APPLICATION OF PRESSURE TREATMENT FOR QUALITY CONTROL IN FRESH FRUITS AND VEGETABLES

Napassawan Liamnimitr, Manasikan Thammawong, Kohei Nakano

The United Graduate School of Agricultural Science, Gifu University, 1-1 Yanagido, Gifu City 501-1193, Japan

ABSTRACT

In the past few decades, there has been an increasing awareness of the importance of consuming a diet high in fresh fruits and vegetables, which has led to substantial changes in food habits and consumption of humans. To accommodate this awareness, novel postharvest technologies are needed for extending the shelf-life of fresh produce. High-, hyperbaric, and hypobaric pressure methods have been introduced to reduce microbial growth, preserve nutritional quality, and enhance antioxidant enzyme activity in fresh produce. The high-pressure method is the most practical for use in food industry, to inactivate microorganisms in processed products; however, excessive pressure causes physical cell damage when applied to fresh produce. The hypobaric and hyperbaric methods are two emerging techniques highly capable of prolonging the shelf-life of fresh produce. Both hypobaric and hyperbaric methods prevent cellular damage and reduce respiration rates, ethylene production, and microbial growth. However, the mechanism of quality preservation underlying these methods needs to be explored in future studies.

Keywords: fresh produce, high-pressure method, hyperbaric method, hypobaric method, quality control

1. Introduction

Fruits and vegetables are important sources of fiber, vitamins, minerals, polyphenols, carotenoids, micronutrients, and are also relatively low in fat and calories. Due to these functional features, fresh fruits and vegetables are considered an important part of a healthy diet for humans. However, as fresh produce undergoes active metabolism after harvest, its quality rapidly deteriorates, the rate of which depends on environmental factors, such as temperature, humidity, atmospheric gas composition, and pressure (Arah et al., 2015). Therefore, controlling these factors becomes critical for extending the shelf-life of fresh produce.

As of now, several technologies have been used to stall the rate of quality deterioration and prolong the shelf life of fruits and vegetables, including refrigeration, modified atmosphere packaging (MAP), controlled atmosphere (CA) storage, heat treatment, irradiation, edible coating, 1-methylcyclopropene (1-MCP), and ethanol vapor treatment. Though there are perceived benefits for all these postharvest techniques, they do suffer from limitations and are applied for specific purposes as shown in Table 1. For instance, irradiation hot-water, and ethanol vapor treatment are used for disinfection; but, refrigeration, CA, MAP, edible coating, and 1-MCP are used for preservation. Thus, postharvest treatments that not only inhibit microbial growth, but also maintain taste and nutritional quality are needed for preserving quality and potentially reducing postharvest loss.

Pressure treatment has been extensively used for preserving fresh produce as well as processed products. It involves using pressure at a level higher or lower than the atmospheric pressure (0.1 MPa). Pressure treatment was first proposed by Royer in 1895 with the objective of killing pathogenic bacteria (Naik et al., 2013). Few years later, Bert Hite, a scientist at the West Virginia University Agricultural Experimental Station demonstrated that the shelf-life of raw milk could be extended by approximately 4 days following pressure treatment at 600 MPa for 1 h at room temperature (Farkas and Hoover, 2000). High-pressure method was first used by the Japanese food industry in early 1990s (Thompson, 2016) and is still considered a highly practical food preservation method because of its advantages over other methods.

During the last decade, although several researchers reported the use of pressure treatment for the preservation of processed
<table>
<thead>
<tr>
<th>Postharvest treatment</th>
<th>Fresh produce</th>
<th>Tentative storage days (storage temp. °C)</th>
<th>Perceived benefits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigeration</td>
<td>Tomato&lt;sup&gt;a&lt;/sup&gt;</td>
<td>14 (13)</td>
<td>-Reduced RR and weight loss</td>
<td>-High energy expenditure</td>
</tr>
<tr>
<td>(basic method for storing fresh produce under low temperature and high relative humidity (85–95%) condition)</td>
<td>Cabbage&lt;sup&gt;b&lt;/sup&gt;</td>
<td>18 (4)</td>
<td>-Reduced RR, C₂H₄ production, and weight loss</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sapodilla&lt;sup&gt;c&lt;/sup&gt;</td>
<td>10 (6)</td>
<td>-Delay in the ripening process and reduced enzyme activity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pear&lt;sup&gt;d&lt;/sup&gt;</td>
<td>150 (5)</td>
<td>-Retained good eating quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grapefruit&lt;sup&gt;e&lt;/sup&gt;</td>
<td>90 (11)</td>
<td>-Prevented chilling injury and maintained AsA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pomegranate&lt;sup&gt;f&lt;/sup&gt;</td>
<td>60–90 (5)</td>
<td>-Reduced weight loss</td>
<td></td>
</tr>
<tr>
<td>MAP</td>
<td>Pomegranate&lt;sup&gt;g&lt;/sup&gt;</td>
<td>100 (6)</td>
<td>-Reduced weight loss and decay</td>
<td>-Moisture condensation inside the package resulting in microbial growth and fresh produce decay</td>
</tr>
<tr>
<td>(storage technique involving modification of gas composition in the package achieved by active or passive method)</td>
<td>Persimmon&lt;sup&gt;h&lt;/sup&gt;</td>
<td>112 (0 followed by 7, 2, and 5)</td>
<td>-Texture preservation and maintained visual appearance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cucumber&lt;sup&gt;i&lt;/sup&gt;</td>
<td>15 (5)</td>
<td>-Reduced weight loss and alleviated chilling injury</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tomato&lt;sup&gt;j&lt;/sup&gt;</td>
<td>70 (13)</td>
<td>-Delay in ripening process, texture preservation</td>
<td></td>
</tr>
<tr>
<td>CA storage</td>
<td>Guava&lt;sup&gt;k&lt;/sup&gt;</td>
<td>28 (12.5)</td>
<td>-Reduced RR and weight loss</td>
<td>-Periodic monitoring of gas concentration -High running expenditure</td>
</tr>
<tr>
<td>(system for storing fresh produce under precise controlled atmospheric conditions)</td>
<td>Apple&lt;sup&gt;l&lt;/sup&gt;</td>
<td>240 (0.5)</td>
<td>-Preserved color and texture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mango&lt;sup&gt;m&lt;/sup&gt;</td>
<td>14 (15)</td>
<td>-Reduced RR and C₂H₄ production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Broccoli&lt;sup&gt;n&lt;/sup&gt;</td>
<td>7 (10)</td>
<td>-Enhanced bioactive compound</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pear&lt;sup&gt;o&lt;/sup&gt;</td>
<td>7 (20)</td>
<td>-Reduced C₂H₄ biosynthesis</td>
<td></td>
</tr>
<tr>
<td>Heat treatment</td>
<td>Pomegranate&lt;sup&gt;p&lt;/sup&gt;</td>
<td>75 (2)</td>
<td>-Reduced chilling injury and skin browning</td>
<td>-High energy expenditure</td>
</tr>
<tr>
<td>(process of short-term heating to different temperatures by hot water or hot air and subsequent cooling)</td>
<td>Tomato&lt;sup&gt;q&lt;/sup&gt;</td>
<td>7 (20)</td>
<td>-Reduced microbial load</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mango&lt;sup&gt;r&lt;/sup&gt;</td>
<td>-Killed insects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Broccoli&lt;sup&gt;s,t,u&lt;/sup&gt;</td>
<td>6 (15)</td>
<td>-Suppressed Chl degrading enzyme activities&lt;sup&gt;s,t&lt;/sup&gt;</td>
<td>-Reduce AsA loss&lt;sup&gt;u&lt;/sup&gt;</td>
</tr>
<tr>
<td>Irradiation</td>
<td>Potato, Onion&lt;sup&gt;v&lt;/sup&gt;</td>
<td>180 (4.5)</td>
<td>-Inhibited sprouting of stored tubers and bulbs</td>
<td>-Increased browning -Cost of application</td>
</tr>
<tr>
<td>(disinfestation method)</td>
<td>Fresh-cut</td>
<td>-Reduced flesh softening</td>
<td>-AsA degradation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pine apple&lt;sup&gt;x&lt;/sup&gt;</td>
<td>-Reduced initial population of <em>Penicillium, Aspergillus and Cladosporium</em></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Citrus fruit&lt;sup&gt;y&lt;/sup&gt;</td>
<td>-A risk to the human</td>
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</tbody>
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2. High-pressure method

2.1 Characteristics of high-pressure method

The high-pressure method, also known as high-hydrostatic pressure processing, is a non-thermal food preservation method. It is used for various purposes, such as disinfection, pasteurization, extraction, and osmotic dehydration (Arroyo et al., 1997; Berkel Kasikci and Bagdlioglu, 2016). Compared with thermal techniques, the high-pressure method does not alter the vitamin and pigment composition of fresh produce (Oey et al., 2008). Additionally, the high-pressure method is energy-saving, because it is applied to the product at room temperature. This, in turn, lowers the cost of the high-pressure method compared with that of thermal techniques (Li et al., 2017b).

In the high-pressure method, pressure >100 MPa is applied to liquid or solid product with or without packaging. The product is uniformly compressed by pressure from all directions and then returns to its original shape upon the release of pressure. This technique can also be combined with thermal technology. Basic components of the pressure system include a pressure vessel, pressure pump, intensifier pump, and pressurization fluid (Figure 2). Commonly used pressurization fluids include water, oil, sodium benzoate, ethanol, and inert gases (Yaldagard et al., 2008). First, the pressurization fluid is transmitted to the pressure vessel wherein the product is kept in its packaging. The pressure is then returned to its original shape upon the release of pressure, and the product is then removed and stored using conventional techniques.

2.2 Application of high-pressure method for fresh produce

The high-pressure method has been frequently applied to processed products, such as jam, juice, and puree to inactivate

<table>
<thead>
<tr>
<th>Edible coating (use of edible biopolymers such as lipid, proteins, and polysaccharide as the surfaces coating material of fresh produce)</th>
<th>Sliced mango</th>
<th>7 (6)</th>
<th>-Reduced weight loss</th>
<th>-Caused off-flavor development</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Guava</td>
<td>8 (25–28)</td>
<td>-Preserved color and texture and reduced weight loss</td>
<td>-Caused anaerobic respiration</td>
</tr>
<tr>
<td></td>
<td>Strawberry</td>
<td>12 (11)</td>
<td>-Reduced weight loss and activities of cell wall degradation enzyme</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Papaya</td>
<td>150 (12)</td>
<td>-Reduced weight loss and retained firmness</td>
<td></td>
</tr>
<tr>
<td>1-MCP (an inhibitor of C2H4 perception by binding to C2H4 receptor)</td>
<td>Apricot</td>
<td>4 (25)</td>
<td>-Delayed the softening process and inhibited pectin related enzymes</td>
<td>-Cost of application</td>
</tr>
<tr>
<td></td>
<td>Pear</td>
<td>-Slowed down fruit softening</td>
<td>-Chemically based</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peach</td>
<td>-Delayed C2H4 production and RR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol vapor treatment (technique exposing produce to ethanol vapors in a closed container)</td>
<td>Broccoli</td>
<td>5 (20)</td>
<td>-Inhibited C2H4 production and delayed yellowing by reducing Chl-degrading enzyme activities</td>
<td>-Chemically based</td>
</tr>
</tbody>
</table>

AsA = Ascorbic acid, CA = Controlled atmosphere, Chl = Chlorophyll, C2H4 = Ethylene, MAP = Modified atmosphere packaging, RR = Respiration rate, 1-MCP = 1-Methylcyclopropene, UV-C = Ultraviolet C, IR = Infrared radiation, WL = Wavelength

enzymes and reduce microbial growth (Riahi and Ramaswamy, 2003; Chauvin et al., 2005; Liu et al., 2013). The efficacy of the high-pressure method in inactivating enzymes depends on the level of pressure applied. For instance, optimum conditions for polyphenol oxidase inactivation in peach juice include a pressure of 600 MPa for 25 min at 25 °C resulting in a maximum inactivation of 79% (Rao et al., 2013). Contrarily, applying the same conditions on strawberry pulp results in only 48% polyphenol oxidase inhibition (Cao et al., 2011).

In microorganisms, high-pressure treatment interferes with transcription and translation of genetic information and induces biological changes, such as enzyme inhibition and protein synthesis, and alterations in cell membrane (Murchie et al., 2005; Torres and Velazquez, 2005; Vogel et al., 2005).

Several researchers have reported the effect of high-pressure treatment on the quality of fresh fruits and vegetables (Table 2). These studies indicate that the high-pressure method reduces respiratory activity and ethylene production and inhibits microbial growth. Baba et al., 1999 hypothesized that the inhibition of ethylene production occurs because of high-pressure-induced irreversible alteration of the enzyme 1-aminocyclopropane-1-carboxylic acid (ACC) oxidase. According to Sun et al. (2002), change in tertiary structure of polyphenol oxidase was observed after treating with 800 MPa. Change in its tertiary structure results in loss of the enzyme’s biological activity.

Despite its beneficial effects, high pressure negatively impacts the textural quality of fresh fruits and vegetables. Textural damage has been reported in cherry tomatoes exposed to a pressure of 400...
MPa (Tangwongchai et al., 2000). Similarly, pressure >100 MPa has been reported to result in cell membrane breakdown, consequently resulting in loss of textural quality (Hernández-Carrío et al., 2014; Wu et al., 2012b). Moreover, abnormal ripening has also been observed in mume fruit subjected to a pressure ≥100 MPa (Baba et al., 1999). To avoid textural damage because of high-pressure method and to better preserve the quality of fresh produce, researchers have developed an alternative food preservation technique, known as the hyperbaric method, which is discussed below.

3. Hyperbaric method
3.1 Characteristics of hyperbaric method
The major differences between the hyperbaric and high-pressure methods are the pressure level and pressurizing medium. The hyperbaric method uses a pressure ranging 0.1–100 MPa, which is lower than that used in the high-pressure method. Moreover, the pressurizing medium used in the hyperbaric method is always a gas. Studies on the application of the hyperbaric method have been continuously increasing because of the technique’s ability to maintain the quality of fresh produce. Moreover, the hyperbaric method has been suggested as a promising technique for short-term storage of fresh produce without refrigeration (Liplap et al., 2013a; Liplap et al., 2014a).

In the hyperbaric method, air, CO₂, or an inert gas is compressed into the storage container to increase the total pressure. The basic equipment used in the hyperbaric method comprises a pressure vessel, high-pressure gas cylinder, and pressure gage (Figure 3).

3.2 Application of the hyperbaric method for fresh produce
The hyperbaric method by pressurized air has been mainly applied to avoid physical cell damage caused by high pressure. This method has been successfully used in tomato fruits to retain firmness and to reduce weight loss, respiration rate, and ethylene production (Goyette et al., 2012a; Goyette et al., 2012b; Liplap et al., 2013b), and to delay the ripening process (Inestroza-Lizardo et al., 2018). Similarly, it has also been used to reduce weight loss in mushroom, mume, sweet corn, and lettuce (Robitaille and Badenhop, 1981; Baba and Ikeda, 2003; Liplap et al., 2013a; Liplap et al., 2014a). Liplap et al. (2013b) hypothesized that the weight loss reduction is because of a decrease in respiration rate and a vapor pressure deficit between the produce and the

### Table 2. The effects of high-pressure method on the quality of studied fruits and vegetables.

<table>
<thead>
<tr>
<th>Fresh produce</th>
<th>Treatment conditions</th>
<th>Major findings</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mume (Prunus mume Sieb. et Zucc.)</td>
<td>100 MPa for 10 min</td>
<td>-Reduced C₂H₄ production</td>
<td>Baba et al., 1999</td>
</tr>
<tr>
<td>Baby lettuce (Lactuca sativa)</td>
<td>100–400 MPa for 20 min at 10°C</td>
<td>-Reduced microbial population</td>
<td>Arroyo et al., 1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Increased browning</td>
<td></td>
</tr>
<tr>
<td>Green bean (Phaseolus vulgaris)</td>
<td>500 MPa for 1 min at 20°C</td>
<td>-Retention of firmness and AsA</td>
<td>Krebbers et al., 2002</td>
</tr>
<tr>
<td>Broccoli (Brassica oleracea)</td>
<td>200 and 400 MPa for 2 min</td>
<td>-No effect on antioxidant capacity</td>
<td>McInerney et al., 2007</td>
</tr>
<tr>
<td>Nectarines (Prunus persica)</td>
<td>200–600 MPa for 3 min at 10°C</td>
<td>-Lower microbial counts</td>
<td>Miguel–Pintado et al., 2013</td>
</tr>
<tr>
<td>Strawberry (Fragaria × ananassa)</td>
<td>800 MPa for 10 min and 600 MPa for 15 min at 18°C–22°C</td>
<td>-Complete inactivation of PPO enzyme</td>
<td>Garcia–Palazon et al., 2004</td>
</tr>
<tr>
<td>Cherry tomato (Lycopersicon esculentum)</td>
<td>200–600 MPa for 20 min</td>
<td>-Cell damage</td>
<td>Tangwongchai et al., 2000</td>
</tr>
<tr>
<td>Freshly-cut apple (Malus domestica Borkh)</td>
<td>150 MPa Ar for 10 min</td>
<td>-Reduced RR and C₂H₄ production, delayed browning, and inhibited microbial growth in sample treated with Ar</td>
<td>Wu et al., 2012b</td>
</tr>
</tbody>
</table>

AsA= Ascorbic acid, C₂H₄ = Ethylene, PPO = Polyphenol oxidase, Ar = Argon gases, RR = Respiration rate
surrounding environment. Although the reason for decreased ethylene production is still unclear, it is suggested to be related to the inactivation of ACC oxidase that catalyzes the conversion of ACC to ethylene (Baba and Ikeda, 2003). In addition to the above effects of hyperbaric method on fresh produce, its efficacy in disease control has also been reported. The growth of microorganisms, such as *Botrytis cinerea* and *Pseudomonas cichorii* is restricted using hyperbaric pressure in the range 0.25–0.85 MPa (Romanazzi et al., 2008; Liplap et al., 2014b), which may be because of the direct impact of pressure, toxicity caused by high O2 levels, or defense system stimulation in plant cells (Liplap et al., 2014b). However, the efficacy of hyperbaric treatment on quality preservation depends on the type of produce and the pressure level applied. For instance, the application of 0.6 MPa hyperbaric treatment reduces weight loss, chilling injury, and CO2 and ethylene production in mume fruits, but causes severe browning injury in sweet basil leaves stored at 4°C (Baba and Ikeda, 2003). Contrarily, browning injury does not occur in basil leaves stored under 0.125 MPa pressure at 4°C (Baba et al., 2008).

Recently, research has been carried out by a team of scientists at the McGill University to investigate the effect of temperature and hyperbaric pressure on quality attributes of fresh produce. Liplap et al. (2014a) examined the effect of hyperbaric treatment on the shelf-life of Boston lettuce. They reported that Boston lettuce stored under hyperbaric pressure ranging 0.2–0.85 MPa at 20°C retains its marketable quality for 5 days, whereas lettuce stored under atmospheric pressure (0.1 MPa) loses its market value. In addition, hyperbaric storage at 20°C reduces weight loss to levels comparable with that obtained using refrigeration (4°C). A similar reduction in weight loss has been observed in tomato; compared with tomato fruits stored under atmospheric pressure (0.1 MPa) at 20°C and 13°C, the weight loss of tomato fruits stored under 0.3 MPa at 20°C for 4 days is reduced by 64% and 56%, respectively (Liplap et al., 2013b). These data suggest that hyperbaric treatment is a promising technique for short-term storage of fresh produce when cooling facilities are not readily available.

In addition to atmospheric air, CO2 and inert gases, such as argon and xenon, have been used as a pressurizing medium for hyperbaric treatment. The application of these gases in the hyperbaric method suppresses the respiration rate, weight loss, chlorophyll degradation, color change, and enzymatic activities, such as those of polyphenol oxidase, catalase, and phenylalanine ammonia-lyase, and also reduces microbial growth (Table 3). Reduction in water loss during storage is suggested to result from lower water mobility in cells and tissues because of the formation of clathrate hydrate, which is the crystalline ices form containing the guest gas molecule inside the cage-like formation constructed by H2O molecules (Li et al., 2017b). The formation of clathrate hydrate within tissues of fruits and vegetables resulting from CO2 hyperbaric treatment has been visualized using phase-contrast X-ray imaging with a diffraction-enhanced imaging technique (Takeya et al., 2016). However, other mechanisms for extending the shelf-life of fresh produce using the hyperbaric method have not yet been verified. Furthermore, the effect of hyperbaric treatment has been tested on only a limited variety of fresh produce. Thus, future studies are warranted to investigate the physiological changes under various hyperbaric conditions in different edible plant parts, including tuber, root, stem, leaf,
flower, and fruit, and in different cultivars of the same plant. Additionally, since the hypobaric method involves storing fresh produce in a hermetic vessel, the influence of higher total pressure on the physiological status of the produce should be discussed. Moreover, according to Dalton’s law, the total pressure exerted by a mixture of gases is equal to the sum of the partial pressures of the component gases. When the total pressure increases, the partial pressure of each gas in the mixture also increases. Thus, the impacts of partial pressures of the component gases such as O₂ and CO₂ should be also evaluated based on the measurement of gas concentration in the vessel. These trials will reveal the optimum hypobaric treatment conditions for each target commodity, ultimately leading to the application of the hypobaric method in fresh produce distribution chain.

4. Hypobaric method

4.1 The characteristic of hypobaric method

The hypobaric method, also known as sub-atmospheric pressure method, is a promising technique for delaying fresh produce deterioration during postharvest storage, similar to the CA storage. The hypobaric method involves storing fresh produce in a hermetic container where the level of internal pressure is below normal atmospheric pressure (0.1 MPa). Under hypobaric conditions, partial pressure of component gases, and consequently the total pressure, is reduced. In general, O₂ is the primary gas molecule for quality preservation of processed foods and fresh produce; therefore, reduction of O₂ partial pressure is the main principle of hypobaric storage. Hypobaric method of fresh produce was first by documented by Workman and colleagues in 1975, where they reported reduced respiration rates in tomato fruits stored under 0.01 MPa pressure at 20°C (Thompson, 2016). Since then, researchers have been continuously interested in the effects of hypobaric storage on the maintenance of fresh produce quality.

Figure 4 schematically represents the hypobaric treatment system. In this system, total pressure is reduced to the desired level using a vacuum pump, and the level is then constantly maintained.

4.2 Application of hypobaric method for fresh produce

Hypobaric storage of bamboo shoots at 50 kPa inhibits ethylene production and promotes lignin and cellulose accumulation (Chen et al., 2013a). The shelf-life of ‘Cuiguan’ pear stored under hypobaric condition can be extended for up to 60 days (Chen et al., 2008). In loquat and pear, hypobaric storage slows down the rate of respiration and juice leakage.

Table 3. Applications of pressurized CO₂ and inert gas to preserve the quality of studied fruits and vegetables.

<table>
<thead>
<tr>
<th>Fresh produce</th>
<th>Treatment conditions</th>
<th>Major findings</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshly-cut carrot (Daucus carota L.)</td>
<td>CO₂; 5.1 MPa for 20 min at 20°C</td>
<td>-Complete inactivation of aerobic bacteria, reduced weight loss, PPO activity, and RR in treated sample</td>
<td>Bi et al., 2011</td>
</tr>
<tr>
<td>Freshly-cut green pepper (Capsicum annuum L.)</td>
<td>Ar; 2.1, 4.1, and 6.1 MPa for 1 h, followed by storage in package with 5 kPa O₂ and 8 kPa CO₂ for 12 d at 4°C</td>
<td>-Delayed quality deterioration; reduced loss of water, AsA, and chlorophyll - Reduced CAT and POD activities</td>
<td>Meng et al., 2012</td>
</tr>
<tr>
<td>Freshly-cut cucumber (Cucumis sativus L.)</td>
<td>Ar; 1.1 MPa for 1 h at 20°C followed by storage in PP box with 35 ±m PP film at 4°C for 12 d</td>
<td>-Inhibited RR, softening, color change, and chlorophyll degradation, and reduced AsA loss</td>
<td>Meng et al., 2014</td>
</tr>
<tr>
<td>Freshly-cut pineapple (Ananas comosus L.)</td>
<td>Ar; 1.9 MPa for 1 h at 4°C, followed by storage in package for 20 d at 4°C</td>
<td>-Delayed microbial growth and maintained quality</td>
<td>Wu et al., 2012a</td>
</tr>
<tr>
<td>Mushroom (Agaricus bisporus)</td>
<td>Ar; 20.1 MPa for 1 h at 4°C, followed by storage in package at 4°C for 15 d</td>
<td>-Reduced weight loss, PPO activity, and RR in treated sample</td>
<td>Lagnika et al., 2011</td>
</tr>
<tr>
<td>Freshly-cut pineapple (Ananas comosus L.)</td>
<td>Ar or N₂; 10.1 MPa for 20 min, followed by storage in PP tray at 4°C for 20 d</td>
<td>-Reduced browning and loss of total phenols and AsA, maintained antioxidant capacity, and inhibited PAL, PPO, and POD activities - No influence of pressure on tissue firmness and juice leakage</td>
<td>Wu et al., 2012c</td>
</tr>
</tbody>
</table>

Ar = Argon, CO₂ = Carbon dioxide, Xe = Xenon, AsA = Ascorbic acid, CAT = Catalase, POD = Peroxidase, RR = Respiration rate, PPO = Polyphenol oxidase, PAL = Phenylalanine ammonia lyase, N₂ = Nitrogen, PP = Polypropylene
and ethylene production, and loss of ascorbic acid, inhibits softening, and reduces fruit browning by decreasing polyphenol oxidase activity (Gao et al., 2006; Li et al., 2017a). The growth of microorganisms, such as Penicillium digitatum, Botrytis cinerea, Alternaria alternate, and Rhizopus stolonifer, is also well inhibited by the hypobaric method (Apelbaum and Barkai-Golan, 1977; Romanazzi et al., 2001; Hashmi et al., 2013). The beneficial effects of hypobaric treatment on the quality of fresh produce are because of low O₂ conditions (Dilley, 2003). Moreover, delayed ripening of peach fruits because of hypobaric treatment has been attributed to enhanced activities of antioxidant enzymes, such as catalase and superoxide dismutase, and delayed reactive oxygen species (ROS) production rate during storage (Wang et al., 2015). Enhanced antioxidant enzyme activities have also been reported in bamboo shoots and Chinese bayberry fruits (Chen et al., 2013a; Chen et al., 2013b).

Collectively, these data suggest that the hypobaric method can be used to maintain the quality and extend the shelf-life of fresh produce. However, this method has the limitation because of the fact that the low O₂ partial pressure condition is created in the hypobaric system. Therefore, the consideration of the “lower O₂ limit” for the target fresh produce is required in order to optimize the pressure condition and avoid an aerobic respiration that can lead to foul odor. Moreover, in the hypobaric system, the pressure is reduced using the vacuum pump by withdrawing air from the hermetic container which may cause water loss from the sample. This is also one of the critical issues that should be solved in hypobaric method.

5. Conclusion

Despite the ability of the high-pressure method to inhibit microbial growth and reduce the rate of respiration and ethylene production of fresh produce, the applications of this method are limited because of the cellular damage induced by high pressure. The hypobaric and hyperbaric methods are alternative techniques that can potentially extend the shelf-life of fresh produce without causing damage to cells and tissues. Although the hypobaric method reduces microbial growth and preserves produce quality, the level of the vacuum pressure must be considered carefully prior to using this method to avoid the anaerobic metabolism. The hyperbaric method also reduces the respiration rate, weight loss, chlorophyll degradation, color change, and ROS production, and enhances antioxidant enzyme activities. Moreover, it does not include the limitation of low O₂ levels, because the O₂ partial pressure is maintained at a level >21 kPa. However, there is still a lack of knowledge regarding the hyperbaric treatment preservation mechanism to optimize the treatment conditions such as pressure level and temperature for each target commodity in practical use. Thus, further studies concerning physiological changes induced by hyperbaric conditions in a broad range of fruits and vegetables are warranted. These studies will enable hyperbaric treatment as a universal postharvest technique for maintaining the fresh produce quality.

REFERENCES


