Fresh-cut fruits preservation: current status and emerging technologies

M.R. Corbo[1,2], B. Speranza[1,2], D. Campaniello[1], D. D'Amato[1,2] and M. Sinigaglia[1,2]

[1]Department of Food Science, Faculty of Agricultural Science, University of Foggia, Via Napoli 25, 71122 Foggia, Italy
[2]Food Quality and Health Research Center (BIOAGROMED), University of Foggia, Via Napoli 25, 71122 Foggia, Italy

Minimally processed fruits are characterized by a shorter shelf life than their whole counterparts, because of higher susceptibility to microbial spoilage, increased respiration rate and ethylene production, which is stimulated by wounding of the tissue. In addition, they may pose a food safety risk because they are consumed raw.

In the last decades, food scientists have attempted to ensure microbiological stability and quality of fresh-cut fruits and several advances in scientific knowledge have been developed. This paper aims to supply information about some approaches recently proposed in literature to extend the shelf life and to minimize the risk of infection or intoxication associated with the consumption of these products. Published research on the use of emerging technologies is critically reviewed and opportunities for future research are explored.

Keywords fresh-cut fruits; shelf life; safety; emerging technologies

1. Introduction

Today's society is characterized by an increasing health consciousness and growing interest in the role of food for maintaining and improving human well-being and consumer health. In addition to their nutritional and sensory properties, foods are currently recognized as active and protective agents. Among the others, fresh-cut horticultural products stand out as convenient novel foods that fit the many needs of a modern lifestyle as they combine technical content with an innovative food concept [1].

Fresh fruit jointly to vegetables are an essential component of a healthy diet, able to decrease the risk of cardiovascular diseases and cancer [2]. In the last years, their consumption has continued to grow rapidly linked to the increased public awareness of their health benefits, even if it remains below the recommended daily intake in many countries, due to barriers such as complacency and lack of willpower to change the diet [3]. On the other hand, this new trend, has also hiked the chances of outbreaks of food poisoning and food infection related to consumption of fresh fruit and uncooked salads [4].

The International Fresh-cut Produce Association (IFPA) defines fresh-cut products as fruit or vegetables that have been trimmed and/or peeled and/or cut into 100% usable product that is bagged or pre-packaged to offer consumers high nutrition, convenience, and flavour while still maintaining its freshness [5]. In particular, fresh-cut fruits attract consumers because they are fresh, nutritious, low priced, and ready-to-eat. As a consequence, a wide assortment of minimally processed fruits has been developed to meet consumer's needs for ''quick'' and convenient products, and to benefit from fruit's healthy image [6]. Minimal processing gives additional value to fresh-cut fruits in terms of convenience and time saving, although several hurdles are encountered due to the difficulty in preserving their freshness during prolonged periods. These products, in fact, are characterized by a shorter shelf life than their whole counterparts, because of higher susceptibility to microbial spoilage, increased respiration rate and ethylene production, which is stimulated by wounding of the tissue; in fact, the process operations (i.e. cutting, splicing, etc.) form lesions in the tissue that determine enzymatic browning, texture decay, rapid microbial growth, weight losses and undesirable volatile production, thus reducing highly the shelf life [7].

In the last two decades, food scientists have attempted to develop new technologies that improve the quality and quantity of fresh-cut products, with the main objective of increasing their production without affecting quality and environment, while fulfilling consumer expectations. In the same time, consumers have also become more critical on the use of synthetic additives to preserve food safety or enhance characteristics such as colour and flavour [8]. Once traditional processing technologies have been able to provide microbiologically safe food products with acceptable quality characteristics, the next step forward is to design mild but reliable new treatments in order to achieve fresh-like quality products with a high nutritional value. The growing demand for slightly processed products with the same guarantees of innocuousness than those treated by traditional methods of preservation has urged researchers to focus most of their efforts on studying new ways of extending the shelf life of fresh-cut produce.

In this paper, the published research on the use of emerging technologies to ensure microbiological stability and quality of fresh-cut fruits is critically reviewed. In particular, the aim of the following sheets is to give an insight into the current knowledge on the technologies mostly suggested to ensure microbiological stability and quality of fresh-cut fruits, in order to supply information about this topic which remains still a major challenge for the food industry. A brief description of the fresh-cut processing technology and of the naturally occurring fruit microflora is also given.

2. Fresh-cut fruits processing: potential impact on quality

It is well known that processing of fruit promotes a faster physiological deterioration, biochemical changes and microbial degradation of the products which may result in degradation of its colour, texture and flavour, even when only slight processing operations are used [9]. Prior to being packaged for consumption, minimally processed fruits are subjected to one or more mild unit operations, as reported in Fig. 1, which include washing ⁄ sanitising, peeling, cutting and/or slicing, dicing, shredding, etc. Each step during the production, packaging and storage, could potentially have an effect on nutrients and quality of the prepared produce. A special attention is necessary for mechanical operations considered very critical to delimit the shelf life of fresh-cut fruit commodities, causing the rupture of many cells and the liberation of intracellular products (such as oxidizing enzymes); at the same time, the surface of produce is exposed to air and to possible contamination with bacteria, yeasts and moulds. It is important to underline that cutting increases the area of injured tissues favoring elevated respiration, promoting further rapid deterioration and microbial proliferation. The damage inflicted by mechanical operations on the cut fruit tissues has greatly influenced by the state of maturity of the processed fruit; previous studies on this matter show that the more advanced the ripeness stage, the more susceptible the fruit is to wounding during processing [10]. The optimal stage of processing to minimize cutting damage also varies greatly, depending on the species, cultivar and multiple crop, harvest, and postharvest conditions [11].

Fruit such as apples, kiwifruits and cactus pears require also peeling. Several peeling methods are available; however, on industrial scale, peeling is normally accomplished mechanically, chemically or in high-pressure steam peelers [6]. This operation should be as gentle as possible; the ideal method is hand peeling using a sharp knife. Coarse and fine abrasion peeling increased the rate of microbial growth over that of hand peeling. So, if mechanical peeling is used, it should ideally resemble knife peeling. Other methods disturb the cell walls of the produce, enhancing the deterioration, and should be avoided.

Within the processing line, the washing operations are the most important steps affecting the quality and the shelf life of the fresh-cut products. A first washing step of whole fruits is generally conducted by rinsing in tap water to eliminate pesticide residues, plant debris and other possible contaminants. Secondly a washing step should be performed after peeling and/or cutting to remove microbes and tissue fluids. The microbiological and sensory quality of the washing water used must be good and its temperature low (below 5°C). By careful washing, the shelf life of minimally processed produce can be prolonged by several days. Fruit is generally subjected to extra handling with a routinely dipping in a sanitizing solution, containing chlorine or other antibacterial compounds. In the fresh-cut production, the aforementioned step is the only one where a reduction in spoilage microorganisms and potential pathogens could be achieved [2].

Recently, problems relative to sanitation of fresh-cut products and wash disinfection have been reviewed by Gil et *al*. [12]. Most of the available literature regarding this topic has concluded that washing operations with or without disinfectants are able to reduce the natural microbial populations on the surface of the product by 2 to 3 log units [13,14]. It was observed that, despite the initial differences, the total bacterial counts after the storage were similar when the produce was washed with tap water or when a sanitizing solution was used [13]. Therefore, despite the general idea that sanitizers are used to reduce the microbial population on the produce, their main effect is maintaining the microbial quality of the water, as it is now specified that “antimicrobials, when used appropriately with adequate water quality, help to minimize the potential microbial contamination of processing water and subsequent cross-contamination of the product” [15]. Washing and disinfection have, besides, economic and environmental implications: one challenge for the food industry is the minimization of water consumption and waste water discharge rates. A technique able to disinfect efficiently both the process water and the product would allow a high ratio of recycling and therefore reducing the wastewater rates with less impact on the environment [16].

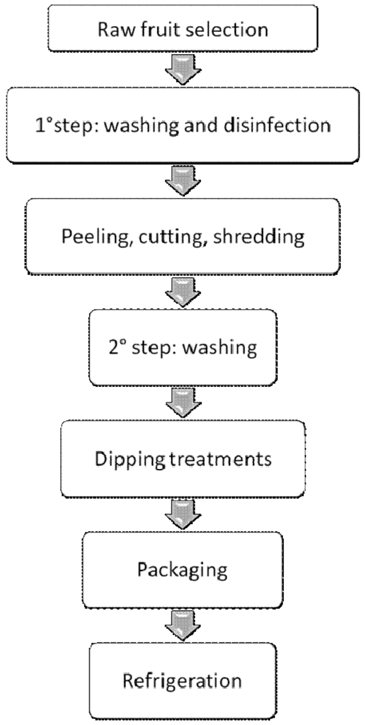

Fig. 1. Flow diagram of fresh-cut fruits

3. Fresh and fresh-cut fruits microflora: potential sources of contamination

Raw fruit, whose internal tissues are normally sterile, is considered a potential target for a wide range of microorganisms, including human pathogens [17]; in fact, the incidence of foodborne outbreaks caused by contaminated fresh fruit has recently increased. For example, numerous cases of *Salmonella* infection by consuming different fresh products are documented, as well as an *Escherichia coli* O157:H7 outbreak [18].

Fruit has generally an external toughness, water proof, wax-coated protective covering, that functions as a barrier for the entry of most microbes; sometimes, fruit surface harbours the microbes which may be the normal microflora, including bacteria (such as *Pseudomonas*, *Erwinia, Enterobacter*, *Lactobacillus* spp., etc.), fungi (*Rhizopus, Aspergillus, Penicillium, Eurotium, Wallemia*), yeasts (*Saccharomyces, Zygosaccharomyces, Hanseniaspora, Candida, Debaryomyces* and *Pichia*), viruses and parasites, or the microbes occasionally occurring during the processing of fresh produce [19]. Furthermore, intrinsic and extrinsic factors might influence the growth of pathogenic microorganisms at any given point throughout the production and pre- and post- harvest handling. Thus, determining the exact source of contamination and the relative method to detect pathogens becomes very important to prevent the risk associated with the consumption of fresh fruit, as it is consumed uncooked. The blowing air, composted soil, insects, or the fruit fly inoculate the skin/outer surface with a variety of bacteria favouring the contamination; likewise, an unscrupulous picking and harsh handling of the fresh produce markedly affect the quality of fruit [19]. The range of microorganisms recovered from raw fruit at harvest reflects very often the microflora present in the field and the contact with soil can add diverse human pathogenic microbes including *Enterobacter, Shigella, Salmonella, E. coli* O157:H7, *Bacillus cereus*, *Campylobacter* spp., *Listeria monocytogenes, Yersinia enterocolitica, Clostridium botulinum*, as well as certain viruses (Hepatitis A Virus, Rotavirus and Norwalk disease virus) and parasites, such as *Giardia lamblia*, *Cyclospora cayetanensis* and *Cryptosporidium parvum* [20]. These microbes remain outside on fruit surface as long as the skins are healthy and intact; any cuts or bruises that appear during the post-harvest processing operations allow their entry to the less protected internal soft tissue.

Contamination can also arise as a consequence of treating soil with organic fertilisers and from irrigation water so that if these waters are contaminated with human pathogens, these microorganisms may be introduced too.

Climatic and agricultural determinants affecting the microbial ecosystem (that may range from 10^4 to 10^8 *per* gram) at harvest include geographical location, history of precipitation, the presence of insects, animals, birds, wind, irrigation practices, pre-harvest, harvest, and post-harvest practices [20]. In this context, containers used to harvest, transport, and display raw fruits could be considered another source of contamination; they are often not effectively cleaned and sanitized, thus encouraging the development of biofilms which may provide protection against potential sanitizers [20]. If pathogens attach to biofilms during transport or processing, their survival and growth may be enhanced and it would increase the probability of cross-contamination of the produce.

After harvesting, potable water is used to wash fruit and during washing some microorganisms will be removed from the product, nutrients will become available, and pathogens can be spread from contaminated parts to uncontaminated parts; with water *E. coli* O157:H7, *Enterobacter, Shigella, Salmonella, Vibrio cholerae, Cryptosporidium parvum, Giardia lamblia, Cyclospora cayetanensis,* and other causative agents of foodborne illness in humans could be added.

Among microorganisms, yeasts and moulds have a competitive advantage over bacteria that may access bruised tissues of many fruits, thanks to their ability to grow at the lower pH range (2.2–5.0), characteristic of much of this produce. In their study on the microbiological quality of fresh minimally-processed fruit, Abadias *et al.* [17] reported that apple, peach, orange, mango and pineapple harboured small microbial populations consisting of yeasts and moulds, while no *Enterobacteriaceae* were detected. They explained this trend with the fact that the investigated fruits were more acidic than other types and the combination of low pH and low temperature during storage also tended to inhibit growth. Since most of fruits have a pH less than 4.0 (with the exception of melons, cactus pears and coconut with a pH value ranging between 5.2 – 6.9), they are not considered substrates to support the growth of pathogens; instead the development of a pH gradient, occurring when surface tissues of fruits are damaged (by insects or mechanical abuse), could provide conditions for growth of pathogenic bacteria. Several authors showed the ability of *Salmonella* and *Shigella* to adapt to different pH conditions and subsequently to grow on sliced apple, papaya, watermelon, cantaloupe and honeydew, especially at ambient temperature [21]. Small fluctuations in pH become more profound if the substrate has low buffering capabilities leading to rapid changes in response to metabolites produced by microorganisms during fermentation. Spoilage of fruit caused by specific moulds and yeasts who utilize organic acids, could lead to further reduced acidity and increased pH, so acidification is often suggested to ensure the safety of fresh products in front of spoilage by foodborne pathogens. Some examples of approximate pH values of fresh fruit are reported in Table 1.

As discussed before, fruit is characterized by natural microflora and/or microflora added during the handling and post harvest processing which can kill or inhibit certain specific types becoming predominant and prevailing in the finished product. With particular regard to fruit safety, the invasion process could be started by two type of pathogen named “true pathogens” and “opportunistic pathogens”: the first are able to infect plant tissues, as they produce degradative enzymes to overcome tough and impervious outer covering of fruit which acts as the foremost effective external protective system. The invasion by true pathogens damages the fruit weakening its defence system and thus favouring the access of opportunistic pathogens.

Table 1 Approximate pH values of some fresh fruits.

Fresh fruits	pH	Fresh fruits	pH
Apple	2.9-3.9	Grape	3.0-4.0
Apricot	3.3-4.4	Grapefruit	2.9-4.5
Banana	4.5-4.7	Lime	1.8-2.4
Blackberry	3.0-4.2	Lemon	2.2-2.6
Cantaloupe	6.2-6.5	Melon	6.3-6.7
Cactus pear	5.8-6.0	Orange	3.3-4.3
Cherry	3.2-4.0	Peach	3.3-4.2
Cranberry	2.5-2.7	Plum	2.8-4.6
Coconut	6.0	Strawberry	3.0-3.9
Fig	4.6	Watermelon	5.2-5.6

Other factors affecting the quality of fresh-cut produce include the fact that harvested fruits continue to respire by utilizing the store available sugars and adjunct organic acids increasing carbon dioxide and ethylene production that leads to rapid senescence [19]. Furthermore, cutting increases the water activity as well as stress-induced ethylene production which accelerates the water loss. Finally, the sugar availability promptly invites enhanced microbial invasion and rapid growth [19].

Jay [22] reported osmophilic yeasts to be associated primarily with the spoilage of cut fruits due to their ability to grow faster than the moulds, particularly the genera such as *Cryptococcus, Rhodotorula* and *Saccharomyces* spp., in fresh fruit and *Zygosaccharomyces rouxii, Hanseniaspora, Candida, Debaryomyces* and *Pichia* spp. in dried fruit. But generally, about 2/3 of the spoilage of fruit is caused by moulds [23], particularly the genera *Penicillium*, *Aspergillus*, *Sclerotinia*, *Botrytis, Eurotium* spp., *Alternaria* spp.*, Cladosporium* spp., and *Rhizopus*. Certain spoilage types create microenvironments suitable for the growth of pathogens leading to an increase of the safety risks. Wade and Beuchat [24] highlighted the crucial role of proteolitic fungi and the associated implications on the changes in pH of the decayed raw fruit in survival and growth of various foodborne pathogens. For example, *Botrytis* and *Rhizopus* spoilage of fruit could help to create environment for the proliferation of *Salmonella enterica* serovar Typhimurium [19], while Dingman [25] observed the growth of *E. coli* O157:H7 in bruised apple tissues. Similar reports of Riordan *et al*. [26] and Conway *et al*. [27] evaluated the impact of prior mould contaminations of wounded apples by *Penicillium expansum* and *Glomerella cingulata* on survival of *E. coli* and *L. monocytogenes.*

As it can be easily inferred, the microbiological shelf life of the fresh-cut commodities depends on the composition and physicochemical properties of the raw fruit. However, processing is crucial because it determines the sources of spoilage caused by the presence of cut surfaces and increased moisture content and by the active metabolism of plant tissue. As these products are minimally processed, sterility or microbial stability can not be ensured longer, thus far many techniques have been studied in order to extend their shelf life, acting on processing or, more usually, on packaging.

3. Fresh-cut fruits preservation

As response to the consumers pressure to reduce or eliminate chemically synthesized additives, food preserved "*as natural as possible*" are gaining more and more attention [8] and numerous efforts are conducted to find natural alternatives to prevent bacterial and fungal growth in fresh-cut fruits. Hence, naturally occurring compounds with antimicrobial capacity such as phenols, chitosan, aldehydes, and organic acids have been tested to prove their effectiveness in these products [28]. Essential oils from coriander, mint, vanillin, parsley and citrus fruit peels, carbonyl compounds, or isothiocyanates obtained from cruciferous vegetables were also tested [29]. Different antimicrobials used as dipping and/or filling solutions and treatments with edible coatings were found to be able to extend shelf life of fresh-cut fruits [2, 7, 28, 29, 30, 31, 32]. Good results were also obtained through the application of Modified Atmosphere Packaging (MAP) and physical methods such as ultraviolet light (UV), thermal treatments and irradiation [2, 29, 30, 33]. Despite the different methodologies and approaches present in literature, in the following published research on the use of emerging technologies is critically reviewed and opportunities for future research are explored.

3.1 Chemical and natural preservatives

Several chemical compounds have been used to reduce bacterial populations on fruit and they are still the most widely used treatments, either before processing or during pre- and post-cutting operations [12]. In particular, the chlorine-based chemicals, such as liquid chlorine, hypochlorite and chlorine dioxide, are usually used at levels of 50-200 ppm free chlorine and with typical contact times of less than 5 min [34]. Treatments with chlorinated water have been and are traditionally applied to decontaminate fresh produce, but in some European countries including Germany, The Netherlands, Switzerland and Belgium, the use of chlorine in ready-to-use products is actually prohibited, since their potential toxicity [16]. In fact, it is recognised the reaction of chlorine with natural organic matter to form carcinogenic halogenated by-products [12]. Moreover, the use of chlorine is also associated with the production of high amounts of wastewater with very high levels of biological oxygen demand [12]. Recent studies have also proved that these chemicals are incapable of completely removing or inactivating microorganisms on fresh produce [17]. Beside chlorine-based dippings, calcium treatments are suggested to reduce microbial populations and extend the shelf life of fruit; in particular, calcium lactate has been widely used for delicate fruit, such as fresh-cut cantaloupes [35] and apples [36]. Antibacterial properties have been reported for calcium propionate for the treatment of honeydew melon, due to its ability to uncouple microbial transport processes [37]. Treatment by dipping in H_2O_2 solution to reduce microbial populations on fresh-cut cantaloupe and honeydew melon are also documented [30].

Chemical food preservatives are responsible of occasional allergic reactions in sensitive individuals, thus the interest in antimicrobial compounds found in nature and the demand from consumers have recently increased [38]. Good synopses about the use of natural preservatives are available in some recent reviews [21, 28]; hence, the critical analysis of literature data indicates that essential oils could represent good candidates compared to chemicals. For example, the methyl jasmonate (MJ), a natural compound detected in *Jasminum* essential oil and other plant species, is known to extend shelf life of whole and fresh-cut mangoes, guavas, and strawberries [39]. Another good evidence is provided by the study of Roller and Seedhar [40] who proposed carvacrol and cinnamic acid to delay microbial spoilage of fresh-cut melon and kiwifruit. Fruits were peeled, deseeded and cut into wedges (kiwifruit) or slices (melon) and subsequently dipped for 1 min in solutions containing 1, 5, 10 or 15 mM of carvacrol or 1 mM of cinnamic acid. Dipping of fresh-cut kiwifruit in carvacrol solutions at 5–15 mM reduced total viable counts from 6.6 to < 2 log CFU/g during 21 days of storage at 4 °C. Also treatment with 1 mM of carvacrol or cinnamic acid reduced viable counts on both the fresh-cut products, extending significantly their shelf life [40]. Shelf life extension of fresh-cut “Fuji” apples at two stages of ripeness (partially ripe and ripe) using natural substances was instead evaluated by Raybaudi-Massilia [41]: a reduction in growth rate and an increase in the lag phase of mesophilic and psychrophilic bacteria, yeasts and moulds were found in dipped fresh-cut apples, which gave as a result an extension of 13 days over the microbiological stability of fresh-cut apples immersed only in water (10.1 days).

An interesting and more recent approach is proposed by D’Amato *et al.* [31] who examined the activity of some natural compounds for extending the storage life of fruit-based salads. In particular, the effect of chitosan, honey and pineapple juice (used as filling solution) on the growth of mesophilic bacteria, psychrotrophic bacteria, lactic acid bacteria and yeasts was investigated. Fruit-based salads were composed by Granny Smith apples, ‘Gialla’ first crop cactus pear fruits and ‘Regina’ table grapes, cut in similar pieces and placed into polypropylene cups filled with different solutions (1:1) that were stored at 4, 8 and 12 °C. Honey showed the greatest antibacterial effect on mesophilic and psychrotrophic bacteria. The antimicrobial activity of chitosan affected the growth of all microbial groups considered, particularly, in conditions of refrigerated storage.

Among the numerous “*natural*” approaches, citric and ascorbic acid were also frequently proposed to reduce microbial populations. The antimicrobial action of these acids is due to pH reduction in the environment, disruption of membrane transport and/or permeability, anion accumulation, or a reduction in internal cellular pH by the dissociation of hydrogen ions from the acid [21]. More specifically citric acid has been accepted as effective in reducing superficial pH of cut fruit such as orange, apple, peach, apricot, kiwifruit, avocado and bananas [21].

Other options for obtaining natural preservative sources are by-products from different processing industries. For example, whey permeate (WP) is a by-product of the cheese industry with potential as a sanitising agent, since it has low pH and could contain lactic acid and thermo-resistant bacteriocins and other small bio-active peptides [42]. At the best of our knowledge, no studies on the application of WP as a decontaminant agent on fruit have been carried out to date, but preliminary studies reported by Martìn-Diana *et al.* [42] with whey permeate in fresh-cut vegetables showed a good antimicrobial activity, thus suggesting, for the future, more studies to be carried out in this direction.

3.2 Active packaging

Headspace artefacts were the first antimicrobial active packaging commercialized in the market, in the form of sachets that are enclosed in the interior of the package or attached to it: those with direct antimicrobial activity include volatile compounds such as sulfur dioxide [43], ethanol [43], organic acids and essential oils [43, 44]. Recently, Ayala-Zavala *et al.* [44, 45] proposed a cyclodextrin essential oil microcapsule that could be successfully used to increase the shelf life of fresh-cut products. Another evidence suggested that the inclusion complexes β-cyclodextrin-hexanal (1.1 µL hexanal/L) and β-cyclodextrin-acetaldehyde (0.12 µL acetaldehyde/L) were effective against *Alternaria alternata*, *Colletotrichum acutatum* and *Botrytis cinerea* [46]. In 2009 the same authors developed and studied a sachet containing different concentrations of 2-nonanone (2.5, 5 and 10 µL), volatile compounds that are naturally found in strawberry fruit, impregnated in alumina as adsorbent solid and incorporated as a part of the active packaging system; results in terms of increased shelf life were promising [47]. Another type of antimicrobial active packaging artefacts are those in which the antimicrobial compound is embedded in the bulk polymer and it has to migrate to the surface in order to interact with the microorganism. Different natural and synthetic polymers have been used as carriers; reviews on this subject have been recently published [44, 48]. Immobilized antimicrobials include peptides, enzymes, polyamines and organic acids [49]. The main inconvenience of this kind of active packaging is that, in order to inhibit the microorganism growth, direct contact between the fresh produce and the polymer is necessary.

Now a decade ago, Lanciotti *et al.* [50] showed that the inclusion of hexanal at levels not exceeding 100 ppm in the storage atmosphere of fresh sliced apples had an important effect on their quality: in fact, it positively affected the shelf life by reducing the growth rate of natural occurring microbial population during storage at 4 and 15 °C. The presence of hexanal at 4 °C totally inhibited mesophilic bacteria and considerably prolonged the lag phase of psychrotrophic bacteria. Also at 15 °C, this compound strongly delayed the growth of moulds, yeasts, mesophilic and psychrotrophic bacteria. The inclusion of hexanal in combination with 2-(E)-hexenal in the atmosphere of fresh sliced apples determined a significant extension of shelf life also when a spoilage yeast such as *Pichia subpelliculosa* was inoculated at levels of 10^3 CFU/g and abuse storage temperatures were used [51]. In addition to their activity on shelf life in terms of control of spoilage microflora, hexanal, 2-(E)-hexenal, as well as hexyl acetate, exhibited also a significant inhibitory effect against pathogenic microorganisms frequently isolated from raw materials, such as *E. coli*, *Salmonella* Enteritidis and *L. monocytogenes* deliberately inoculated in fresh sliced apples packaged in ordinary or modified atmosphere [28]. At the levels used (150, 150 and 20 ppm for hexanal, hexyl acetate and 2-(E)-hexenal, respectively), these compounds displayed a bactericide effect on *L. monocytogenes*, and caused a significant extension of lag phase of *E. coli* and *Salmonella* Enteritidis inoculated at levels of 10^4–10^5 CFU/g.

For the use of the aforementioned compounds as fresh-cut fruits preservatives, the sensorial impact should be necessary considered and minimized.

3.3 Edible coatings

An edible coating is a thin layer of edible material (hydrocolloid or lipid) applied on the surface of a food product with the purpose of generating a semi-permeable barrier to gases, water vapor, and volatile compounds. Edible coatings were found to be able to extend shelf life of fresh-cut products by decreasing respiration and senescence and protecting aroma, texture and colour [29]. Compounds most commonly used to form edible coatings include chitosan, starch, cellulose, alginate, carrageenan, zein, gluten, whey, carnauba, beeswax and fatty acids [29]. Different studies present in literature show good potential for the application on fresh-cut fruits; some examples are reported in Table 2.

Table 2 Some applications of edible coatings on fresh-cut fruits.

Fresh-cut fruits	Coating composition	Reference
Apple	Alginate	[52, 53, 54]
Apple	Whey protein	[55, 56]
Apple	o Whey protein o Hydroxypropyl methylcellulose	[57]
Apple	Trehalose, sucrose and sodium chloride	[58]
Banana	Carrageenan	[59]
Cactus pear	o Sodium alginate o Agar o Fish protein gel	[60]
Litchi	Chitosan	[61]
Mango	Chitosan	[7]
Mango	Mango puree	[62]
Melon	Alginate	[63]
Papaya	Chitosan	[64]
Papaya	Alginate	[65]
Pear	Alginate	[66]
Pear	Hydroxypropyl methylcellulose	[67]
Plum	Hydroxypropyl methylcellulose	[68]
Strawberries	Chitosan	[32]

In most cases, some additives are added to the coating formulation to help the preservation of the quality of fresh-cut produce [1, 44] and, in particular, the functionality of edible coatings can be expanded by incorporating antimicrobial compounds [69, 70]. More specifically, the effectiveness against several microorganisms of different antimicrobial substances such as lysozyme, nisin, organic acids, essential oils (and their derivatives) was demonstrated to be satisfactory for ensuring both quality and safety [69, 70, 71, 72, 73]. To guarantee shelf life and safety of fresh-cut melon, the effectiveness of malic acid and essential oils (EOs) of cinnamon, palmarosa and lemongrass incorporated into an alginate-based edible coating was investigated by Raybaudi-Massilia *et al.* [74]. In this study melon pieces (50 g) were coated before to be packed in air filled polypropylene trays and stored at 5 °C. Melon pieces were inoculated with a *Salmonella* Enteritidis (10^8 CFU/mL) culture before applying the coatings to safety study. The edible coating acting alone was yet effective to improve shelf life of fresh-cut melon from microbiological (up to 9.6 days) and physicochemical (more than 14 days) points of view in comparison with non coated fresh-cut melon, where microbiological and physicochemical shelf life was up to 3.6 days and lower than 14 days, respectively. Moreover, in same cases the incorporation of EOs prolonged the microbiological shelf life by more than 21 days, due probably to an enhanced antimicrobial effect of malic acid *plus* EOs. Significant reductions ($p<0.05$) of *Salmonella* Enteritidis population were achieved, depending on the EOs or the active compound and their concentrations. According to these authors, palmarosa oil incorporated at 0.3% into the coating appears to be a promising preservation alternative for fresh-cut melon, since it maintained the fruit quality parameters, inhibited the native flora growth and reduced significantly the pathogen population. A similar reduction of *Salmonella* cell load was also attained by Ukuku and Fett [75]: these authors measured a 1.4 Log CFU/g reduction of *Salmonella* in fresh-cut melon treated with 50 µg/mL of nisin, 2% sodium lactate and 0.02% potassium sorbate. On the other hand, a higher reduction of *Salmonella* was found by Eswaranandam *et al.* [71] when evaluated the antimicrobial activity of citric, lactic, malic or tartaric acids and nisin-incorporated soy protein film against *Salmonella* Gaminara, reporting that only the incorporation of malic acid onto the soy protein film resulted in a reduction of 6 log cycles of *Salmonella* population.

3.4 Modified Atmosphere Packaging

MAP is one of the most important techniques used to achieve safety in fresh-cut fruits and/or to prolong their shelf life, even if other alternative approaches (UV, blanching, infrared radiation, irradiation and high pressures) are gaining increasing use.

Fresh fruit continues to respire, consuming oxygen and producing carbon dioxide and water vapour. Owing to the great variability of fruit in terms of composition, constituents, natural microflora, pH, texture and colour it is impossible to define an univocal mixture of gases; thus for each type of fruit the appropriate MAP must be studied, taking into account the risk of pathogen growth. Very successful applications of MAP are reported for fresh-cut pineapple [76, 77], apples [78], kiwifruit [79], honeydew [80], bananas [81] and mangoes [82]. In general, low levels of O_2 and high levels of CO_2 were employed to reduce the produce respiration rate, with the consequence of prolonging shelf life. Atmospheres with low O_2 levels inhibit the growth of most aerobic spoilage microorganisms while the growth of pathogens, especially the anaerobic psychrotrophic, nonproteolytic clostridia, may be allowed or even stimulated. Very low O_2 atmospheres may instead trigger anaerobic metabolism in fresh-cut fruit and result in an increase in fermentation [11]. On the other hand, high CO_2 concentrations inhibit several enzymes of the Krebs' cycle [21]. However, exposure to O_2 or CO_2 levels outside the limits of tolerance may lead to anaerobic respiration with the production of undesirable metabolites and other physiological disorders [83].

It is known that beneficial modified atmospheres within fresh-cut fruit packages are attained by correctly choosing packaging materials that will provide the appropriate levels of oxygen and carbon dioxide into packets [33]. In fact, there are a wide variety of polymers and gas mixtures available for packaging fresh-cut produce that should be optimize for each commodity. Fresh-cut Conference pears packaged under different modified atmosphere conditions and stored in refrigeration were evaluated by Soliva-Fortuny and Martin-Belloso [21] who found that the use of plastic bags of a permeability of 15 cm^3 $O_2/m^2/bar/24$ h and initial atmospheres of 0 kPa O_2 extended their microbiological shelf life for at least 3 weeks of storage. Marrero and Kader [76] reported on post-cutting life of fresh-cut 'Smooth Cayenne' pineapple pieces from 4 days at 10 °C to over two weeks at 0 °C under 10% CO_2 combined with a maximum of 8% O_2, while González-Aguilar *et al.* [84] reported 14 days at 10 °C for the same cultivar under 2–5% CO_2 and 12–15% O_2. Fresh-cut cantaloupe cubes placed in film sealed containers, when flushed with 4 kPa O_2 + 10 kPa CO_2, maintained better their saleable quality at 5 °C (assuming that the pressure inside vessels was ca. 1 atm, we could try to convert these quantities into percentages; therefore, 4 kPa O_2 + 10 kPa CO_2 could be 4% and 10%, respectively) [85]. The changes in sensory quality and proliferation of spoilage microorganisms on lightly processed and packaged cactus pear fruit were investigated as a function of storage temperature and MAP (65% N2, 30% CO2, 5% O2) by Corbo *et al.* [86]: it was found that cactus pear fruit packed under modified atmosphere had longer shelf life at 4 °C. Fresh-cut Amarillo melon had quality improved when was stored under passive MAP for 14 days at 5 °C using three commercial films [87]. In 2008 Saxena *et al.* [88] investigated the effect of different MAP for extending the shelf life of fresh-cut jackfruit (*Artocarpus heterophyllus L.*) kept under low temperature conditions. A MAP consisting in 3 kPa O_2 + 5 kPa CO_2 (with balance of N_2) was flushed into polyethylene (PE) bags. Prior to MAP, fresh-cut jackfruits were given a post-cutting phytosanitation wash followed by a dip pre-treatment with calcium chloride, ascorbic acid and sodium benzoate under mild acidified conditions. The data highlighted the efficacy of pre-treatments in interaction with MAP in restricting the microbial load. In particular, the samples pre-treated with a combination of $CaCl_2$,(1% w/v), ascorbic acid (0.02% w/v), citric acid (1% w/v) and sodium benzoate (0.045% w/v) showed higher shelf life compared to the samples treated only with $CaCl_2$ (1% w/v) and ascorbic acid (0.02% w/v). As expected, the MAP conditions were helpful in reducing microbial counts.

Other works have studied the effect of MAP conditions on the microbial safety of fresh-cut fruits. Larson and Johnson [89] reported the presence of *Cl. botulinum* toxin in fresh-cut cantaloupe and honeydew melons after 9 days storage at 15 °C under a passively modified atmosphere, whereas botulinal toxin was not detected in samples incubated at 7 °C. Sinigaglia *et al.* [90] studied the effects of MAP (65% N_2, 30% CO_2, 5 O_2%) on the growth of *L. monocytogenes* inoculated (low inoculum: 10^2 CFU/g and high inoculum: 10^5 CFU/g) in coconut pieces stored under different temperatures. Coconut (the white nut-meat) is characterized by low acidity (about pH 6.0) and in this study it has confirmed as a good substrate for *L. monocytogenes* growth, thus underlining the capability of serious pathogens to well proliferate on fresh-cut produce with high pH value. Similar results were obtained by Corbo *et al.* [91] who followed the behaviour of *L. monocytogenes* and *E. coli* O157:H7, deliberately inoculated (10^5 CFU/g) on fresh-cut cactus-pear fruits before packaging under modified atmosphere (65% N_2, 30% CO_2, 5 O_2%) and stored at four different temperatures (4, 8, 12 and 20 °C). *L. monocytogenes* was able to proliferate during storage in all experimental conditions, whereas *E. coli* O157:H7 was able to grow at 4 and 8 °C, even under modified atmospheres, being completely suppressed at the higher temperatures.

It is clear that the atmosphere concentrations recommended for preservation depend on the fruit considered, but fortunately good overviews about the use of this approach to extend shelf life of different fresh-cut fruits are provided in literature [33].

3.5 Physical treatments

Recently, many studies have demonstrated the effectiveness of surface decontamination techniques to reduce the microbial risk involved with the consumption of fresh fruit [92, 93]. Non-ionizing, artificial ultraviolet-C (UV-C) radiation is extensively used in a broad range of antimicrobial applications including disinfection of water, air, food preparation surfaces, food containers [94] and surface disinfection of vegetable commodities [95]. Treatment with ultraviolet energy could offer several advantages to fresh-cut fruit processors as it does not leave any residue, and does not have legal restrictions, it is easy to use and lethal to a wide broad of microorganisms, and does not require high economic investment and expensive safety equipment to be implemented [96]. UV is a non-ionizing radiation with wavelengths from 100 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). UV-C irradiation has its maximum at 254 nm and is, of the three, the one with the highest germicidal action, and the most used for surface decontamination and control of microorganism growth in whole and fresh-cut products [97]. UV acts as an antimicrobial agent directly due to DNA damage and indirectly due to the induction of resistance mechanisms against pathogens [29]. In addition, exposure to UV also induces the synthesis of health-promoting compounds such as anthocyanins and stilbenoids [98]. Several studies have been already published on UV-C as a method to preserve the quality of different fruits [99, 100]. For example, deterioration of sliced ‘‘Tommy Atkins’’ mangoes was reduced by UV-C irradiation during storage at 5 °C [99]. UV-C treatments induced a stress that simulates the production of phenylalanine ammonia-lyase (PAL), an enzyme that plays a key role in the synthesis of phytoalexins, phenolic compounds that improve the resistance of fruits to microorganisms [101, 102]. The activation of the secondary metabolism of fresh products enhances the synthesis of phytochemicals with nutraceutical activity [103, 104]. Artés-Hernández *et al.* [105] evaluated the effects of four pre-packaging UV-C illumination doses (1.6, 2.8, 4.8 and 7.2 kJm^{-2}) on quality changes of watermelon cubes stored up to 11 days at 5 °C . Higher UV-C doses induced slightly higher CO_2 production throughout the storage period, while no changes in C_2H_4 production were monitored. UV-C decreased microbial counts just after illumination: after 11 days at 5 °C, mesophilic, psychrophilic and enterobacteria populations were significantly lower in UV-C treated watermelon. As a main conclusion, UV-C radiation can be considered a promising tool for keeping overall quality of fresh-cut fruits. Combination of UV-C pre-treatment with high CO_2 MAP deserves attention since it can extend reduction of microbial growth in several fresh-cut commodities [106].

As a decontaminant treatment, the use of blanching in the minimally processed products industries is also suggested: this operation consists in heating at high temperature, generally in water at 85-100 °C or with steam, less frequently with microwaves, radiofrequency or infrared radiation [107]. This treatment is able to reduce initial bacterial counts, but unfortunately it itself introduces deleterious changes in the product by the loss of nutrients through thermal degradation, diffusion and leaching, and alteration of texture and colour [30]. Heat-shock is a method which usually implies a washing step at a temperature ranging 45-70 °C for a few minutes, usually less than 5 min [30]. Also this treatment appears to be very useful as a quality preservation agent for fresh-cut produce by preventing quality deterioration and helping to maintain texture and colour qualities longer [35, 108].

Irradiation was approved by the FDA for use on fruit and vegetables at a maximum level of 1.0 kGy [109]. In some instances, the produce quality is extended while in others it results in a loss of quality attributes [30]. Microbiological studies carried out in Cantaloupes [110] showed that samples irradiated had a lower and more stable rate of respiration than non-irradiated samples over about 20 days with total plate counts significantly higher in non-irradiated control samples through storage.

Finally, high pressures in the range 3000-8000 bars were recently suggested to be applied on some foods in order to inactivate microorganisms and enzymes without the degradation in flavour and nutrients associated with traditional thermal processing [111]. Unfortunately there are some problems associated with the use of this treatment on fresh-cut products, as it affects the integrity of porous ones as a consequence of the compression and expansion during pressurization and decompression of the air confined in the food matrix [111].

4. Concluding remarks

Most of the preservation techniques reviewed in this chapter have not yet been adopted by the fresh-cut industry. However, judging from the available literature, it could be concluded that there are many and very different technologies that can be presently used to reduce loss of quality and increase safety of fresh-cut fruits, but any of them has the final solution to control all the parameters that maintain the quality and shelf life of minimally processed products. It would be expected that combinations of methods, would have additive, synergistic or antagonistic interactions.

According to this, the hurdle technology looks to the combination of different techniques as a preservation strategy: the intelligent selection of hurdles in terms of the number required, the intensity of each and the sequence of applications to achieve a specified outcome are expected to have significant potential for the future of fresh-cut produce.

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