Effect of Minimal Processing on Physiology and Quality of Fresh-Cut Potatoes: a Review

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ABSTRACT

Fresh-cut fruit and vegetable are minimally processed products that have to maintain their quality (appearance, texture, flavour and nutritive value) similar to those of the fresh product. The fundamental principle underlying the quality of these commodities is that they are metabolic active tissues and, as a consequence, show physiological response to preparation procedures as well as to the environment created in the package in which they are enclosed. Minimal processing for fresh-cut potato production includes raw material selection, washing, peeling and cutting, pre-treatments, drying, weighing and packaging. The purpose of this review is to analyse the effects of the different minimal processing steps on the physiology and related quality of fresh-cut potatoes. Particular attention is given to the newest studies on processing innovation and innovative scientific approaches for a better understanding of fresh-cut products as biological systems. In this direction the use of ozone sanitization, natural dipping pre-treatments and/or coatings (e.g. edible film enriched in ascorbic and citric acid), and modified atmosphere packaging at high O2 levels result the most promising and non-invasive techniques for the preservation of fresh-cut potatoes. As far as physiological studies of the product are concerned, fundamental metabolic research for process optimisation and quality assurance is needed. For this aim isothermal calorimetry may provide a versatile tool to conduct fundamental metabolic studies of the effect of different processing steps on the quality and shelf-life of fresh-cut potatoes.

Keywords: cutting, dipping, peeling, shelf-life, wounding response
Abbreviations: AA, ascorbic acid; CA, citric acid; FCFV, fresh-cut fruit and vegetable; LC, l-cysteine; MAP, modified atmosphere packaging; MP, minimal processing; PPO, polyphenol oxidases; ROS, reactive oxygen species

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INTRODUCTION

Fresh-cut fruit and vegetable (FCFV) are minimally processed products that have to maintain their quality (appearance, texture, flavour and nutritive value) similar to those of fresh product (Alzamora et al. 2000). These new products were rapidly known as “fourth range” in commercial terminology ("quatrième gamme" in France, “quarta gamma” in Italy). Fruits and vegetables are fresh in the first range, canned in the second, frozen in the third, and fresh-cut or minimally processed in the fourth (Varoquaux and Mazoli 2002).

The fundamental principle underlying quality of FCFV is that they are metabolic active tissues, and as a consequence, show physiological response to minimal processing (MP) procedures as well as to the environment created in the package in which they are enclosed (Toivonen and DeEll 2002). After MP, a relatively stable agricultural product with a shelf-life of several weeks or months will become a product that has only a very short shelf-life (Ahvenainen 1996). It is worth noting that quality loss of FCFV is mainly due to physiological ageing caused by the
loss of cellular compartmentation in operations such as peeling and cutting, that causes the mixing of enzymes with substrates and an overall increase of metabolic activity (Rolle and Chism 1987).

In this product category, fresh-cut potatoes (Solanum Tuberosum L.) could have a great importance from a commercial point of view, because of their high convenience, even if they are susceptible to a variety of physiological and microbiological phenomena during storage. Because of economic, labour and hygiene considerations, the potato processing industry has seen promise in the idea of purchasing potatoes as fresh-cut product (pre-peeled, fresh-cut or sliced) (Laurila et al. 1998b). MP for the production of fresh-cut potatoes includes selection of the raw material, washing, peeling and cutting, pre-treatments, drying, weighing and packaging. From a biological point of view, industrial treatments for fresh-cut potato production can cause stress to the tuber and therefore, knowledge of how the plant material will be affected in relation to time, environment, and industrial manipulation is of fundamental importance for process optimization and quality assurance (Gómez Galindo et al. 2007). We here focus our attention to review and analyse the effects of the different MP steps on the physiology and related quality of the final product. Particular attention is given to the newest studies on processing innovation and innovative scientific approaches for a better understanding of fresh-cut potatoes as biological systems.

**PRODUCTION OF FRESH-CUT POTATOES**

It is obvious that the quality of the raw material is one of the most important factors determining the quality of fresh-cut potatoes (Varoquaux and Mazollier 2002). The correct choice of cultivar is particularly important. Specifically, the most important criteria in assessing the suitability of potato cultivars to MP are low sensitivity to physiological disorders and microbial diseases, mechanical resistance of the tissue, resistance to elevated CO$_2$ concentration and/or low O$_2$ and/or low respiration rate (Varoquaux et al. 1996; Varoquaux and Mazollier 2002).

Potatoes suitable for MP have to satisfy some quality requirements according to its destination with specific chemical (dry matter, reducing sugars and starch content), morphological (shape and size) and organoleptic (texture, taste, flavour, colour) characteristics. In particular raw tubers for industry should have no defects, regularity in shape, good organoleptic properties, low susceptibility to darkening and suitability for long-term storage. The suitability of potatoes for MP is strictly related to their susceptibility to browning phenomena that can appear during processing, storage, commercialization periods and cooking at home. It has to be kept in mind that if the home-processing destination of the fresh-cut potato products is frying, the reducing sugars content is a very important aspect. The role of reducing sugars in the colour of fried potatoes has been widely described in the literature (Smith and Davis 1975; Mazza 1983; Fuller and Hughes 1984; Marquez and Añón 1986; Brown et al. 1990; Pritchard and Adam 1994). A high concentration of reducing sugars disqualifies potatoes from being used for processing because they have an adverse effect on the colour and taste of cooked products. Reducing sugars (mainly glucose and fructose) are involved in the non-enzymatic browning reaction, known as the Maillard reaction (Mackay et al. 1990), occurring between reducing sugars and free amino compounds. Chemical darkening, known as after-cooking darkening, results from a reaction between polyphenols and bivalent iron which, oxidized by atmospheric oxygen to trivalent iron, develop a dark pigment.

Enzymatic browning is the main phenomenon that can compromise the shelf-life of peeled and cut potatoes leading to a decrease in food quality, since it implies spoilage (Limbo and Piergiovanni 2006), deterioration of flavour, colour and nutritional quality (Friedman 1997). Browning becomes evident when food material is subjected to processing or mechanical injury. Geographical origin, growing and storage conditions, ripening stage and cultivar can influence and/or modify the potato capacity for enzymatic browning. The choice of cultivar has been reported to have an effect on the browning potential of prepared potatoes, since different potato cultivars may have different chemical composition (Laurila et al. 1998b). The different susceptibility of a cultivar for browning is closely connected with the dry matter, reducing sugars, phenolic contents and the enzymatic activity of tubers. Among the post-harvest techniques that may affect browning, storage of intact potatoes has been shown to play a very important role (Laurila et al. 1998b). This is an important issue, as the industry commonly store tubers for several months in refrigerated conditions. It should be underlined that specific cultivar characteristics or environmental factors affecting browning on one potato cultivar can not be used to predict the behaviour of other cultivars. The choice of suitable potato cultivars and pre-processing storage conditions is a very important area of research to obtain high quality processed products and avoid the indiscriminate use of anti-browning chemical compounds (Laurila et al. 1998a).

Potatoes are particularly susceptible to mechanical stress. Physically stressed tuber tissue produces melanin-based pigments, leading to the blue-black discoloration of subdermal tissues, known agronomically as black-spot bruising (Johnson et al. 2003). This is a serious agronomic problem manifested during harvesting, handling and storage, leading to significant levels of rejection of raw tubers (Potato Marketing Board 1994). In addition, mechanical stress during handling (caused, e.g. by falls and collisions) induces wounding responses leading to undesirable physiological changes, further reducing quality and storability (Gómez Galindo et al. 2007).

In Fig. 1 a schematic flow-chart of MP for fresh-cut potatoes production is reported.

Harvested potatoes, which are covered with soil, mud and sand, should be carefully pre-washed before processing (Alvenainen 2000). This is an important first step that should avoid cross contamination caused mainly by peeling and cutting operations. A second washing can usually be done after peeling and/or cutting (Alvenainen and Hurme 1994; Wiley 1994). Washing after peeling and cutting removes microbes and tissue fluids, thus reducing microbial growth and enzymatic oxidation during storage. Washing in combination with the flowing of air-bubbling is more preferable than merely dipping into water (Ohta and Sugawara 1987). The recommended quantity of water that should be
used is 5-10 kg\(^{-1}\) of product before peeling and/or cutting and 3-1 kg\(^{-1}\) after peeling and/or cutting (Huxsoll and Bolin 1989). The microbiologic and sensory quality of the washing water used must be good and its temperature low, preferably below 5°C. In general, in order to monitor the quality characteristics of the washing water, its conformity with drinking water requirements must be controlled (e.g. absence of Coliform and Enterobacter, right colour and flavour). (The EU regulation see the Drinking Water Directive 98/83/EC).

Preservatives can be used in the washing water for the reduction of microbial load and to retard enzymatic activity, thereby improving the shelf-life. When the fresh potatoes reach the processing line for MP, they are typically peeled, sliced, diced, or shredded before packaging. These operations cut through cells and leave intact cells of previously internal tissues exposed. In this case, enzymes can also be exposed to oxygen and start to act on the exposed substrates. This oxidation is targeted at reducing the respiration rate of the fresh potato, affecting the physiological status with respect to metabolic changes occurring during MP procedures, including the intrinsic physiology and quality of the raw material, the packaging environment in which the potato tissues are enclosed and post-processing handling and treatments (Gómez Galindo et al. 2004).

Respiration and metabolic consequences of minimal processing

The respiration rate of fresh vegetable slices is, in most cases, 3 to 5 times that of the intact organ, but aging of the sliced tissue elicits an additional increase. Thus, the respiration rate of an aged slice may be 25 times that of the intact organ (Latties 1978). Respiration rate is associated with the product shelf-life, with high rates of respiration being correlated with short shelf-life (Kader 1987; Rolle and Chism 1987). Gunes and Lee (1997) found that at 2°C intact potatoes had a respiration rate of 1.22 mL CO\(_2\) kg\(^{-1}\) h\(^{-1}\), while peeled and sliced potatoes had 2.55 and 6.1 mL CO\(_2\) kg\(^{-1}\) h\(^{-1}\) respectively. Wounding respiration is also hypothesized to be a consequence of elevated ethylene production, although in potato slices ethylene production has been reported to be very low: 1-8 \(\mu\)g kg\(^{-1}\) h\(^{-1}\) at 7.2°C and 2.5% O\(_2\) level (Kader et al. 1989). The basis for the rise in respiration may not always be cut-induced, but rather a result of general enhancement in aerobic respiration. It has been demonstrated that in cut potatoes the rise in respiration after cutting or wounding is at least partially a result of \(\alpha\)-oxidation of long-chain fatty acids (Martin and Stumpf 1959; Latties 1964; Latties et al. 1972). This increase in O\(_2\) consumption associated with \(\alpha\)-oxidation coincides with membrane deterioration processes. In addition, the increase in respiration has also been assumed to be due to mitochondrial respiration and enhancement of mitochondrial respiration. This assumption is supported by the fact that wounding induces mitochondria proliferation as well as structural changes in mitochondrial structure (Asahi 1978).

Fresh-cut potatoes are still metabolically active organisms and produce heat as a result of metabolism. Metabolic activity has been measured using the novel research tool known as thermal calorimetry (for a review on this technique and applications of FCVF, see Gómez Galindo et al. (2005)), which measures the rate of heat production (thermal power), assessing the level of biological activity (Gómez Galindo et al. 2006). Measuring heat is a way of studying a biological system without going into detail; in that way it is similar to spirometry. However, it can provide further information on metabolic pathways and the efficiency of energy utilisation when metabolic heat, O\(_2\) consumption and CO\(_2\) production are measured simultaneously (Criddel et al. 1991a,
One of the aims in MP of fruit and vegetable is the prevention of suberization, together with dehydration following abrasion peeling. This can be visually noticed on fresh-cut potatoes as discolouration results from the action of PPO that act as catalyst in two different reactions: the hydroxylation of monophenols to o-quinones are highly reactive compounds that react non-enzymatically to give rise to brown, black or red pig-

dition and potential penetration by pathogens (Satoh et al. 1991b; Hansen et al. 1997). This technique was first used by Wadsö et al. (2004) to study the heat production of root and tuber tissues in response to wounding. Samples with different surface-to-volume ratios were prepared from potatoes and the total metabolic heat was measured in closed glass ampoules in a TAM Air isothermal calorimeter (Thermometric AB, Järfalla, Sweden). The effect was evaluated by assuming that a certain rate of heat production per volume tissue was associated with normal metabolic activity, and that any excess heat production (per unit surface area) was associated with the wounding response. The results showed that the proportion of heat produced in response to wounding was high; in some cases almost half the heat resulted from the wounding response.

Increase in metabolic activity is the consequence of a large number of biosynthetic events taking place during wound healing (Laties 1978). When plant tissues are wounded, the cells near the site of the wounding stress strengthen their cell walls by the secretion of additional structural components such as lignin or suberin, creating a protective layer immediately below the site of damage, to prevent dehydration, the cells near the site of the wounding stressful event strengthen their cell walls by the secretion of additional structural components such as lignin or suberin, creating a protective layer immediately below the site of damage, to prevent dehydration, and to become impregnated with a poly(phenolic) matrix containing the deposition of a poly(aliphatic) matrix between the plasmalemma and carbohydrate cell wall (Friedman 1997; Bernard et al. 1999; Gómez Galindo et al. 2007). In response to wounding, and in association with suberization, plant tissues generate reactive oxygen species (ROS), including superoxide (O2\textsuperscript{-}), hydrogen peroxide (H2O2), and the hydroxyl radical (OH\textsuperscript{-}). Immediately after wounding, a rapid increase in oxygen uptake is followed by an initial burst of ROS (oxidative burst) (Bolwell et al. 1995). In wounded potatoes, this burst reaches a maximum within 30 to 60 min and it is followed by at least three other massive bursts at 42, 63, and 100 h post-wounding. The initial deposition of suberin in potato requires approximately 18 h at 18°C (Lulai and Corsini 1998) and reaches a stage in which the suberized layer has sufficient structural integrity to be peeled off intact 3 days after wounding (Razem and Bernards 2002; Gómez Galindo et al. 2007).

Suberization, together with dehydration following abrasion peeling can be visually noticed on fresh-cut potatoes as the formation of a white material on their surface. Therefore, suberin deposition may limit the acceptability of the final product because consumers relate the white colour to mould growth (Bolin and Huxsoll 1991; Tatsumi et al. 1991; Cisneros-Zevallos et al. 1995).

**Quality modifications**

Quality of FCFV is a combination of attributes, properties or characteristics that determine their value to the consumer and it includes appearance, texture, flavour and nutritive value. In addition to the quality attributes of the fresh-cut potatoes detectable from the consumer at the time of purchasing and during home preparation and consumption, the relative importance of each quality parameter of this product is strictly bound to its final cooking destiny (e.g. boiling, frying, baking).

**Colour and visual quality**

The radiant energy that is perceived by the human eye by means of the stimulation of the retina gives rise to colour vision (Dorantes-Alvarez and Chirlat 2000). Within the food industry, colour sensory measurement is the most commonly used means of assessing attributes of appearance (Hutchings 2002). Anyway instrumental techniques (such as colorimeters or image analysis) allow accurate and reproducible measurements of the colours not influenced by the observer or surroundings. Conventional colorimeters usually provide readings in XYZ, RGB, and L*a*b* colour spaces (Clydesdale 1978; Mendoza and Aguilera 2004).

The consumer colour perception of foodstuffs is decisive when buying a product. Colour, apart from hedonic connotations, can inform us about many other properties, such as ripeness degree in fruit and vegetable and/or product alterations (Dorantes-Alvarez and Chirlat 2000).

One of the aims in MP of fruit and vegetable is the preservation of the original colour to ensure consumer acceptance. Nevertheless, MP operations promote enzymes and substrates to come into contact, mainly at the surface of the products, bringing about enzymatic reactions related to colour deterioration (Kader 2002).

As discussed in previous sections, enzymatic browning is one of the most limiting factors on the shelf-life of fresh-cut potatoes. Discoloration results from the action of a group of enzymes called polyphenol oxidases (PPO), which have been reported to occur in all plants (Kader 2002). Enzyme-catalysed browning reactions involve the oxidation of phenolic compounds by PPO that act as catalyst in two different reactions: the hydroxylation of monophenols to o-diphenols and the oxidation of o-diphenols to o-quinones. These o-quinones are highly reactive compounds that react non-enzymatically to give rise to brown, black or red pig-

![Fig. 2 Principal component comparison of different potatoes varieties on the bases of dry matter, polyphenols content, PPO (polyphenol oxydases) activity, colour kinetics (L*, luminosity; h°, hue angle) results. Colour modification kinetics have been obtained by linear regression of L*, h° data measured on potato slice surfaces during 24 h of air exposure at 23°C using a tristimulus colorimeter (illuminant D65). (Unpublished data).](image-url)
ments, called melanins, that are responsible for color browning (Tomás-Barberán and Espin 2001; Cantos et al. 2002).

As an example, Fig. 2 shows the results of a study in which 12 different potato varieties were assessed for suitability for industrial fresh-cut manufacture after harvest. In particular, the susceptibility to enzymatic browning was tested on the basis of some related parameters such as: PPO activity, polyphenols content, dry matter and kinetic constants of color parameters (luminosity and hue angle). In this case, color could be considered as an indirect but global assessment of the enzymatic browning phenomena. As shown in Fig. 2, tested potato varieties, differently separated by principal components had different susceptibility to enzymatic browning, confirming the great importance of the choice of potato cultivar in the product quality maintenance during processing and storage.

Texture

Food texture is defined as “all the rheological and structural (geometrical and surface) attributes of a food product perceptible by means of mechanical, tactile and where appropriate visual and auditory receptors” (ISO 1981; Redgwell and Fischer 2002). According to Bourne (1982), texture belongs under the mechanical or rheological subheading of physical properties. From the sensorial point of view, texture can be defined as the sensory manifestation of the kinaesthetic sense in the muscles of the hand, tongue, jaw or lips; tactile feel properties, measured as geometrical particles or moisture properties by the tactile nerves in the surface of the skin of the hand, lips or tongue (Meilgaard et al. 1999).

Tissue softening and associated loss of integrity and leakage of juice from fresh-cut potatoes can be an important cause of poor quality and un-marketability. In some cases, wounding response can cause hardening due to cross-linking of cell wall components and suberin deposition, as discussed earlier. As a consequence of peeling and cutting operations, enzymes responsible for softening (pectinesterase, polygalacturonase and β-galactosidase) come into contact with substrates, causing a faster softening (agar et al. 1999). It has been shown that their function and activity is strongly correlated to the texture of fruits and vegetables (Alzamora et al. 2000).

Water loss is one of the main factors responsible of textural changes of FCFV, because it is directly related to the decrease of turgor pressure (Tolédano and DeEll 2002). Water loss of potatoes is determined by many factors, probably the most important being the resistance of the outer periderm to transpirational movement of water vapour (Ben-Yehoshua 1987). The removal of protective periderm and the reduction of bulk tissues (i.e. increase in surface area to volume ratio) due to peeling and cutting, cause the increase of the water loss from the product. Peeled ‘Majestic’ potatoes have a water loss of 3.3–3.9 mg H₂O cm⁻² mbar wpd⁻¹h⁻¹, while non-peeled, cured potatoes have a moisture loss rate of 0.007 mg H₂O cm⁻² mbar wpd⁻¹h⁻¹ (Ben-Yehoshua 1987). In specific raw material and processing conditions, instead of softening, the hardening promoted by the deposition of suberin may cause detrimental quality characteristics. For example, in the production of pre-peeled potatoes, a common industrial product in Scandinavia, hardening of the tuber surface takes place (Kaack et al. 2002b). These potatoes are too hard for consumption, even after cooking at 98–100°C for one hour. Microscopic examination showed that when hard potatoes are cooked, brick-like cells at the potato surface remain intact. It was demonstrated that potato hardening was significantly correlated to the mechanical impact of the peeler, and was increased by blows during sorting or transport (Kaack et al. 2002a). However, the hardening of potato tissue does not occur if the tubers are steamed or cooked immediately or a few hours after peeling, probably because the exposed intact cells are killed. The understanding of the dynamics and time scales of the metabolic processes taking place in vegetables during industrial unit operations is of great importance in processing design and optimization (Gómez Galindo et al. 2007).

Microbial spoilage

Microbial metabolism of dead or decaying matter is a naturally occurring process in the environment, and is essential for the recycling of nutrients. Microbial metabolism of foodstuffs, however, that leaves them either unfit or unacceptable for human consumption, is commonly termed microbial spoilage (Ellis and Goodacre 2006).

During the last 30 years, increasing per capita consumption of fresh and lightly processed potato products in the United States and other countries has resulted in a growing number of outbreaks of gastroenteritis attributed to contaminated products such as potato salads and other ready-to-eat potato products.

The fact that most of fresh-cut vegetable fall into the low-acid category (pH 5.6 – 6), the high humidity and the large number of cut surfaces, can provide ideal conditions for the growth of microorganisms (Ahvenainen 1996). Therefore, microorganisms are likely to proliferate on the product, but their behaviour may be influenced by plant tissue metabolism and by the modified atmosphere created by the combined effects of product respiration and the permeability of the packaging film (Nguyen-the and Carlin 1994).

The microbiological quality of fresh-cut potatoes is influenced by the natural microflora of the raw material, MP and storage conditions. Due to their close proximity with soil, the exterior of potatoes is normally contaminated with bacteria and fungi. In addition, during peeling, cutting and shredding, the surface of the product is exposed to the air and to contamination with bacteria, yeasts and moulds. In Table 1, the microflora found in fresh-cut potatoes (peeled and cut) in previous investigations are reported (Doan and Davidson 2000). Fuller et al. (1965) isolated 40 different bacteria, yeasts and moulds from samples of processed potatoes. The processing included abrasion peeling, trimming, cutting into french-fry cuts, rinsing in water, immersing in sodium bisulfite (10,000 μg/ml SO₂) for 30 s, draining, and packaging in polyethylene bags before storage at 4 °C. The fact that most of fresh-cut vegetable fall into the low-acid category (pH 5.6 – 6), the high humidity and the large number of cut surfaces, can provide ideal conditions for the growth of Microorganisms (Ahvenainen 1996). Therefore, the hardening of potato tissue does not occur if the tubers are steamed or cooked immediately or a few hours after peeling, probably because the exposed intact cells are killed. The understanding of the dynamics and time scales of the metabolic processes taking place in vegetables during industrial unit operations is of great importance in processing design and optimization (Gómez Galindo et al. 2007).

<table>
<thead>
<tr>
<th>Microflora isolated</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gram-negative rods</td>
<td>Fuller et al. 1965</td>
</tr>
<tr>
<td>Gram-positive rods</td>
<td>Lund 1968</td>
</tr>
<tr>
<td>Gram-positive cocci</td>
<td>Lund 1972</td>
</tr>
<tr>
<td>Yeast</td>
<td>Giuliani and Zaritzky 1990</td>
</tr>
<tr>
<td>Molds</td>
<td>Bryan et al. 1992</td>
</tr>
<tr>
<td>Psychrotrophs</td>
<td>Giuliani and Zaritzky 1993</td>
</tr>
</tbody>
</table>

Table 1 Microflora of fresh-cut potatoes. (modified from Doan and Davidson 2000)
10°C. These investigations did not identify any of the isolated microorganisms but concluded that pectinolytic organisms contributed to softening and exudation and were the primary factors contributing to early spoilage of the commercially processed potatoes. Lund (1968) examined the microflora associated with potatoes that were washed and peeled prior to sulfite treatment. The tubers were stored in various packaging films at 6 and 23°C. Prior to storage of the...
strips stored in a high CO₂ (20%) atmosphere (Tudela 2002a). The accumulation of AA following potato wounding at the cut surface (Nicolas et al. 2002) could prevent melanin formation resulting in less browning.

According to Tudela et al. (2002a), significant differences were observed in the content of flavonols, caffeic acid derivatives and aromatic amino acids in the cooked potato strips when compared to uncooked ones. Each individual flavonol decreased after cooking to half of their initial content. Both individual and total flavonol decreased after cooking to half of their initial contents in all treatments. No significant differences among cooking processes were observed. Both individual and total flavonols were still present in important amounts in the cooked potato strips. The flavonoid loss was significantly pronounced during microwaving and frying. In the case of caffeic acid derivatives, half of their initial content was retained after steam-cooking, whereas only one third of the original value was detected in the case of boiling and frying.

Table 2 Effect of home processing on the loss of ascorbic acid (AA) on the central part of ‘Dejima’, ‘Sumi’, and ‘Chaju’ potato tubers (modified from Han et al. 2004)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>‘Dejima’ potato AA lost (%)</th>
<th>‘Sumi’ potato AA lost (%)</th>
<th>‘Chaju’ potato AA lost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>boiling</td>
<td>88.4</td>
<td>77.2</td>
<td>84.0</td>
</tr>
<tr>
<td>boiling, 1% salt</td>
<td>77.0</td>
<td>75.2</td>
<td>79.1</td>
</tr>
<tr>
<td>boiling, 3% salt</td>
<td>58.7</td>
<td>61.3</td>
<td>61.2</td>
</tr>
<tr>
<td>preheating</td>
<td>65.0</td>
<td>60.2</td>
<td>55.6</td>
</tr>
<tr>
<td>frying</td>
<td>78.9</td>
<td>55.1</td>
<td>69.1</td>
</tr>
<tr>
<td>sautéing</td>
<td>63.2</td>
<td>61.4</td>
<td>66.9</td>
</tr>
<tr>
<td>braising</td>
<td>62.9</td>
<td>50.4</td>
<td>57.2</td>
</tr>
<tr>
<td>baking</td>
<td>50.9</td>
<td>33.2</td>
<td>49.1</td>
</tr>
<tr>
<td>microwaving</td>
<td>29.4</td>
<td>20.8</td>
<td>32.6</td>
</tr>
</tbody>
</table>

Sanitization

The use of sanitizers for containers and equipment is an important hurdle in order to remove microorganisms from the surfaces of whole and fresh-cut fruit and vegetable. The use of chlorine and other chemicals, some of which may not be allowed in some countries, as sanitizers for FCFV has been extensively studied (Beuchat 2000; Davidson and Branan 2000).

Chemicals containing SH-groups, including sulfites, are commonly used to prevent microbial growth and browning in vegetables such as minimally processed potatoes. However, the application of these compounds in fresh-cut commodities may cause bronchial asthma (Peroni and Boner 1995) and undesirable flavors, in addition to a significant reduction in the nutritional value in potatoes (Chalom et al. 1995).

Agents that are chlorine based are routinely used as sanitizers in wash, spray, and flume waters used in FCFV industries (Beuchat 2000). There are three major groups of chlorine compounds (liquid chlorine, hypochlorites and chlorine dioxide) that exhibit various degrees of antimicrobial activity. Chlorine is commonly used at 200 ppm (available chlorine) and at a pH below 8.0, with a contact time of 1-2 minutes (Garcia et al. 2002).

The production of algenated organic compounds such as trihalomethanes, which are potential carcinogens (Fawell 2000), has created the need to investigate the efficiency of non-traditional sanitizers and other alternative technologies. The use of ozonated water has been suggested as an interesting alternative to traditional sanitizers due to its efficacy at low concentrations and short contact times as well as the breakdown to non-toxic products (Graham 1997; Rice 1999). The use of ozone to decontaminate various types of foods has been extensively investigated (Aguayo et al. 2005; Mahapatra et al. 2005). Preservation of fish (Haraguchi et al. 1969), reduction of aflatoxin in peanuts and cottonseed meals (Dwankanath et al. 1968) and reduction of microbial populations on poultry (Sheldon and Brown 1986), bacon, beef, butter, cheese, eggs, mushrooms, potatoes and some FCFV (Kaess and Weidemann 1968; Gamm and Kerelak 1973; Beuchat 1998; Kim et al. 1999; Roccui et al. 2005) using gaseous ozone have been studied.

Beltrán et al. (2005) studied the effectiveness of different traditional and non-traditional sanitizers on the sensory and microbial quality of fresh-cut potatoes stored under passive MAP and vacuum packaging. Six different washing treatments consisting of water, sodium sulfite, sodium hypochlorite, peroxyacetic acid (Tsunami™), ozone and the combination of ozone-Tsunami™ were evaluated.

Initially, no significant differences were found between the number of microorganisms in fresh-cut potatoes washed with the sanitizers and those samples washed in water. Only sodium sulfite and hypochloride dips achieved 0.6 and 0.7 log-reductions, respectively, on anaerobic microorganisms. Therefore, the tested sanitizers were not effective in reducing the initial microbial counts except for anaerobic microorganisms. These results are in good agreement with previous studies in fresh-cut lettuce and potato strips where microbial populations were not controlled by chlorine and hypochlorite dips (Gunnés et al. 1997; Delaquis et al. 2004). This could be a consequence of the neutralization of sanitizers by components leaching from the surfaces of the cut products (Adams et al. 1989).

The use of ozonated water alone was not effective in reducing total microbial populations. Ozone-Tsunami™ resulted in the most effective treatment to control microbial growth achieving 3.3, 3.0 and 1.2 log-reductions for lactic acid bacteria, coliforms and anaerobic bacteria, respectively. As discussed earlier, control of these microbial groups is important since they are microorganisms present in fresh-cut vegetables and responsible for the spoilage of fresh produce (Zagory 1999).

HURDLE TECHNOLOGY AND FRESH-CUT POTATOES

The microbial stability and the sensory quality of most food products are based on a combination of hurdles (Leistner 1995; Leistner and Gorris 1995). This is true for traditional foods with inherent empric hurdles, as well as for novel products for which the hurdles are intelligently selected and intentionally applied (Leistner 1995; Leistner and Gorris 1995). Traditionally, the most important hurdles commonly used for FCFV stabilization are washing and/or dipping in aqueous solution of sanitizing and anti-browning agents, use of edible coatings, low temperature (refrigeration) and MAP. It is important to underline that the combination of gentle hurdles is essential for keeping fresh-like quality in FCFV.
Pre-treatments

The control of enzymatic browning is frequently achieved through the use of different types of chemicals, generally referred to as anti-browning agents. The chemical effects of these substances on browning prevention have been well documented (for reviews see McEvily et al. 1992, Laurila et al. 1998b). Among the chemicals used in the control of browning, the most effective act directly as inhibitors of PPO, to avoid the development of the browning reaction, and others react with the products of the PPO activity avoiding the formation of dark pigments.

While the optimum pH for PPO has been reported as ranging from acidic to neutral, in fresh-cut potatoes, optimum PPO activity is observed at pH 6.0–6.5. In general, little activity is detected below pH 4.5 (Whitaker and Lee 1995). Therefore, the use of chemicals that lower the product pH finds widespread application in the control of enzymatic browning. Hence, the role of acidulants is to maintain the pH well below the optimal for catalytic activity (McEvily et al. 1992). The most widely used acidulant in the food industry for prevention of browning is citric acid (CA) (McEvily et al. 1992). CA may have a dual inhibitory effect on PPO by reducing the pH and by chelating the copper at the enzyme active site. Acidulants are frequently used in combination with other types of anti-browning agents, because it is difficult to achieve efficient browning inhibition solely through pH control.

Reducing agents cause chemical reduction of colourless o-quinones resulting from PPO activity back to o-diphenols (McEvily et al. 1992). Reductants are irreversibly oxidized during the reaction, which means that the protection they confer is only temporary because they are consumed in the reaction with pigment intermediates, endogenous enzymes, and metals such as copper (McEvily et al. 1992; García and Barret 2002). When all the added reducing agent is oxidized, the o-quinones may undergo further oxidation reactions (not involving PPO) and finally rapid polymerization leading to the formation of brown pigments. AA and its various neutral salts and other derivatives have been generally recognized as safe (GRAS) antioxidants for use in fresh-cut potatoes and their solutions to prevent browning and other oxidative reactions (Dorantes-Alvarez and Chiralt 2000). AA, probably the most widely used antibrowning agent, is a moderate reducing compound, acidic in nature, forms neutral salts with bases, and it is water soluble (Dorantes-Alvarez and Chiralt 2000). Its function in food systems is to act as a free radical scavenger preventing oxidation, to alter the redox potential of the system and to reduce undesirable oxidation (McEvily et al. 1992). The main role of AA in prevention of enzymatic browning is its ability to reduce the o-benzoquinones back to o-diphenols (Whitaker and Lee 1995). Unfortunately, once added, AA is completely oxidized to dehydro-ascorbic and quinones can accumulate and undergo browning (Laurila et al. 1998b).

Thiol-containing compounds, such as L-cysteine (LC), are also reducing agents that inhibit enzymatic browning. The action of this amino acid is complex, it forms additional compounds with phenolic substrates and also reduces quinines and forms thiol adducts, thus preventing the formation of pigments. Friedman and Bautista (1995) proposed that the mechanism of action of LC includes the breakage of the copper-nitrogen from a hystidine link in the active centre of PPO. They suggested that there is a strong affinity of the hystidine residues that link copper to the rest of the protein, thus producing changes in the conformation of PPO. However, for complete browning control, the amount of LC required (cysteine-to-phenol ratios above 1) is often incompatible with product taste (Richard-Forget et al. 1992).

There are consumers who want to avoid any type of food preserve. Consumers perceive fresh-cut products as minimally processed, with characteristics close to their raw, unprocessed material. Therefore, some processors would rather not use chemical additives that could change that perception of a “natural” product (Kader 2002). This may be one of the reasons that AA, which may be labelled as vitamin C, is frequently preferred as an anti-browning agent, an added value to the product. Other chemicals of natural origin or identical to natural compounds such as CA are also often preferred.

It has been frequently reported that the most effective prevention of browning in fresh-cut products is achieved by using a combination of treatments (Ahvenainen 2000; Dorantes-Alvarez and Chiralt 2000). A typical combination may include a chemical reductant (e.g. AA) and an acidulant (e.g. CA). In many cases, the enhanced activity of the combined ingredients is additive, although synergism has also been claimed for several blends of anti-browning agents (Ahvenainen 2000).

As an example, in Fig. 3, results of WI (whitening index), a* (red index) and L* (luminosity) of fresh potato slices (Fresh), slices treated for 3 min with distilled water (Control) and with aqueous solutions of AA, CA and LC at three different concentrations (0.5, 1 and 2% w/w) evaluated by a computer vision technique are reported (Rocculi et al. 2007). Results showed that after 24 h of air exposure at 20°C, the samples treated with aqueous solutions of LC at 0.5, 1 and 2% (w/w) showed similar chromatic characteristics when compared with the fresh samples (group A), while AA and CA treatments at higher concentrations seemed to cause an excessive whitening of potato surface colour (group B). When increasing the concentration of AA and CA (from 0.5 to 2% w/w), L* and WI results increased, evidencing an excessive whitening of potato surface colour. Moreover, colour red index (a*) results for these samples evidenced a shift to the red zone, which was similar to the Control 24 h of exposure to air. A sensory analysis could be performed on potato samples, after cooking, in order to assess the effect of the different anti-browning treatments on product flavour.

The extensive literature published on the effects of different anti-browning substances used for colour preservation of FCVF has not explored the effects these treatments have on the metabolism of the wounded tissue. This important aspect for quality has been recently explored by Rocculi et al. (2007) using isothermal calorimetry. Potato slices were treated with commonly used browning inhibitors and the metabolic activity was evaluated using isothermal calorimetry. Interestingly, potato cylinders treated in solutions of AA, CA and LC (0.5, 1 and 2% w/w solutions) showed a faster and more intense metabolic activity compared to the control, during 24 h of analysis at 20°C (Fig. 4). Using a different calorimetric set-up, it was possible to combine the heat measurements with measurements of the consumption rate of O₂ or the production rate of CO₂ of dipped samples. The treated potato pieces consumed the oxygen inside the...
coating of an anti-browning agent could increase their effect on the potato tissue. Baldwin et al. (1996) showed that AA delayed browning on fresh-cut potatoes more effectively when applied in an edible coating than in an aqueous solution.

**Modified atmosphere packaging**

A key operation in producing FCFV is packaging. Previous investigations showed that, by vacuum packaging, 2 weeks shelf-life could be achieved for fresh-cut potatoes after treating them with anti-browning agents (O’Beirne and Ballantyne 1987). However, vacuum packaging of FCFV would create anaerobic conditions and thus, may not be safe due to possible growth of anaerobic pathogens such as Clostridium botulinum (Hotchkiss and Banco 1992).

The most promising packaging method for FCFV is MAP that is a way of changing the storage atmosphere of the packaged produce. MAP technique for FCFV uses permeable polymeric films that allow gas exchange between the atmosphere inside the package and the outside atmosphere (Kader et al. 1989). This atmosphere alteration can be obtained using either active or passive modification (Zagory and Kader 1987; Jacobsson 2004). Active MAP involves the creation of a slight vacuum inside the package, which is then replaced by the desired mixture of gases to quickly obtain the desired atmosphere (Kader et al. 1989; Jacobsson 2004). In passive MAP, modification of the atmosphere is achieved within the packages as the result of the respiration rate of the plant tissue and gas diffusion characteristics of the film (Kader et al. 1989; Jacobsson 2004). The O2 concentration decreases and the CO2 concentration increases inside the package, resulting in the respiration rate of the produce being reduced (Kader 1986). It is expected that the composition of the atmosphere to be established within a couple of hours. However, in practice, it may take a couple of days before equilibrium is achieved (Jacobsson 2004). It is important to choose the right packaging material since the correct film should match the physiological characteristics of the commodity. If the internal oxygen level falls below a certain concentration, it may result in anaerobic respiration and the consequent shift of the respiration pathway towards fermentation (Jacobsson 2004). If the produce is packaged in a film of excessive O2, CO2 and H2O permeability, little or no modification of the atmosphere inside the package will occur and the produce will lose its moisture (Jacobsson 2004). In this direction, most studies have been made on the effects of different CO2 and O2 levels on metabolism as well as the extension of shelf-life of whole and fresh-cut fruit and vegetable (Lee et al. 1991; Mathisko 1996; Watada et al. 1996; Gil et al. 1998; Beaudry 2000). Specific levels of CO2 and O2 may reduce the rates of metabolic reactions and inhibit respiration rate, ripening, microbial growth and ethylene production (Limbo and Piergiovanni 2007).

Fig. 4 Heat production of potato cylinders washed for 3 min with distilled water (Control) and treated with aqueous solutions at 1% w/w of ascorbic acid (AA), citric acid (CA) and l-cysteine (LC) during 24 h of analysis at 20°C. (Modified from Rocculi et al. 2007).
atmospheric O$_2$ (21%). Hence, under reduced or elevated O$_2$ levels, there would be inhibition of aerobic microorganisms. In addition, high O$_2$ levels would inhibit undesirable fermentation reactions (Day 1995). Moreover, it is hypothesized that high oxygen levels may cause substrate inhibition of PPO, or alternatively, high levels of colourless quinones subsequently formed may cause feedback production of PPO.

High oxygen MAP seems to reduce respiration rate of FCFV. The hypotheses about this reduction are different. Mostardini and Piergiovanni (2002) attributed it to a marked inhibition of CO$_2$ production, as high oxygen could block the tricarboxylic acid cycle between citrate and α-ketoglutarate. At super-atmospheric concentrations, O$_2$ could enhance the production of reactive oxygen species, damaging the cytoplasm and inhibiting various metabolic processes.

Limbo and Piergiovanni (2006) studied the effects of high oxygen partial pressures in combination with AA and CA on the development of the enzymatic browning of peeled and cut potatoes that were packaged in flexible pouches and stored at 5°C for 10 days. Results showed that browning could be reduced by maintaining a high and constant oxygen partial pressure around the product. The initial oxygen level inside the pouches was the most important factor that affected enzymatic browning. Even if the treatments with the highest oxygen partial pressure (100 kPa O$_2$) have shown some positive effects on enzymatic browning, it could be difficult to maintain it in a package and the industry could face flammability risk.

In a later work Limbo and Piergiovanni (2007) found that a modified atmosphere of 10 kPa O$_2$ gave the lowest results in terms of respiration rate and hexanal accumulation. High O$_2$ partial pressure (55 and 100 kPa) did not stop the production of hexanal but had an inhibitory effect on the anaerobic production of volatiles.

For optimization of MAP for fresh-cut potatoes, a specific calorimetric set-up could be used to study the behaviour of the vegetable mixtures under the influence of a gas (e.g. N$_2$, CO$_2$, O$_2$, N$_2$O, Ar) or a certain mixture of gases. In this case, the calorimeter should be adapted so that a continuous input of gas from an external cylinder could be circulated constantly through the sample while measuring the metabolic heat. Some metabolic volatile compound produced by the sample (e.g. ethylene) could also be analysed from the output flux.

**Refrigeration**

Refrigeration throughout the production chain to consumption is a mandatory preservation method for all FCFV in order to slow down deteriorative physiological disorders and microbial spoilage, and reduce the risk from pathogens. Longest shelf-life is generally achievable at temperatures close to the freezing point of the product (i.e. -1.5 to 0°C) (Reyes 1996).

Delays between harvesting and cooling or processing can result in quantitative losses (due to water loss and decay) and qualitative losses (losses in flavour and nutritional quality). Temperature has a tremendous effect on respiration rates, increasing the temperature from 2 to 10°C resulted in about threefold increase in respiration rate of fresh-cut potatoes (Gunes and Lee 1997).

According to Cacace et al. (2002) the effectiveness of different anti-browning dipping treatments was strongly affected by storage temperature. These authors found that the sensory quality of fresh-cut potatoes stored at 1°C differed little from freshly prepared product after 14 days of storage. In contrast, perceptible changes were detected after 7 days at 6°C. In addition results showed that quality retention in fresh-cut potatoes requires the application of appropriate chemical treatments in conjunction with low storage temperatures for the control of physico-chemical and microbiological alterations. Temperature must be controlled precisely during storage of packaged fresh-cut potatoes to prevent formation of anaerobic conditions (Watabe et al. 1996; Garcia and Barrett 2002).

**FUTURE PERSPECTIVES**

From an industrial point of view, fresh-cut potatoes can be manufactured on the bases of several different working principles. If the principle is that products are prepared today and consumed tomorrow, then very simple processing methods can be used. Such products are suitable for catering, but not for retailing purposes. The greatest advantage of this principle is the low requirement for investment (Ahvenainen 1996). 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 (Leistner and Gorris 1995) are needed.

In terms of raw material characteristics, it is probable that in the future, potatoes intended for MP will be cultivated under controlled conditions, and furthermore that plant genetics will select and create cultivars or hybrids that are adapted to the specific requirements of MP (Varoquaux and Wiley 1994). As stated by Reyes (1996), proper post-harvest handling and good manufacturing practices are not preservation methods but essential steps in product preparation and processing that have to be guaranteed. The use of ozone sanitization, natural dipping pre-treatments (e.g. edible film enriched in AA, CA) and high O$_2$ MAP result the most promising and non-invasive techniques for the preservation of fresh-cut potatoes.

Approaching the matter in terms of nutritional consumer needs, recent investigations suggest that MP promotes the increase of vitamin C and polyphenols content of the final product. Unfortunately, AA in potatoes is highly susceptible to degradation during boiling and frying and less so during braising, sautéing and pressure-cooking. Baking and microwaving had the least impact on the stability of the vitamin (Han et al. 2004). These results suggest that it is probably safe to fortify fresh-cut potatoes with vitamin C with a specific dipping pre-treatment, in order to increase its content in the final product. On the other hand, fresh-cutting and subsequent storage of the product can induce the accumulation of flavonols, a significant part of which are preserved in the food after cooking. Although cooking decreases the total flavonoid and caffeic acid derivative contents of the potato, this does not mean that cooking cannot exert an overall positive effect on flavonoid bioavailability. Cooking has a positive effect on the release of phytochemicals from the food matrix into the gastrointestinal tract and their further absorption in the intestine, as is the case of lycopene in tomato (van den Berg et al. 2000) and ellagic acid in strawberry (Zafirilla et al. 2001; Tudela et al. 2002a). Further research of the effect of MP on nutritional aspects of fresh-cut potato is needed.
As far as physiological studies of the products are concerned, fundamental metabolic research for process optimization and quality assurance are needed. As previously reported, isothermal calorimetry may provide a versatile tool to conduct fundamental metabolic studies of the effect of different processing steps on the quality and shelf-life of fresh-cut potatoes (Gómez Galindo et al. 2005). In addition, the carbon and oxygen metabolism of plant cells is connected to several processes of which we have limited understanding. These include ROS metabolism and signalling, cell survival, stress resistance and redox homeostasis. Industrial practices involved in the production of fresh-cut potatoes are likely to influence these metabolic processes and, therefore, research is needed to gain knowledge on novel (i.e. not found in nature) tissue stress conditions during processing operations in the food industry (Gómez Galindo et al. 2005). In investigating the genetic and metabolic profiling of metabolism during industrial processing of fresh-cut potatoes, through techniques such as transcriptomics and metabolic profiling, will provide knowledge on the consequences of industrial practices essential for quality assurance and optimization (Gómez Galindo et al. 2007).

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