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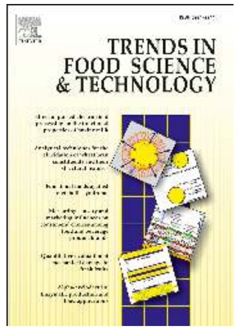

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Recent Developments in Novel Shelf Life Extension Technologies of Fresh-cut Fruits and Vegetables

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ABSTRACT

Background

Fresh-cut fruits and vegetables have gained much more attention worldwide in the past decades. Due to the increased awareness of consumers in sensorial and nutritional qualities of fresh-cut fruits and vegetables, as well as the serious concerns towards public health caused by foodborne outbreaks owing to inappropriate handling or preservation of fresh-cut fruits and vegetables, fresh-cut industry is in urgent need of new and improved technologies for shelf life extension.

Scope and Approach

In this review the **recent development** in novel shelf life extension technology applied to fresh-cut fruits and vegetables, including physical, chemical and biopreservation methods are described. These novel technologies better maintain or improve the quality and safety of fresh-cut fruits and vegetables. However, reduction in microbial load without compromising in sensory and nutritional qualities could not be easily achieved by one technique alone. Some combination application of these techniques proved to be very effective in both shelf life extension and microbial inhibition of fresh-cut fruits and vegetables.

Key Findings and Conclusions

Future research needs to consider **varieties of further combined applications** of physical, chemical and biopreservation technologies, which may allow a better maintenance of the fresh-like characteristics of the raw produce. Meanwhile, consumer's acceptance, safety and legal aspects, and commercial availability, such as

the efficacy, cost-effectiveness ratio and convenient manipulation, should also be taken into consideration in future studies.

***Keywords*: Fresh-cut, Fruits, Vegetables, Shelf life extension**

1. Introduction

Fresh-cut fruits and vegetables, with the advantages of health, convenience, high nutrition and flavor while still maintaining freshness, have gained great popularity among customers worldwide. This has led to a global trend of increased consumption and research investment of fresh-cut fruits and vegetables in recent years (Oliveira, et al., 2015a; Siddiq, Sogi, & Dolan, 2013). However, fresh-cut produce deteriorates faster than the unprocessed raw materials, mainly due to the damages caused by minimally processing methods (peeling, slicing, dicing, shredding, etc.). These processing operations usually shorten the shelf life of fresh-cut fruits and vegetables by a series of typical symptoms, such as tissue softening, cut surface browning, decreased nutritional value, presence of off-flavor and microbiological spoilage during storage (Curutchet, Dellacassa, Ringuelet, Chaves, & Viña, 2014; Finnegan & O'Beirne, 2015; Kim, Kim, Chung, & Moon, 2014; Mantilla, Castell-Perez, Gomes, & Moreira, 2013). Moreover, the exposed surface after minimally processing also benefits the growth of some pathogenic microorganisms. The dramatically increased cases in recently reported foodborne disease outbreaks associated with fresh-cut produces have caused serious concerns towards public health (Abadias, Alegre, Oliveira, Altisent, & Viñas, 2012; Callejón, et al., 2015; Stephan, et al., 2015).

Preservation and shelf life extension have still been a major concern towards fresh-cut produce since they were first available to consumers in the 1940s (Rico, Martín-Diana, Frías, Henehan, & Barry-Ryan, 2006). Tremendous attempts and progress have been made by producers and researchers since the 1980s, when the supply expansion of fresh-cut fruits and vegetables occurred as a result of the booming of fast food restaurants.

In general, traditional preservation methods of fresh-cut fruits and vegetables could be broadly classified into three categories, namely physical-based preservation, chemical-based preservation and biopreservation technology. Physical-based preservation technology refers to the methods that adjust environmental temperature, humidity, pressure and gas composition for shelf life extension (Krasaekoopt & Bhandari, 2010). Cold storage is one of the most commonly used physical-based methods to improve shelf-life of fresh-cut fruits and vegetables. It is highly efficient but also high in energy demand. Furthermore, cold damage may be caused due to different optimal storage temperature of different varieties of fresh-cut fruits and vegetables when stored under the same condition. In terms of chemical-based preservation technology, a number of natural or synthetic preservatives have been used to prolong the shelf life of fresh-cut fruits and vegetables in the past decades (Meireles, Giaouris, & Simões, 2016). However, consumers have also become more critical of the use of synthetic additives as their awareness of health and food safety has increased. This has called for the synthetic additive-free or natural additive-based preservation techniques in recent years. As for traditional biopreservation, with a long history of safe use, it refers to the rational utilization of the antimicrobial potential of natural microorganisms and their antibacterial products to extend the shelf life and enhance the safety of foods (Stiles, 1996). With the rapid development of biotechnology in the past few decades, particular attention has been paid to novel biopreservation techniques, including the uses of bacteriophages, bacteriocins and bioprotective microorganisms.

In spite of the rapid growth in both marketing and scientific research in recent years, limited shelf life is still the greatest hurdle to the further development of fresh-cut fruits and vegetables industry. The objective of this article is to present an overview of the recent developments in novel technologies used for shelf life extension of fresh-cut fruits and vegetables. The disadvantages of these technologies and the prospect of further researches are also briefly discussed.

2. Quality of fresh-cut fruits and vegetables

Generally, the quality of fresh-cut fruits and vegetables is primarily evaluated from sensorial, nutritional and safety aspects. At retail stores, fast estimation for sensory quality of fresh-cut fruits and vegetables, including appearance, color, flavor, texture, is commonly performed subjectively by consumers. Deterioration of these properties would influence the shelf life and acceptance of a product, particularly when these attributes drop below the acceptable level. Moreover, these qualities are usually taken into consideration as first priority in consumers' acceptance of a certain fresh-cut produce. The major causes of quality loss of some fresh-cut vegetable are presented in Table 1.

The appearance, including color, gloss, shape, size, and absence of defects and decay, is the main factor affecting consumers' choice. One of the primary problems with fresh-cut fruits and vegetables is the change of an undesired brown color, which greatly limited their shelf life. Browning is caused by the interaction of polyphenol oxidase (PPO) with the phenols released during minimally processing (Zambrano-Zaragoza, et al., 2014). And this exists in a wide varieties of fresh-cut fruits and vegetables.

Texture is a critical quality attribute that helps both the industry and consumer determine the acceptability of food. Fresh-cut fruits and vegetables with better maintenance in firmness, crispness and crunchy texture are highly desired by consumers due to their close association with tissue deterioration. Loss of firmness is primarily associated with enzymatic degradation of pectins catalyzed by pectin methylesterase (PME) and polygalacturonase (PG) (Barbagallo, Chisari, & Caputa, 2012). It is well documented that consumers or panelists are usually more sensitive to small differences in texture than flavor.

Flavor is another factor affecting the quality of fresh-cut produce. It involves tastes like sweet, sour, astringent, bitter, aroma, and off-flavors. The specific flavor of a fresh-cut produce depends on the product composition (sugar, organic acids, phenolic compounds, volatile compounds, etc.), genetic factors, maturity, and postharvest treatments. Fruit aroma is characterized by a high content of volatile oils and aliphatic esters, which have a higher threshold of perception, compared to volatiles responsible for vegetable aroma, which are mainly nitrogen and sulphur compounds (Francis, et al., 2012).

From the point of view of nutritional and/or health aspect, fruits and vegetables are a major source of essential dietary nutrients such as vitamins and minerals, as well as a good source of fiber and carbohydrates (Sagar & Suresh Kumar, 2010). Moreover, polyphenols, such as anthocyanins, flavonols and phenolic acids, constitute one of the most numerous and ubiquitous groups of plant metabolites. They are an integral part of both human and animal diets and are also assumed to be beneficial for human health due to their biological activities, including antioxidant, anti-inflammatory, antibacterial, and antiviral functions (Fang & Bhandari, 2010). These above mentioned minor components in fruits and vegetables are reported to be highly conducive to the prevention and control of a series of chronic diseases, such as hypertension (Nunez-Cordoba, et al., 2009), coronary heart disease (Yong, et al., 2015), stroke (Larsson, Virtamo, & Wolk, 2013), osteoporosis (Xie, et al., 2013). Furthermore, there is some evidence that a decreased risk of certain cancers is associated with the high consumption of fruits and vegetables (Freedman, et al., 2008; Jansen, et al., 2013; Zhang, et al., 2009). A recommended minimum daily intake of 400 g of fruits and vegetables was proposed by the World Health Organization (WHO) in 2003 (Who & Consultation, 2003).

In addition to the physicochemical, organoleptic and nutritional properties, fresh-cut fruits and vegetables are particularly susceptible to microbial attack due to the processes used for its preparations (e.g. peeling, cutting, and slicing). Microbial contamination can occur in one or more procedures during harvesting, processing, packaging, preservation, transportation and distribution. In view of the fact that all fruits and vegetables must undergo a series of pretreatments before being processed, most of the microorganisms may be present on the cut surface during processing procedure. Abundant researches have been performed on spoilage induced by bacteria, molds and yeasts in the past decades. However, some recently reported foodborne disease outbreaks caused by pathogenic organisms are receiving most attention worldwide. *Listeria monocytogenes*, *Salmonella* and *Escherichia coli* O157:H7, with the potential to cause serious diseases, have been demonstrated to be the most important pathogens implicated in numerous human illness associated with consumption of fresh-cut produce, such as listeriosis, diarrhea and chill, and hemolytic uremic syndrome (Griffin & Tauxe, 1991; Swaminathan & Gerner-Smidt, 2007; Vandamm, Li, Harris, Schaffner, & Danyluk, 2013). Therefore, these above mentioned quality deteriorations and safety concerns have brought an urgent demand for novel technologies for shelf life extension of fresh-cut fruits and vegetables.

3. Novel technologies for shelf life extension of fresh-cut fruits and vegetables

3.1 Physical technologies

3.1.1 Modified atmosphere packaging (MAP)

Modified atmosphere packaging (MAP) is one of the most effective techniques that has been widely and successfully used for extending the shelf-life of fresh and fresh-cut produce (Sandhya, 2010). MAP refers to the modification of the gas composition surrounding the product or the replacement with inactive gases before sealing in containers or packages (Mangaraj, Goswami, & Mahajan, 2009). CO_2, O_2 and N_2 are the most frequently used gases in MAP. The application of MAP has a history of nearly 90 years. In the 1920s, MAP was used to prolong the shelf life of apples in an atmosphere with reduced O_2 and increased CO_2 concentrations (Phillips, 1996). Since the 1980s the effects of MAP on the qualities of various fresh-cut produce have been extensively investigated. Up to date there is a wide variety of fresh-cut fruits and vegetables available in retail market as MAP technology, chill chain and food processing technology developed (Gorny, 1997).

High-oxygen MAP was firstly proposed as an alternative to low-oxygen MAP in 1996, as it can inhibit the enzymatic activity and the growth of certain microorganisms, prevent moisture loss and the decay of fresh-cut fruits and vegetables (Day, 1996).

Jacxsens et al.(2001) found that high O_2 concentrations (> 70%) was effective in inhibiting enzymatic browning and yeast growth of grated celeriac, shredded chicory endives and mushroom slices. The overall scores for color evaluation of the three fresh-cut produce did not exceed the upper limits after 6 to 7 days under high O_2 MAP. Whereas, control samples (5% O_2 compensated with N_2) were rejected after 3 to 4 days. The growth of yeast on grated celeriac and shredded chicory endives in control samples exceeded the limit (10^5 CFU/g) on day 3 and 4, respectively. While samples under high O_2 MAP exceeded that limit on day 6 and 7, respectively. In general, compared to the 3-day-shelf life of control samples, a doubled overall shelf life stored at 4 °C could be reached to 6d, 7d, and 6d for each of these produce, respectively. High O_2 (50 or 90% O_2 compensated with N_2) MAP is reported to have strong effect of anti-browning, inhibition of microbial growth for fresh-cut lettuce stored at 7 °C during 6 days storage (López-Gálvez, et al., 2015). Compared with low O_2 MAP (3% of O_2 balanced by N_2) and control sample (air packaging), significantly lower browning was observed in both high O_2 MAP at the end of the storage. However, the accumulation of ethylene and development of russet spotting were also induced, and the selection of less susceptible cultivars and the use of inhibitors of ethylene was further suggested. Amaro et al.(2012) found that higher O_2 concentration is conducive to the preservation of aroma volatile like acetate esters in fresh-cut cantaloupe and honeydew melons stored at 5 °C for 12d. Furthermore, the effects of combining high oxygen with ascorbic acid were reported to be highly conducive to the inhibition of polyphenol oxidase (PPO) and peroxidase (POD) activities and the maintenance of total phenolic and soluble solid content as well as the integrity of the cell membrane of fresh-cut eggplant, resulting in a prolonged shelf life of 12 days at 4 °C (Li, Jiang, Li, Tang, & Yun, 2014). Although control samples (water dip + air MAP) was microbiologically accepted after 12 days of storage, its sensory score was significantly lower than that of the sample under high O_2 MAP. In fact, sensory score of sample under high O_2 MAP on day 12 was almost equal to that of control sample on day 6, indicating that 6 more days of shelf life were obtained by high O_2 MAP.

High oxygen combined with high carbon dioxide was proposed to provide further improvement of conventional MAP in fresh-cut vegetables. Shelf life of sliced carrots stored under 50% O_2 and 30% CO_2 could be prolonged by 2 to 3 days in contrast with the control (stored in air), representing similar or better quality than those stored under 1% O_2 and 10% CO_2 at 8°C after 8 to 12 days (Amanatidou, Slump, Gorris, & Smid, 2000). However, oxygen levels above 70% resulted in poor product quality when combined with 10% to 30% CO_2. Zhang et al.(2013) reported that MAP with 50% O_2 and 50% CO_2 showed strong inhibition effect on the growth of yeasts and their production of volatile organic compounds in fresh-cut pineapple, and they suggested high oxygen and high carbon dioxide MAP as an effective method for extension of the shelf-life of fresh-cut pineapple. Similar results were followed by their further studies on fresh-cut honeydew melon (Zhang, Samapundo, Pothakos, Sürengil, & Devlieghere, 2013). Lower populations of yeasts and lactic acid bacteria and lower quantities of volatile organic compounds were observed in fresh-cut honeydew melon under high O_2 MAP (50% O_2 and 50% CO_2) after 5 days of storage at 7 °C. Nevertheless, slightly stronger browning occurred in samples under high O_2 MAP compared to the control (air). In general, an extended shelf life from 3 to 5 days of fresh-cut honeydew melon was achieved by high O_2 MAP compared to the control (packaged in air).

Although with controversial use for two decades, low level use of carbon monoxide (CO) was approved as generally recognized as safe (GRAS) as an MAP gas for its reduction of metmyoglobin and maintenance in cherry-red color of meat in the retail packaging in the USA in 2004 (Jeong & Claus, 2011; Lyte, et al., 2016). In contrast with the CO use in meat industry, however, extremely limited data is available in literature on its application and benefits in fresh-cut fruits and vegetables. Zhang et al.(2013) proposed that a low level of CO (< 175 mL/L) treatment for 20 min could effectively inhibit browning of fresh-cut lotus root slice by reducing the activities of PPO and POD. They also found that malonaldehyde (MDA) content and phenylalanine ammonialyase (PAL) content of fumigated samples were 17% lower and 40% higher than that of the non-fumigated samples after 8 days storage at 5 ℃, respectively. Thus, application of CO was suggested as a promising method for preventing browning and maintaining quality of fresh-cut lotus root slices. Similarly to the controversy over the application in meat, its toxicity continues to call into questioning the use of CO in fresh-cut fruits and vegetables.

Recently, particular attention has been paid to the use of some inactive or noble gases, such as argon (Ar), helium (He), and nitrous oxide (N_2O) (Char, et al., 2012; González-Buesa, et al., 2014; Rocculi, Romani, & Rosa, 2004). These gases do not directly affect the metabolism of plant tissues through modification of enzymes, however, they may increase the diffusivity of O_2, C_2H_4 and CO_2 from plant tissues because of their higher density than nitrogen, or inhibit respiration by affecting cytochrome oxidase C activity in the mitochondria(Gorny & Agar, 1998; Sowa & Towill, 1991). Rocculi et al.(2004) found that percentage of browning areas of sliced apples under high N_2O and Ar (90% N_2O, 5% CO_2, 5% O_2, and 65% N_2O, 25% Ar, 5%CO_2, 5% O_2) MAP were about 15% and 25%, respectively, whereas that of the control was more than 60% after 12 days storage at 5 °C. On the other hand, an increase in initial firmness and total soluble solid content of sliced apples under high N_2O and Ar MAP were also observed during storage. Furthermore, similar beneficial effects were found in their further studies on firmness and color retention of fresh-cut kiwifruits, using same mixture of N_2O (90% N_2O, 5% CO_2, 5% O_2) (Rocculi, Romani, & Rosa, 2005). The firmness of kiwifruit slices decreased only by 10% after 8 days in the sample packed in N_2O, while about 70% firmness loss was detected in the control sample (air) after just 4 days of refrigerated storage. Although sample stored under high Ar MAP (90% Ar, 5% CO_2, 5% O_2) represented a positive effect on firmness maintenance, it was not so for color preservation. It was reported that Ar-enriched MAP was the most suitable choice to preserve the overall postharvest quality of fresh-cut watercress (Pinela, et al., 2016). Nevertheless, Silveira et al.(2014) compared the effects of noble gas enriched (89.9% Ar, 90.1% He, 89.3% N_2O) MAP and air packaging on quality of fresh-cut watercress. Results showed that respiration rates and C_2H_4 emission of fresh-cut watercress in noble gas MAP were lower than that of control (air-packaged), yet no clear effect on the growth of psychrotrophic and

Enterobactericeae was observed. Thus, they suggested a combination of noble gas MAP with other technologies to ensure microbial safety of fresh-cut watercress.

3.1.2 Pressurized inert gases

Inert gases such as xenon (Xe), neon (Ne), krypton (Kr), argon (Ar) and nitrogen (N_2) can form ice-like crystal called clathrate hydrate when dissolved in water under higher pressure (Ando, et al., 2009; Purwanto, Oshita, Seo, & Kawagoe, 2001; Tanaka, 1995). The gas molecules are trapped in a cage-like structure by water molecules through physical bonding via van der Waals forces. Clathrate crystals can easily developed into visible size, and they are stable at temperatures above 0°C under certain pressure (Reid & Fennema, 2008).

Pressurized inert gases have been successfully used for the preservation of some fresh and fresh-cut fruits and vegetables in recent years (Artés, Gómez, Aguayo, Escalona, & Artés-Hernández, 2009; Zhang, Quantick, Grigor, Wiktorowicz, & Irven, 2001). Zhang et al.(2008) found that shelf life of fresh-cut green asparagus spears could be extended from 3-5d to 12d at 4 °C by treatment of a mix of argon (Ar) and xenon (Xe) gases under 1.1 MPa (Ar and Xe at 2:9 (v:v) in partial pressure) for 24h. Meng et al.(2012) found that pressurized argon (4 MPa) treatments on fresh-cut green peppers for 1h could reduce water mobility as well as loss of water, ascorbic acid and chlorophyll, the growth of yeast and molds, and maintain the cell integrity by inhibiting the production of MDA, as well as the activities of catalase (CAT) and POD. This treatment resulted in an extended shelf life of 12d stored at 4 °C, which was 4 days longer than that of the control (untreated). Further studies on the effect of pressurized argon treatment on fresh-cut cucumber were reported then (Meng, Zhang, Zhan, & Adhikari, 2014). Shelf life of fresh-cut cucumbers was prolonged by 3 to 4 days by pressurized Ar (1.0 MPa) treatment for 60 min at 20 °C, compared to that of the control (untreated). Better maintenance in the quality characteristics (water loss, firmness, soluble solids, chlorophyll contents, and ascorbic acid contents) and inhibition of microbial growth were observed during 12d storage at 4 °C. Thus pressurized Ar (1.0 MPa) treatment was proposed as an effective method for preservation of fresh-cut cucumber. Moreover, Wu et al. (2012; 2012b) reported that shelf life of fresh-cut pineapples and apples could be extended from 9d and 7d to 15d and 12d, by high pressure Ar treatment at 1.8 MPa for 60 min and at 150 MPa for 10 min, respectively. However, samples treated by pressurized Ar presented lower scores in firmness than that of the control. Their further studies on the application of mixed argon and nitrogen, as well as argon and xenon also presented a promising method for preserving fresh-cut pineapples and apples (Wu, Zhang, & Adhikari, 2013). Significant lower growth of *Escherichia coli* and *S. cerevisiae* were observed in fresh-cut apples and pineapples by treatment of a mix of argon (Ar) and xenon (Xe) gases under 1.8 MPa (Ar and Xe at 2:9 (v:v) in partial pressure), compared to the control samples. On the other hand, lower browning, loss of total phenols and ascorbic acid, respiration rate and ethylene production were found in high-pressure (10MPa) argon and nitrogen treated fresh-cut pineapples (Wu, Zhang, & Wang, 2012a). Besides, no significant reduction in tissue firmness or increase in juice leakage were found during 20 days of storage at 4 °C compared to the control samples.

3.1.3 Electron beam irradiation (EBI)

Food irradiation may be considered as a second big breakthrough after pasteurization. Irradiation causes minimal modification in the flavor, color, nutrients, taste and other quality attributes of foods. Conventional and the most frequently used food irradiation mainly refers to the exposure of cobalt-60 (or much infrequently of cesium-137) radioisotopes for the purpose of shelf life and safety enhancement (Farkas & Mohácsi-Farkas, 2011). Extensive researches and applications of lower doses of irradiation on food have been reported since it was considered as a safe treatment for food (Roberts, 2014). However, the potential to cause cancers, as well as public misunderstanding towards it, have called into questioning the use of conventional irradiation in food (Kong, et al., 2014). Electron beam irradiation, as opposed to gamma radiation, does not require radioactive isotopes to generate ionizing radiation. Electron beams are generated from machines capable of accelerating electrons very close to the speed of light at high energy levels in the 0.15-10 MeV range in a vacuum environment (Mami, Peyvast, Ziaie, Ghasemnezhad, & Salmanpour, 2014). Commercial electricity is the energy source and the generator can be easily switched on and off.

EBI helps to eliminate microbial contamination, and it has been demonstrated to be effective in reducing pathogenic microorganisms. The mechanism of microorganism inactivation by EBI is primarily attributed to the destruction of DNA structure, as well as the denaturation of enzymes and membrane proteins, resulting in the loss of the reproductive capabilities and other functions of the cell (Lung, et al., 2015).

The effects of EBI depends primarily on food type and irradiation dosage. Under-dosage probably would result in ineffectiveness, but over-dosage is costly and sometimes may cause tissue damages. When blueberries suffered EBI at 2.3 kGy and 3.13 kGy, the population of surviving *Escherichia coli* decreased significantly from 8.9 log CFU/g to 28 CFU/g and 6 CFU/g, respectively (Kong, et al., 2014). Likewise, fresh-cut cabbage treated with 2.3 kGy and 4.0 kGy exhibited greater than a 4.0 log and 7.0 log reduction of *Escherichia coli,* respectively (Grasso, Uribe-Rendon, & Lee, 2011). Besides, EBI treatment at the exposure of 0.7 and 1.5 kGy resulted in significant decrease in *Salmonella enterica* serotype Poona inoculated on fresh-cut cantaloupe, compared with the control (non-irradiated). After 21 days of storage, *Salmonella enterica* counts in the control samples was above 6.0 log CFU/g, while those in irradiated samples at 0.7 kGy and 1.5 kGy were 3.4 and 2.2 log CFU/g, respectively. However, yeasts grew slowly and steadily during 21 days storage at 5 °C and no significant reduction was observed in all samples (Palekar, Taylor, Maxim, & Castillo, 2015).

EBI also has the potential to increase the shelf life and maintain the overall quality of food, as well as maintain their freshness. Kong et al.(2014) reported that 39% decay of untreated blueberries was observed after 14 d storage at 4 °C, while only 8% and 3% decay were found in blueberries treated with 2 kGy and 3 kGy, respectively, concluding a positive correlation between the shelf life of blueberries and the irradiation dosage. Mushrooms are highly perishable and have an extraordinary short shelf life. This is mainly due to enzymatic browning, weight loss and texture changes. Compared with untreated samples, EBI at 2 kGy presented a higher whiteness, the highest total antioxidant capacity and the lowest electrolyte leakage of mushroom, however significant decrease in vitamin C content was also observed (Mami, Peyvast, Ziaie, Ghasemnezhad, & Salmanpour, 2014). Additionally, shelf life extension of fresh-cut products without compromising in sensory and nutritional qualities, sometimes may be achieved by combined use of several treatments. In an earlier study, fresh-cut cantaloupe, which was treated at 1 kGy EBI and placed in modified atmosphere packaging, presented lower and more stable respiration rates, the highest sweetness and cantaloupe flavor intensity scores, as well as the lowest off-flavor scores after 14-20 days of storage (Boynton, et al., 2006). Moreover, no clear trends in color or texture changes was found in all samples. Yurttas et al. (2014) reported that EBI at 1 kGy combined with vacuum impregnation with 2 g/100 g of ascorbic acid and 1 g/100 g of calcium lactate could better maintain the whiteness and firmness of sliced mushrooms. The impregnated-irradiated samples showed consistently higher scores than the controls after 15 days of storage, however, controls exhibited significant quality loss and became unacceptable on day 15.

Despite of these advantages and successful applications mentioned above, low level of irradiation is required for preservation of fresh fruits and vegetables. Among fruits and vegetables, the US Food and Drug Administration (FDA) currently restricts the maximum irradiation level for fresh fruits and vegetables to 1.0 kGy, with only two exceptions of fresh lettuce and spinach that can be irradiated up to 4.5 kGy (Abolhassani, Caporaso, Rakovski, & Prakash, 2013; Shahbaz, Akram, Ahn, & Kwon, 2015). In spite of the current debate on the maximum dosage for fresh and fresh-cut fruits and vegetables, the safety and feasibility of a higher level up to 4.5 kGy irradiation for all fresh fruits and vegetables are under evaluation. Despite of the limited literatures on the application and the strict restrictions of EBI on its application on fresh-cut fruits and vegetables, the encouraging and promising results can be the driving force for future research.

3.1.4 Pulsed light (PL)

Pulsed light (PL) has emerged as a non-thermal technique for the rapid surface decontamination of food or packaging materials by the inactivation of microorganisms through short-duration and high-power pulses (Barbosa-Canovas, Schaffner, Pierson, & Zhang, 2000). These pulses are generated by an inert-gas (mainly xenon) flash lamp and involve a broad-spectrum white light (from ultraviolet to near infrared wavelength). The main mechanism of microbial inactivation by PL is attributed to the photochemical effect on structural changes in cell and DNA of bacteria, viruses, and other pathogens that prevent cells from replicating (Heinrich, Zunabovic, Bergmair, Kneifel, & Jäger, 2015). The major advantages of this novel technique are mainly concluded as the significant microbial reduction in very short treatment times, the lower energy cost, the lack of residual compounds and its great flexibility (Oms-Oliu, Martín-Belloso, & Soliva-Fortuny, 2010). It has been successfully applied for the decontamination of meat, egg and some liquid foods, such as milk and fruit juice (Ferrario, Alzamora, & Guerrero, 2015; Ganan, Hierro, Hospital, Barroso, & Fernández, 2013; Innocente, et al., 2014; Lasagabaster, Arboleya, & de Marañón, 2011).

In the past few years, applications of PL in fresh-cut fruits and vegetables have gained much attention. It has been reported to be not only effective in inactivation of microorganisms, but also in maintenance of the nutritional and sensory properties of fresh-cut fruits and vegetables (as shown in Table 2).

Similar to electron beam irradiation, the efficiency of PL treatment also depends primarily on the type of foods and microorganisms, as well as intensity and numbers of pulses conducted. Under-intensity may result in ineffectiveness, but over-intensity is likely to cause some undesirable damages. Charles et al.(2013) claimed that PL was conducive to the preservation of firmness, color and carotenoid content of fresh-cut mangoes after 7 days of storage at 6 °C, whereas high loss of firmness and color change were observed in the control after 3 days of storage. Moreover, carotenoid content was about 9 mg/g dry matter in PL treated fresh-cut mangoes, while that of the control sample was only 2mg/g dry matter in control samples after 7 days. On the other hand, compared to those of the control sample, an increase in PPO activity, the maintenance of nutritional qualities, including PAL activity, phenol and total ascorbic acid contents were also stated in their study. Likewise, reduction in yeasts and molds, as well as maintenance of chlorophyll a and b in fresh-cut avocado were reported when treated with 6 J/cm^2 PL dose (Aguiló-Aguayo, Oms-Oliu, Martín-Belloso, & Soliva-Fortuny, 2014). On the other hand, significant reductions in *Escherichia coli* and *Listeria innocua* were observed when fresh-cut mushroom were exposed to high fluences (12 J/cm^2) (Ramos-Villarroel, Aron-Maftei, Martín-Belloso, & Soliva-Fortuny, 2012b). This could be explained by the significant damage in cell cytoplasm and cytoplasmic membrane through the observation by transmission electron microscopy (TEM). Nevertheless, cells treated with 6 J/cm^2 did not show obvious changes in their cytoplasmic membrane. Worse still, high fluences (12 J/cm^2) resulted in significant lower L* and toughness values throughout storage. Similarly, greater reduction in *Listeria innocua*, *Escherichia coli* and *Saccharomyces cerevisiae* was reported in fresh-cut apple exposed to high PL fluencies (Gómez, Salvatori, García-Loredo, & Alzamora, 2012). However, browning of cut surface was also promoted. The browning of cut surface is probably due to the temperature increase or thermal damage during the use of high fluences, which could cause enzymatic and non-enzymatic browning. Moreover, some negative effect of PL on sensory qualities, color and texture in some fresh and fresh-cut products were also reported. Aguiló-Aguayo et al.(2013) observed severe weight loss and noticeable appearance of wrinkles in PL treated tomatoes after 3 days, which severely reduced the acceptability of product quality. However, these changes were not appreciable in untreated tomatoes and no physical damages were observed throughout the 7 days of storage. Likewise, negative effects on the color, texture and headspace gas composition occurred in fresh-cut watermelon treated with higher pulses (6 J/cm^2) (Ramos-Villarroel, Aron-Maftei, Martín-Belloso, & Soliva-Fortuny, 2012a). Values of color parameters (L*, a* and b*) of untreated fresh-cut watermelon were significant higher than those of the PL treated samples after 15 days of storage. The firmness of PL treated sample was even lower with a value of 1.95 ± 0.11 N, while that of the untreated sample was 3.06 ± 0.10 N at 15 d of storage. Besides, PL treatments also stimulated the respiration of fresh-cut watermelon and led to significant decrease in O_2 concentrations and greater CO_2 accumulation through storage, compared to the untreated samples. Although current literature on negative effects is scarce, these reported undesirable effects are worth of attention.

In order to overcome the disadvantages mentioned above, combined method was proposed to achieve better effects of PL treatment on fresh-cut fruits and vegetables. To overcome the accelerated browning of fresh-cut apple, Gómez et al.(2012) investigated the effect of PL treatment combined with anti-browning pretreatment. Dipping into mixed solution of 1% (w/v) ascorbic acid plus 0.1% (w/v) calcium chloride combined with an up to 71.6 J/cm^2 PL dose was demonstrated to be effective in minimizing browning on fresh-cut apple. Ramos-Villarroel et al. (2011) achieved a better maintenance in color and firmness of fresh-cut avocado by using PL combined with L-cysteine (2%), citric acid (1%), and calcium lactate (1%). However, most of the current combined methods focus on chemical solutions or edible coatings (Gómez, et al., 2012; Moreira, Tomadoni, Martín-Belloso, & Soliva-Fortuny, 2015; Ramos-Villarroel, Martín-Belloso, & Soliva-Fortuny, 2011; Ramos-Villarroel, Martín-Belloso, & Soliva-Fortuny, 2015). Therefore, further works need to be done for a better understanding and then more attention should be paid to an improved application of pulsed light combined with other proper technologies.

3.1.5 Ultraviolet light (UV)

Ultraviolet light (UV) refers to a type of non-ionizing radiation with wavelength ranging from 100 nm to 400 nm, which is usually classified into three types: UV-A (315-400 nm), UV-B (280-315 nm), and UV-C (100-280 nm) (González-Aguilar, Ayala-Zavala, Olivas, de la Rosa, & Álvarez-Parrilla, 2010). UV-C irradiation at 254 nm presents the maximum germicidal action. The generally recognized mechanism of microbial inactivation of UV is mainly attributed to the direct DNA damage in living organisms. UV induces the formation of DNA photoproducts, such as cyclobutane pyrimidine dimers and pyrimidine 6-4 pyrimidone, which inhibit transcription and replication and eventually lead to mutagenesis and cell death (Gayán, Condón, & Álvarez, 2014).

The major advantages of UV are primarily summarized as the wide applicability to most types of microorganism, the lower cost and the convenient manipulation. Although the poor penetration limited its application in food field, UV-C is particularly suitable for surface decontamination of fresh-cut fruits and vegetables as microbial spoilage and enzymatic deteriorations mainly occur on the cut surface (Manzocco, et al., 2011).

Many studies have revealed the appropriate results from the use of UV to reduce microbial load in fresh-cut fruits and vegetables. Manzocco, et al. (2011) found that total viable counts of fresh-cut apples treated with 1.2kJ/m^2 UV-C dose remained about 2 log units lower than that of the untreated ones for up to 8 days of storage at 6 °C. Martínez-Hernández, et al. (2015) also reported significant inhibition of *E. coli*, *S. Enteritidis* and *L. monocytogenes* on the surface of fresh-cut kailan-hybrid broccoli during shelf life. Apart from microorganisms, the oxidation of phenolic compounds by PPO or POD is a major cause of enzymatic browning in fresh-cut fruits and vegetables. UV-C has been verified to be conducive to the inhibition of PPO activity and browning of fresh-cut carambola. After treatment with dose of 12.5 kJ/m^2, fresh-cut carambola represented a fresh-like appearance even after 21 days of storage (Moreno, et al., 2017). Similarly, significant reduction of browning reactions in UV treated fresh-cut apples was also observed (Chen, Hu, He, Jiang, & Zhang, 2016). In addition, maintenance in firmness and crunchy texture are highly desired because texture is generally associated with freshness and wholesomeness. Rodoni, Zaro, Hasperué, Concellón, and Vicente (2015) showed that firmness of UV-C treated fresh-cut peppers was 50% higher than that of untreated samples after 12 d storage. On the other hand, maintenance of antioxidant activity (DPPH activity), total phenolic compound and vitamin C contents of fresh-cut paprika (Choi, Yoo, & Kang, 2015) and mandarin(Shen, et al., 2013) by UV-C was also reported.

Unfortunately, the potential application of UV-C is limited due to the negative effects on fresh-cut produce including sensory characteristic and nutritional components. Pan and Zu (2012) showed that extened exposure time accelerated browning in the fresh-cut pineapples. Meanwhile, significant decrease in content of vitamin C was also observed. Likewise, high dose of UV-C is responsible for the increases in electrolyte leakage and weight loss of fresh-cut green onion (Kasim, Kasim, & Erkal, 2008). On the other hand, shelf life of fresh-cut watermelon treated with low UV-C (1.6 and 2.8 kJ/m^2) was extended to 11 days at 5 °C, whereas the maximum shelf-life of high UV-C (4.8 and 7.2 kJ/m^2) treated samples was 8 days (Artés-Hernández, Robles, Gómez, Tomás-Callejas, & Artés, 2010). Therefore, the combination use of UV-C with citric acid (Chen, Hu, He, Jiang, & Zhang, 2016), malic acid (Raybaudi-Massilia, Calderón-Gabaldón, Mosqueda-Melgar, & Tapia, 2013), modified atmosphere packaging (Choi, Yoo, & Kang, 2015), gaseous ozone (Gutiérrez, Chaves, & Rodríguez, 2016) and electrolyzed water (Santo, Graça, Nunes, & Quintas, 2016) have been developed.

Currently, UV-C is not the only effective range applied to fresh-cut produce. Sliced parsnip treated with UV-B at 1.3 kJ/m^2 showed 2.3 times increase in total soluble phenolic due to the combination effect of wounding and UV-B light exposure after 3 days incubation, while that of fresh-cut lettuce treated at 3.1 kJ/m^2 of UV was 2.5 times after 10 days of storage (Du, Avena-Bustillos, Breksa Iii, & McHugh, 2014). Similarly, UV-B also contributed to the significant increases in total soluble phenolic, total phenolic and total antioxidant capacity of fresh-cut carrot (Du, Avena-Bustillos, Breksa Iii, & McHugh, 2012; Formica-Oliveira, Martínez-Hernández, Díaz-López, Artés, & Artés-Hernández, 2017).

In recent years, UV-light emitting diodes (LEDs) have been developed due to advantages such as low cost, energy-efficient, long life expectancy, no harm for human eyes and skin, convenient manipulation and no production of mercury waste (Li, et al., 2010; Mori, et al., 2007). UVA-LED has been demonstrated to contribute to the increase in quercetin glycoside content of watercress (Kanazawa, Hashimoto, Yoshida, Sungwon, & Fukuda, 2012) and in anthocyanin, vitamin C and total phenolics of strawberry (Kim, et al., 2011). Although only a few studies of UVA-LED on fresh-cut produce are currently available, UVA-LED showed great potentiality as an effective food disinfection and process technology by contributing to a significant reduction on *E. coli* of fresh-cut cabbage and lettuce while inducing no loss of vitamin C (Aihara, et al., 2014). On the other hand, although anti-browning effect is associated with irradiance, exposure time and the fruit cultivar, effective inhibition of browning on fresh-cut apple and pear was achieved (Lante, Tinello, & Nicoletto, 2016).

3.1.6 Cold plasma (CP)

Cold plasma (CP) is a novel non-thermal and green food process technology with great potential applications for food preservation or decontamination. Plasma is described as the fourth state of matter following solid, liquid and gas. It refers to a quasi-neutral ionized gas which consists of particles including photons, free electrons, positive or negative ions, excited or non-excited atoms and molecules (Fernández, Shearer, Wilson, & Thompson, 2012). Currently, air, oxygen, nitrogen, or a mixture of noble gases (helium, argon and neon) are the most frequently used gases in CP. Plasma can be produced by the application of energy in several forms including electricity, lasers, microwaves, radiofrequency, magnetic field, alternating current and direct current (Niemira, 2012; Thirumdas, Sarangapani, & Annapure, 2015). When those active particles recombined with each other, the energy is released as visible and UV light in the process of recombination.

The active particles in the plasma can react with the food substrate, releasing the stored energy into the bacteria or viruses to be targeted (Niemira, 2012). Although the exact mechanism of microbial inactivation by CP is still not fully understood, the primary mechanisms is currently attributed to 1) direct chemical interaction of cell membranes with reactive species and charged particles, 2) damage of cellular components and membranes by UV, and 3) DNA strands breakage by UV (Niemira, 2014). However, the specific energy source and proportion of the gas mixtures applied to foods depend not only on chemical composition, density and temperature of the plasma they generated, but also on the water activity, protein and fat content, texture, pH and type of the foods being treated (Lacombe, et al., 2015; Lee, Kim, Chung, & Min, 2015).

Cold plasma can be generated at atmospheric pressure and room temperature, at which food is treated at low temperatures and without a marked temperature increase during the process. This mild operation condition contributed to the continuous food processing, meanwhile no undesired phase transitions is caused compared to applications at reduced pressure ($p < 1013$ mbar) or low pressure ($p < 10$ mbar) (Schlüter, et al., 2013).

Cold plasma treatment has been successfully applied for microbial decontamination on strawberry, lettuce, potato, cherry tomato, cabbage and milk, representing great potential as a novel sterilization method. Lee, Kim, Chung, and Min (2015) observed 0.3-2.1 log CFU/g reduction of *Listeria monocytogenes* on cabbage and 1.5 log CFU/g reduction of *Salmonella Typhimurium* on cabbage and lettuce, respectively. Similarly, 2.72, 1.76 and 0.94 log reductions of *Salmonella Typhimurium* on lettuce, strawberry and potato were achieved by CP, respectively (Fernández, Noriega, & Thompson, 2013). Misra, et al. (2014) claimed 12-85% reduction of total mesophilic count and 44-95% reduction of yeast and mould count in CP treated strawberries. Besides no significant changes in respiration rate, color and firmness of CP treated samples were observed. Likewise, no significant changes in weight loss, pH and firmness were generated in CP treated cherry tomato (Misra, Keener, Bourke, Mosnier, & Cullen, 2014). Ziuzina, Patil, Cullen, Keener, and Bourke (2014) found that atmospheric CP treatment for 10, 60 and 120 s resulted in reduction of *Salmonella*, *E. coli* and *L. monocytogenes* populations on tomato to undetectable levels from initial populations of 3.1, 6.3, and 6.7 log10 CFU/sample, respectively. However, an extended treatment time was needed to reduce bacterial populations attached on the more complicated surface of strawberries. When blueberries treated with atmospheric CP for 0, 15, 30, 45, 60, 90, or 120 s, significant reductions of total aerobic plate count and yeast/molds ranging from 0.8 to 1.6 log CFU/g and 1.5 to 2.0 log CFU/g were observed compared to the control after 1 and 7 days, respectively (Lacombe, et al., 2015). However, treatments longer than 60 s and 90 s resulted in significant reductions in firmness and anthocyanins, respectively. Besides, surface color were significantly reduced after 120 s for the L* and a* values and increased after 45 s for the b* values.

Previous studies have demonstrated the potential application of CP in some fresh products, however this novel technology applied to the fresh-cut sector is still in an early stage of development. Currently only a few literatures regarding its effects on physicochemical and nutritional properties of fresh-cut fruits and vegetables are available. Tappi, et al. (2014) reported a 65% decrease of browning area in fresh-cut apples treated by CP for 30min compared to the control ones after 4h of storage.

Besides, reductions of PPO activity ranging from 12% to 58% were also observed. In addition, about 17% of POD and 7% of PME activities inhibition of fresh-cut melon were achieved by CP treatment (Tappi, et al., 2016). Ramazzina, et al. (2015) claimed that CP treatments improved color retention and reduced the darkened area formation of fresh-cut kiwifruit during storage without inducing any textural change compared with the control samples. Although an immediate slight loss of pigments was caused, a better pigments retention was observed during storage. In addition, no significant changes in antioxidants content and antioxidant activity were observed among CP treated samples and control ones. Similarly, only slight reductions (up to 10%) of antioxidant content and antioxidant capacity were observed in CP treated fresh-cut apples (Ramazzina, et al., 2016).

CP processing of foods has gained much attention during the last decade by showing novel and promising applications in various areas of food industry. However, information about its effects on food quality and exact mechanism is still largely lacking. Hence further studies should continue to focus on the changes in physicochemical, sensorial and nutritional properties of foods, physicochemical reaction kinetics, and penetration depths of CP. In addition, limited investigations have been performed so far on whether toxic compounds are formed during the CP treatment process. The safety of CP treated food has not been widely verified. Therefore, integrated risk assessment of CP must be conducted by authorities in future works before it is commercially applied to food industry. On the other hand, as the technology developed from lab scale to commercial scale, absolute capital costs will naturally increase but may be offset by improvements in energy efficiency and overall engineering scale efficiencies (Niemira, 2012).

3.2 Chemical technologies

3.2.1 Acidic electrolyzed water (AEW)

Acidic electrolyzed water (AEW) was initially developed in Japan and has also been described as functional water (Huang, Hung, Hsu, Huang, & Hwang, 2008). It is produced by passing a diluted salt solution (sodium chloride and potassium chloride are most frequently used) through an electrolytic cell, within which the anode and cathode are separated by a membrane. The anode side of the electrolytic cell, from which AEW is obtained, produces various chlorine compounds and ions such as HOCl, Ocl^-, and Cl_2 gas (Gil, Gómez-López, Hung, & Allende, 2015). Acidic electrolyzed water offers the potential ability to inactivate microorganisms with minimal negative effects on human and the organoleptic and nutritional quality of food. For these reasons, acidic electrolyzed water (AEW) has been used as a new disinfectant and an alternative to chlorine decontamination for the purpose of safety ensurance and shelf life extension of fresh-cut fruits and vegetables in the past years (Park, Alexander, Taylor, Costa, & Kang, 2009).

In contrast with the disadvantages in the use of NaClO, such as skin and membrane irritation and toxicity, AEW is not corrosive to skin, mucous membranes, or organic material (Huang, Hung, Hsu, Huang, & Hwang, 2008). Therefore, there is currently an increasing interest in the use of AEW for its high efficacy in inactivation of microorganisms and minimal effects on nutritional value at low available chlorine concentrations. Acidic electrolyzed water is reported to provide effective inactivation of microbials on fresh-cut apples (Graça, Abadias, Salazar, & Nunes, 2011). With a lower concentration of free chlorine, AEW could achieve the same or better disinfection results as sodium hypochlorite solutions does. Similarly, fresh-cut mizuna baby leaves subjected to AEW (260 mg/L available chlorine, 2 min) showed a noticeable inhibition of natural microbial growth, resulting in a significant lower microbial counts than those of the control samples throughout 11 days at 5 °C (Tomás-Callejas, Martínez-Hernández, Artés, & Artés-Hernández, 2011). Although the total antioxidant activity showed an approximately 35% decrease after shelf life, AEW treatment did not affect the surface structure of the leaves, compared to the control (deionized water). Besides, the main sensory qualities (visual appearance, browning, dehydration, off-odors and off-flavors) were well maintained throughout 11 days at 5 °C, whereas those of the control sample were not acceptable after 7 days. AEW (70 and 100 mg/L available chlorine, 2 min) treated fresh-cut broccoli showed higher total phenolic content than NaOCl-disinfected samples, while preserving the same antioxidant enzyme activities as NaOCl-treated samples throughout 19 days of storage at 5 °C (Navarro-Rico, et al., 2014).

Recently, slightly acidic electrolyzed water (SlAEW) has gained much more attention because of its strong antimicrobial activity and much less adverse effect to human health. It provides an even lower available chlorine concentration (10 < available chlorine < 30 mg/L, 5.0 < pH < 6.5) than that of strong AEW (20 < available chlorine < 60 mg/L, pH < 2.7). This low available chlorine concentration of SlAEW could result in the maximized use of hypochlorous acid, reduction of the corrosion on the surfaces, and reduction of the human health and safety issues from Cl_2 gas. In the past few years, slightly acidic electrolyzed water has been described to be effective as sanitizer in some fresh-cut vegetables. It presented a stronger bactericidal efficacy than that of the strong acidic electrolyzed water in fresh-cut oyster mushroom after 3 min treatment at room temperature (Ding, Rahman, & Oh, 2011). Likewise, higher reduction of microbial and pathogens (*E. coli* O157:H7 and *L. monocytogenes*) was observed in fresh-cut spinach treated with slightly acidic electrolyzed water compared to those treated with strong acid electrolyzed water, deionized water, aqueous ozone, 1% citric acid and sodium hypochlorite (NaOCl) (Rahman, Ding, & Oh, 2010). Some other application of SlAEW are shown in Table 3.

Another new application is neutral electrolyzed water (NEW). NEW is generated like AEW, but part of the product formed at the anode is then redirected into the cathode chamber, then resulted in a neutral solution (pH 8.0 ± 0.5) (Abadias, Usall, Oliveira, Alegre, & Viñas, 2008). The bactericidal success of NEW is mainly due to its high oxidation reduction potential along with the presence of free available chlorine and a surfactant-type action caused by the presence of free OH− groups

(Monnin, Lee, & Pascall, 2012). It is readily able to penetrate cell membranes but less corrosive to equipment and less irritating to operator skin and mucous membranes. Fresh-cut broccoli treated with NEW showed better bioactive compounds (antioxidant capacity, phenolics,and antioxidant enzymes) retention than that of NaClO (Graça, Abadias, Salazar, & Nunes, 2011).

Numerous studies have been reported concerning the application of electrolyzed water on fresh-cut fruits and vegetables in the past decades, however, most of them primarily used electrolyzed water as a sanitizer. On the other hand, only a few researches were conducted on the efficacy of electrolyzed water on sensory and nutritional characteristics of fresh-cut fruits and vegetables. But the results of the current studies have shown a promising prospect of electrolyzed water in fresh-cut industries.

3.2.2 Nanotechnology

Nanotechnology is an emerging field of study that could offer new materials and new techniques to prolong food shelf life. It involves the research and development of materials with one or more dimensions that are in the range of 1-100 nm in length (Mihindukulasuriya & Lim, 2014). Nano-sized particles can significantly modify the physical and chemical properties of the specific material, such as improvement in mechanical strength, thermal stability, electrical conductivity, and so on (Kalia & Parshad, 2013).

Silver nanoparticles is well known as a promising antimicrobial material for its antibacterial properties against a large amount of microorganisms (Duan, Zhang, Li, & Mujumdar, 2008; Kuorwel, Cran, Orbell, Buddhadasa, & Bigger, 2015). They often act as a source of silver ions inside the cell. In particular, silver ions can disrupt or kill the microorganisms by a series of damages, including DNA damage, activation of antioxidant enzymes, depletion of antioxidant molecules (e.g., glutathione), binding of proteins, and structural changes in the cell wall and nuclear membrane (Mastromatteo, et al., 2015; McShan, Ray, & Yu, 2014). An earlier study on quasi-nanoscale silver particles (101-109 nm) showed effective result for the preservation of vegetable juice (Zhang, Duan, Shan, & An, 2005). Then, application of silver nanoparticles-PVP coating was reported beneficial to quality maintenance of green asparagus, leading to an extended shelf life of 25 days at 2 °C and 20 days at 10 °C, respectively, whereas those of the controls are 15 days at 2 °C and 10 days at 10 °C, respectively (An, Zhang, Wang, & Tang, 2008). Fernández et al. (2010) developed a cellulose-silver nanoparticle hybrid material combined with MAP for the preservation of fresh-cut melon stored at 4°C for 10 days. It retarded the senescence of the fresh-cut melon, presented remarkably lower yeast counts, while maintained a juicier appearance after 10 days of storage, prolonging the shelf life of fresh-cut melon by 5 days compared to the controls.

As one of multifunctional inorganic nanoparticles, ZnO nanoparticles also have the potential to inhibit microbial growth. Li et al.(2011) developed a novel polyvinyl chloride film mixed with ZnO nanoparticles powders for preservation of fresh-cut apples. The results showed that the ZnO nanopackaging significantly reduced the decay rate by 21.9% and improved the shelf-life of fresh-cut "Fuji" apples by 6 days compared to the control sample (PVC film packaging). Meng et al. (2014) reported that ZnO nanoparticles coating combined with ultrasound could delay the ripening process significantly by slowing down the mass loss and the softening of texture. The combined application of ultrasound and ZnO nanoparticles coating was capable of effectively delaying the senescence and significantly extending the storage life of fresh-cut kiwifruit by 4 days.

Recently, along with silver nanoparticles and ZnO nanoparticles, some application of other materials in nano-scale (nanoclays, chitosan nanoparticles, packing materials containing metal oxide nanoparticles) or the use of them combined with other techniques have captured attention in fresh-cut fruits and vegetables. For example, Chawengkijwanich and Hayata (2008) developed a TiO_2 nanoparticle-coated oriented polypropylene (OPP) packaging film. After one day of storage, a decrease of *E. coli* from 6.4 to 4.9 log CFU/g in fresh-cut lettuce packaged in this bag irradiated with UVA light was observed, while that of samples stored in an uncoated OPP film bag irradiated with UVA light decreased from 6.4 to 6.1 log CFU/g. Other recent applications of nanotechnology in fresh-cut fruits and vegetables are presented in Table 4.

Another new application is nanoemulsions, which is particularly suitable for the fabrication of encapsulating systems for functional compounds as it prevents their degradation and improves their bioavailability (Silva, Cerqueira, & Vicente, 2012). Nanoemulsions can result in higher stability in terms of gravitational separation, flocculation, and coalescence of oil droplets and enhanced bioactivity of emulsified oils due to the smaller droplet size and a higher surface area to droplet volume ratio (Kim, Oh, Lee, Song, & Min, 2014). Recently due to the formation of a protective atmosphere around fresh produce, there has been increasing interest in the utilization of nanoemulsions and nanoemulsion-based coatings. Kim, Oh, Lee, Song, and Min (2014) inoculated grape berry with *Salmonella* and *Escherichia coli* and then subjected it to lemongrass oil nanoemulsion. This treatment reduced *Salmonella* and *Escherichia coli* by more than 3.2 and 2.6 log CFU/g, respectively, without significant changes in its flavor and glossiness. Moreover, this treatment was also responsible for the maintenance of firmness, phenolic compound concentration and antioxidant activity of grape berry. Bhargava, Conti, da Rocha, and Zhang (2015) achieved an up to 3.44, 2.31, and 3.05 log CFU/g reductions in *Listeria monocytogenes*, *Salmonella Typhimurium* and *Escherichia coli* of fresh-cut lettuce by 0.05% oregano oil nanoemulsions, respectively. Likewise, nanoemulsion-based edible coatings with lemongrass essential oil (LEO) contributed to a faster and greater inactivation of *Escherichia coli* of fresh-cut apple during storage time compared with conventional emulsions (Salvia-Trujillo, Rojas-Graü, Soliva-Fortuny, & Martín-Belloso, 2015).

Unfortunately, although firmness was maintained, significant browning was observed during storage on fresh-cut apples coated with high concentration LEO nanoemulsions.

In the past few years, the food industry has benefited a lot from antimicrobial nanomaterials. However, safety concerns should be taken into consideration before they are applied commercially. The much larger surface area of nanoparticles promotes a greater contact with cell membranes, as well as greater capacity for absorption and migration. Hence, nano-sized materials frequently present different properties than that of the normal sized materials. Once migrating into food, they may cause sensory changes of foods. The potential toxicity issue of nanotechnology can be even more critical than its advantages brought to preservation and protection of food. Therefore, applications of nanotechnology in food preservation and packaging require further studies focusing on the potential toxicity of nano-sized materials.

3.2.3 Ozone

Due to the possible formation of carcinogenic chlorinated compounds in water by chlorination, ozone is attracting more interest as an alternative sanitizer to chlorine (Akbas & Ölmez, 2007). In 1997, ozone was granted Generally Recognized as Safe (GRAS) status and has since been fully approved by the US FDA as a direct contact food sanitizing agent (Tzortzakis, Singleton, & Barnes, 2007).

Ozone rapidly reacts with intracellular enzymes, nucleic material, and components of envelope, spore coats, or viral capsids of microorganisms. It also decomposes rapidly without traces from oxidation and does not produce any toxic halogenated compounds. Ozone decomposes impulsively during water treatment through mechanisms involving the generation of hydroxyl free radicals (•OH). The •OH radicals are the principal reactive oxidizing agents and are highly effective for inhibition of bacteria and virus. Ozone will oxidize organic chemicals into safer elements, e.g., breaking down ammonia and cyanide into nitrogen and water. In all reactions, the main byproduct after oxidation is oxygen (Krasaekoopt & Bhandari, 2010).

A number of studies have been performed on the microbial reduction by applying ozone to fresh-cut produce in either aqueous or gaseous form. Karaca and Velioglu (2014) demonstrated that gaseous ozone treatment (950μL/L, 20 min) contributed to 1.0-1.5 log reductions in *Escherichia coli* and *Listeria innocua* inoculated on sliced lettuce and spinach. When exposed to 9 ppm gaseous ozone for 6 h, reductions of 2.89, 2.56 and 3.06 log in *E. coli* O157, *Salmonella Typhimurium* and *L. monocytogenes* populations were achieved in fresh-cut bell pepper, respectively (Alwi & Ali, 2014). Likewise, significant reduction in total bacteria counts of fresh-cut apple was also reported by aqueous ozone (1.4 mg/ L, 5-10 min) treatments, while ethylene production, PPO and POD activities, total phenol and MDA content were reduced (Liu, Ma, Hu, Tian, & Sun, 2016). Moreover, the similar effects of ozone have been demonstrated on fresh-cut melon (Botondi, Moscetti, & Massantini, 2016) and papaya (Yeoh, Ali, & Forney, 2014).

Despite above mentioned advantages, ozone can cause significant negative effects on samples treated with ozone. Ascorbic acid, total phenolic contents and antioxidant activity in ozone-treated (950μL/L, 20 min) sliced parsley were 40.1%, 14.4%, and 41.0%, respectively, less than the control samples (Karaca & Velioglu, 2014). Besides, enhanced antioxidant capacity of ozone treated fresh-cut guava, pineapple and banana was achieved by a compromised reduction in vitamin C content (Alothman, Kaur, Fazilah, Bhat, & Karim, 2010). Moreover, Kim, et al. (2006) reported that the surface texture of the fresh-cut lettuce was damaged by ozonated water above 5 ppm.

Although ozone has been applied to fresh and fresh-cut produce for quite a long period, special attention must be paid to the detrimental health effects induced by the exposure to high concentration and extended time of ozone. It is reported that increasing exposure and concentration of ozone is associated with headache, eye, nose, throat and respiratory irritation, lung damage with chronic respiratory disease, edema, and hemorrhage (de Candia, Morea, & Baruzzi, 2015). In this regard, the Federal Occupational Safety and Health Administration (OSHA) in the United States specified the threshold limit value of 0.1 ppm for long-term (8 hours) and 0.3 ppm for short-term (15 minutes) continuous exposure to ozone in the working environment (Horvitz & Cantalejo, 2014).

3.3 Biopreservation technologies

3.3.1 Bacteriophages

Bacteriophages are used as a novel, environmentally-friendly and effective biopreservation method for the control of food quality. They could specifically and effectively infect and multiply in their respective host bacterial cells (Meireles, Giaouris, & Simões, 2016). Thus, they are harmless to humans, animals, and plants.

Promising results using bacteriophage have been reported for the three dominant foodborne pathogens, namely *Salmonella spp.*, *L. monocytogenes* and *E. coli* O157:H7 (Hudson, et al., 2013; Spricigo, Bardina, Cortés, & Llagostera, 2013). The first reported application of the bacteriophage mixture for decontamination of fresh-cut fruits (fresh-cut honeydew melon and apple slice) was proposed by Leverentz et al (2001). A significant reduction of *Salmonella* was observed on fresh-cut honeydew melon stored at 5, 10 and 20 °C. However, similar results were not found on fresh-cut apples at any of the three temperatures. This corresponded to the number of viable phages on the two foodstuffs. Later they observed a significant reduction of *L. monocytogenes* on fresh-cut melon, but not on fresh-cut apple again (Leverentz, et al., 2003). Although bacteriophages could not completely eliminate foodborne pathogens, they are suggested as a novel and environmentally-safe alternative to chemical sanitizers for decontamination of some fresh-cut fruits and vegetables.

Although bacteriophages have been used in some fresh-cut fruits and vegetables, most of the literatures are focused on the antimicrobial effects. Little has been done on their effect on physicochemical and sensory properties of treated foods. Despite the fact that literatures on the application of antimicrobial activity of bacteriophages for fresh-cut fruits and vegetables are still limited, these current results are encouraging and have attracted extensive research interest for the decontaminating of fresh-cut fruits and vegetables in recent years (as presented in Table 5). However, under certain circumstances, it took a long time for specific bacteriophage to contact with corresponding microorganism (Spricigo, Bardina, Cortés, & Llagostera, 2013). Thus further research is required to reduce the contact time.

3.3.2 Bacteriocins

Bacteriocins can be generally defined as antimicrobial peptides or proteins capable of inhibiting some spoilage and disease-causing microorganism (Balciunas, et al., 2013). They are produced by a large number of bacteria and have been used for biopreservation, shelf-life extension, clinical antimicrobial action and control of fermentation microflora. They cover a very broad field of application, including both the food industry and the medical sector. Bacteriocins produced by lactic acid bacteria (LAB) are receiving great attention because they are produced by bacteria that are generally considered beneficial to human health and food production (Oliveira, et al., 2014). Currently only two bacteriocins are being used commercially as food preservatives. One is nisin produced by *Lactococcus lactis* and the other one is carnocyclin A produced by *Carnobacterium maltaromaticum* UAL307 used in ready-to-eat meat products (O'Connor, Ross, Hill, & Cotter, 2015). They are approved as GRAS by the U.S. Food and Drug Administration, in particular when they are applied to the specific food product.

Leverentz et al. (2003) reported a significant reduction of *L. monocytogenes* up to 3.2 log units and 2.0 log units on fresh-cut melon and apple treated with bacteriocins stored at 10 °C after 7 days of storage, respectively. Moreover, higher reductions (up to 5.7 log units on fresh-cut melon and up to 2.3 log units on fresh-cut apple) were achieved when nisin was used in combination with bacteriophage.

Randazzo et al. (2009) also observed an up to 2.7 log units reduction of *L. monocytogenes* on fresh-cut lettuce sprayed with bacteriocin compared with the sample without bacteriocin after 7 days of storage at 4 °C. Although *L. monocytogenes* was not completely eliminated on the fresh-cut lettuce, the results proposed the potential use of bacteriocins as a novel and safe sanitizer to improve microbial safety of fresh-cut fruits and vegetables.

Barbosa et al. (2013) developed a antimicrobial cellulose film containing 25% nisin to extend the shelf life of minimally processed mangoes for 12d storage at 5 °C. They found the maintenance of physicochemical characteristics (pH, total titratable acidity, vitamin C content, browning index and soluble solids) of minimally processed mangoes packed with antimicrobial films for 9 days during storage. Moreover, a significant reduction of *L. monocytogenes* was observed. Fresh-cut mangoes packed with antimicrobial films showed a 1000-fold reduction in the number of viable cells after two days of storage, and no viable cells were detected after 4 days even after an initial contamination of 10^7 CFU/mL. However, *L. monocytogenes* remained at high level (10^6 to 10^7 CFU/mL) in control samples (packed without nisin) throughout 12 days of storage. Hence, they suggested a promising use of nisin in packaging to improve the safety of minimally processed mangoes.

Later, Narsaiah et al. (2015) reported the application of bacteriocin-incorporated alginate coating on the preservation of minimally processed papaya, which extending its shelf life to 21 days compared to 15 days for the control. Significant inhibition of microbial growth, as well as maintenance or slight changes in physical and chemical properties were observed in samples treated with the bacteriocin-incorporated alginate coating. The total plate count was only at 10^3 CFU/g as compared to 10^7 CFU/g in the control after 21 days of storage. Besides, firmness and weight loss in coated samples were 8.7 and 7.4 times less than those of the control, respectively.

Bacteriocins are expected to behave differently on different target bacteria and under different environmental conditions. Since the efficacy of bacteriocins depends on environmental factors, it is necessary to determine more precisely the most effective conditions for application of each particular bacteriocin. Similar to the application of bacteriophage, only a few literature applied bacteriocins to fresh-cut fruits and vegetables are available. The effective antimicrobial effects of bacteriocins on fresh-cut melon, apple, mango, lettuce and papaya are supported by the currently limited studies. As consumers are increasingly demanding for the natural foods, food processed without any addition of chemical preservatives are becoming more attractive. Therefore, promising findings currently available on fresh-cut fruits and vegetables will be the driving force for its future development if well combined with other proper techniques.

3.3.3 Bioprotective microorganism

Due to the inability to completely inactivate microorganisms, the potential toxicity to human, the residues on food and the negative effects of chemical preservatives on the sensorial properties of fresh and fresh-cut fruits and vegetables, some bioprotective microorganisms have been proposed as alternatives to them (Leverentz, et al., 2006; Oliveira, et al., 2015b; Trias, Bañeras, Badosa, & Montesinos, 2008). It is feasible to prevent microbial growth by introducing other competitive microorganisms that are beneficial to human (Meireles, Giaouris, & Simões, 2016). Lactic acid bacteria (LAB) are generally recognized as GRAS by the US FDA. They have a long history of safe use in foods as natural microflora of meat, milk, vegetables and fish, both as protective cultures and bacteriocin producers.

Some bioprotective microorganisms isolated from LAB have already shown its potential for application in fresh-cut fruits and vegetables. For example, the strains B2 of *Lactobacillus plantarum* and PBCC11.5 of *Lactobacillus fermentum* inhibited the growth of *L. monocytogenes* on fresh-cut cantaloupe (Russo, et al., 2015). The main physicochemical and nutritional qualities of the fresh-cut cantaloupe were unaffected by the bioprotective microorganisms, except for some nutritional or sensorial quality attributes (ascorbic acid content, sucrose content, off odor and off flavor) when fresh-cut cantaloupe were inoculated with *Lactobacillus plantarum* B2. This was probably due to a more intense metabolic activity as supported by the higher O_2 and sucrose consumption rates of *Lactobacillus plantarum* B2. Their findings indicated that careful selection of bioprotective strains should be taken into consideration before its commercial application in fresh-cut fruits in order to avoid quality changes. Luo et al. (2015) isolated a strain of LAB RD1 from traditional Chinese fermented radish and investigated its efficacy on inhibition of *Salmonella* on fresh-cut apples. Significant inhibitory efficiency against the growth of *Salmonella* on fresh-cut apple pieces was observed, without any discriminable odor or visible appearance changes after 7 days of storage at 10 °C. However, *Salmonella* counts in the control samples was above 5.0 log CFU/g on day 4, while those in LAB treated samples ranged from 3.5 to 4.8 log CFU/g throughout the 7 days of storage. Siroli et al. (2015) applied the strains CIT3 and V7B3 of *Lactobacillus plantarum* in combination with natural antimicrobials (2-(E)-hexenal/hexanal, 2-(E)-hexenal/citral for apples and thyme for lamb's lettuce) to fresh-cut apples and lettuce, extending the shelf life by 8 to 10 days compared to the control.

The scientific community has never stop continuing search for novel use of bioprotective microorganisms for the purpose of food preservation. Recently, the application of a novel strain of *Pseudomonas graminis* CPA-7 has been reported to prevent the growth of foodborne pathogens in some fresh-cut produce (Alegre, et al., 2013a; Alegre, et al., 2013b). The results showed an effective reduction in foodborne phathogens (*E. coli* O157:H7*, Salmonella, L. monocytogenes and Listeria innocua*) on minimally processed apples and peaches under both laboratory and simulated commercial conditions. Moreover, no significant changes was found on color, while an increase in firmness was observed. Thus, a combined use of *Pseudomonas graminis* CPA-7 with other disinfection techniques, such as low temperature storage and MAP was proposed.

Then studies on fresh-cut melon using *Pseudomonas graminis* CPA-7 combined with MAP were investigated (Abadias, et al., 2014). Significant reduction of *Salmonell*a and *L. monocytogenes* was observed on fresh-cut melon after 2 days of storage at 10 °C and 5 days of storage at 20 °C, respectively. Moreover, no significant differences were found in soluble solids content, titratable acidity, pH and firmness of fresh-cut melon in CPA-7 treated and untreated samples. With regard to color parameter, it decreased significantly both in samples stored at 5 and 10 °C. Although lower scores of visual appearance were found in CPA-7 treated samples stored at 5 °C, all treatments under air or MAP packaging represented good visual quality scores after 8 days of storage. However, visual appearance of sample stored at 10 °C showed a drastic decrease after 5 days of storage. Further study showed that by the treatment of CPA-7, antioxidant properties and vitamin C content of fresh-cut melon were retained. Although PPO activity increased during storage regardless of the addition of CPA-7, POD activity was higher than that of the untreated samples during 8 days of storage at 5 °C (Plaza, Altisent, Alegre, Viñas, & Abadias, 2016).

These researches proposed a promising alternative, if well combined with other proper techniques, to chemical preservation of fresh-cut fruit and vegetables. Although, at laboratory scale, applications of these novel bioprotective microorganisms reached successful achievement in preservation of fresh-cut fruits and vegetables, it should be pointed out that particular attention should be paid to further studies concerning safety aspect and careful selection of targeted bioprotective microorganisms before commercial applications are officially approved.

4. Future outlook and challenges in fresh-cut fruits and vegetables

This paper reviewed recent developments in shelf life extension technologies which have been applied to fresh-cut fruits and vegetables. These novel technologies include physical, chemical and biopreservation technologies, such as modified atmosphere packaging, pressurized inert gases, electron beam irradiation, pulsed light, ultraviolet light, cold plasma, acidic electrolyzed water, nanotechnology, ozone, bacteriophage, bacteriocins and bioprotective microorganisms. Each emerging technique has its advantages and limitations and can be applied to different fresh-cut fruits and vegetables.

The fresh-cut industry is expected to continue expanding rapidly in the forthcoming year, to which novel technologies for longer shelf life of fresh-cut produce have been applied. However, extended shelf life of fresh-cut products without compromising in sensory and nutritional qualities, sometimes may be achieved by well combination of several proper techniques. Future studies should aim at improving organoleptic quality and nutritional value of fresh-cut produce by reasonable combinations of these novel technologies.

On the other hand, application of some novel technologies is still in an early stage of development and only exists at the laboratory level. This requires extensive trials at pilot scale and industrial scale in the future work. Moreover, food safety oriented techniques are perceived better than convenience oriented ones. Therefore, the potential toxicity and integrated risk assessment of some novel technologies, such as cold plasma and nanotechnology, must be conducted by authorities in the future. Last but not least, further progress in terms of the efficacy, legislation, cost-effectiveness ratio and convenient manipulation of these novel technologies should also be highlighted in the future works.

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Table 1 Main causes of quality loss of some fresh-cut fruits and vegetables

Fresh-cut Products	**Main causes of degradation**
apple	browning
pear	browning
mango	browning, decaying
watermelon	juice leakage, softening
lettuce	browning
potato	browning
carrot	browning, loss of moisture, lignin formation
eggplant	browning, softening
broccoli	chlorophyll degradation
cucumber	softening, fermentation
onion	softening, browning

1737 **Table 2** Application of pulsed light in fresh-cut fruits and vegetables

Products	Treatment	Effects	References
fresh-cut mushroom	4.8 Jcm^{-2}	Effective inhibition of aerobic mesophilic and psychrophilic microorganisms, yeasts and moulds; no significant changes in sensory and antioxidant properties.	(Oms-Oliu, Aguiló-Aguayo, Martín-Belloso, & Soliva-Fortuny, 2010)
fresh-cut apple	11.9 Jcm^{-2}	higher microbial reduction of *Listeria innocua*, *Escherichia coli*, and *Saccharomyces cerevisiae*, while maintenance in color	(Gómez, Salvatori, García-Loredo, & Alzamora, 2012)
fresh-cut apple	23.9 Jcm^{-2}, combined with pretreatment of ascorbic acid(1%) and calcium chloride(0.1%) dipping	effective in inbition of browning and microbial growth	(Gómez, et al., 2012)
fresh-cut mushroom	12 Jcm^{-2} PL treatments of full wavelength spectrum (180-1100 nm)	3 and 2 log reductions in *Escherichia coli* and *Listeria innocua*, while significant lower firmness and lightness	(Ramos-Villarroel, Aron-Maftei, Martín-Belloso, & Soliva-Fortuny, 2012b)
fresh-cut watermelon	12 Jcm^{-2} PL treatments of full wavelength spectrum (180-1100 nm)	effective inactivation of *Escherichia coli* and *Listeria innocua;* significant decrease in ethylene production; higher negative effect on the color and texture	(Ramos-Villarroel, Aron-Maftei, Martín-Belloso, & Soliva-Fortuny, 2012a)
fresh-cut mangoes	8 Jcm^{-2}	maintenance of the firmness, color and nutritional quality (carotenoid content, phenol and total ascorbic acid)	(Charles, Vidal, Olive, Filgueiras, & Sallanon, 2013)
fresh-cut avocado	3.6, 6.0 and 14 Jcm^{-2}	3.6 Jcm^{-2} of PL led to the lowest growth of yeasts and molds; 6.0 Jcm^{-2} of PL led to the best maintenance of chlorophyll a and b ; 14 Jcm^{-2} of PL led to the highest relative hue values	(Aguiló-Aguayo, Oms-Oliu, Martín-Belloso, & Soliva-Fortuny, 2014)
fresh-cut apple	17.5 Jcm^{-2}	effective maintenance in color; no significant changes in firmness	(Ignat, Manzocco, Maifreni, Bartolomeoli, & Nicoli, 2014)
fresh-cut apple	14 Jcm^{-2} of PL combined with gellan-gum based (0.5% w/v) edible coatings	effective retardation of microbiological deterioration and maintenance in sensory quality	(Moreira, Tomadoni, Martín-Belloso, & Soliva-Fortuny, 2015)
fresh-cut avocado, watermelon and mushroom	12 Jcm^{-2} of PL combined with malic acid (2% w/v) dips	more than 5 log reductions of *Listeria innocua* and *Escherichia coli* throughout storage	(Ramos-Villarroel, Martín-Belloso, & Soliva-Fortuny, 2015)

Table 3 Application of slightly acidic electrolyzed water in fresh-cut fruits and vegetables

Products	Treatment	Effects	References
fresh-cut cabbage	SlAEW (pH 6.1±0.0, 20±1.2 mg/L available chlorine), 10 min	efficacy of SlAEW was equivalent to or higher than that of NaOCl solution.	(Koide, Takeda, Shi, Shono, & Atungulu, 2009)
fresh-cut daikon sprout, lettuce, and Chinese celery	SlAEW (pH 5.8±0.5, 21.4±0.9 mg/L available chlorine), 5 min	significant reduction of the total aerobic mesophilic bacteria of Chinese celery, lettuce and daikon sprouts by 2.7, 2.5 and 2.45 log CFU/g, respectively; significant reduction of *E. coli* by 2.7, 2.8 and 2.8 log CFU/g, and of *Salmonella spp.* by 2.87, 2.91 and 2.91 log CFU/g of Chinese celery, lettuce and daikon sprouts, respectively	(Issa-Zacharia, Kamitani, Miwa, Muhimbula, & Iwasaki, 2011)
fresh-cut carrot slices	SlAEW (pH 5.5±0.1, 23.0±1.2 mg/L available chlorine), 10 min, combined with mild heat	no significant differences in color and hardness; higher reduction of the total aerobic bacteria,as well as molds and yeasts than that of SlAEW under room temperature and tap water	(Koide, Shitanda, Note, & Cao, 2011)
fresh-cut cucumber	SlAEW (pH 6.28±0.03, 19.8±1.2 mg/L available chlorine), 5 min	higher reduction of aerobic bacteria counts and mold and yeast counts than that of NaClO treatment	(Liu, Dong, & Jiang, 2011)
fresh-cut cilantro	SlAEW (pH 5.85±0.05, 19.46±0.32 mg/L available chlorine), 5 min, combined with mild heat	maintenance in flavor, firmness and level of electrolyte leakage; no significant changes in color	(Hao, Li, Wan, & Liu, 2014)
fresh-cut bell pepper	SlAEW (pH 5.0-5.2, 28-30 mg/L available chlorine) combined with ultrasound and mild heat, at 60 °C for 1 min	effective in reduction of *L. monocytogenes* and *S. Typhimurium*; no significant changes in color and hardness	(Luo & Oh, 2016)

Table 4 Application of nanotechnology in fresh-cut fruits and vegetables

Products	Type of nanoparticles	Effects	Shelf life	Ref.
fresh-cut kiwifruit and pineapple	silver-montmorillonite nanoparticles (Ag-MMT) 20 mg of Ag-MMT	effective in inhibiting microbial growth, while maintaining sensorial quality	14-16 days	(Costa, Conte, Buonocore, & Del Nobile, 2011)
fresh-cut carrot	calcium-alginate coating loaded with silver-montmorillonite nanoparticles film thickness of 20 µm	effective in control of microbial growth and maintenance of color, odor, firmness and overall quality	62-70 days	(Costa, Conte, Buonocore, Lavorgna, & Del Nobile, 2012)
fresh-cut apple	polyvinyl chloride (PVC) film loaded with ZnO nanoparticles	significant reduction in the decay rate, MDA, PPO, POD, inhibition of browning	12 day	(Li, et al., 2011)
fresh-cut kiwifruit	ZnO nanoparticles combined with ultrasound treatment (40 KHz, 350 W, 10 min),	significantly slowed down ethylene and CO_2 production, loss of water and firmness	10 days	(Meng, Zhang, & Adhikari, 2014)
fresh-cut *Zizania latifolia*	chitosan/nano-chitosan composite coating	effective in prevention of browning and lignification, inhibition of PAL and POD, improvement of SOD and CAT	12 days	(Luo, Jiang, Bao, Wang, & Yu, 2013)
fresh-cut sugarcane	nano-CaCO3-based low density polyethylene	efficient retardation for growth of microorganisms, inhibition of respiration and ethylene production, prevention of increases in NI, AI, PAL, PPO and POD activities, delaying browning	5 days	(Luo, Wang, Wang, & Feng, 2014)
fresh-cut Chinese yam	nano-CaCO3-based low density polyethylene	efficient for retarding growth of microorganisms, inhibiting respiration and ethylene production, preventing increases in PAL, PPO and POD activities, delaying browning	5 days	(Luo, Wang, Jiang, & Xu, 2015)
fresh-cut apple	chitosan-ripolyphosphate nanoparticles	effective for antimicrobial activity against moulds and yeasts, and mesophilic and psychrotrophic bacteria, no influence on color and firmness	8 days	(Pilon, et al., 2015)

Table 5 Application of bacteriophage in fresh-cut fruits and vegetables

Products	Type of bacteriophage	Targeted pathogen	References
fresh-cut honeydew melon and apple	bacteriophage mixture (SCPLX-1)	*Salmonella spp.*	(Leverentz, et al., 2001)
	bacteriophage mixture (LM-103 and LMP-102)	*L. monocytogenes*	(Leverentz, et al., 2003)
fresh-cut cantaloupes and lettuce	ECP-100	*E. coli 0157:H7*	(Sharma, Patel, Conway, Ferguson, & Sulakvelidze, 2009)
organic baby spinach and baby romaine lettuce	bacteriophage mixture (family Caudovirales)	*E. coli 0157:H7*	(Viazis, Akhtar, Feirtag, & Diez-Gonzalez, 2011)
fresh-cut lettuce and spinach	phage cocktail	*E. coli 0157:H7*	(Boyacioglu, Sharma, Sulakvelidze, & Goktepe, 2013)
fresh-cut lettuce	EcoShield (Lytic bacteriophages)	*E. coli 0157:H7*	(Ferguson, Roberts, Handy, & Sharma, 2013)
fresh-cut melon, apple and pear	Listex P100	*L. monocytogenes*	(Oliveira, et al., 2014)
fresh-cut lettuce	Listex P100	*L. monocytogenes*	(Oliveira, Abadias, Colás-Medà, Usall, & Viñas, 2015)
	Salmonelex	*Salmonella spp.*	

Recent Developments in Shelf Life Extension Technologies of Fresh-cut Fruits and Vegetables

Highlights

Bullet point 1: Recent developments in novel shelf life extension technologies applied for fresh-cut fruits and vegetables are reviewed.

Bullet point 2: Characteristics of novel shelf life extension technologies methods are discussed briefly.

Bullet point 3:Novel methods are presented in the following order: Physical technologies, chemical technologies and biopreservation technologies.

Bullet point 4: Non-thermal preservation technologies, synthetic additive-free or natural additive-based preservation techniques are presented.