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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 O_2 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 Mazollier 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

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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 Añon 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 (Ahvenainen 2000). This is an important fist 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 (Ahvenainen 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

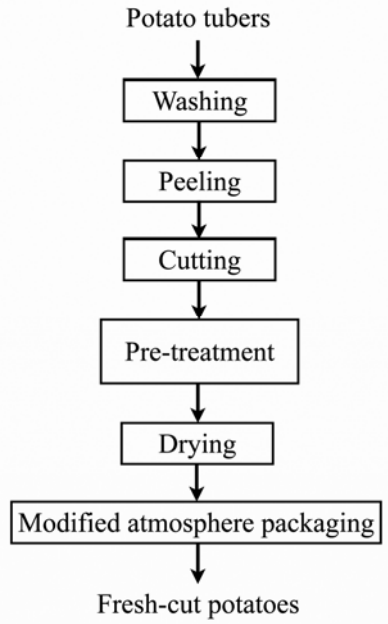

Fig. 1 Schematic flow-chart of minimal processing (MP) for fresh-cut potatoes production.

used is 5-10 l kg^{-1} of product before peeling and/or cutting and 3 l 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) (for 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. These postharvest and processing operations are traumatic for the cells proximal to the damage site and induce a complex series of metabolic events aimed at repairing the damage caused to the tissue, known as wounding response (Surjadinata and Cisneros-Zevallos 2003) that will be discussed in further sections.

From the industrial point of view, the severity of browning in pre-peeled potatoes is related to surface damage during peeling (Sapers *et al.* 1995). There are several peeling methods available, but on an industrial scale, the peeling is normally accomplished mechanically (e.g. rotating, carborundum drums), chemically, or in high-pressure steam peelers (Ahvenainen 2000). However, the ideal method would be hand peeling with a knife because peeling should be as gentle as possible (Gunes and Lee 1997). However, even in the case of a gentle peeling, this operation causes injury that could be minimized by using very sharp knives (Bolin and Huxsoll 1991). According to Laurila *et al.* (1998b), when peeling is done gently, it is possible to maintain adequate quality of whole pre-peeled potatoes for 7 days without browning inhibitors. In industrial scale, this is not easy considering that classical stainless steel used to manufacture blades is rather soft, and intensively used knives should be sharpened very often (every hour). Carbon steel used for scalpel blades is brittle, may be dangerous for operators and releases iron ions that may be involved in brown discoloration. Ceramic blades are also breakable and are very expensive (Varoquaux and Mazollier 2002). Since the cutting should take place under water, one of the approaches tested in France has been water jet cutting (Béguin *et al.* 1995). As the leaking liquid of injured cells is removed by the water flow, browning is markedly reduced compared to any commercial cutting technique (Varoquaux and Mazollier 2002).

If the peeled and cut product is washed or pre-treated with anti-browning solutions, it is recommended to gently remove the washing water from it because excessive free water in packs may result in rapid bacterial spoilage, specially at the product-film interface (Solomos 1994). Two methods are presently used for this operation: centrifugation and drying in air tunnel. Centrifugation seems to be the best one, but time and rate should be chosen carefully (Ohta and Sugawara 1987; Bolin and Huxsoll 1991) in order to remove only loose water and not break tissue cells. Air tunnel drying is a new technique developed in Italy that is currently used in several processing plants in Europe and in the United States. The drying tunnel is composed of a series of vibrating tables transporting the product and a battery of air drying units. The product progression is in counter current with both air temperature and dryness (Varoquaux and Mazollier 2002).

The final, but not the least important operation in producing fresh-cut potatoes is packaging. The packing room must be clean and refrigerated at 1–2°C and separated from the washing section (Varoquaux and Mazollier 2002). Packing could be performed using an associative weighing machine or a vacuum compensated thermo-sealer. The most studied packaging method for fresh-cut potatoes is modified atmosphere packaging (MAP). MAP has become a widely used food preservation technique that alters the gases surrounding a commodity, producing an atmospheric composition different from that of air (Day 1996). This technology is targeted at reducing the respiration rate of the fresh product slowing senescence (Wills *et al.* 1998).

If the packages are exposed to high temperatures during distribution or storage, there is a risk of reducing the O_2 concentration in the packages and a consequent accumulation of anaerobic metabolites. Although 0°C is generally the desirable temperature for most fresh-cuts, many are prepared, shipped and stored at 5°C and sometimes as high as 10°C. Under these conditions, deterioration may increase substantially because the Q_{10} (the factor by which a process increases when the temperature changes by 10 K) of biological reactions ranges from 3 to 4 and possibly as high as 7 within this temperature region (Schlimme 1995).

PHYSIOLOGY AND QUALITY OF FRESH-CUT POTATOES

After harvesting, the postharvest potato cell has the ability to complete a complex series of physiological transitions that will influence raw material quality and further processing operations. Therefore, it is important to investigate the physiological status with respect to metabolic changes occurring during MP procedures, including the intrinsic physiology and quality of the raw material, the package 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 (Laties 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 μL 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 completely explained by an 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 α-oxidation of long-chain fatty acids (Martin and Stumpf 1959; Laties 1964; Laties *et al.* 1972). This increase in O_2 consumption associated with α-oxidation coincides with membrane deteriorative processes. In addition, the increase in respiration has also been assumed to be due to enhanced aerobic 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 of isothermal calorimetry (for a review on the technique and applications of FCFV, 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 respirometry. 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 (Criddle *et al.* 1991a,

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, Järfälla, 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 and potential penetration by pathogens (Satoh *et al.* 1992; Kaack *et al.* 2002b). The synthesis of several secreted proteins, such as hydroxyproline-rich glycoproteins, and their cross-linking in the cell wall after wounding has also been observed (Bradley *et al*. 1992). Suberization is a regulated process whereby the intercellular spaces in tissues become impregnated with a poly(phenolic) matrix concomitant with the deposition of a poly(aliphatic) matrix between the plasmalemma and carbohydrate cell wall (Friedman 1997; Bernards *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 (O^{-2}), hydrogen peroxide (H_2O_2), and the hydroxyl radical (OH.). 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 Chiralt 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 Chiralt 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-

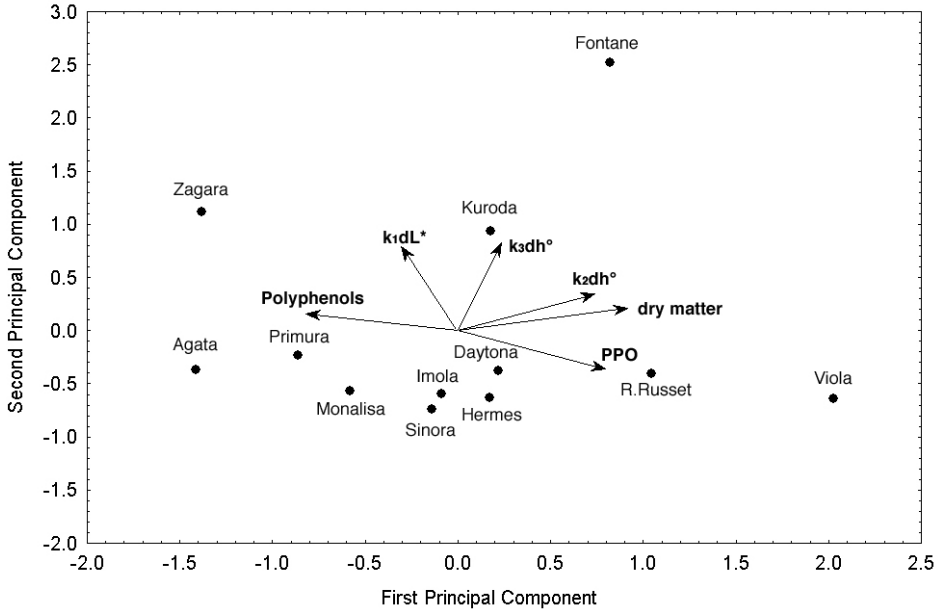

Fig. 2 Principal component comparison of different potatoes varieties on the bases of dry matter, polyphenols content, PPO (polyphenol oxydases) activity, colour kinetics (L*, luminosity; h°, hue angle) results. Colour modification kinetics have been obtained by linear regression of L* and h° data measured on potato slice surfaces during 24 h of air exposure at 23°C using a *tristimulus* colorimeter (illuminant D65). (Unpublished data).

ments, called melanins, that are responsible for colour browning (Tomás-Barberán and Espín 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 colour parameters (luminosity and hue angle). In this case, colour 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 structure or inner makeup of products in terms of: reaction to stress, measured as mechanical properties by 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 (Toivonen 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 H_2O cm^{-2} mbar $wpd^{-1}h^{-1}$, while non-peeled, cured potatoes have a moisture loss rate of 0.007 mg H_2O cm^{-2} mbar $wpd^{-1}h^{-1}$ (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 shows 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 SO_2) for 30 s, draying, and packaging in polyethylene bags before storage at

Table 1 Microflora of fresh-cut potatoes. (modified from Doan and Davidson 2000)

Process	Storage temperature (°C)	APC [b] (log CFU)	Microflora isolated	Reference
AP, C	10	variable	Gram-negative rods; Gram-positive rods; Gram-positive cocci; yeast; molds	Fuller *et al.* 1965
AP, C, D	6, 23	3.15 – 9.30	*Corynebacterium Pseudomonas Enterobacter-Hafnia Erwinia herbicola*	Lund 1968
P	20	NR[c]	*Clostridium butyricum*	Lund 1972
P, C, D	4, 7, 10	4.0 cm^{-2}	*Bacillus cereus Enterobacter cloacae Hafnia alvei*, *Klebsiella oxytoca Pseudomonas fluorescens Staphylococcus aureus* coliforms	Giannuzzi and Zaritzky 1990
P, C	25	6.2	*Staphylococcus aureus* coliforms	Bryan *et al.* 1992
P	4	5.0	psychrotrophs *Rhodotorula*, *Alternaria*, *Penicillum*, *Aspergillus*, *Cladosporium*	Giannuzzi and Zaritzky 1993

[a] AP, abrasion peeled; C, cut; D, dipped; P, hand peeled
[b] APC, aerobic plate count in log CFU g^{-1} raw potatoes
[c] NR, not reported

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 treated potatoes, gram-positive cocci, gram-positive rods (coryneform and bacilli), fluorescent pseudomonas, nonfluorescent oxidative organisms, and *Enterobacter-Hafnia* sp. were isolated (Doan and Davidson 1999). After storage, *Enterobacter-Hafnia* sp. and *Erwinia herbicola* were the predominant microflora. In a separate study, Lund (1972) isolated a pectolytic clostridium from raw potatoes that was tentatively identified as *Clostridium butyricum*.

Even if fresh-cut potatoes must be prepared and stored at refrigerated temperatures to achieve a sufficient shelf-life and microbiological safety, some pathogens such as *Listeria monocytogenes*, *Yersinia enterocolitica*, *Salmonella* spp. and *Aeromonas hydrophila* may still survive and even proliferate at low temperatures (Ahvenainen 1996). The normal spoilage organisms in the refrigerated product are also usually psychotropic and, therefore, have a competitive advantage over most pathogens (Laurila and Ahvenainen 2002).

Several studies have demonstrated that anaerobic conditions in the package headspace of fresh-like potato products can promote the growth of *Clostridium botulinum*, *Listeria monocytogenes*, *Bacillus cereus*, *Salmonella typhimurium* and *Staphilococcus aureus* (Notermans *et al.* 1981, 1985; Lund *et al.* 1988; Dodds 1989; Solomon *et al.* 1994; Juneja *et al.* 1998; Doan and Davidson 2000). Production of toxins by pathogenic bacteria on minimally processed potato products may occur before products are considered spoiled or unacceptable for consumption by consumers (Notermans *et al.* 1981; Solomon *et al.* 1998; Doan and Davidson 2000).

As mentioned earlier, cutting or shredding has direct consequences on microbiological spoilage. Therefore, the relations between the degree of cutting/shredding, the overall metabolic activity of the vegetables and their susceptibility to spoilage must be established. Gómez Galindo *et al.* (2005) found a relation between the wounding intensity and susceptibility to spoilage by anaerobes when fresh-cut potato samples were left inside the calorimeter ampoules long enough to cause oxygen depletion. Two peaks were obtained from calorimetric measurements of potato samples with different wounding intensities. The first peak could be associated with the metabolic activity of the potato pieces. An easily detectable odour of spoiled potato was associated with the second peak. Heat production by microorganisms growing in foodstuffs is well documented in the literature (Riva *et al.* 2001; Alklint 2003).

Flavour

Flavour, as an attribute of foods, beverages, and seasonings, has been defined as the sum of perceptions resulting from stimulation of the sense ends that are grouped together at the entrance of the alimentary and respiratory tracts, but for purposes of practical sensory analysis, the term can be restricted to the impressions perceived via the chemical senses from a product in the mouth (Meilgaard *et al.* 1999).

An acceptable subjective visual appraisal does not necessarily imply that a product has satisfactory flavour quality. Flavour includes sweetness, sourness (acidity), astringency, bitterness, aroma and off-flavours (Kader 2002). Flavour modifications of fresh-cut potatoes during storage can be caused by the synthesis and accumulation of volatile compounds associated with endogenous fermentative metabolism, such as acetaldehyde, ethanol and ethyl acetate (Perez and Sanz 2001). After cell disruption, enzymatic and oxidative attack on inherent lipids results in a vast array of unsaturated and saturated aldehydes and alcohols, some of which have extremely low odour thresholds and thus have a possible negative impact on vegetable flour (Petersen *et al.* 1998). Little is known on the effect of storage temperature on volatile production on FCFV. Most processors sanitize the fresh-cut materials, but some choose not to "wash away" flavours from the products. Subsequently, flavour quality and consumer acceptance of FCFV based on aroma and flavour remains a challenging area for the industry.

To our knowledge no researches have been studied the flavour characteristics of fresh-cut potatoes after cooking, as a function of raw material variety and physiological stage, processing and storage conditions of the fresh-cut product and/or home-processing method. This field could be an interesting issue giving important information in the field of food science, engineering and gastronomy.

Nutritional aspects

MP operations can cause different effects on the nutritional content of fresh-cut potatoes. The understanding of the consequences of physiological modification due to wounding stress on vitamin C and polyphenol content of fresh-cut potatoes and, in general of FCFV, is still a challenge for food scientists.

Previous studies showed that potato tubers contain caffeic acid derivatives (chlorogenic acid) as the main phenolic constituents (Brandl and Herrmann 1984; Friedman 1997; Dale *et al.* 1998) and that the biosynthesis of these compounds is affected by external factors such as bruising and wounding (Friedman 1997). An increase in chlorogenic acid content has been reported in some cultivars after bruising (Dale *et al.* 1998) and slicing (Laanest *et al.* 1995). An increase in the content of chlorogenic acid and other phenolic compounds was observed in light-exposed potato slices stored for 9 days (Laanest *et al.* 1995). Tudela *et al.* (2002a) investigated the effect of cutting and subsequent cold storage on phenolic compounds from five potato cultivars ('Agria', 'Cara', 'Liseta', 'Monalisa' and 'Spunta') during long-term storage. The authors found that cutting induced the biosynthesis of three flavonols, which were identified as quercetin 3-rutinoside, quercetin 3-diglucoside and quercetin 3-glucosylrutinosidee. The flavonol induction was higher in fresh-cut potatoes stored under light than in the dark.

Despite having only a modest ascorbic acid (AA) content (10-30 mg 100 g^{-1} FW), potatoes are the major source of AA in the Western diet because of the large quantities consumed (Davey *et al.* 2000). The concentration of AA depends on several factors including cultivar, production practices, harvest and storage conditions (Augustin *et al.* 1978). According to Lee and Kader (2000), the AA content of most vegetables decreases when bruising, trimming and cutting occur. However, in potato tubers, wounding and subsequent storage tend to increase the AA content from 250 to 400% (Tudela *et al.* 2002a). Peeling and cutting and subsequent cold storage appear to trigger a cascade of events in potato tissue involving overlapped anabolic and catabolic reactions (Tudela *et al.* 2003), such as the biosynthesis of antioxidant flavonols through the induction of the enzyme phenylalanine ammonia-lyase (Tudela *et al.* 2002a), the well known induction of oxidative enzymes, such as polyphenol oxidase and peroxidase (Cantos *et al.* 2002), as well as the induction of vitamin C synthesis (Tudela *et al.* 2002b).

In this context, a recent study showed the retention of vitamin C in fresh-cut potatoes stored in air, whereas vitamin C content decreased in fresh-cut potatoes stored under MAP (Tudela *et al.* 2002b). The authors suggested that this phenomenon could be related to the influence of the atmosphere on the enzymatic activity of L-galactono-γ-lactone dehydrogenase, which catalyzes the final step of AA biosynthesis.

Tudela *et al.* (2003) showed that potato strips retained their vitamin C content for 6 days under refrigerated storage in air at 4°C. In addition, they found that vacuum packaging could be recommended for storing fresh-cut potatoes in the attempt to preserve both vitamin C content and colour. The authors also reported the loss of vitamin C content in potato

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)

Conditions	'Dejima' potato AA lost (%)	'Sumi' potato AA lost (%)	'Chaju' potato AA lost (%)
boiling	88.4	77.2	84.0
boiling, 1% salt	77.0	75.2	79.1
boiling, 3% salt	58.7	61.3	61.2
pressure-cooking	65.0	60.2	55.6
frying	78.9	55.1	69.1
sautéing	63.2	61.4	66.9
braising	62.9	50.4	57.2
baking	50.9	33.2	49.1
microwaving	29.4	20.8	32.6

strips stored in a high CO_2 (20%) atmosphere (Tudela *et al.* 2002a). The accumulation of AA following potato wounding could prevent melanin formation resulting in less browning at the cut surface (Nicolas *et al.* 1994).

Antibrowning pre-treatments based on AA can also be considered as a vitamin C fortification of the product, as it has been recently reported for fresh-cut apples (Cocci *et al.* 2006). The considerations about nutritional content of fresh-cut potatoes have to be integrated with the modification caused by their final cooking procedure; the amount of vitamin C and polyphenols content is significantly reduced after the fresh-cut potatoes are subjected to home or catering processing conditions to make them edible.

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 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.

Han *et al.* (2004) studied the influence of home-processing conditions on the AA content of three potato varieties with low ('Dejima', 16 mg/100 g), intermediate ('Sumi', 32 mg/100 g) and high ('Chaju', 42 mg/100 g) AA contents. In **Table 2** the effect of the home-processing conditions on the AA lost (%) for these three potato varieties is reported. These results confirmed that the vitamin C content of potatoes is influenced by both preharvest conditions (soil, climate, genotype, etc.) and postharvest storage and processing of the harvested potatoes and possibly also by contamination with microorganisms. According to the authors, this finding suggests the need to create new high-vitamin C potato cultivars.

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 empiric 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.

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 extensive studied (Beuchat 2000; Davidson and Branen 2005).

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 flavours, 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 and Barrett 2002).

The production of alogenated 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; Mahopatra *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; Gammon and Kerelak 1973; Beuchat 1998; Kim *et al.* 1999; Rocculi *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 (Gunnes *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).

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, some act directly as inhibitors of PPO, others 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 acid 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; Garcia 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 system is to act as a free radical scavenger preventing oxidation, to alter the redox potential of the system and to reduce undesirable oxidative products (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 preservative. 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

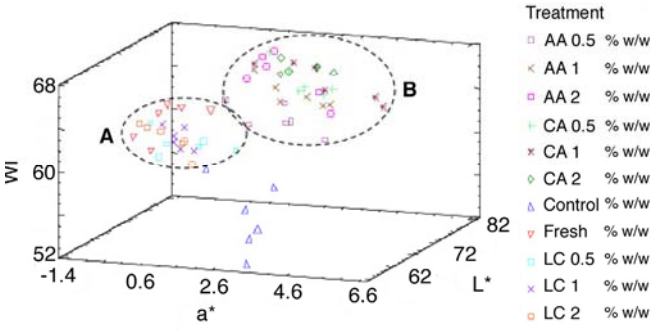

Fig. 3 Three-dimensional chart of colour results (WI (whitening index), a* (red index) and L* (luminosity)) of fresh potato slices (Fresh), slices washed for 3 min with distilled water (Control) and treated with aqueous solutions of ascorbic acid (AA), citric acid (CA) and L-cysteine (LC) at three different concentrations (0.5, 1 and 2% w/w). Colour parameters were measured using a *tristimulus* colorimeter (illuminant D65) after 24 h of air exposure at 20°C and in a saturated atmosphere. (Modified from Rocculi *et al.* 2007).

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 FCFV 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 O_2 or the production rate of CO_2 of dipped samples. The treated potato pieces consumed the oxygen inside the

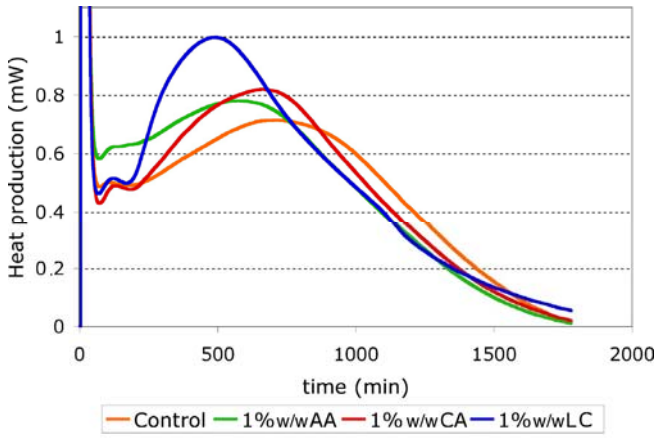

Fig. 4 Heat production of potato cylinders washed for 3 min with distilled water (Control) and treated with aqueous solutions at 1% w/w of ascorbic acid (AA), citric acid (CA) and L-cysteine (LC) during 24 h of analysis at 20°C. (Modified from Rocculi *et al.* 2007).

calorimeter ampoules about 8h faster that the untreated one. These results provide evidence that metabolic activity of fresh-cut potatoes was affected by the tested anti-browning treatments. An increased physiological aging can lead potato tissue to faster senescence, corresponding to a decrease of the shelf-life of fresh-cut potato products and the loss of other quality attributes bound to the physiological state of the potato tissue. This knowledge will be of practical importance as a tool to test different anti-browning substances specifically directed to achieve a decrease in the overall metabolic activity of fresh-cut potatoes before packaging (Gómez Galindo *et al.* 2005; Rocculi *et al.* 2007).

Traditionally, conventional food processing achieves the prevention of browning through heat inactivation of PPO, as with blanching and cooking. Heat inactivation is an effective method of browning prevention, and PPO is considered an enzyme of low thermostability, although differences in heat stability are reported for different cultivars and PPO isoforms (Zawistowski *et al.* 1991). Nevertheless, the use of heat has also the potential to cause nutritional losses as well as detrimental effects of some food quality attributes, such as texture and flavour. If heat treatments are applied, they should be minimized and should not cause a cessation of respiration (Garcia and Barret 2002). Sapers *et al.* (1995) found that a treatment with heated AA/CA might be an alternative to the use of sulfites to control browning in pre-peeled potatoes.

Other kinds of pre-treatments have been reported in the literature for preventing texture loss. It is well known that calcium is involved in maintaining the textural quality of vegetables (Garcia and Barrett 2002). Calcium ions form cross-links or bridges between free carboxyl groups of the pectin chains, resulting in strengthening of the cell wall. A common treatment used to improve tissue firmness is the dipping in calcium solutions. Frequently, calcium chloride and calcium lactate have been used as a firming agent; however, calcium lactate may confer undesirable bitterness to the product (Rico *et al.* 2007).

An interesting pre-treating method is the use of edible films and coatings (thin layer of material that can be eaten by the consumer as part of the whole food product) as a possible additionally "packaging" method for extending the storage life of FCFV (for reviews see Baldwin *et al.* 1995; Guilbert *et al.* 1995). At least theoretically, edible coatings have the potential to reduce moisture loss, restrict the entrance of O_2, lower respiration, seal in flavour volatiles, and carry additives that retard discoloration and microbial growth. In the review of Baldwin *et al.* (1995) some patented and commercially available edible film solutions is mentioned. Those which are based on sucrose polyesters of fatty acids and the sodium salt of carboxymethyl cellulose delayed water loss or browning. The inclusion in edible 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 1988; 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 O_2 concentration decreases and the CO_2 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 beyond 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 O_2, CO_2 and H_2O 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 CO_2 and O_2 levels on metabolism as well as the extension of shelf-life of whole and fresh-cut fruit and vegetable (Lee *et al.* 1991; Mathooko 1996; Watada *et al.* 1996; Gil *et al.* 1998; Beaudry 2000). Specific levels of CO_2 and O_2 may reduce the rates of metabolic reactions and inhibit respiration rate, ripening, microbial growth and ethylene production (Limbo and Piergiovanni 2007).

Gunes and Lee (1997) found that the level of oxygen significantly affected respiration rate of fresh-cut potatoes. Decreasing O_2 from 21 to 3% resulted in a reduction of about four fold of respiration rate (from 6.1 to 1.7 mL CO_2 kg^{-1} h^{-1}) while Kader (1986) found that elevated CO_2 reduces respiration rate. CO_2 was reported to inhibit some steps in the Krebs cycle through inactivating some enzymes.

As far as novel MAP for fresh-cut potatoes is concerned, there is a great interest for high oxygen MAP (Limbo and Piergiovanni 2006, 2007). High oxygen MAP have been found to be particularly effective in inhibiting enzymatic discoloration, preventing anaerobic fermentation reactions and inhibiting aerobic and anaerobic microbial growth, achieving surprisingly results in quality maintenance of FCFV (Day 1996). The inhibition of aerobic and anaerobic microbial growth by high O_2 conditions can be explained by the growth profile of anaerobes and aerobes (**Fig. 5**). Generally speaking, anaerobes grow best under very low O_2 levels and therefore anaerobes would be inhibited under high O_2 conditions. On the other hand, aerobes grow best under

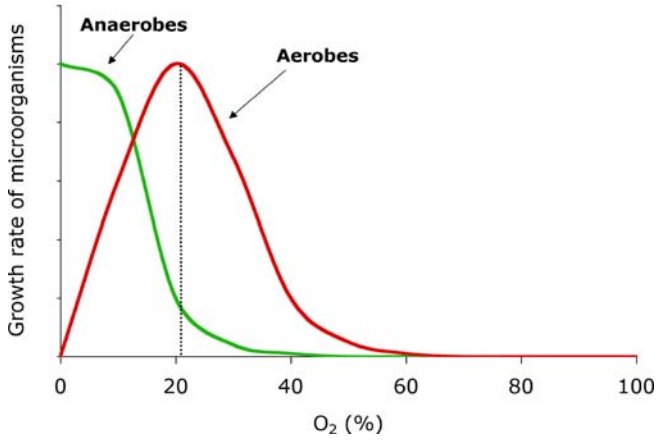

Fig. 5 Growth rate of microorganisms at different oxygen concentrations. (Modified from Day 1997).

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_2O, 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 (Watada *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 (Zafrilla *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 optimisation 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.* 2007). Investigation of the genetic control 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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