New approaches in improving the shelf life of minimally processed fruit and vegetables

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The aim of this review article is to describe an integrated approach to modern minimal processing of fresh produce. Current know-how on all of the steps involved in minimal processing of fresh produce from raw materials to packaged products is introduced. Shelf life and quality aspects of minimally processed produce are also presented.

For reasons of expense, labour and hygiene, the catering industry aims to purchase vegetables and fruit that are already peeled and possibly also sliced, grated or shredded, that is, minimally processed. Consumers are increasingly demanding convenient, ready-to-use and ready-to-eat fruit and vegetables with a fresh-like quality, and containing only natural ingredients[1]. In Europe, particularly in France but also in the UK, the market for minimally processed fruit and vegetables grew explosively at the start of the 1990s (Ref. 2). In the USA, it is believed that the market share of fresh-cut produce will account for 25% of all produce sales in the US retail market by the year 2000 (Ref. 3).

With regard to the rationalization of production and the utilization of peeling waste, it is reasonable to aim for centralized peeling and minimal processing of fruit and vegetables. Minimal processing of raw fruit and vegetables has two purposes. First, it is important to keep the produce fresh, yet supply it in a convenient form without losing its nutritional quality. Second, the product should have a shelf life sufficient to make its distribution feasible to its intended consumers[4]. In an ideal case, minimal processing can be seen as 'invisible' processing. The microbiological, sensory and nutritional shelf life of minimally processed vegetables or fruit should be at least 4–7 d, but preferably even longer, up to 21 d depending on the market; the loss of ascorbic acid and carotenes is the main limiting factor of nutritional quality[5,6].

The aim of this article is to present the quality and safety aspects of minimally processed fruit and vegetables, and to describe an integrated approach to the modern minimal processing of produce. Up-to-date know-how on all of the steps of the food chain, beginning with raw materials, through processing methods and ending with packaging factors, that affect the quality and shelf life of minimally processed fresh prepared fruit and vegetables will be introduced (Box 1). Some factors may seem self-evident, but it is important to remember that the minimal processing of vegetables is often practised by small family businesses, where the importance of hygiene may not always be sufficiently recognized.

Reasons for quality changes in minimally processed produce

As a result of peeling, grating and shredding, produce will change from a relatively stable product with a shelf life of several weeks or months to a perishable one that has only a very short shelf life, even as short as 1–3 d at chill temperatures.

Minimally processed produce deteriorates because of physiological ageing, biochemical changes and microbial spoilage, which may result in degradation of the colour, texture and flavour of the produce[7,8]. During peeling and grating operations, many cells are ruptured, and intracellular products such as oxidizing enzymes are liberated.

Physiological and biochemical changes

The most important enzyme with regard to minimally processed fruit and vegetables is polyphenol oxidase, which causes browning[5,7]. Enzymatic browning requires the presence of four different components: oxygen, an oxidizing enzyme, copper and a suitable substrate. To prevent browning, at least one of these components must be removed from the system. Another important enzyme is lipooxidase, which catalyzes peroxidation

Box 1. The key requirements in the minimal processing of fruit and vegetables

- Good quality raw materials (correct cultivar variety, correct cultivation, harvesting and storage conditions)
- Strict hygiene and good manufacturing practices, use of hazard analysis and critical control point principles
- Low temperatures during processing
- Careful cleaning and/or washing before and after peeling
- Good quality water (sensory, microbiology, pH) for washing
- Use of mild additives in washing water for disinfection or the prevention of browning
- Gentle spin drying following washing
- Gentle peeling
- Gentle cutting, slicing and/or shredding
- Correct packaging materials and packaging methods
- Correct temperature and humidity during distribution and retailing

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Table 1. Effect of unit operations of commercial processing lines on aerobic microbial plate counts from various vegetables[a]

Unit operation	Vegetable	APC × 10^4/g Before	APC × 10^4/g After
Shredder	Cabbage	2.0	78
	Lettuce	1.8	140
Slicer	Onion	0.4	12
Peeler	Carrot	610	3.6
Centrifuge	Shredded cabbage	63	68
Stick cutter (4 in)	Peeled carrot	65	59
Water bath	Spinach	160	78
Chlorinated ice water	Carrot sticks	64	57
	Shredded cabbage (red)	96	110
	Shredded lettuce	14	0.25
Conveyor belt	Shredded cabbage	78	63
	Cauliflower floret	8.0	5.2

[a] Data taken from Ref. 11 (by N. Garg *et al.* of the Department of Food Science and Technology, Cornell University, New York State Agricultural Experiment Station, Geneva, NY 14456, USA; reprinted with permission from *Journal of Food Protection*. Copyright held by the International Association of Milk, Food and Environmental Sanitarians, Inc.); no mention is made about whether the vegetables were pre-washed before the unit operation was carried out
APC, Aerobic plate count, in colony-forming units

reactions, causing the formation of numerous bad-smelling aldehydes and ketones[7].

Ethylene production can also increase following minimal processing, and because ethylene contributes to the biosynthesis of enzymes involved in fruit maturation, it may be partially responsible for bringing about physiological changes in sliced fruit, such as softening[7].

Furthermore, the respiration activity of minimally processed produce will increase 1.2–7.0-fold, or even more, depending on the produce, cutting grade and temperature[7,9]. If packaging conditions are anaerobic, this leads to anaerobic respiration and thus the formation of ethanol, ketones and aldehydes[10].

Microbiological changes

During peeling, cutting and shredding, the surface of produce is exposed to air and to possible contamination with bacteria, yeasts and moulds. According to Garg *et al.*[11], major sources of in-plant contamination are the shredders used to prepare chopped lettuce and also cabbage for coleslaw (Table 1). In particular, in the case of minimally processed vegetables, most of which fall into the low-acid category (pH 5.8–6.0), the high humidity and the large number of cut surfaces can provide ideal conditions for the growth of microorganisms[12].

The bacterial populations found on fruit and vegetables vary widely. The predominant microflora of fresh leafy vegetables are *Pseudomonas* and *Erwinia* spp., with an initial count of approximately 10^5 colony-forming units (cfu) per g, although low numbers of moulds and yeasts are also present[7,12]. During cold storage of minimally processed leafy vegetables, pectinolytic strains of *Pseudomonas* are responsible for bacterial soft rot[7,12]. An increase in the storage temperature and the carbon dioxide concentration in the package will shift the composition of the microflora such that lactic acid bacteria tend to predominate[11,13–18].

Microbial counts of commercial minimally processed products have also been studied in Italy[13,18,19] and in the USA[11]. Even the initial total counts of various bacteria were high in vegetables for soup packed in modified atmospheres, approximately 10^8 cfu/g, 5.6×10^6 cfu/g, 1.5×10^7 cfu/g and 10^6 cfu/g for aerobic bacteria, coliforms, *Pseudomonas* spp. and lactic acid bacteria, respectively[18]. Manzano *et al.*[18] concluded that the high level of initial microbial flora of vegetables for soup was probably due to the machinery, the environment, as well as human and natural contamination. Marchetti *et al.*[13] also found high initial counts for psychrotrophic bacteria and total mesophilic bacteria, exceeding even 10^8 cfu/g, in various commercial vegetable salads. Mixed salads and carrots were on average found to be more contaminated than either red or green chicory. These authors also found surprisingly high initial counts for *Aeromonas hydrophila*, even as high as 10^6 cfu/g. Furthermore, *A. hydrophila*, a species frequently associated with human disease, can grow well in ready-to-eat salads.

The high initial load of microorganisms makes it difficult to establish the cell-number threshold beyond which a product can be considered spoiled. Many studies show that a simple correlation does not exist between spoilage chemical markers, such as pH, lactic acid, acetic acid and carbon dioxide levels and sensory quality, and the total microbial cell load[13,16–18]. In fact, different minimally processed fruit and vegetable products seem to have different spoilage patterns, which vary according to the characteristics of the raw materials[4,13].

Safety aspects of minimally processed produce

Because minimally processed fruit and vegetables are not heat treated, regardless of the use of additives or packaging, they must be handled and stored at refrigeration temperatures, at ≤5°C to achieve a sufficient shelf life and ensure microbiological safety. Basic food science books as well as research carried out on minimally processed produce demonstrate the importance of low temperature[14]. For example, temperature has a greater

Table 2. Requirements for the commercial manufacture of pre-peeled and/or sliced, grated or shredded fruit and vegetables[a]

Working principle	Demands for processing	Customers	Shelf life at 5°C (days)	Examples of suitable fruit and vegetables
Preparation today, consumption tomorrow	• Standard kitchen hygiene and tools • No heavy washing for peeled and shredded produce; potato is an exception • Packages can be returnable containers	Catering industry, restaurants, schools, industry	1–2	Most fruit and vegetables
Preparation today, the customer uses the product within 3–4 d	• Disinfection • Washing of peeled and shredded produce at least with water • Permeable packages; potato is an exception	Catering industry, restaurants, schools, industry	3–5	Carrot, cabbages, iceberg lettuce, potato, beetroot, acid fruit, berries
Products are also intended for retailing	• Good disinfection • Chlorine or acid washing for peeled and shredded produce • Permeable packages; potato is an exception • Additives	Retail shops, in addition to the customers listed above	5–7[b]	Carrot, Chinese cabbage, red cabbage, potato, beetroot, acid fruit, berries

[a] Data taken from Ref. 6
[b] If longer shelf life, up to 14 d is required, the storage temperature must be 1–2°C

effect on respiration activity than other factors such as slicing grade[9]. However, some pathogens such as *Listeria monocytogenes*, *Yersinia enterocolitica*, *Salmonella* spp. and *A. hydrophila* may still survive and even proliferate at low temperatures[14,20]. On the other hand, Brackett[14] regards minimally processed fruit and vegetables to be relatively safe when compared with other foods, especially fruit products as they are generally acidic enough to prevent the growth of pathogens. Usually, those spoilage microorganisms that are present in refrigerated produce are psychrotrophic and, therefore, have a competitive advantage over most pathogens. However, systematic studies on the microbiological safety of refrigerated minimally processed fruit and vegetables are still needed. Furthermore, it is self-evident that correct hygiene including the application of HACCP (hazard analysis and critical control point) principles and good manufacturing practices is of utmost importance to prevent the risk of microbiological contamination[4–6,17,21].

Nutritional changes

A recently published book, edited by Wiley[5], clearly shows that most studies on fresh and minimally processed fruit and vegetables have been concerned with market quality as determined objectively and subjectively by colour, flavour and texture measurements as well as by microbiological determinations. Little is known about the nutritive value, that is, the vitamin, sugar, amino acid, fat and fibre contents of minimally processed produce[5]. However, some data on the effects of washing on the vitamin content of minimally processed produce are given in the chapter entitled 'Cleaning, washing and drying'. It is clear that more research is needed with regard to the nutritional quality of minimally processed fruit and vegetables.

Methods to improve the shelf life and safety of minimally processed produce

Minimally processed vegetables can be manufactured on the bases of several different working principles (Table 2)[6]. If the principle is that products are prepared today and consumed tomorrow, then very simple processing methods can be used. Most fruit and vegetables are suitable for this type of preparation. Such products are suitable for catering, but not for retailing, purposes. The greatest advantage of this principle is the low requirement for investment.

If products are required to have a shelf life of several days up to one week, or even more in the case of products intended for retailing, then more advanced processing methods and treatments using the hurdle concept[5,6,22] are needed, as well as the correct choice of raw materials that are suitable for minimal processing. Preservation is based on a combination of several treatments. As the table shows, not all produce is suitable for this type of preparation.

Raw materials

No-one has published systematic studies on the matching of raw materials and processing requirements in the minimal processing of fruit and vegetables[5]. However, it is self-evident that vegetables or fruit intended for pre-peeling and cutting must be easily washable and peelable, and their quality must be first class. Correct and proper storage of vegetables and careful trimming before processing are vital for the production of prepared vegetables of good quality[5,6,8].

The Ministry of Agriculture and Forestry in Finland financed a project during 1991–1994 (part of an EU COST 94 Action on 'Post-harvest Treatment of Fruit and Vegetables'), which included a preliminary study of the suitability of various cultivar varieties of eight different vegetables to minimal processing[6]. The results revealed that not all varieties of a particular vegetable can be used to manufacture prepared vegetables. The correct choice of variety is particularly important in the case of carrot, potato, rutabaga and onion. For example, carrot and rutabaga varieties that give the most juicy grated product cannot be used in the production of grated products that need to have a shelf life of several days, whereas poor colour and flavour become problems if the variety of potato is wrong[23]. Furthermore, the results showed that climatic conditions, soil conditions, agricultural practices, including the use of fertilizers and the harvesting conditions, can also significantly affect the 'behaviour' of vegetables, particularly that of potatoes, during minimal processing. These aspects of minimal processing should be studied further.

It is probable that in the future, fruit and vegetables intended for minimal processing will be cultivated under specified controlled conditions, and furthermore that plant geneticists will select and create cultivars or hybrids that are adapted to the specific requirements of minimal processing[7,24].

Peeling, cutting and shredding

Some vegetables or fruit, such as potatoes, carrots or apples, require peeling. Several peeling methods are available; however, on an industrial scale, peeling is normally accomplished mechanically (e.g. using rotating carborundum drums), chemically or in high-pressure steam peelers[5]. However, the results from two research projects, one just completed in Finland at VTT[6] and another in progress in Ireland[25], have demonstrated that peeling should be as gentle as possible. The ideal method is hand peeling using a sharp knife. O'Beirne[25] found that the hand peeling of carrots increased the respiration rate over that of unpeeled carrots by approximately 15%, whereas abrasion peeling (both fine and coarse) of new season Irish carrots almost doubled the respiration rates compared with the rate for hand-peeled carrots. In the case of stored carrots, the respiration rates recorded for coarse abrasion-peeled carrots were almost threefold higher than those recorded for hand-peeled carrots. Coarse and fine abrasion peeling increased the rate of microbial growth over that of hand peeling. From the point of view of sensory quality, hand-peeled carrots were somewhat better than abrasion-peeled carrots.

The project at VTT showed that the browning of potatoes peeled with carborundum was much greater than that of hand-peeled potatoes[6]. Carborundum-peeled potatoes must be treated with a browning inhibitor, whereas washing in water is enough for hand-peeled potatoes. So, if mechanical peeling is used, it should ideally resemble knife peeling. Carborundum, steam peeling or caustic acid disturb the cell walls of a vegetable, enhancing the possibility of microbial growth and enzymatic changes.

Many studies confirm that cutting and shredding must be performed with knives or blades that are as sharp as possible, these being made from stainless steel. Ohta and Sugawara[26] found that sharp blade slicing or rotary cutting of lettuce were both superior to either dull blade slicing or chopping. O'Beirne[25] has obtained similar results with carrot discs. Carrots cut with a razor blade were more acceptable from both a microbiological and a sensory point of view than carrots cut using various commercial slicing machines. It is clear that slicing with dull knives impairs the retention of quality because it ruptures cells and releases tissue fluid to a great extent. Mats and blades that are used in slicing operations can be disinfected, for example, with a 1% hypochlorite solution. A slicing machine must be installed securely, because vibrating equipment may impair the quality of sliced surfaces.

Cleaning, washing and drying

It is clear that if incoming vegetables or fruit are covered with soil, mud or sand, they should be carefully cleaned before processing. Usually, a second washing step must be performed after peeling and/or cutting[5,6]. For example, Chinese cabbage and white cabbage must be washed after shredding; however, carrot must be washed before grating[16,17]. Washing after peeling and/or cutting removes microorganisms and tissue fluid, thus reducing microbial growth and enzymatic oxidation during subsequent storage. Washing the produce in flowing or air-bubbling water is preferable to simply dipping it in water[26]. Both the microbiological and the sensory quality of the washing water must be good and its temperature low, preferably <5°C. The recommended quantity of water that should be used is 5–10 l/kg of product before peeling and/or cutting[4] and 3 l/kg after peeling and/or cutting[16,17].

Preservatives can be used in the washing water to reduce microbial numbers and retard enzymatic activity, thereby improving both the shelf life and sensory quality of the product. Wiley[5] has presented an excellent overview of possible preservatives for use in the minimal processing of fruit and vegetables. However, only some of them are currently used in commercial lines, and information about the effectiveness of the others is lacking. Furthermore, the use of some of them such as chlorine compounds is not necessarily allowed in all countries.

According to several researchers, 100–200 mg of chlorine or citric acid per litre is effective in the washing water before or after peeling and/or cutting to extend shelf life[5,8,16,17,25]. However, when chlorine is used, vegetable material should subsequently be rinsed to reduce the chlorine concentration to that found in drinking water and to improve the sensory shelf life[16]. The effectiveness of chlorine can be enhanced by using a

Table 3. The effects of various washing methods and storage times on the α-carotene and β-carotene content of air-packed grated carrot[a]

	α-Carotene (mg/100 g fresh weight)			β-Carotene (mg/100 g fresh weight)		
Sample and washing method[b]	**2 days**	**4 days**	**8 days**	**2 days**	**4 days**	**8 days**
Fresh grated carrot						
No washing	2.0			8.1		
Stored grated carrot						
No washing	2.0	2.2	1.8	7.0	7.6	5.9
Washing with normal tap water; +6°C, 1 min	1.8	2.0	1.6	6.6	7.2	5.4
Washing with normal tap water containing 100 mg/l active chlorine; +6°C, 1 min	2.0	2.1	1.9	7.1	7.2	6.4
Washing with normal tap water containing 0.5% citric acid; +6°C, 1 min	2.0	2.0	1.6	6.9	7.0	5.0
Washing with normal tap water containing 100 mg/l active chlorine; +30°C, 1 min; and with normal tap water; +6°C, 1 min	1.9	2.0	1.5	6.7	6.7	4.9

[a] Data taken from Ref. 27; the results are the mean values from four parallel samples
[b] Whole pre-washed and pre-peeled carrots (cv. *Navarre*) were washed. The amount of washing liquid was 3 l water/1 kg carrot. After washing, carrots were grated into 3-mm strips, and packed in heat-sealed 40 μm oriented polypropylene film, 1 kg of grated carrot per bag

low pH, high temperature, pure water and correct contact time[5,8]. According to Kabir[8], the optimum contact time is 12–13 s, if the chlorine concentration is 70 mg/l.

Data on the effectiveness of chlorine compounds on the microorganisms found on fresh fruit and vegetables are contradictory, even though chlorine compounds are quite effective for inactivating microorganisms in solutions and on equipment[8,11,14]. It seems that chlorine compounds reduce the counts of aerobic microorganisms at least in some leafy vegetables such as lettuce[5,11], but not necessarily in root vegetables or cabbages (Table 1)[11,17]. However, Torriani and Massa[19] found that washing sliced carrots in chlorinated water (20 mg free chlorine per litre) resulted in a significant reduction of the coliforms, whereas the number of aerobic bacteria was not affected.

However, careful washing with water containing 100 mg chlorine per litre and subsequent rinsing improved the sensory shelf life of minimally processed vegetables by several days, up to 7–8 d (Refs 16, 17). Even the sensory shelf life of grated carrot improves markedly if whole carrots are washed in a citric acid or chlorine solution after peeling[17]. Washing does not decrease the vitamin content (vitamin C and carotenes) of grated carrot, shredded Chinese cabbage or peeled potatoes significantly; the main reducing factor is storage time, as Table 3 shows for grated carrots[27].

It is recommended that the washing water is removed gently from the product[5]. Centrifugation seems to be the best method. However, the centrifugation time and rate should be chosen carefully[21,28]. Ohta and Sugawara[26] obtained the best shelf life for shredded lettuce by drying it in basket-type centrifuge (basket diameter 52 cm, at 1000 rpm) for 30 s.

Browning inhibition

In the case of fruit and vegetables, such as pre-peeled and sliced apple and potato, for which the main quality problem is browning, which causes a particularly poor appearance, washing with water is not effective enough to prevent discoloration[5,23]. Traditionally, sulphites have been used to prevent browning; however, their use has some disadvantages. In particular, they can cause dangerous side effects for people with asthma. For this reason, the US Food and Drug Administration (FDA) partly restricted the use of sulphites in the spring of 1990 (Ref. 29), and there is increasing interest in substitutes for sulphites[30].

Citric acid (CA) combined with ascorbic acid (AA), alone or in combination with potassium sorbate in the case of potato (Table 4)[5,23] or 4-hexylresorcinol in the case of apple[31], seem to be promising alternatives for sulphites, particularly when hand peeling is used. Furthermore, Sapers and Miller[32] have obtained promising results by treating pre-peeled (abrasion or high-pressure steam peeled) potatoes with a heated solution of AA and CA. Potatoes were heated for 5–20 min in a solution containing 1% AA and 2% CA at 45–55°C, cooled and then dipped for 5 min in a browning inhibitor solution containing 4% AA, 1% CA and 1% sodium acid pyrophosphate. The combined treatment inhibited potato discoloration for 14 d at 4°C, compared with 3–6 d with the browning inhibitor treatment alone.

The most attractive methods to inhibit browning would be 'natural' ones, such as the combination of particular salad ingredients with each other. Lozano-de-Gonzales *et al.*[33] have obtained promising results with pineapple juice, which appears to be a good potential alternative to sulphites for the prevention of browning

Table 4. The effects of washing time with some browning prevention chemicals[a] and heat treatment[b] on the browning index[c] of pre-peeled sliced potatoes (cv. *Nicola*)[d] left to stand for two hours

Browning prevention treatment	Concentration	No heat treatment		Heat treatment	
		1-min wash	3-min wash	1-min wash	3-min wash
No treatment		145			
Water		13	8	5	3
AA	0.1%	11	9	3	2
AA	0.5%	7	5	2	2
CA	0.1%	5	4	4	2
CA	0.5%	2	1	1	0
AA + CA	0.1% + 0.5%	3	2	3	2
AA + CA	0.3% + 0.5%	3	2	1	0
AA + CA	0.5% + 0.5%	2	1	0	0
AA + CA + $CaCl_2$	0.3% + 0.3% + 0.1%	4	1	1	1
AA + CA + potassium sorbate	0.5% + 0.5% + 0.2%	2	1	1	1
Sodium benzoate	0.5%	2	1	2	1
CA + 4-hexylresorcinol	0.5% + 0.005%	3	2	4	1

[a] Data taken from Ref. 23
[b] Heat treatment: 2 weeks at +15°C
[c] Browning was measured by the so-called browning index, which is based on the sensory evaluation of 20 slices, cut from the middle of 20 different potatoes, by a trained panellist. This method is used in industrial practice. The browning index value should be below 10 for a potato lot to be regarded as suitable for processing. If the browning index is in the range 0–5, browning is not considered to be a problem for a potato lot
[d] Potatoes were winter-stored for 8 months before the experiment
AA, Ascorbic acid; CA, Citric acid

in fresh apple rings. The browning susceptibility of potatoes could also be reduced to some extent by heat treatment (2 weeks at 15°C) before pre-peeling (Table 4). The main reason for this is that the levels of reducing sugars decrease during the heat treatment[23].

Modified-atmosphere packaging

The final, but not the least important, operation in producing minimally processed fruit and vegetables is packaging. The most studied packaging method for prepared raw fruit and vegetables is modified-atmosphere packaging (MAP). Kader *et al.*[34], Powrie and Skura[10], Day[35] and Riquelme *et al.*[20] have presented excellent overviews on the principles and modelling of the MAP of fruit and vegetables, as well as some aspects of the packaging of minimally processed fruit and vegetables. Several chapters in the recent book edited by Wiley[5] cover retail, bulk and transport packaging methods specifically intended for minimally processed fruit and vegetables.

The basic principle in MAP is that a modified atmosphere can be created either passively by using properly permeable packaging materials, or actively by using a specified gas mixture together with permeable packaging materials. The aim of both principles is to create an optimal gas balance inside the package, where the respiration activity of a product is as low as possible, but the levels of oxygen and carbon dioxide are not detrimental to the product. In general, the aim is to have a gas composition of 2–5% CO_2, 2–5% O_2 and the rest nitrogen[34,35].

However, this aim is the most difficult of all the tasks involved in manufacturing raw ready-to-use or ready-to-eat fruit and vegetable products of good quality and with a shelf life of several days. The main problem is that none of the packaging materials that are available on the market is permeable enough[35]. Most films do not result in optimal O_2 and CO_2 atmospheres, especially when the produce has a high level of respiration. However, one solution is to make microholes of a defined size and of a defined number in the material to avoid anaerobis[36]. This procedure significantly improves the shelf life of grated carrots, for example[17]. Other solutions include the combination of ethylene vinyl acetate with oriented polypropylene and low-density polyethylene or the combination of ceramic material with polyethylene. Both of the composite materials have a significantly higher gas permeability than either polyethylene or the oriented polypropylene much used in the packaging of salads; however, gas permeability should be even higher still. Both these materials have good heat-sealing properties, and they are also commercially available[6]. The shelf life of shredded cabbage and grated carrot packed in these composite materials is 7–8 d at 5°C, and therefore 2–3 d longer than in the oriented polypropylene that is generally used in the vegetable industry. Products can be packed in normal air in these composite materials[16,17]. Recently, a new breathable film has been patented, which has a three-layer structure consisting of a two-ply blown co-extrusion approximately 25 μm thick with an outer layer of K-Resin KR10 and an inner metallocene polyethylene layer. It is claimed that fresh salads washed in chlorine solution and packaged in this film have a shelf life of 16 d at 1–2°C (Ref. 37).

A lot of work has been done in different laboratories to attempt to model gas changes occurring inside package atmospheres. The research has been carried out mainly with whole produce[5,34]. Most attempts recognize the interaction of respiration by the packaged product and the diffusion of respiratory gases through the package. It is obvious that no universal model for minimally processed produce (peeled, sliced, grated, shredded) can be created. On the other hand, even if an exact model and gas balance inside the package could be created, it would only be possible to extend the shelf life by a few more days. This is because respiration is not the only cause of quality changes in minimally processed produce: enzyme and microbial activity, as well as, in some cases, ethylene also result in the development of colour problems, off-odours and off-tastes[6].

Moderate-vacuum packaging

One interesting modified-atmosphere packaging method is moderate-vacuum packaging (MVP)[38]. In this system, respiring produce is packed in a rigid, airtight container under 40 kPa of atmospheric pressure and stored at refrigeration temperature (4–7°C). The initial gas composition is that of normal air (21% O_2, 0.04% CO_2 and 78% N_2) but at a reduced partial gas pressure. The lower O_2 content stabilizes the quality of the produce by slowing down metabolic activity and the growth of spoilage microorganisms. Gorris *et al.*[38] found that MVP improved the microbial quality of red bell pepper, chicory (endive), sliced apple and sliced tomato; the sensory quality of apricot and cucumber; and both the microbial and sensory quality of mung-bean sprouts and a mixture of cut vegetables. Gorris *et al.*[38] also conducted pathogen challenge tests with *L. monocytogenes*, *Y. enterocolitica*, *Salmonella typhimurium* and *Bacillus cereus* on mung-bean sprouts at 7°C. All of the pathogens lost viability quickly during storage in MVP.

Heimdal *et al.*[39] applied MVP to flexible 80 μm polyethylene bags (evacuated to a pressure of 46 kPa). They compared the shelf life of shredded iceberg lettuce in MVP with its shelf life in three other packaging systems: (1) 59 μm multi-layer co-extruded film bags containing atmospheric air; (2) 59 μm multi-layer co-extruded film bags containing 80% O_2 and 20% CO_2; and (3) 80 μm polyethylene bags containing 80% O_2 and 20% CO_2. MVP and the third packaging system inhibited enzymatic browning during storage for 10 d at 5°C, whereas the visual quality, in particular, of lettuce was poor in the first packaging system after 3 d. When lettuce was packaged in 80% O_2 and 20% CO_2, browning was greater in the multi-layer film bags than in the polyethylene bags. Storage time in excess of 10 d should, however, be avoided because of increasing off-flavour development in bags despite good visual quality.

Active packaging

Active packaging, that is, packaging that includes various gas absorbents and emitters, is another interesting packaging method for minimally processed fruit and vegetables[35]. Active packaging of this type of product is still in its infancy, and only a few reports are available. However, it appears that it is possible to affect respiration activity, microbial activity and plant hormone activity by correct active packaging. Howard *et al.*[40] have examined the quality changes of diced onions with and without a commercial gas absorbent that is based on potassium permanganate and activated alumina. The gas absorbent removed ethylene effectively, and reduced the levels of sulphur volatiles and CO_2 in the package of diced onions. Howard *et al.*[40] concluded that acceptable-quality diced onions can be kept for 10 d at 2°C using the potassium permanganate gas absorbent.

Edible films and coatings

Another possible 'packaging' method for extending the postharvest storage life of lightly processed fruit and vegetables is the use of edible coatings, that is, thin layers of material that can be eaten by the consumer as part of the whole food product. The idea is not new; edible films were already in use in 12th-century China for citrus fruit. However, once the minimal processing of foods started to gain popularity and it was recognized that packaging should be minimized for environmental reasons, interest in edible coatings increased significantly throughout the world. An extensive book[41] as well as a couple of good reviews[42,43] on edible films and coatings have appeared recently.

At least theoretically, edible coatings have the potential to reduce moisture loss, restrict the entrance of oxygen, lower respiration, retard ethylene production, seal in flavour volatiles, and carry additives that retard discoloration and microbial growth[43]. Baldwin *et al.*[43] describe some patented and commercially available edible film solutions. Those based on sucrose polyesters of fatty acids and the sodium salt of carboxymethylcellulose delayed water loss or browning; those based on cellulose derivatives retarded the discoloration of cut mushrooms, and the development of a physiological disorder of peeled carrots known as white blush. Carrageenan and chitosan coatings are also promising for lightly processed fruit and vegetables, but the FDA has not yet approved carrageenan as a component of coatings, and approval of chitosan as a food additive is still pending in the USA; however, Baldwin *et al.*[43] concluded that approval is considered quite likely.

Future research needs

Much research is still needed to develop minimally processed fruit and vegetable products that have a high sensory quality, microbiological safety and nutritional value. Products intended for retailing are in particular need of further development. It seems that it is possible to achieve a shelf life of 7–8 d at refrigeration temperatures (5°C), but for some markets this is not enough: a shelf life of 2–3 weeks is sometimes necessary. More information about the growth of pathogenic bacteria and the occurrence of nutritional changes in minimally processed fruit and vegetables with long shelf lifes is needed.

A characteristic feature of minimal processing is an integrated approach, where raw materials, handling, processing, packaging and distribution must all be properly considered to make shelf-life extension possible. New cultivars need to be selected and created or hybrids adapted to meet the specific requirements of minimal processing. The equipment used in unit operations, such as peeling and shredding, needs further development so that it can process produce more gently. There is no sense in disturbing the quality of produce by rough treatment during processing, and patching it up afterwards by the use of preservatives.

Hurdle technology that makes use of natural preservatives, such as inhibitors produced by lactic acid bacteria, and the matching of correct processing methods and ingredients to each other are two approaches that should be applied more often to the minimal processing of produce. Active-packaging systems and edible films, as well as more-permeable plastic films that better match the respiration activity of fruit and vegetables need to be further developed. Exama *et al.*[36] have also proposed a safety-valve system, which prevents excessive O_2 depletion and excessive CO_2 accumulation when a transient temperature increase occurs. This type of system might be particularly suitable for bulk and transport packages of fruit and vegetable products.

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Review

MALDI mass spectrometry for food analysis

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Matrix-assisted laser desorption ionization mass spectrometry (MALDI-MS) has developed into an analytical technique that has many advantages for food analysis. MALDI-MS has no theoretical mass limit, can be used to analyze crude extracts that have been prepared using almost any solvent, is rapid, requires only picomole quantities of sample, and can simultaneously quantify analytes of differing masses. Although the major research focus has been on the analysis of large molecules (>20 000 Da), MALDI-MS is also applicable to analytes with intermediate and smaller masses. When instrument costs drop sufficiently, MALDI-MS could become the preferred analytical technique for the analysis of many compounds in foods.

Mass spectrometry (MS) has long been used as a powerful tool to identify and study molecules (further background information on MS can be obtained from the Internet sites listed in Box 1). The first step for any MS method is ionization of the sample molecules in the gas phase. Following ionization to a negatively or positively charged species (most commonly the latter), the molecules or their fragments can be separated and identified on the basis of their mass-to-charge ratio (m/z).

Over the years, many of the advances in MS have involved new ionization techniques. The first widely used technique was electron impact ionization, in which thermally volatile molecules were ionized by using a beam of electrons. The resulting ionized molecules also absorbed a portion of the energy of the original electron, leading to further fragmentation. Although this fragmentation was helpful in determining structural features, parent molecular ions were often small or not present, making identification of the molecule more difficult. In the 1960s, the development of chemical ionization enhanced the versatility of MS. Volatilized molecules were 'soft' ionized by using ionic gases, resulting in considerably less molecular fragmentation. Further developments such as fast atom bombardment and plasma desorption extended the MS mass range into the low kilodalton region. However, with the advent of electrospray ionization and, in the late 1980s, matrix-assisted laser desorption ionization (MALDI)[1–5], the mass barrier was broken, making ionization of molecules with masses of up to several million daltons possible[3]. MALDI could have a major impact on how food analyses are performed in the future, and is the subject of this article.

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