aware of ethylene's significance and ethylene research blossomed into an important field of plant science (see page 528 of literature[1]). Pan Yonggui *et al.*[46] reported that in 1959, Burg *et al.* utilized gas chromatography for the first time to investigate the sensitivity of C_2H_4 detection at the 10^{-9} level, marking a significant advancement in the study of C_2H_4 (page 50). This individual, referred to as Burg, is none other than the American scientist Stanley P. Burg, who is cited in this paper. In chapter 1 of the history of LP, Burg noted that Western scientists may be motivated to reevaluate LP in light of recent Chinese publications that present commendable LP outcomes for various commodities (see page 9 of literature [2]). In the work of Burg[2] (pages 9-11), a total of 47 items, including fruits, vegetables, fish, shrimp, beef, pork, chicken, steamed bread, buns, and tofu, are enumerated. The document cites approximately 80 references. Additionally, it is noted that the Science and Technology Committee of Shanghai issued a grant in 2010 to assist in developing a hypobaric warehouse. In 2011, the Science and Technology Committee of the People's Republic of China provided funds to build a hypobaric storage unit for use onboard warships. Furthermore, in 2011, China sold a 50 m^3 hypobaric refrigerator specifically designed for the storage of fish. A research institute affiliated with the Chinese Navy is engaged in investigations pertaining to hypobaric storage. In 2012, the Quartermaster Institute's Department of General Logistics filed five joint patents on LP storage vehicles with Shanghai Kind-water Preservation Fresh Tech Co., Ltd., and in 2013 they filed a patent on the hypobaric cold chain for preserving fresh-cut vegetables. Burg's research on LP technology indicates that China currently holds a temporary lead in this field on a global scale. The mechanisms and commercial investigations into the '5 prolonging' subsequent preservation advantages are anticipated to pave a new avenue for the research and application of LP technology.

5.2 Conclusions In summary, it is evident that Burg's two monographs on LP theory and technology do not have any foundational relationship with CA and exhibit significant and substantial differences when compared to methods such as MAP, vacuum packaging, and vacuum pre-cooling technology. In addition to the effects of dynamic low pressure itself, which include the effective inhibition of respiration, Vc, and pathogen growth, lowering the gas concentration both inside and outside the product, maintaining product quality such as odor, killing insects, and influencing the activity of enzymes associated with maturation and senescence. It is precisely the extremely low O_2 concentration achieved by the dynamic low pressure that effectively inhibit respiration, Vc, and pathogen growth, and kill insects. These outcomes cannot be achieved under static low pressure conditions, such as CA with low O_2 concentrations or vacuum packaging. The extremely low concentration of CO_2 achieved by the dynamic low pressure attained results in the opening of plant stomata during the dark phase to facilitate enhanced diffusion. Additionally, this condition inhibits the production of C_2H_4 and prevents the accumulation of succinic acid, an effect that cannot be replicated with varying CO_2 concentrations at atmospheric pressure. The low concentration of C_2H_4 achieved by the dynamic low pressure attained effectively postpones the maturation and senescence processes of raw horticultural products in a manner that cannot be achieved with C_2H_4 concentrations at atmospheric pressure. In summary, the interplay between dynamic low pressure and the associated low concentrations of O_2, CO_2, and C_2H_4, both internally and externally, constitutes the fundamental advantages of LP technology. These conditions effectively inhibit water loss, respiration and C_2H_4 action, and the proliferation of pathogenic organisms in postharvest fresh horticultural commodities, while also killing insects and influencing the maturation and senescence of enzymatic activity. Consequently, LP technology can significantly extend the post-harvest lifespan of fresh horticultural commodities and mitigate quality deterioration, a feat that cannot be accomplished through physical technologies such as cold storage, CA, MAP, vacuum pre-cooling, and vacu-

um packaging. As society continues to develop, LP and hypobaric treatment technologies are expected to play a significant role in facilitating the non-freezing preservation and circulation of fresh agricultural products.

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