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Characterization of Potato Flavours: An Overview of Volatile Profiles and Analytical Procedures

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ABSTRACT

Potatoes may be cooked by several methods such as boiling, baking and frying; they are also used as an ingredient for numerous home-made and mass-produced foods like sticks, chips and other snacks. An important factor affecting consumer preferences of these products is their flavour, which is defined as the combined perception of aroma, taste and mouthfeel sensations. Flavour, and in particular the volatile profile of potatoes, has been widely investigated in the last few years, and complex patterns have been found. Although raw potatoes possess little aroma, more than 140 volatile compounds have been identified in boiled potatoes, whereas over 250 have been found in baked potatoes and more than 500 compounds have been isolated in French fries. Among these, many lipid oxidation and Maillard reaction products have been reported, together with smaller amounts of indigenous flavour compounds. Many extraction methods have been developed to characterize the aroma of potatoes, with the goal of reducing analytical detection limits, avoiding formation of artefacts during isolation and reducing analysis cost and time; among these are distillation techniques, solvent and direct solvent extraction techniques, static and dynamic headspace methods and solid-phase microextraction. As regard isolation and quantification of potato volatiles, gas chromatography-mass spectrometry and gas chromatography/olfactometry are frequently used. The analytical approach is often completed with the sensory evaluations. This review describes the flavour profile of the main forms of cooked potatoes, taking into account their mechanism of generation; extraction and analysis procedures are also considered, reporting both conventional and innovative methods.

Keywords: analytical techniques, characterization, extraction, flavour, potatoes

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INTRODUCTION

Potato (*Solanum tuberosum* L.) cultivation is widespread worldwide as a result of its appreciated sensory and nutritional properties, in addition to its adaptability to different climatic conditions. Potatoes may be cooked in many different ways such as boiling, baking or frying; various potato-based products are also produced, including extruded, dehydrated and potato snacks. Recently, the ready-to-use and ready-to-eat market has extensively utilized potato preparations.

One of the most important qualitative criteria in assigning different potato varieties to a fresh or processed food market is the flavour profile. The volatile profile of raw potatoes is weak, but is quite different from that of cooked potatoes. Additionally, the volatiles produced from major cooking procedures differ significantly each other (Whitfield and Last 1991). Therefore, when studying the volatile fraction of potato tubers a distinction must be made between raw (Petersen *et al.* 1998), boiled (Nursten and Sheen 1974; Josephson and Lindsay 1987; Petersen *et al.* 1998; Oruna-Concha *et al.* 2002b), baked (Buttery *et al.* 1973; Coleman and Ho 1980; Coleman *et al.* 1981; Duck-ham *et al.* 2001, 2002), microwaved (Oruna-Concha *et al.* 2002a, 2002b), fried (Carlin *et al.* 1986; Wagner and Grosch 1997, 1998) and manufactured products such as extruded (Majcher and Jelén 2009) and dehydrated (Nissen *et al.* 2002; Laine *et al.* 2006) potatoes.

Sugars, amino acids and lipids are the main precursors of potato volatile compounds (Whitfield and Last 1991);

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Invited Review

Table 1 Current SDE applications in potato volatiles analysis.

Sample	Distillation (t-T)[a]	Extraction solvent	Instrumental technique[b]	Reference
Boiled potatoes	30 min - n.a.	Diethyl ether/pentane (1:1)	GC-MS (DB-WAX; 68.3 min)	Jensen *et al.* 1999
	120 min - 100°C	Dichloromethane	GC-MS (INNO-Wax; 90 min) GC-PND (INNO-Wax; 90 min) GC-O (INNO-Wax; 43.3 min)	Ulrich *et al.* 2000
	n.a. - 60°C	Dichloromethane	GC-MS (FFAP; 70 min)	Blanch *et al.* 2009
Baked potatoes	120 min - n.a.	Pentane/diethyl ether (9:1)	GC-MS (BPX-5; 66.75 min)	Oruna-Concha *et al.* 2001
Extruded potato snacks	120 min - 100°C	Ethyl ether/pentane (1:1)	GC-O and GC-MS (SBP-5; 30 min - Supelcowax 10; 40.5 min)	Majcher and Jelén 2009
Potato flakes	30 min - n.a.	Diethyl ether	GC-MS (n.a.)	Nissen *et al.* 2002

[a] Distillation time (min) and temperature (°C)
[b] Separation and detection technique (column stationary phase; analysis time, min)
n.a. Not available data

their formation can be due to enzymatic or chemical reactions that have been recently overviewed (Dresow and Böhm 2009). The flavour profile of potatoes depends both on the cooking procedure and numerous other factors like cultivar selection, agronomic and storage conditions. Moreover, the extraction technique used during the analysis may affect the nature and the quantity of volatiles isolated.

Potato flavour has been widely investigated in recent reviews by Dresow and Böhm (2009) and by Jansky (2010), with emphasis on the role of agricultural environments on flavour compounds. In 1994, Maga described the occurrence, formation and control procedures of volatile and non-volatile flavour components of raw and processed potatoes.

The present review updates the information on the volatile components of potato tubers, and gives particular attention to the cooking or processing method. In the first part, a brief summary of the main extraction and analytical techniques used in potato flavour analysis is presented. As this study takes into account the sensory analysis of potatoes, and the findings concerned with the volatile profile are reported, a brief explanation of the definitions used should be made. "Flavour" is usually defined as the complex combination of the olfactory (orthonasal and retronasal perceptions), gustatory and trigeminal sensations perceived during tasting. Volatile, non-volatile components and mouthfeel sensations interact to determine food flavour. The term "Odour" refers to the direct olfactory component of flavour (orthonasal perception), while "Aroma" describes the attributes perceptible by the olfactory organ via the back of the nose (International Standard ISO 5492, 2008-10-15). However, these terms are sometimes used with different meanings, e.g. "Flavour" may refer to the volatile profile only or to the retronasal olfactory perception during tasting. For accuracy, in this review focusing on the sensory and instrumental analysis of the volatile fraction of raw and processed potatoes, the terms aroma and flavour are used synonymously, limiting them to the olfactory stimuli, without taking into account taste and mouthfeel sensations.

INSTRUMENTAL ANALYSIS

To determine which compounds are responsible for the flavour of a food product, one crucial step is to select a suitable method for their isolation. This procedure should allow the extraction of all compounds that contribute to flavour of the food product, but not alter the profile of characteristic volatiles, and in particular it should not form artefacts. An additional difficulty in the isolation of volatile compounds is their presence in a wide range of concentrations from ng/kg to mg/kg, and their odour thresholds, which are often below detection limits using conventional GC detectors. Therefore, GC-MS and gas chromatography–olfactometry (GC–O) are usually used to characterize the aroma profile of a food product. Several extraction methods for isolating crucial compounds of potatoes have been used; among these are distillation techniques like simultaneous distillation and extraction (SDE) (Nickerson and Likens 1966), solvent extraction techniques such as solvent-assisted flavour evaporation (SAFE) (Engel *et al.* 1999), headspace methods such as static and dynamic headspace and solid-phase microextraction (SPME) (Pawliszyn 1997).

Extraction and concentration techniques

1. Simultaneous distillation and extraction (SDE)

The SDE method, developed by Nickerson and Likens in 1966, was essentially based on steam distillation of volatile compounds at high temperatures for extended times, but it has been performed with numerous variations from the original version (Buttery *et al.* 1970; Nursten and Sheen 1974; Mutti and Grosch 1999; Ulrich *et al.* 2000).

Due to the analytical conditions required, this process may lead to the creation of new aromatic substances, especially during extended treatments. This extraction is performed with dedicated equipment and assures good detection limits. **Table 1** reports recent SDE applications in potato analysis.

2. Solvent and direct solvent extraction techniques

Solvent extraction is a simple and efficient technique for aroma isolation. The major limitation of this method is that if the food contains lipids, they will also be extracted along with the aroma constituents, and consequently they must be removed prior to further analysis. The separation of aroma components from extracts containing lipids can be performed via molecular distillation, steam distillation and dynamic headspace. Despite bias added by further distillation procedures, this combination (solvent extraction followed by distillation) has been widely applied due to its efficiency at isolating a broad range of volatiles. Engel *et al.* (1999) developed a much more rapid and yet highly efficient Solvent Assisted Flavour Evaporation (SAFE) distillation head, which is now widely used.

The extraction procedure has been employed in several investigations by Petersen *et al.* (1998, 1999, 2003) to explore the volatile fraction of raw shredded and boiled potatoes. They developed a mild extraction procedure in which a large quantity of sample (from 150 to 280 g of food matrix) was homogenized with variable amounts of tap water to ensure sufficiently low viscosity prior to extraction with diethyl ether/pentane (1: 1). The sample was stirred until an emulsion was created, frozen and non-frozen organic phases were discarded. After drying by adding Na_2SO_4, the sample was concentrated and finally analyzed by GC-MS and GC-O.

In order to reduce the interference of starch and oils and increase the concentration of the extract, Petersen (1999) also evaluated the vacuum distillation of volatiles. In this case, a large quantity of boiled potatoes (333 g) was mixed with water and the suspension was distilled at 36-39°C at a vacuum pressure of 20 mbar. The distillate was extracted with ether/pentane under magnetic stirring, the phases were separated using a funnel and the organic phase dried and concentrated by blowing nitrogen on the surface. A similar

Table 2 Current DH applications in potato volatiles analysis.

Sample	Ext. gas[a]	Ext. time[b]	Adsorption polymer	Trap dimensions	Desorption conditions	Instrumental technique[c]	Reference
Boiled potatoes	120 mL/min	20 min	Tenax TA (85 mg)	105 mm - 3 mm	10 min - 260°C	GC-MS (CP-SIL 8 CB low bleed; 70.5 min)	Oruna-Concha *et al.* 2002b
	200 mL/min	60 min	Tenax (100 mg)	n.a.	n.a.	GC-MS (J&W DB-Wax; 68.3 min)	Thybo *et al.* 2006
Baked potatoes	120 mL/min	20 min	Tenax TA (85 mg)	105 mm - 3 mm	10 min - 260°C	GC-MS (CP-SIL 8 CB low bleed; 70.5 min)	Duckhman *et al.* 2001, 2002; Oruna-Concha *et al.* 2002a, 2002b
Fried potatoes	50 mL/min	30 min	Tenax TA (100 mg)	100 mm - 3 mm	5 min - 245°C	GC-FID, GC-MS, GC-O (MDN-5S; 66.5 min)	Van Loon *et al.* 2005
	40 mL/min	60 min	Tenax TA (85 mg)	155 mm - 3 mm	5 min - 280°C	GC-MS (Cp-Sil8; 62 min)	Martin and Ames 2001
Potato flour	40 mL/min	45 min	Tenax TA (85 mg)	3.5 in. - 0.25 in.	10 min - 300°C	GC-MS (DB-5; VF-WAXms; 54.5 min)	Elmore *et al.* 2010

[a] Flow of the extraction gas (mL/min)
[b] Extraction time (min)
[c] Separation and detection technique (column stationary phase; analysis time, min)

procedure was used by Majcher and Jelén (2009) who applied the SAFE technique to extruded and dried potato snacks by using a small amount of sample to extract volatile compounds (20 g).

Direct solvent extraction is a very simple and convenient technique, and it is frequently carried out with a Soxhlet extractor. It has been applied to isolate potent odorant from both boiled potatoes (Mutti and Grosch 1999) and French fries (Wagner and Grosch 1997, 1998).

Samples were dried, ground finely, placed in a Soxhlet thimble and extracted with dichloromethane (Wagner and Grosch 1998; Mutti and Grosch 1999) or diethyl ether (Wagner and Grosch 1997). The extract was concentrated by distilling off the solvent; the aromatic fraction and the solvent were purified by distillation under high vacuum, using the apparatus reported by Sen *et al.* (1991) and Jung *et al.* (1992). Next, volatiles were separated into neutral/basic and acidic fractions before their identification on HRGC/MS and HRGC/O equipments.

3. Headspace analysis

The original headspace procedure, named Static Headspace (SH), involves static recovery in which the sample is equilibrated in a sealed container at a controlled temperature; however, low sensitivities are usually obtained (Sides *et al.* 2000). The Dynamic Headspace (DH) technique, in contrast, is based on the stripping of volatile components with a flow of inert gas (e.g. N_2, He), their subsequent adsorption by polymers and desorption in GC. Quantitative extraction is granted by high temperatures, such as those employed by Salinas *et al.* (1994), who extracted the aromatic compounds from cooked and reconstituted dehydrated potatoes at 100°C for 1 h, or by extended treatments such as those described by Josephson and Lindsay (1987) who performed extraction for 15 h at 21°C. Under these conditions, enzymatic reactions may take place and synthesize *ex novo* aromatic components that were not present before the extraction. The DH is extensively used in volatile extraction from potato samples and current applications are shown in **Table 2**. In all applications, the carrier gas used is nitrogen, and the flask containing the sample was frequently held in a water bath at 37°C during extraction.

Only three applications of SH have been recently reported in potato flavour analysis. Limbo and Piergiovanni (2007) used a static headspace analyser to extract volatiles from raw potatoes; Wagner and Grosch (1998), moreover, applied the SH analysis to isolate methylpropanal, 2,3-butanedione and methanethiol from frozen French fries; a similar technique was applied to investigate perceivable odours in fresh and stored French fries (Wagner and Grosch 1997).

4. Solid-Phase Microextraction (SPME)

In 1990, solid-phase microextraction (SPME) was developed by Arthur and Pawliszyn as a sample pre-concentration method, as an alternative to DH, before chromatogramphic analysis. In this technique, an inert fibre, coated with a stationary phase, is placed in the headspace of the sample (Headspace Solid-Phase Microextraction, HS-SPME) or inside the sample itself if the liquid (Direct Immersion Solid-Phase Microextraction, DI-SPME) allows volatile adsorption. The loaded fibre is thermally desorbed into a GC carrier gas flow, and the volatiles released are analyzed (Reineccius 2006). The optimization of solid-phase microextraction conditions includes, in addition to the selection of the operative mode (HS-SPME and DI-SPME) and the fibre coatings, the equilibration, adsorption and desorption conditions (temperature and duration). With regards to the fibre coatings, different stationary phases are available, including polydimethylsiloxane (PDMS) carbowax/divinylbenzene (CW/DVB), divinylbenzene/carboxen/polydimethylosiloxane (DVB/CAR/PDMS), carboxen/polydimethylsiloxane (CAR/PDMS) and polydimethylsiloxane/divinylbenzene (PDMS/DVB).

This technique has been applied to various food flavour and off-flavour analyses (vegetables and fruits, beverages, dairy products, oils and other food), pesticides, agrochemicals and food contaminants (Kataoka *et al.* 2000). To the best of our knowledge, only the headspace operative mode (HS-SPME) has been used in volatile analysis of potatoes, as summarized in **Table 3**.

Separation and identification techniques

1. Gas Chromatography - Mass Spectrometry (GC-MS)

Mass spectrometry is used to either determine the identity of an unknown volatile compound or can also act as a mass-selective GC detector. It is advisable that MS identifications are supported by other data such as GC retention data, infrared spectroscopy or nuclear magnetic resonance. MS can be operated in selected ion detection mode (SIM), multiple-ion mode (MIM) or full scan mode. In the SIM or MIM mode, the MS measures only selected ions at very short time intervals throughout a GC run, leading to greater sensitivity and a larger number of scans than full scan detection mode.

The magnetic sector or quadrupole requires significant time to scan a typical mass range, while ion trap (GC-ITMS) and time-of-flight (GC-TOFMS) MS detectors, in contrast, can collect spectra much faster (ion trap about 10–15 spectra/sec and TOF up to 500 spectra/sec). The TOF instrument can take a large number of spectra across a GC peak and reduce noise, thereby improving both sensitivity and detection limits. Another advantage is the deconvolution of mixed spectra, i.e. the resolution of the MS data of

Table 3 Current HS-SPME applications in potato volatiles analysis.

Sample	Fiber	Equilibration (t-T)[a]	Extraction (t-T)[b]	Desorption (t-T)[c]	Instrumental technique[d]	Reference
Raw potatoes	DVB/CAR/PDMS (50/30 μm)	5 min - 80°C	20 min - 60°C	5 min - 250°C	GC-MS (Rtx-1; 86.7 min)	Longobardi *et al.* 2010
Boiled potatoes	DVB/CAR/PDMS (50/30 μm)	10 min - 37°C	30 min - 37°C	3 min - 250°C	GC-MS (ZB-WAX; 63.3 min)	Blanda *et al.* 2010
Steamed potatoes	PDMS (85 μm)	n.a.	20 min - 50°C	2 min - 280°C	GC-MS (DB1701; 42 min)	Morris *et al.* 2010
Potato chips	PDMS (100 μm)	5 min - 30°C	60 min - 30°C	5 min - 250°C	GC-ITMS (HP-VOC fused silica; 41 min)	Lojzova *et al.* 2009
	CW/DVB (65 μm)					
	DVB/CAR/PDMS (30/50 μm)			2 min - 250°C	GC-TOFMS (HP-VOC fused silica; 38 min)	
	PDMS/DVB (65 μm)				GC x GC-TOFMS (HP-VOC fused silica and Supelcowax 10; 38 min + 38 min)	
	DVB/CAR/PDSM (50/30 μm)	n.a.	15 min - 60°C	3 min - 250°C	GC-FID (SP2330 fused silica; 35 min)	Pangloli *et al.* 2002
	PDMS/DVB (65 μm)					
Potato crisps	DVB/CAR/PDSM (50/30 μm)	5 min - 70°C	20 min - 70°C	5 min - 250°C	GC-MS (DB-5; 22 min)	Sanches-Silva *et al.* 2004
	CAR/PDMS (75 μm)	5 min - 70°C	20 min - 70°C	3 min - 260°C	GC-MS (DB-5; 22 min)	Sanches-Silva *et al.* 2005
	PDMS/DVB (65 μm)					
	DVB/CAR/PDMS (50/30 μm)					
Extruded potato snacks	PDMS	10 min - 50°C	30 min - 50°C	5 min	GC-O and GC-MS (SBP-5; 30 min - Supelcowax 10; 40.5 min)	Majcher and Jelén 2009
	CW/DVB					
	DVB/CAR/PDMS					
	PDMS/DVB					
	CAR/PDMS					
Potato flakes	PDMS	10 min - 35°C	60 min - 35°C	270°C	GC-MS (CP-WAX 52 CB; 35.5 min)	Laine *et al.* 2006
	CAR/PDMS/DVB					
	PDMS/DVB					
	CAR/PDMS					

[a] Equilibration conditions: time (min) and temperature (°C)
[b] Extraction conditions: time (min) and temperature (°C)
[c] Desorption conditions: time (min) and temperature (°C)
[d] Separation and detection technique (column stationary phase; analysis time, min)

one compound from a mixture of compounds that co-elute. The deconvolution process may also be implemented using two-dimensional GC, which involves collecting part of a GC run and re-chromatographing it on a different chromatographic phase. These systems typically permit the collection of a selected part of several GC runs, improving sensitivity (Reineccius 2006). All these techniques have been used for analysis of raw and processed potato volatiles, as shown in **Tables 1-3**.

2. Gas Chromatography/Olfactometry (GC/O), Gas Chromatography-FID/Olfactometry (GC-FID/O), Gas Chromatography-MS/Olfactometry (GC-MS/O)

In GC/O, the human nose is used as a selective and sensitive detector of volatile compounds, and the odour character of GC peaks is shown in an aroma profile. The effluent from the GC column is mixed with air and water vapour and is perceived by human assessors who identify the odours of compounds eluting from the column. Several parameters have to be considered in the optimisation process, but usually the most significant error factors are those that affect the perception of aromas by sensory panellists (Reid 2003). The GC column effluent can be split in two portions, one going to a sniffing port and the remainder going to a flame ionization (FID) or a mass (MS) detector. In alternative, the GC run may be made by passing all of the GC column effluent to the nose at one time: the column is then connected to the instrument detector, and a second run made (Reineccius 2006).

Although a large number of volatile compounds are present in foods, not all contribute to aroma. Patton and Josephson (1957) proposed to estimate the importance of an aroma compound in defining the sensory character of a food by calculating the ratio of the concentration of the compound to its sensory threshold in that food. This ratio is known as the odour activity value (OAV) (also referred to as odour value, odour unit, flavour unit, or aroma value). Only compounds present above their sensory threshold concentrations in a food are likely to be significant contributors to aroma.

The major screening procedures for determining the key odorants in food are based on Aroma Extract Dilution Analysis (AEDA), developed by Ullrich and Grosch (1987), Aroma Extract Concentration Analysis (AECA), described by Kerscher and Grosch (1997), and CHARM Analysis developed by Acree and Barnard (1984). Diluted (or concentrated) samples, prepared by using one of the extraction techniques previously described, are evaluated by GC/O. The occurrence of an aroma (its retention time or Kovats index) is recorded in each dilution, and a greater number of dilutions in which an odorant is detected, is reflected in a higher CHARM or Dilution Value. AEDA has been used to identify the major odorants from boiled potatoes (Mutti and Grosch 1999) and French fries (Wagner and Grosch 1997, 1998).

SENSORY ANALYSIS

The sensory evaluation of a food can be made through discriminative, descriptive or affective tests. Discriminative tests investigate whether there is a sensory difference between samples (Stone and Sidel 1992). The most common are the triangle test, duo-trio test and paired comparison test.

Descriptive tests involve the detection and description of both qualitative and quantitative sensory components of a product by trained panels. Descriptive tests can establish relationships between descriptive sensory and instrumental or consumer preference measurements. There are several different methods of descriptive analysis, such as Flavour Profile and the Quantitative Descriptive Analysis (QDA).

The affective tests have the primary objective to assess

the personal response from users or potential users of a product (acceptance, preference, or consumer tests). A large number of individuals are required to take part in a sensory acceptance test (> 100). Preference can be measured directly by comparing two or more products with each other, or indirectly by determining which product is the most appreciated in a multiproduct test. The two most widely used methods to measure preference and acceptance are the paired comparison and the 9-point hedonic scale tests.

The sensory tests most frequently used for the evaluation of raw and processed potatoes are the Flavour Profile, QDA and the preference tests, as detailed in the following paragraphs.

VOLATILE COMPOUNDS IN RAW POTATOES

About 159 volatile compounds have been identified in raw potatoes (Dresow and Böhm 2009), but their aromatic profile has not been widely studied. Most investigations have focused on cut or sliced potatoes, and the main volatiles identified were those derived from oxidation and enzymatic activity. In particular, many compounds such as aldehydes, ketones and alcohols, derived from the lipoxygenase activity on unsaturated fatty acids were detected (Mazza and Pietrzak 1990; Maga 1994; Petersen *et al.* 1998). Significant products of potato lipid oxidation are hexanal, octenal and isomeric forms of 2,4-decadienal (Maga 1994). Some alcohols, like 2-methyl and 3-methylbutanol derived from leucine and isoleucine metabolism (Drawert *et al.* 1975). Other compounds identified in raw potatoes, and responsible for vegetable-like odours are methoxypyrazines. Their mechanism of formation has been investigated, and the biosynthetic pathway in potato tubers, or production from microflora present in soil or on the potato surface, have been hypothesized (Maga 1994; Dresow and Böhm 2009).

Longobardi *et al.* (2011) carried out HS-SPME/GC-MS on three potato cultivars ('Arinda', 'Sieglinde', and 'Red Cetica') produced in three different locations in Italy (Sicily, Apulia, Tuscany). 32 volatile compounds were identified and a discriminant function analysis (DFA) was applied on normalized data. The complete separation of potato samples of different geographical origin was achieved and the recognition ability was 100% for each class. The prediction ability was 91.7% and among 36 samples analysed, only four samples were incorrectly classified. The same classification results were obtained applying these statistical methods on the complete data set, including also isotopic data.

Recently, increasing attention has been given to ready-to-eat and ready-to-use vegetables with the specific aim of increasing the shelf life of these products since manufacturing operations promote the development of enzymatic browning and microbial growth (Beltrán *et al.* 2005). Modified atmospheres, in particular high oxygen partial pressures (10, 55 and 100 kPa O_2) in combination with ascorbic and citric acid dipping, have been applied to potato slices; the accumulation of volatile compounds (ethanol, acetaldehyde and hexanal) has been studied after 3, 7 and 10 days of storage at 5°C (Limbo *et al.* 2007). The higher pressures applied (55 and 100 kPa) had an inhibitory effect on the production of anaerobic volatiles (acetaldehyde and ethanol). In contrast, the lowest hexanal accumulation was obtained at 10 kPa O_2, and a substantial increase was recorded in potatoes that were not submitted to the treatment solution and stored at 100 kPa.

The sensory quality of fresh cut potatoes was investigated also by Beltrán *et al.* (2005) who evaluated the effect of traditional and non-traditional sanitizers on potato strips stored under modified atmosphere and vacuum packaging. Sodium hypochlorite, sodium sulphite, peroxyacetic acid and ozone were used either alone or in combination. The aroma of the strips was evaluated by an expert panel after 5, 11 and 14 days of storage. The best sensory characteristics, were obtained with vacuum packaging. When the modified atmosphere was used, the application of sodium sulphite prevented browning, but it conferred off-odours to potato strips. When the dipping process was carried out in ozonated water and in ozone plus peroxyacetic acid solutions, potato strips stored under vacuum conditions maintained the typical full aroma even after storage for 14 days at 4°C; the authors concluded that the latter treatment was optimal as it could also preserve the microbial quality of the potato strips.

VOLATILE COMPOUNDS IN PROCESSED POTATOES

The sensory profile of processed potatoes is related to the way of cooking but also cultivar selection has an important role, as reported in the following investigations. Sensory properties of different potato varieties have been evaluated by Pardo *et al.* (2000) through the assessment of satisfaction on a verbal hedonic scale. The authors compared 7 varieties ('Bartina', 'Caesar', 'Desirée', 'Agria', 'Edzina', 'Monalisa' and 'Victoria') and found that 'Bartina' was preferred for the flavour in fried products, while 'Victoria' and 'Desirée' were best in terms of flavour for boiled potatoes. These different scores, depending on frying or boiling, suggest a specific use for each potato variety.

Seefeldt *et al.* (2011a) investigated visual, texture, taste and flavour attributes of 11 potato varieties ('Asparges', 'Ballerina', 'Bintje', 'Ditta', 'Folva', 'Hamlet', 'Liva', 'Spunta', 'Sava', 'Saturna' and 'Vivi') grown in loamy and sandy locations and used for three culinary preparations (mashed, oven-fried and boiled potatoes). They found that texture and appearance were the most important attributes for the sensory evaluation of the different culinary preparations, whereas flavour played a minor role for describing potato quality. Also the effect of soil type on flavour and taste was relatively low for all preparations.

Relevant investigations carried out after 1995 and concerning the volatile profile of boiled, baked, fried, dehydrated and extruded potato products are presented. In **Table 4** are reported new volatile compounds detected in boiled potatoes respect those summarized by Dresow and Böhm (2009); advances in the aromatic profile of fried (chips, French fries and crisps), dehydrated and extruded potatoes are also shown, updating the results reported by Maga (1994).

Boiled potatoes

The aroma of boiled potatoes is weak, although it is distinct and very different from the aroma of raw potatoes. Several mechanisms are responsible for the thermal formation of aroma compounds in boiled potatoes, including lipoxygenase-initiated reactions of unsaturated fatty acids that take place after disruption of cells and create large amounts of 2,4-decadienal, (*E*)-2-octenal and hexanal; the autoxidation reactions are responsible for pentanal generation and the Maillard and Strecker reactions lead to components like pyrazines, phenylacetaldehyde and methional (Maga 1994).

Petersen *et al.* (1998) compared the aroma of raw and boiled potatoes of the 'Bintje' variety using a mild extraction technique to ensure major preservation of the more labile compounds of potato aroma. 29 and 25 compounds were identified in raw and boiled extracts, respectively, by GC-MS. The results were in agreement with those previously reported by Josephson and Lindsay (1987), who found that raw shredded potatoes contained relatively high amounts of 2,4-decadienal, (*E*)-2-octenal and hexanal. After boiling, the concentration of the first two compounds decreased, while hexanal increased to become the dominant volatile. Moreover, GC odour profiling of raw and boiled potatoes was performed by evaluating the odour quality and intensity of potato extracts after separation on GC column. 33 odour impressions were detected in boiled potatoes: 8 of them were identified by GC-MS (2-ethyl furan, hexanal, heptanal, (*E*)-2-heptenal, acetic acid, methional, (*E,Z*)-2,6-nonadienal and phenylacetaldehyde) and 4 by the retention index and quality odour ((Z)-4-heptenal, 2-heptanol, 2-

Table 4 New volatile compounds identified in processed potatoes.

	Boiled[a]	Fried[b]	Ext-De[c]		Boiled[a]	Fried[b]	Ext-De[c]
Hydrocarbons				Undecanal	9		
Propylcyclopentane		5		2-Undecenal	9		
Butylcyclopentane		5		4-Ethylbenzaldehyde	9		
Propylcyclohexane		5		2-Hydroxybenzaldehyde		5	
2,2,4,6,6-Pentamethyl heptane			3	4-Hydroxy-3-methoxybenzaldehyde		7	
Bicyclo-2,2,2-1-methyloctane		11		5-Ethyl-1-cyclopentene-1-carboxaldehyde		5	
Hexadecane	9			**Ketones**			
3-Ethyl-2-methyl-1,3-hexadiene	9			2,3-Butanedione			4
1-Heptene		5		6-Methyl-5-penten-2-one	6		
6-Methyl-1-heptene		11		2-Methyl-3-hexanone		5	
1-Octene		5		1-Octen-3-one		7;8	
(E)-2-Octene		5		3-Octen-2-one	9		3
(Z)-2-Octene		5		*(E)*-3-Octen-2-one		11	
Styrene		5		1,5-Octadien-3-one			4
α-Ionone			3	*(Z)*-1,5-Octadien-3-one		7	
α-Curcumene			3	3,5-Octadien-2-one			3
Alcohols				3-Nonen-2-one		11	
Ethanol			4	6-Undecanone	9		
2-Propanol		5		6-Dodecanone	9		
1-Undecanol		5		β-Damascenone			4
Dodecanol	6			**Esters**			
1-Dodecen-3-ol	9			Pentyl methanoate		11	
Tetradecanol	6			Methyl acetate		5	
1,5-Heptadiene-3,4-diol		11		*n*-Hexyl acetate	9		
Acids				Methyl 2-propenoate		5	
2-Octenoic acid		11		Hexyl-propanoate	9		
Phenyletanoic acid		7		Methyl butanoate	9		
Aldehydes				*(E)*-Methyl 2-butenoate		5	
Acetaldehyde			1	Butyl butanoate	9		
Propanal			1	Methyl 3-methylbutanoate		5	
Methylpropanal		2		Methylbutyl butanoate	9		
2-Methyl propanal			3	Hexyl-butanoate	9		
Butanal			4	Butyl hexanoate	9		
2-Methyl butanal			3	Pentyl hexanoate		11	
3-Methyl butanal			3	Hexyl hexanoate	9		
(E)-2-Ethyl-2-butenal		5		Ethyl octanoate	9		
Pentanal	6		3	**Lactones**			
Hexanal			1;3;4	γ-Octalactone		8	
(E)-2-Hexenal			4	γ-Nonalactone		8	
Heptanal			4	γ-Decalactone		8	
2-Heptenal			3	δ-Decalactone		8	
(E,Z)-2,4-Heptadienal		5		4-Hydroxynonanoic acid lactone		7	
Octanal			4	4-Hydroxy-2-nonenoic acid lactone		7	
(E)-2-Octenal			4	**Pyrrole compounds**			
Nonanal			4	Pyrrole		5;10	
(Z)-3-Nonenal		7		2-Acetylpyrrole		10	
(E,E)-2,4-Nonadienal			1	3-Acetyl-1-methylpyrrole		10	
(E,Z)-2,6-Nonadienal		7		2-Methylpyrrole		5	
2,6-Nonadienal			4	2-Methyl-1(*H*)-pyrrole		10	
trans-4,5-Epoxy-*(E)*-2-nonenal		7		3-Methyl-1(*H*)-pyrrole		10	
(E)-2-Decenal		7		1-Ethylpyrrole		5	
(E)-4,5-Epoxy-*(E)*-2-decenal		7;8		1-Ethyl-1(*H*)-pyrrole		10	
(E,E)-2,4-Decadienal			1	2-Ethyl-1(*H*)-pyrrole		10	
1-Butyl-1-(*H*)-pyrrole		10		2-Acetylpyrazine		7	4
1-Pentyl-1(*H*)-pyrrole		10		2-Acetyl-6-methylpyrazine		10	
2-Pyrrolidinone		10		2-Butyl-3-methylpyrazine		10	
1-Methyl-2-pyrrolidinone		5;10		2-Ethenyl-3-ethyl-5-methylpyrazine		7;8	
2-Acetyl-1-pyrroline			4	2-Ethenyl-5-methylpyrazine		10	
1-(*H*)-pyrrole-2-carboxaldehyde		10		2-Ethenyl-6-methylpyrazine		10	
1-Methyl-1(*H*)-pyrrole-2-carboxaldehyde		10		2-Isobutyl-3-methoxypyrazyne		7	
1-Pyrrolidinecarboxaldehyde		10		2-Methyl-3,5-diethylpyrazine			4
Oxazoles				2-Methyl-5-(1-propenyl)-pyrazine		10	
4,5-Dimethyloxazole		5		2-Vinyl-6-methylpyrazine		2	
Indols				3,5-Diethyl-2-methyl-pyrazine		10	
2,3-Dihydroindole		5		3,5-Dimethyl-2-isobutyl-pyrazine		10	
Furan compounds				3-Isobutyl-2-methoxypyrazine		8	
2-Methylfuran		5		5-Ethyl-2,3-dimethylpyrazine		5	
2-Ethylfuran		5		5-Methyl-2,3-diethylpyrazine			4
2-Ethyl-5-methylfuran		5		5-Methyl-5(*H*)-cyclopentan-pyrazine		10	
2-Vinylfuran		5		Dimethylisobutylpyrazine isomer		5	
2,5-Dihydro-3,4-dimethylfuran		5		Ethenylpyrazine		10	

Table 4 (Cont.)

	Boiled[a]	Fried[b]	Ext-De[c]
Tetrahydrofuran		5	
Tetrahydro-2-methyl furan		11	
5-Ethyl-dihydro-2(3)-furanone		11	
5-Pentyl-2(5)-furanone		11	
5-Hexylhydro-2(3)-furanone		11	
3-Hydroxy-4,5-dimethyl-2(*5H*)-furanone		7;8	4
4-Hydroxy-2,5-dimethyl-3(*2H*)-furanone		7;8	4
2,5-Furandione		5	
2-Furfurylthiol			4
2,5-Dimetyl-3-furanthiol			4
Pyrane compounds			
trans-Tetrahydro-5,6-dimethyl-2(*H*)-2-pyranone		11	
3-Hydroxy-2-methylpyran-4-one		7	
Pyridine compounds			
Pyridine		10	
2-Methyl pyridine		10	
3-Methyl pyridine		10	
2,6-Dimethyl pyridine		10	
3-Ethyl pyridine		10	
Acetyl pyridine		10	
n-Acetyl-4(*H*)-pyridine		10	
1-Acetyl-1,2,3,4-tetrahydro-pyridine		10	
1-(2-Pyridinyl)-1-propanone		10	
2-Pyridinecarboxaldehyde		10	
Pyrazines			
(1-Methylethenyl)-pyrazine		10	
2-(*n*-Propyl)-pyrazine		10	
2,3,5,6-Tetramethylpyrazine		10	
2,3-Diethylpyrazine		5;10	
Ethylpyrazine		2;5;10	
Isopropenylpyrazine		5	
Tetramethylpyrazine		10	
Vinylpyrazine		2	
5,6,7,8-Tetrahydroquinoxaline		10	
Sulphur compounds			
Methanethiol			3;4
Phenyl methanethiol			4
Dimethyl disulfide			3
Dimethyl trisulfide			4
2-Methylthiophene		5	
3-Methylthiophene		5	

[a] New volatiles in boiled potatoes respect Dresow and Böhm (2009)
[b] New volatiles in chips, French fries and crisps respect Maga (1994)
[c] New volatiles in extruded an dehydrated potato products respect to Maga (1994)
1 Nissen *et al.* 2002
2 Martin and Ames 2001
3 Laine *et al.* 2006
4 Majcher and Jelén 2009
5 Van Loon *et al.* 2005
6 Blanch *et al.* 2009
7 Wagner and Grosch 1997
8 Wagner and Grosch 1998
9 Blanda *et al.* 2010
10 Lojzova *et al.* 2009
11 Sanches-Silva *et al.* 2005

methoxy-3-isopropylpyrazyne and 2-methoxy-3-isobutylpyrazine). The remaining odours were not found because they were present at concentrations below the detection limits of GC-MS.

In 1999, Mutti and Grosch evaluated the potent odorants of boiled potatoes (variety 'Sieglinde') by aroma extract dilution analysis, aroma extract concentration analysis and GCO of static headspace samples. The volatiles isolated from potato samples were separated into neutral/basic and acidic fractions. In the neutral/basic fraction, 29 odorants were detected and the most odour active compounds were found to be methional (boiled potato odour) and 4,5-epoxy-(*E*)-2-decenal (metallic odour), evaluated on the basis of the flavour dilution (FD) factor. In the acidic fraction, the highest FD factor was shown by vanillin.

Ulrich *et al.* (2000) used sensory techniques and instrumental analysis to illustrate the differences in aroma among 3 German varieties ('Adretta', 'Likaria' and the breeding clone St 1,365) of potato after boiling. The off-flavours components contributed more than the positive ones to differentiate the aroma of the varieties tested, and the main compounds implicated in these differences included (*E*)-2-pentenal, 2-methylbutanol, 2-pentylfuran, pyrrole and different dienals. Essential aroma compounds, similar between the three varieties, were methional, diacetyl and 5 substituted pyrazines, in agreement with former investigations (Salinas *et al.* 1994; Ulrich *et al.* 1997, 1998).

A sensory profiling of several Danish potato varieties grown in different locations has recently been carried out (Kreutzmann *et al*. 2011). A tailor-made sensory profile was developed for different cooking procedures: boiled, mashed, oven-fried and oven-cooked potatoes. The study showed that flavour and taste attributes were significantly correlated and they had a great importance in describing the variations between potato cultivars. In particular, the flavour of boiled potatoes was correlated to the bitterness attribute, while in mashed potatoes potato the flavour was found to be inversely correlated to graininess. The relevance of using sensory descriptors to define appropriateness of potato cultivars for different culinary preparations has been discussed also by Seefeldt *et al*. (2011b).

Currently, several investigations have been carried out concerning off-flavour development in potatoes, and mostly related their development during storage of raw potatoes, and dehydrated potato products (Maga 1994). Moreover, it was noted that when boiled potatoes are stored they rapidly develop off-flavours, one of the most important of which is described as a cardboard-like note. Petersen *et al.* (1998) performed a sensory evaluation of freshly boiled and boiled stored potatoes, followed by GC-MS and GC-sniffing to identify and quantify the compounds responsible for potato off-flavours (POF). Eight compounds (pentanal, hexanal, nonanal, (*E*)-2-octenal, 2,4-heptadienal, (*E*)-2-nonenal, (*E,E*)-2,4-nonedienal and 2,4-decadienal) were identified as potential contributors to POF.

The authors assumed that such potato off-flavours, mainly represented by aldehydes and some alcohols, were produced during 24 h storage from the breakdown of hydroperoxides, resulted from lipoxygenase initiated oxidation of linoleic and linolenic acid during boiling.

To better explain the mechanism of formation of off-flavours in boiled potatoes, with particular emphasis to lipoxygenase activity, Petersen *et al.* (2003) monitored lipoxygenase activity and the content of volatile compounds mainly responsible for the formation of off-flavour (pentanal, hexanal, (*E*)-2-octenal, (*E*)-2-nonenal, (*E,E*)-2,4-nonadienal and (*E,E*)-2,4-decadienal) in potatoes during winter storage. Aroma compounds were determined at 3, 4 and 7 months after harvest in raw, freshly boiled and in boiled potatoes refrigerated for 24 h. It was found that lipoxygenase activity increased during long-term storage of raw potatoes, starting from 4 months after harvest. However, the increasing lipoxygenase activity during winter storage was accompanied by a decrease in production of the off-flavour compounds when potatoes were stored after boiling. The production of off-flavours during storage of boiled potatoes could not be explained by changes in lipoxygenase activity, and the authors highlighted the needing for further investigations on the availability of substrates leading to production of important aroma compounds in boiled potatoes.

Conventionally, potatoes are stored for long periods after harvest in order to provide a yearlong supply for industry and final consumers. Storage conditions before cooking is an important factor in determining the composition of sensory characteristics of boiled potatoes. In fact, several modifications occur in tuber composition during storage: fatty acids, sugars and amino acids are particularly involved in these changes.

Blanch *et al.* (2009) studied the effect of storage temperature before cooking on boiled potato lipid and sugar-derived volatile constituents by comparing 2 genotypes of *S. phureja* and one of *S. tuberosum*, stored at 4 and 8°C. It was

found that the storage temperature affected lipid-derived volatile components, on the basis of the variety studied, but in general the sugar-derived volatile constituents increased when lower temperatures were used, probably due to a slow metabolism. These conditions inhibited lipid oxidation and lowered the levels of lipid-derived compounds in the final product. The authors recommended to store potato tubers at 8°C since the formation of Maillard products was minimised and no signal of sprouts was observed.

Several agronomic factors may influence the sensory quality of boiled potatoes in addition to variety, including the type of fertilizer and method of application, soil type and climatic factors. Thybo *et al.* (2002) investigated the effect of 6 different organic treatments (cattle slurry and cattle deep litter applied in three ways, corresponding to an equal supply of total nitrogen) on the chemical, rheological and sensory quality of cooled potatoes. Regarding sensory quality, minor differences were found among the organic treatments investigated. Despite such small differences, statistical analysis showed that compared with deep litter, slurry increased the off-odour perception and decreased the typical potato odour and flavour, probably due to the delay in maturation retarding the production of the flavour components. Moreover, potatoes matured with slurry had slightly higher off-odour and off-flavour, but the differences were extremely small.

Minimally-processed potatoes have been studied in recent years with regards to sensory quality and chemical components, some applications of which include raw pre-peeled and precooked vacuum-packed potatoes. Thybo *et al.* (2006) compared 6 different cultivars ('Berber', 'Arkula', 'Marabel', 'Sava', 'Folva' and 'Agria') and evaluated their suitability to be processed as pre-peeled potatoes, taking into account the effects of wound healing and storage time. Concerning the volatile profile, variations in several aroma components were found, such as methional, linalool, *p*-cymene, nonanal and decanal, mainly caused by the effects of cultivar and storage. The highest concentrations of nonanal and decanal were found in the 'Marabel' and 'Berber' cultivars, which showed a high intensity of rancidness and a low intensity in potato flavour. Owing to the high moistness and the low firmness, the 'Marabel' variety seemed to be a less appropriate cultivar for this type of product.

Jensen *et al.* (1999) used precooked vacuum-packed potatoes to evaluate the development of potato off-flavours (POF) in 4 varieties ('Jutlandia', 'Bintje', 'Sava' and 'Dali') grown in two different locations in Denmark. They found statistically significant differences in the content of POF compounds between the growing location (mainly for 'Jutlandia' and 'Sava') among some of the varieties. The growing location effect can be explained by the environmental conditions throughout the period of growing, harvest and storage. The most potent POF compounds, evaluated on the basis of their aroma values (Rothe and Thomas 1963), were (*E,E*)-2,4-nonadienal and (*E,E*)-2,4-decadienal, followed by hexanal, (*E*)-2-octenal and (*E*)-2-nonenal. The results of this study showed that agronomic conditions can influence POF formation in precooked vacuum-packed potatoes.

Off-flavour development in boiled potato slices has also been studied by Blanda *et al.* (2010). The authors performed a sensory evaluation system, using a quantitative-descriptive analysis (QDA) scheme, and defined the odour, flavour and texture features of boiled potato slices. A HS-SPME-GC-MS method was developed to determine the volatile components in boiled potatoes, and investigation of the mechanism of generation of off-odours and off-flavours during storage showed that they did not increase linearly with time, but reached a maximum value after 6 h of storage, further decreasing after 8 and 10 h and finally increasing again after 24 h of storage. This trend was explained by a kinetic mechanism involving the formation of hydroperoxides during the first hours of storage. POF formation was strongly correlated with a high content of aldehydes such as 2-penthylfuran, 2-pentenal, 2-hexenal, 2-heptenal and 2-decenal, and good agreement between the sensory evaluation and the HS-SPME/GC-MS analysis was found. Treatment of potato slices with several food additives (ascorbic acid, citric acid, sodium acid pyrophosphate and meta-bisulphite) after cooking was also investigated. Interestingly, ascorbic acid and citric acid did not prevent the formation of POF, but actually enhanced it; although potassium meta-bisulphite prevented POF formation, it caused the formation of other off-flavours. The best additive was sodium pyrophosphate, which did not change the flavour of potato slices during storage.

The impact of volatile and non-volatile metabolites on potato flavour attributes was investigated by Morris *et al.* (2010). Tubers (*S. tuberosum* group Phureja and *S. tuberosum* group Tuberosum) were sampled at harvest and following 3 months' storage. Quantitative descriptive analysis (QDA) was carried out on boiled potatoes by a trained panel and aroma related attributes were evaluated. Moreover the cooked tuber volatile profile was analysed by SPME/GC-MS.

The authors found that hexanal and 2-methylbutanoic acid methyl ester were strongly negatively correlated with aroma intensity but positively correlated with flavour intensity, creaminess and savouriness. Conversely, metabolites positively associated with aroma intensity such as 2-methylbutanal, 3-methylbutanal, and furan were strongly negatively correlated with flavour intensity, savouriness and creaminess. Significant changes in flavour were related to storage: several aldehydes were found at higher levels after storage.

Baked potatoes

One of the most popular ways to cook fresh potatoes is by baking (Lin and Yen 2004). However, unlike boiled potatoes, which have been thoroughly investigated, baked potato flavour has been somewhat neglected, and up to 1994, only 11 publications have been reported (Maga 1994).

Volatiles from baked potatoes are usually classified based on the mechanism of formation. Fatty acids, sugars and amino acids are the main precursors of the compounds responsible for the flavour of baked potatoes (Whitfield and Last 1991). A high proportion of the compounds identified came from lipid oxidation, and many volatiles are formed from the Maillard reaction, with or without the involvement of sulphur-containing amino acids. Smaller amounts of indigenous flavour compounds such as terpenes and methoxypyrazines have also been identified.

Recent studies on baked potatoes have investigated the different flavour profile of skin and flesh potatoes, as well as the effect of storage, varietal and environmental factors on final aroma. Additionally, new cooking methods such as microwave baking have been studied and compared to traditional ones.

Oruna-Concha *et al.* (2001) reported the volatile flavour compounds of 4 different potato cultivars ('Cara', 'Marfona', 'Fianna' and 'Nadine') after baking and separately studied the volatile composition of skin and flesh. It was reported that their composition varied quantitatively and qualitatively among cultivars grown at different sites. Sugar degradation and/or the Maillard reaction were the major sources of volatiles in skin, largely due to pyrazines, in 'Cara', 'Marfona' and 'Fianna' cultivars. Solavetivone was the major volatile in 'Nadine' skins, suggesting that tubers of this cultivar were under stress during storage. Pyrazines, including 2,5- and/or 2,6-dimethylpyrazine, were the most abundant representatives in every cultivar.

'Fianna' gave the weakest volatile profile in flesh (85 ng/g), whereas 'Cara' gave the strongest (869 ng/g); lipid degradation was the predominant source of volatiles in 'Cara' (93% of the total volatiles, corresponding to 810 ng/g), and a major source in 'Fianna' (75% corresponding to 64 ng/g), but accounted only for 15% (14 ng/g) and 19% (21 ng/g), respectively, of the total volatiles in 'Nadine' and 'Marfona'. Levels of volatiles from sugar degradation and/or the Maillard reaction were similar (14-58 ng/g) in

the analysed cultivars.

The odour unit values were taken into account to select the key aroma compounds of skin and flesh baked potatoes. For skin, 2-isopropyl-3-methoxypyrazine has the highest odour unit value and has an important contribution to aroma only in 'Marfona', clearly distinguishing this cultivar from others. In flesh, (*E,E*)-2,4-decadienal appeared to be the most important contributor to aroma in 'Cara' and 'Fianna'. 'Marfona' was distinguished from the other cultivars by the contribution of dimethyl disulphide.

A varietal study was also carried out by Duckman *et al.* (2001) who examined the volatile flavour components in the flesh of 11 potato cultivars ('Nadine', 'Golden Wonder', 'Fianna', 'Estima', 'Cara', 'Saxon', 'Kerr's Pink', 'Maris Piper', 'Desiree', 'Marfona' and 'Pentland Squire') grown in the same location in Spalding. 81 volatile compounds were identified in this study and semiquantitative results, represented by relative GC peak area units, were reported.

Lipid oxidation and Maillard reaction were found to be the major sources of flavour compounds of baked potato flesh, even though other components (sulphur compounds, methoxypyrazines and terpenes) were also present at lower levels. Abundant representatives of lipid-derived products were hexanal, nonanal and decanal. The most abundant representatives of the Maillard reaction and/or sugar degradation were the Strecker aldehydes of isoleucine and leucine, i.e., 2- and 3-methylbutanal, which were identified in every cultivar and contributed to 75-96% of the volatiles in this category. 3,5-dimethyl-2-(2-methylpropyl)pyrazine was first reported in this study. Methional, considered to be one of the most important contributors to the aroma of baked potatoes (Whitfield and Last 1991), has been identified in only 5 cultivars ('Nadine', 'Desiree', 'Marfona', 'Maris Piper' and 'Pentland Squire'). In contrast, dimethyl disulphide (which can form from methional) was present in all cultivars and dimethyl trisulphide was reported in all except 'Golden Wonder'.

14 terpenes were identified, and 11 (α-pinene, *Z*-ocimene, *E*-ocimene, linalool, isophorone, β-cyclocitral, β-damascenone, α-copaene, geranyl acetone, α-aromadendrene and δ-guaiene) had not previously reported to be components of baked potato aroma.

2-isobutyl-3-methoxypyrazine, 2-isopropyl-3-methoxypyrazine, β-damascenone, dimethyl trisulphide, decanal and 3-methylbutanal were found to be major contributors to flavour in at least one cultivar.

Few studies have examined the effect of storage on flavour development after cooking. An extensive investigation was carried out by Duckham *et al.* (2002), who examined the effects of storage time (2, 3 and 8 months at 4°C) on the amounts of selected volatile flavour components in baked potatoes. Five potato cultivars ('Estima', 'Saxon', 'Golden Wonder', 'Kerr's pink' and 'Desiree') grown in different sites were analysed, and several significant differences were found in the levels of individual compounds, compound classes and total monitored compounds in terms of the individual effects of cultivar and storage time and their two-way interactions. A significant increase in the total amount of compounds between 2 and 3 months and between 3 and 8 months storage was recorded. The compounds derived primarily from lipids increased with storage time, as well as the total levels of Maillard/sugar-derived compounds. Individual terpenes (except 3-carene) and 2-isopropyl-3-methoxypyrazine were significantly higher after 3 months compared to the other storage times. Methional was the only sulphur compound that showed a significant storage time effect, decreasing between 3 and 8 months.

The authors suggested that cultivar, agronomic factors and tuber storage conditions affected the levels of flavour precursors and activities of enzymes that mediated the formation of flavour compounds.

Oruna Concha *et al.* (2002b) investigated the effects of 3 cooking procedures, boiling, conventional baking and microwave baking, on the profiles of flavour compounds of 2 cultivars of potato ('Estima' and 'Maris Piper') and identified 95 flavour compounds. The authors noted that microwave-baked potatoes had the weakest isolates of volatiles compounds among tested procedures. In particular, the total amounts of compounds derived from sugar degradation and/or the Maillard reaction, largely represented by 2- and 3-methylbutanal, were highest for conventionally-baked potatoes. However, the lipid-derived compounds were 1.2-1.5-fold higher with microwave baking. Sulphur compounds, such as terpenes and methoxypyrazine, showed no significant differences between conventional and microwave baking. The quantitative and qualitative differences for the flavour compounds were explained by variations in heat and mass transfer processes.

Oruna-Concha *et al.* (2002a) evaluated the effect of cultivar on volatile flavour compounds in potato baked in a microwave oven. The flavour components of the flesh of 8 cultivars ('Marfona', 'Desiree', 'King Edward', 'Fianna', 'Nadine', 'Pentland Squire', 'Saxon' and 'Cara') were isolated by headspace trapping onto Tenax and analysed by GC-MS. Each potato cultivar possessed a unique profile of volatile compounds. Cara had the lowest overall total amount of all categories of compounds, while King Edward had the highest. 80 compounds were identified in this study: 60 were lipid-derived, in contrast to 33 reported by the same authors from conventionally-baked potatoes (Oruna-Concha *et al.* 2001). Seven terpenes (one monoterpene and 6 sesquiterpenes), which were tentatively identified, had not been previously reported as volatile components of potatoes. No alkylpyrazines were identified in the microwave-baked potatoes, since they were more favoured by the conditions encountered during conventional baking of potato tubers. The authors suggested that total levels of compounds and variations among their profiles could be attributed to differences in the activities of lipid enzymes and levels of flavour precursors considering the range of cultivars investigated. Moreover, they recommended sensory analysis to identify the best cultivar for microwave baking.

Jansky (2008) evaluated the contributions of genotype and environment on the sensory properties of baked potatoes, including "potato-like" flavour and off-flavour intensities. Moreover, the relationship between the individual flavour components and the overall quality perception was determined. A trained panel evaluated 16 potato cultivars (russets, whites, reds and specialty clones) grown in different locations and stored for 2 years. Several differences among cultivars and production environments were found. Stored potatoes received higher quality perception scores than fresh potatoes. Potato-like flavour intensity was positively associated with quality perception, and a strong negative association between off-flavour and quality perception was also detected.

The sensory properties of organically farmed and conventionally produced potatoes have been recently investigated by Gilsenan *et al.* (2010), Hajšlová *et al.* (2005) and Wszelaki *et al.* (2005). No significant differences between organic and conventional cooked potatoes for aroma attributes were found.

Potato chips and French fries

Deep-fat frying is one of the oldest processes of food preparation, and consists in the immersion of food pieces in hot oil. The high temperature causes the evaporation of water, which moves away from the food into the surrounding oil that replaces some of the lost water. The aim of deep-fat frying is to seal the food by immersing it in hot oil so that all flavours and juices are retained by the crisp crust (Moreira *et al.* 1995).

The flavour of potato chips is influenced not only by potato tuber cultivar, but also by frying oil composition, temperature and time of frying (Martin and Ames 2001). More than 500 compounds have been identified in the volatile fraction of French fries and potato chips showing a similar aroma.

Wagner and Grosch (1997) identified potent odorants in

French fries by application of both aroma extract dilution analysis (AEDA) and GC-O of headspace samples. Potato strips of the Agria variety were fried in palm oil, and a total of 48 odorants were revealed; 23 components were reported for the first time as components of fried potatoes, also due to a difference in the analytical strategy employed, which enabled them to identify odorants that were not visible as peaks in the gas chromatogram. Among the odorants showing higher (FD) factors, methional, 2,3-diethyl-5-methylpyrazine, (*E,E*)-2,4-decadienal, 4-hydroxy-2,5-dimethyl-3 (2H)-furanone and 3-methylbutanal were used as reference stimuli for flavour profile analysis of French fries. The deep-fried note (caused by (*E,E*)-2,4-decadienal) predominated when French fries were nasally evaluated, whereas the deep-fried and boiled potato-like smells (caused by methional) were mainly perceived in the retronasal test.

In 1998, the same authors (Wagner and Grosch) evaluated the main contributors to the flavour of French fries prepared in palm oil (PO) and coconut fat (CF). The coconut-like note in the flavour profile of CF was mainly stimulated by γ-lactones with 8 and 10 carbon atoms, while the character impact odorants of PO were 2-ethyl-3,5-dimethylpyrazine, 3-ethyl-2,5-dimethylpyrazine, 2,3-diethyl-5-methylpyrazine and 3-isobutyl-2-methoxypyrazine (earthy odour); (*E,Z*)-2,4-decadienal, (*E,E*)-2,4-decadienal and (*E*)-4,5-epoxy-(*E*)-2-decenal (stimulating the deep fried impression); 4-hydroxy-2,5-dimethyl-3(*2H*)-furanone (caramel-like note); methylpropanal, 2-methylbutanal and 3-methylbutanal (malty notes); and methanethiol (sulphurous, cabbage-like odour). The odorants showing relatively high OAV were dissolved in sunflower oil to give two model systems, and a sensory study was undertaken. The flavour profile of the model obtained (MPO) was compared to that of the real PO for similarity. Furthermore, changes in the overall flavour of MPO were evaluated after omission of one or more odorants to determine their contributions to the flavour of PO. The absence of methional in MPO was not perceived by the sensory panel, supposing that this molecule did not contribute to the flavour of French fries, while a greater impact on flavour was imparted by methanethiol, another degradation product of methionine.

Martin and Ames (2001) evaluated the effect of frying oils (palmitolein and silicone fluid) on flavour compounds formed in chips. The flavour profile was examined in relation to the heat-transfer process and precursor formation from frying medium. Strecker aldehydes and sulphur compounds did not differ significantly between the frying media. Potatoes were presumed to provide all the precursors required for the formation of these compounds. Although pyrazines were significantly lower when potato slices were fried in silicone fluid, comparing the percentage relative amount of pyrazines in chips fried in palm olein or silicone fluid it was observed that the amount of total pyrazine was similar in the two frying media. The authors suggested that the reaction pathways leading to pyrazine formation in palm olein and silicone fluid were the same, and palm olein did not provide a source of flavour precursors. However, the kinetics of pyrazine formation appeared to be different, probably due to differences in heat transfer in potato slices. With regard to lipid oxidation products, the amounts of 2,4-decadienal were significantly higher in palm olein-fried chips, but there was no significant difference in hexanal levels between samples.

Hawrysh *et al.* (1996) evaluated the quality and storage stability of potato chips deep fried in canola (CO), partially hydrogenated canola (PHCO), soybean (SBO), and cottonseed oils (CSO). Sensory evaluation was made after accelerated (0, 6, and 12 days at 60°C) and practical storage (18 weeks at 23°C). The quality of potato chips was influenced by frying oil and storage conditions. Fresh CO and CSO chips had higher characteristic potato chip odour and lower off odour/flavour than SBO and PHCO chips. During accelerated storage, chips developed off odour/flavour depending on frying oil. At practical storage conditions, CO chips had higher characteristic potato chip odour/flavour and lower off odour/flavour than other chips. The results of this study indicate considerable potential for CO and PHCO as suitable alternative frying oils for snack food manufacture.

Pangloli *et al.* (2002) evaluated the flavour stability of potato chips fried in cottonseed, sunflower oils and palm olein/sunflower oil blends. All the potato chips contained abundant and similar amounts of hexanal and (*E,E*)-2,4-decadienal, deriving from the oxidation of linoleic acid, which was the most abundant fatty acid found in the frying oils. Sensory evaluation showed that the intensity of potato chip flavour was similar among oils and blends and did not change during storage; however oxidative rancidity and off-flavour increased in chips fried in cottonseed oil after 6 weeks storage. This off-flavour was due to 1-decyne, identified by SPME analysis. The authors found that the addition of 20 or 40% of palm olein oil to sunflower oil produced chips more stable to oxidation during storage, without losing the characteristic potato chip flavour.

Warner *et al.* (1997) determined the effects of fatty acid composition of frying oils on intensities of fried-food flavour and off-flavours in potato chips and french-fried potatoes. Cottonseed oil (CSO) and high-oleic sunflower oil (HOSUN) were blended to produce oils with 12 to 55% linoleic acid and 16 to 78% oleic acid. Hexanal, pentanal, 2,4-decadienal, octanal, and nonanal were used to monitor oxidation of the oil during potato chip storage. Volatile compounds were monitored in fresh and aged (6 months at 25°C) potato chips. Analytical sensory panels evaluated french-fried potatoes and pilot plant-processed potato chips; fried-food flavour intensity was the best indicator of overall flavour quality in fresh potato chips. The authors found that the fried-food flavour decreased with decreasing levels of linoleic acid and 2,4-decadienal, a breakdown product of linoleic acid oxidation. HOSUN (78% oleic acid) produced the lowest levels of hexanal and pentanal, indicating greater frying oil stability and oxidative stability of the food. However, fresh potato chips fried in HOSUN had the lowest intensities of fried-food flavour and lowest overall flavour quality. No oil analysis could predict flavour stability of aged potato chips.

Brewer *et al.* (1999) assessed selected volatiles (pentanal, hexanal, (*E*)-2-hexenal, heptanal, (*E*)-2-heptenal, 2-pentylfuran, (*E*)-2-octenal, nonal, (*E, E*)-2,4-decadienal) and sensory characteristics of frying fats (low linolenic acid soybean oil, creamy partially hydrogenated soybean oil, liquid low linolenic acid hydrogenated soybean oil, and liquid partially hydrogenated soybean oil) and of French fries fried in those fats. Odour characteristics of French fries reflected those of the oils in which they were fried. Hexanal in the French fries was an indicator of loss of "positive" odour attributes and development of rancid, grassy, painty and acrolein odours. Hexanal content in French fries was highest for those fried in low linolenic acid soybean oil and lowest for those cooked in low linolenic acid hydrogenated soybean oil.

Van Loon *et al.* (2005) identified odour active compounds in French fries (Agria variety) at mouth conditions, created to mimic release of volatile compounds from the food to the nose epithelia, where odour is sensed. The amount of product in relation to mouth volume, the temperature and the mixing of the product with artificial saliva were taken into account. 122 compounds were identified by GC-MS: 85% of them originated from sugar degradation and/or Maillard reaction. 2-Methylpropanal, 2-methylbutanal, 3-methylbutanal were the main representatives. 26 pyrazines were found of which 5 had not been previously reported from potato (**Table 4**). Fifteen percent of the volatiles were lipid-derived and ethanol, 2-propanol, hexanal, and nonanal showed the highest relative areas of this group. About 50 odour active compounds were responsible for 41 odours perceived by the panel. The compounds with the highest detection frequencies caused strong malty and fried potato notes, combined with caramel/buttery, green, spicy and deep-fried notes. Chemical and sweaty odours were also observed.

Several methods have been developed by Lojzova *et al.* (2009) for the analysis of substituted pyrazines and other aromatic compounds formed during the Maillard reaction in potato chips. The original aim of this study was to find possible volatile markers of acrylamide formation during potato chips preparation, and as previously reported, the release of alkylpyrazines was shown to correlate with acrylamide formation. After HS-SPME, the authors compared 3 different separation/detection approaches: gas chromatography–ion trap mass spectrometry (GC–ITMS), gas chromatography–time-of-flight mass spectrometry (GC–TOFMS) and comprehensive two-dimensional gas chromatography–time-of-flight mass spectrometry (GC×GC–TOFMS). They identified 13 target alkylpyrazines (**Table 4**). The major problem encountered was the resolution of 3 isomeric pyrazine pairs (2,5/6-dimethylpyrazine, 2-ethyl-5/6-methylpyrazine with 2,3,5-trimethylpyrazine and 2-ethyl-3,5/6-dimethylpyrazine with 2,3-diethylpyrazine). Full chromatographic resolution of all isomeric pairs could not be achieved in any of the systems tested, but the use of GC×GC–TOFMS offered the best solution, mainly because of the lower limits of quantification (LOQs) and better signal-to noise ratio.

In addition to the target pyrazines, another 46 nitrogen-containing heterocyclic compounds (pyrazines, pyrrols, pyridines, pyrrolidinones, and tetrahydropyridines) were tentatively identified in potato chips by GC(x GC)-TOFMS, and only 13 had been previously reported in earlier studies.

The effect of chemical and biological pre-treatments were tested by Anese *et al.* (2009) in order to reduce acrylamide formation and favour the development of the desired sensory properties of deep-fried potatoes. Lactic fermentation in the presence or in the absence of glycine, as well as immersion in an aqueous solution of the amino acid alone, was considered as pre-treatments for potato cubes before deep-frying. The effects of each pre-treatment on deep-fried potatoes were also compared by evaluating sensory attributes and preference. All pre-treatments significantly reduced acrylamide formation in deep-fried potatoes, but lactic acid fermentation in the presence of glycine was the most effective. The dipping treatments did not significantly affect the flavour of deep-fried potatoes; the same result was obtained by a pair comparison preference test carried out on consumers, which showed no differences in preferences between water and chemical or biological dipping.

The sensory effects of different pre-treatments of potato slices (Panda and Desirée varieties) before vacuum and atmospheric frying were also evaluated by Troncoso *et al.* (2009). Control or unblanched slices without pre-drying were analysed; blanched slices in hot water at 85°C for 3.5 min and air-dried at 60°C until a final moisture content of 0.6 kg water/kg dry solid; control slices soaked in a sodium meta-bisulphite solution (pH 3) at 20°C for 3 min. Pre-treated slices were then fried at 120 and 140°C under vacuum conditions (5.37 kPa, absolute pressure) and under atmospheric pressure until they reached a final moisture content of 1.8 kg water/100 kg. Concerning the sensory results, the best flavour was obtained for control potato chips, but no significant differences were found in terms of overall quality between control and chips pre-treated with meta-bisulphite.

Potato crisps

Few investigations have been published on the flavour profile of potato crisps. As for chips, potato crisps also contain a significant amount of frying oil that provides substantial vulnerability to oxidative rancidity. Notable attention has been paid to the study of flavour profile generated by oxidation processes.

Sanches-Silva *et al.* (2005) developed a SPME sampling method for the investigation of volatile compounds released during storage of potato crisps. Crisps were packaged in a transparent film in order to evaluate the changes in the profile of volatiles under accelerated oxidation. After 3 months, 31 compounds were identified. From a quantitative point of view, carboxylic acids were the most important volatiles identified, mainly represented by hexanoic acid. The second most important class of compounds was aldehydes, followed by alcohols, ketones, furans and other compounds that resulted from degradation/rearrangement of lipids and carbohydrates. Hexanal, formed during the oxidation of linoleic acid via the 13-hydroperoxide, was also studied as an indicator of lipid oxidation in potato crisps, stored in darkness or with natural light at room temperature (Sanches-Silva *et al.* 2004). The authors noted that there was a relevant increase of hexanal, starting from 8 days only in samples stored under light conditions.

Another problem arising during the frying of crisps is acrylamide formation. The sensory properties of potato crisps were evaluated when several additives, mitigating acrylamide formation, were added to blanching water (Mestdagh *et al.* 2008). The authors found that some sensory defects occurred when some acrylamide-lowering additives were used, leading to rejection of product by the panel. In particular, citric acid and acetic acid plus L-lysine induced suppression of the regular taste of potato crisps and enhanced sourness and the perception of popcorn-like flavours, respectively, leading to unacceptable final product quality.

Dehydrated potato products

In the potato industry, potato flakes are a crucial by-product obtained with a raw material that can not be used by other means. Unfortunately, non-enzymatic browning reactions occur during processing, and oxidative reactions occurring during storage lead to off-flavour formation (Sapers 1975) with important economic losses. Although potato flakes have a low lipid content, oxidation is important for limiting the deterioration of quality (Löliger and Jent 1983). In fact, the lipid fraction is composed primarily of linoleic and linolenic acids that are quite susceptible to oxidation in presence of air (Buttery *et al.* 1961). Few papers on volatile compound analysis in potato flakes are available, but up to now several aspects have been taken into consideration, such as the detection of non-enzymatic browning and oxidative compounds, the improvement of flavour in dehydrated potatoes, and the evolution of off-flavours during storage.

Laine *et al.* (2006) evaluated the volatile profile of potato flakes (cultivar 'Bintje') by SPME-GC-MS, and in particular, studied off-flavour formation during 6 months of storage. Thirteen volatile compounds were identified at very low levels, and hexanal was the main compound that appeared from the 12th to the 24th week of storage. The non-enzymatic formation of hexanal, mainly derived from linoleic acid hydroperoxide, was demonstrated after the analysis of lipoxygenase activity in potato flakes.

Nissen *et al.* (2002) also evaluated the oxidative status of potato flakes. In particular, they evaluated the potential use of electron spin resonance spectroscopy and investigated the development of oxidation during storage, detecting differences between products protected by different natural antioxidants (i.e. rosemary, green tea, coffee, and grape skin extracts). The oxidative deterioration of dried potato flakes during storage was also monitored by measurement of volatile compounds, at the beginning of storage and after 12 weeks, using headspace GC. Sensory analysis was carried out as a quantitative sensory profiling to evaluate the intensities of a number of defined descriptors for the smell and taste characteristics. Longer chain compounds (e.g. decadienal) decreased during storage, while shorter chain compounds (such as hexanal) derived from breakdown of secondary lipid oxidation products, increased. Sensory evaluation was found to be inconclusive as no significant variations with storage time or treatment were detected; the authors supposed that these results could be due to the oxidative changes in unprotected potato flakes during

storage and to the protection of potato flakes by antioxidants.

Extruded potato products

Much attention has been paid to the formation of flavour compounds via the Maillard reaction during the extrusion process and the potential loss of flavour volatiles during steam distillation after extrusion. The formation of alkylpyrazines in potato flakes, due to the interaction of reducing sugars and free amino acids, was related to this manufacture step (Maga 1994).

Majcher and Jelén (2009) compared the utility of three extraction methods: SPME (solid-phase microextraction), SAFE (solvent-assisted flavour evaporation) and SDE (simultaneous distillation and extraction) for characterization of flavour compounds from extruded potato snacks. Isolated compounds were analyzed using GC–O and GC/MS. The results showed that for GCO analysis the most suitable extraction method was SAFE, which led to identification of 25 most potent odorants out of 30 (identified by mass spectrometry). Due to the low temperature of extraction applied (40° C), SAFE avoided formation of artefacts, in contrast to SDE. The SAFE method also proved to be adequate for identification of flavour components by GC/MS, showing high precision with adequate limits of detection.

SPME was not able to reveal 7 important components at olfactometry port (1-octen-3-ol, 2-ethyl-3,5-dimethylpyrazine, 4-hydroxy-2,5-dimethyl-3(2H)-furanone, 3-hydroxy-4,5-dimethyl-2(5H)-furanone, 5-methyl-2,3-diethylpyrazine, β-damascenone and an unknown with a flavour of fresh pepper), but it was suitable for the identification of the highest number of volatiles (13 in SPME, compared to 12 and 11 in SAFE and SDE, respectively). In contrast to SDE and SAFE, SPME extraction identified low boiling compounds that co-elute with solvents used in other methods. Additionally, SPME was able to attain very low detection limits (reaching values of 0.2 - 0.3 ppb for hexanal, heptanal 2-ethyl-3,5-dimethyl pyrazines), which made it highly suitable for identification of flavour compounds present at trace levels.

The authors confirmed that SDE should not be used for food products that are rich in carbohydrates, amines or unsaturated fatty acids, which can serve as flavour precursors during long-term heat treatment used in SDE extraction; in this investigation, 2-furfurylthiol, 2,5-dimethyl-3-furanthiol, octanal, (*E*)-2-octenal and nonanal were recognized as artefacts. SPME and SAFE extraction methods were recommended for full characterization of odour-active compounds in extruded potato snacks.

Other potato-based products

Ogunjobi *et al.* (2005) evaluated the sensory properties of Irish potato (*Solanum tuberosum*) slices after fermentation in 2.0% brine solution for 5 days at room temperature. A trained panel of 15 assessors evaluated several sensory traits, including the aroma and overall acceptability, of fermented and fresh potato slices cooked by boiling, frying with palm oil or a different vegetable oil and roasting.

The result of sensory evaluation revealed that the flavour of roasted fermented potato was not different from the fresh control. The flavour and the general acceptability of both fried samples (palm and vegetable oil) were preferred by the panel over controls. Boiled fermented potatoes, in contrast, had the lowest scores.

Elmore *et al.* (2010) studied the effect of sulphur deprivation on the formation of acrylamide and volatile compounds in cooked potato flour. Potato flour was heated at 180°C for 20 min and volatile compounds of three varieties ('King Edward', 'Prairie' and 'Maris Piper'), grown with and without sulphur fertilizer, were compared.

49 compounds were present in at least one of the headspace extracts of the heated flour. 41 compounds were affected by sulphur treatment and 42 compounds were affected by variety. For freshly-harvested potatoes, sulphur deprivation during cultivation resulted in reduced acrylamide formation in cooked tuber flour and an overall increase in aroma volatiles. Many of such compounds were Strecker aldehydes and molecules formed from their condensation, whereas benzaldehyde was found at higher concentrations in the sulphur-sufficient flour, as acrylamide.

PERSPECTIVES

The aroma profile of food products is a key factor for the determination of consumer preference. The volatile profile of raw and processed potatoes has been widely investigated with several analytical techniques, but a detailed characterization of aroma components is difficult to obtain.

The main biochemical components of processed potato flavour have been identified and classified according to their mechanism of formation. However many aromatic molecules are strictly related to a specific culinary preparation; moreover also agronomical measures (varieties, agricultural systems, fertilization and storage conditions) have to be taken into account.

These prefaces highlight the need of further investigation on the factors that can influence the volatile fraction formation, mainly in processed potatoes. The results obtained could led to the use of certain potato cultivars for specific food preparations, owing to their aromatic profile. Investigations on volatile profiles should always be accompanied by sensory analysis in order to take into account the perception of the volatile molecules during tasting and their global effect on product acceptability.

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