

## The influence of volatile compounds of the flavour of raw, boiled and baked potatoes: Impact of agricultural measures on the volatile components

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### Abstract

The article deals with the development and identification of volatile compounds in raw, boiled and baked potatoes and their relevance for potato flavour. It outlines the influence of agronomic measures, such as the choice of variety, fertilization and storage, as well as the influence of diverse preparation possibilities on the formation of volatiles.

Flavour is created by aromatic volatile compounds that are biosynthesized in the plant during metabolic processes and further modified by cooking or processing. Especially the thermal reaction products are of decisive importance and responsible for the boiled and baked potato flavour. A multiplicity of reaction products are the consequence. Based on the literature research, there were 159 volatiles identified in raw potatoes, 182 in boiled and 392 in baked potatoes.

The flavour of raw, respectively processed, potatoes is variety specific, which means genetically defined. But the natural habitat determinants, the fertilization, storage conditions as well as the processing also have an influence on the forming of volatile compounds and could therefore affect the sensory quality. Although it is scientifically documented that particularly the fertilization and the storage conditions have an influence of the potato ingredients, there are hardly findings concerning volatile compounds in this context.

This stresses the future need for research, in particular regarding the effects of agronomic measures on the volatile compounds and sensory quality of raw as well as processed potatoes. By comparing the volatiles of raw potatoes with those of processed potatoes, positive or negative impacts by the raw product on the final product-flavour could be determined. This information could serve for breeding new varieties with certain properties which eventually comply with consumer demand.

*Keywords: Potato, flavour, volatile compounds, agricultural measures, preparation methods*

### Zusammenfassung

#### **Der Einfluss flüchtiger Verbindungen auf das Aroma roher, gekochter und gebackener Kartoffeln: Einfluss agronomischer Maßnahmen auf die flüchtigen Verbindungen**

In dem Beitrag werden die Entstehungswege flüchtiger Verbindungen in rohen, gekochten und gebackenen Kartoffeln und deren Bedeutung für das Kartoffelaroma aufgezeigt. Des Weiteren wird der Einfluss von agronomischen Maßnahmen und verschiedenen Zubereitungsformen auf die Bildung flüchtiger Verbindungen herausgearbeitet.

Das Aroma wird durch flüchtige Verbindungen, die durch metabolische Prozesse in der Pflanze bzw. durch den Verarbeitungsprozess entstehen, hervorgerufen. Für das Aroma gekochter bzw. gebackener Kartoffeln sind besonders die thermischen Reaktionsprodukte von ausschlaggebender Bedeutung. Die Literaturrecherche ergab, dass bislang 159 flüchtige Aromastoffe in rohen Kartoffeln, 182 in gekochten sowie 392 in gebackenen Kartoffeln identifiziert wurden.

Das Aroma ist sortenspezifisch, d. h. genetisch festgelegt, aber auch Standort, Düngung, Lagerung, sowie Verarbeitung haben einen Einfluss auf die Bildung flüchtiger Verbindungen und können die sensorische Qualität beeinflussen. Während umfassend belegt ist, dass insbesondere Düngung und Lagerung einen deutlichen Einfluss auf Inhaltsstoffe haben, gibt es nur wenige Arbeiten über die Auswirkungen unterschiedlicher Bewirtschaftungsmaßnahmen auf die Entstehung flüchtiger Verbindungen.

Es wird deutlich, dass ein hoher Forschungsbedarf hinsichtlich des Einflusses agronomischer Maßnahmen auf die sensorische Qualität von Kartoffeln besteht. Durch den Vergleich von Aromastoffen in rohen und zubereiteten Kartoffeln könnte auf positive bzw. negative Einflüsse von Roh- auf Endproduktaroma geschlossen werden. Diese Informationen könnten in der Züchtung genutzt werden, um Sorten mit bestimmten, den Konsumentenwünschen entsprechenden sensorischen Qualitäten zu etablieren.

*Schlüsselworte: Kartoffel, Aroma, Flüchtige Verbindungen, agronomische Maßnahmen, Zubereitungsmethoden*

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## 1 Introduction

Potatoes (*Solanum tuberosum* L.) are the world's most popular vegetable, a source of many essential nutrients and rich in vitamin C, potassium, and other vital nutrients. The annual world production of potatoes is around 300 million tons, and areas planted cover more than 18 million hectares (Cipotato, 2008).

The secret of the potato's success is its great diversity in colours, textures and tastes (FAO, 2008). One more reason for its vast popularity is that the tuber can be prepared in a number of different ways, including simple boiling, baking, deep-fat frying and dehydration. Its relatively neutral and bland, yet characteristic, flavour is another reason for the wide acceptance of the potato (Maga, 1994).

The flavour of a food is created by aromatic chemicals that are biosynthesized during normal metabolic processes in plants and animals, and possibly further modified by cooking or processing (Reineccius, 1999). Finally, human perception of flavour is influenced by numerous psychological and cultural factors (Jones, 2008).

This review concerns the formation and significance of the various volatile compounds that have been identified in raw, boiled and baked potatoes and the influence of agronomic measures like cultivar, fertilization, storage and different kinds of preparations on the forming of the flavour compounds.

Due to the widespread popularity of the potato, former potato flavour reviews exist (Johnson et al., 1971; Maga, 1994; Self, 1967; Solms and Wyler, 1979; Faulks, 1981) but they lack updates, are limited in scope in that they do not contain current information, and only a few papers deal with the influence of agronomic measures on the volatiles (Fischer, 1991; Hunnius et al., 1978; Khan et al., 1977; Jensen et al., 1999).

The volatiles in raw (Buttery and Ling, 1973; Fischer and Müller, 1991; Khan et al., 1977; Meigh et al., 1973; Self et al., 1963b) and boiled (Buttery et al., 1970; Buttery and Ling, 1974; Gumbmann and Burr, 1964; Josephson and Lindsay, 1987; Self et al., 1963b), respectively, baked potatoes (Buttery et al., 1973; Coleman and Ho, 1980; Ho and Coleman, 1980; Pareles and Chang, 1974) have been studied extensively.

Efforts have been made to differentiate which of these components are important for the characteristic flavour and which are specific to the type of cooking and preparation. Cultivar differences and influences due to agronomic and storage conditions have also been addressed (Dobson et al., 2004; Duckham et al., 2001; Duckham et al., 2002; Oruna-Concha et al., 2001; Oruna-Concha et al., 2002a; Oruna-Concha et al., 2002b).

But overall, the key contributors to potato flavour and taste have not been definitely identified (Morris et al.,

2007), nor is it entirely clear which agronomic measures influence the formation of volatile compounds.

## 2 Flavour nomenclature

The appreciation of flavour is a universal, everyday experience and is the integrated sensual response to a complex mixture of stimuli. Most predominant are the senses of smell and taste, but also decisive are sight (colour and appearance), tactile sensations (texture and mouth-feel) and pain (pungency) (Reineccius, 1999; Belitz et al., 2008; Kays and Wang, 2000).

The definition of flavour is the overall sensation resulting from the impact of the food on the chemical sense receptors in the nose and mouth. Taste is caused by stimulation of the gustatory cells of the buccal surface by soluble substances, nearly all of them non-volatile, released from the food into the saliva. Most of the flavour, however, is thought to be due to odorous volatile substances, released from the food into the air in the mouth and carried to the olfactory epithelium in the nose (Land, 1979). When the odorous molecules pass from the mouth to the nose via the inner passages during the eating process, then the complex sensation of taste and odour is called flavour. But the most important characteristic of flavour is the odour (Reineccius, 1999). This becomes obvious when a person catches a cold and can only sense flavour characteristics by the taste, tactile and temperature responses (Brillat-Savarin, 1962; Reineccius, 1999; Land, 1979; Heath and Reineccius, 1986).

It is important to note that a taste or odour is not an inherent property of a specific compound but is the psychological assessment of the individual sensing it. Therefore, the same compound can be perceived differently by different individuals or by the same individual at different times (Kays and Wang, 2000).

## 3 Volatile compounds

The presence and the level of volatile compounds generally determine the aroma and perceived flavour of a food (Whitfield, 1992; Maarse, 1991). Among the 7000 identified volatile compounds in foods, a relatively small number (300-400), in specific ratios, determine the characteristic odours of the product (Belitz et al., 2008). Analyses demonstrated that some very important aromas are not produced as a result of the presence of a unique characterizing compound; but rather a result of a reproducible blend of a particular number of components in proper balance. The compounds in potatoes predominantly include aldehydes, alcohols, ketones, acids, esters, hydrocarbons, amines, furans and sulphur compounds. The pattern and the number of volatile components obtained from potatoes can be

quite different, depending whether raw potatoes are used or the method used to prepare them (Self et al., 1963; Johnson et al., 1971; Whitfield and Last, 1991). Food produced with thermal process contains many more volatiles than the raw material (Belitz et al., 2008). These differences in amounts of volatiles depend on types of reactions which increased with higher temperatures (s. 3.1.2).

Several factors make the analysis of flavours somewhat challenging, these include their presence at low concentrations (ppm, ppt), complexity of mixtures, extremely high volatility (high vapor pressures), and instability of some flavour compounds in dynamic equilibria with other constituents in foods (Lindsay, 1996). The analysis of volatile compounds is generally conducted with gas chromatography (GC) combined with fast-scan mass spectrometry (MS) (Lindsay, 1996; Reineccius, 1999). As soon as the flavour of a food has been extracted, concentrated, separated and defined, a major question arises concerning each chemical's meaning for the flavour. The instrument response for the flame ionization detector used in GC re-

lates to the number of carbon-carbon bonds, whereas the human olfactory system varies greatly in response to different odours (Reineccius, 1999). So it could be that the smallest peak in a GC can be more important to flavour formation than the largest peak. It must also be accepted that the GC provides no appreciation of the flavour character of each component (Reineccius, 1999).

### 3.1 Volatile formation and its impact on flavour

The flavour of a raw or processed potato is very different, and it is quite difficult to specify the role of precursors in the various stages of the processes taking place in the raw and processed vegetable (Vernin, 1982). The aroma of vegetables may be considered to originate from the basic nutrients such as carbohydrates, particularly the monosaccharide and disaccharide, proteins, and free amino acids, and fats, triglycerides or their derivatives, as well as vitamins and minerals. These nutrients are produced by photosynthetic and related metabolic activities occurring

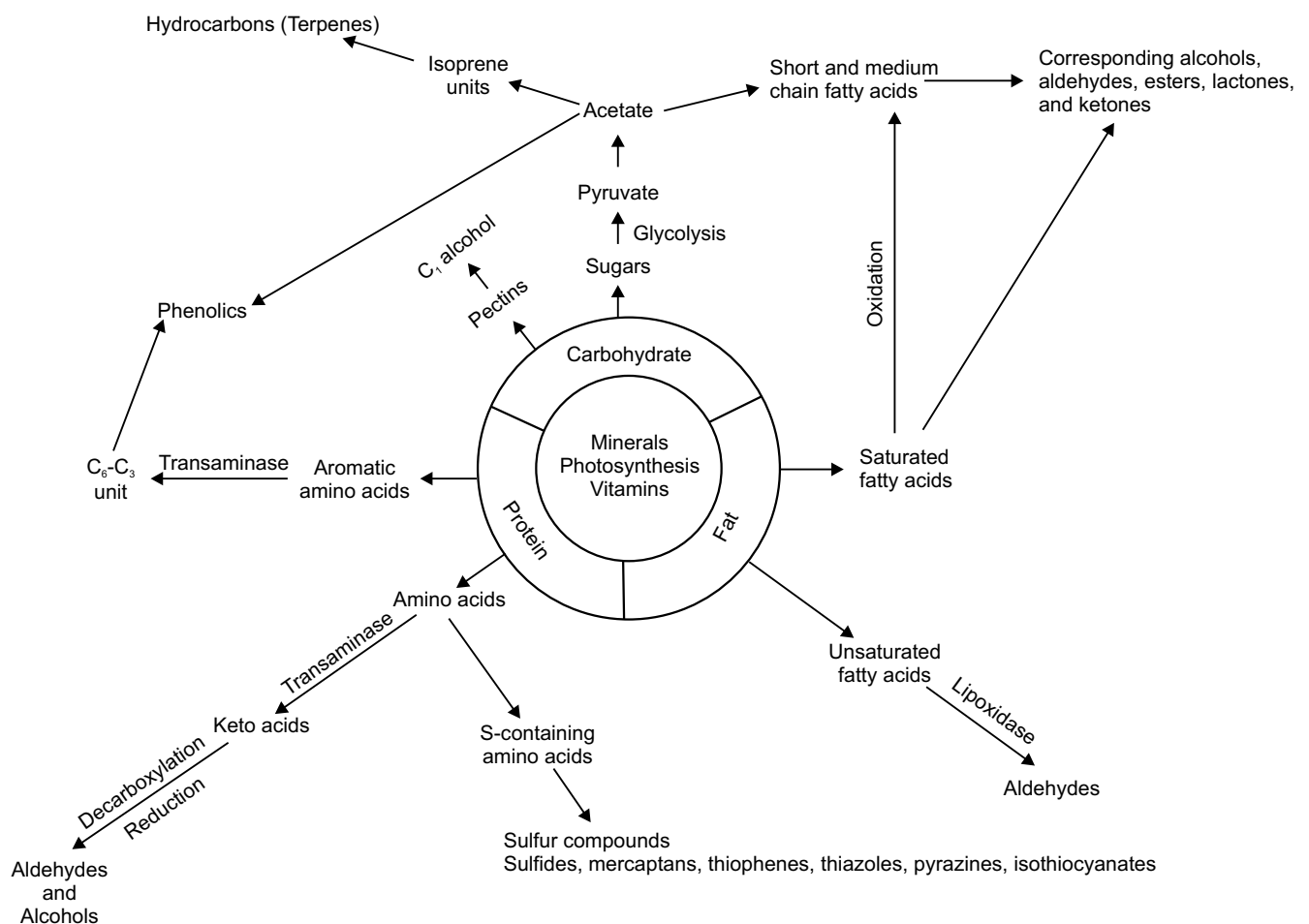


Figure 1: Formation of volatile aroma in fruits and vegetables (Salunkhe and Do, 1976).

in the plant (Salunkhe and Do, 1976). In the following, the various groups of volatile aroma compounds are illustrated schematically (Figure 1), and the nutrients from which they derived are listed in the next table (Table 1).

All vegetables have their own characteristic aroma which is genetically controlled by the individual species (Heath and Reineccius, 1986). But aroma is also influenced by cultivar, maturity, and horticultural practices (Reineccius, 1999). However, only few studies exist on the biogenetic pathways of most of the aromatic components identified in raw potatoes.

Reasons for the limited amount of studies on the biogenetic pathways in the raw potato could be that mainly processed potatoes (boiled, baked, or in the form of French fries or chips) are consumed, and a lot of volatile compounds are formed during thermal processing. Thereby

the temperature, blending speed and time, holding time, pH, and oxygen availability had a significant impact on the aroma profile (Salunkhe and Do, 1976).

In the following, the different pathways of volatile formation and their impact on flavour are described.

### 3.1.1 Enzymatic volatile formation

Some volatile components may exist per se in the intact tissue of vegetables, but mainly physical damage and mechanical stress, including cellular disruption due to cutting a vegetable prior to use, to cooking, or to the chewing process permits the mixing of enzymes and non-volatile precursors which had been separated within the cell, resulting in the generation of volatile flavour substances (Heath and Reineccius, 1986) which contribute significantly to the

Table 1:

Predominant nutrients and their role in the production of aroma components in foods (Salunkhe and Do, 1976).

Nutrient	Aroma Component
Carbohydrates Glucose Fructose Sucrose	Organic acids: Pyruvic acid, acetic acid, propionic acid, acetoacetic acid, butyric acid, hexanoic acid, octanoic acid Esters: Pyruvates, acetates, propionates, butyrates, acetoacetates, hexanoates, octanoates Alcohols: Ethanol, propanol, butanol, hexanol, octanol Aldehydes: Acetaldehyde, propanal, butanal, hexanal, octanal Terpenes: Monoterpene, linalool, limonene, $\alpha$ -pinene, citronellal, citral, geranial
Amino acids Alanine Valine Leucine Isoleucin Phenylalanine	Pyruvic acid, acetaldehyde, ethanol Isopropanal, isopropanol, $\alpha$ -keto-isobutyric acid 3-Methylbutanal, 3-methylbutanol, $\alpha$ -keto-isocaproic acid 2-Methylbutanal, 2-methylbutanol Benzaldehyde, phenylacetaldehyde, cinnamaldehyde, Hydrocinnamaldehyde, $p$ -hydroxybenzaldehyde, $p$ -Hydroxy phenylacetaldehyde, $p$ -hydroxy-cinnamaldehyde, $p$ -hydroxy cinnamaldehyde
Serine Threonine Glycine Cystine/cysteine Serine	Pyruvic acid Thiazoles Glyoxal
Fatty acids Linoleic acid Linolenic acid	<i>trans</i> -2- <i>trans</i> -4-Decadienal, hexanal, <i>trans</i> -2-octanal <i>trans</i> -2-Pentanal, <i>trans</i> -2-hexenal, hexanal, <i>cis</i> -3-Hexenal, <i>cis</i> -3-hexenol, <i>trans</i> -2- <i>trans</i> -4-Heptadienal, propanal
Organic acids Citric acids Oxaloacetic acid Malic acid Lactic acid	Glyoxylic acid, glyoxal, pyruvic acid, acetaldehyde Ethanol
Vitamins Carotenoids $\beta$ -Carotene Thiamine	$\beta$ -Ionene Thiazoles

isolated aroma (Salunkhe and Do, 1976). Furthermore, enzymes can be involved indirectly in flavour formation by procuring precursors, for example amino acids from proteins, saccharide from polysaccharide and *o*-quinone from phenolic compounds, which then react non-enzymatically to flavour compounds. In this way, enzymes are able to intensify the flavour (Belitz et al., 2008; Tressl et al., 1975). The nonvolatiles are cysteine sulfoxides, thioglucosinolates and unsaturated fatty acids, which are transformed into volatile thio compounds and carbonyls (Reineccius, 1999; Tressl et al., 1975).

Lipids comprise a significant portion of horticultural crops and are primary components of the cell's membrane system. Lipolytic acyl hydrolase liberates free fatty acids from phospholipids and glycolipids, the major lipids in potato (Galliard and Matthew, 1973). Lipid content of the raw potato tuber is 0.2 to 0.3 g/100 g FM, of which the polyunsaturated fatty acids, linoleic and linolenic acids, account for 0.05 and 0.01 g, respectively (Galliard, 1973).

Lipoxygenase (LOX) is one of the most widely studied enzymes in plants and animals. It catalyses the oxygenation of polyunsaturated fatty acids to form fatty acid hydroperoxides. The enzyme contributes to flavour formation, but it also has negative implications for the colour, off-flavour and antioxidant status of plant-based foods (Baysal and Demirdoven, 2007).

The enzymatic influence on volatile flavour formation is only of little importance, because the potato is not consumed raw like other vegetables. Potatoes are consumed after processing and therefore, the thermal impact plays the most important role for the volatile flavour formation.

### 3.1.2 Volatile formation by thermal impact

Precursors can also split by chemical reactions during the heating process. The volatile profile obtained from boiled and baked potatoes contains many process-derived compounds which contribute to the overall potato flavour (Buttery et al., 1970; Maarse, 1991). Important thermally driven reactions include the Maillard reaction, Strecker degradation and the thermal and enzymatic degradation of fatty acids (Figure 2) (Taylor et al., 2007).

The Maillard reaction, sugar degradation and lipid degradation (oxidative and thermal) are the most important reactions for the formation of volatile compounds in cooked and processed foods (Whitfield, 1992).

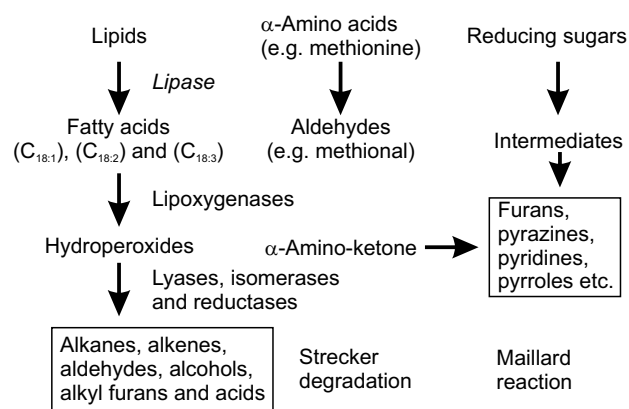


Figure 2:

Origin of flavour volatiles released from boiled potatoes. Precursor metabolites are shown at the top, and the main products in boiling are shown in solid boxes (Taylor et al., 2007).

#### 3.1.2.1 Maillard reaction and Strecker degradation

The Maillard reaction (MR) and the Strecker degradation (SD) of  $\alpha$ -amino acids are responsible for the formation of many heterocyclic compounds with distinctive aromas and low odour thresholds. The MR takes place when compounds possessing a carbonyl group, typically reducing sugars, react with components with a free amino group such as amino acids (Taylor et al., 2007; Whitfield, 1992). The MR does not require high temperatures, however, the reaction rate increases markedly with temperatures associated with cooking. Furthermore, the reactions occur most frequently in areas of the product that have been dehydrated, such as near the surface (Kays and Wang, 2000). The steps of the MR usually feature reactions with other intermediates, such as amino compounds or amino acid or lipid degradation products. Volatiles synthesized by the MR can be classified according to their primary precursor:

1. sugar degradation/fragmentation products, such as furans, pyrones (e.g., maltol), cyclopentenones, carbonyl compounds, and acids;
2. amino acid degradation products, such as aldehydes, sulfur compounds such as hydrogen sulfides and methanethiol, and nitrogen compounds such as ammonia and amines and
3. volatiles produced by further reactions, such as pyrroles, pyridines, pyrazines, imidazoles, oxazoles, compounds from aldol condensations, thiazoles, thiophenes, di- and trithiolanes, di- and trithianes, and furanthiols (Nursten, 1980). Especially the pyrazines have a great diversity in odour within a class (Kays and Wang, 2000).

The Strecker degradation (SD) of amino acids into their structurally related volatile counterparts is also very important in relation to the formation of a series of volatile flavour

compounds (Cremer et al., 2000; Rizzi, 2008; Whitfield, 1992). The SD of amino acids has mainly been viewed as a corollary of the MR, and the primary reactants have been considered to be protein, i.e., amino acids and carbohydrates. According to Rizzi (2008), many of the numerous compounds that have been described in the literature as SD reaction products can be interpreted in terms of Maillard intermediates. However, in addition to carbohydrate reactants, it is also known that other important food ingredients like lipids and polyphenolic compounds can play a part in SD reactions to produce novel flavour compounds (Rizzi, 2008). The SDs located in foods and during food processing are usually the reaction of  $\alpha$ -amino acids with  $\alpha$ -dicarbonyl compounds derived from concurrent Maillard reaction pathways. During the reaction, an  $\alpha$ -amino acid undergoes decarboxylation and is transformed into a structurally related aldehyde (Strecker reaction) (Rizzi, 2008). These corresponding "Strecker aldehydes" contain one less carbon atom than the original amino acids, and an  $\alpha$ -amino ketone (Whitfield, 1992). With cysteine, in addition to the two normal products the reaction yields hydrogen sulphide, ammonia, acetaldehyde, and the regenerated dicarbonyl compound. The amino ketones can act as reducing agents, and it has been proposed that hydrogen sulphide is also formed by the reduction of cysteine itself or 2-mercaptoacetaldehyde (Whitfield, 1992). The Strecker degradation of methionine is another source of sulphur-containing intermediates. In this case, the reaction involves the interaction of  $\alpha$ -dicarbonyl compounds, intermediates the Maillard reaction, with methionine, resulting in the formation of 2-methylthiopropional, also called as methional (Lindsay, 1996) and methanethiol with 2-propeanal as the co-product (Fujimaki et al., 1969). Methional is deemed to be the key compound of boiled potato flavour (Petersen et al., 1998).

The interaction of the Maillard reaction products with those of the Strecker degradation led to the formation of many important classes of flavour compounds. These include pyrazines, oxazoles, thiophenes, and other heterocyclic compounds with more than one sulphur atom. But also lipid and lipid degradation products can be involved in these reactions, leading to the formation of additional compounds and the reduction or prevention of the formation of the normal products of a Maillard reaction (Whitfield, 1992).

### 3.2 Raw potatoes

Although potato tubers are only consumed after cooking, there is an interest to identifying the volatiles in the raw product (Taylor et al., 2007). This provides a reference point when evaluating the formation of flavour compounds during the processing of various potato products.

The state of knowledge about the spectrum of volatile compounds in raw potatoes, which is characterized by a weak but typical odour, is very limited (Fischer and Müller, 1991). About 159 volatiles have been identified in raw potatoes, independent of the analytical method, varieties, and whether peeled or unpeeled. These are summarized in Table 2 at the end of Chapter 3.2.

Most of studies have concentrated on cut or sliced potatoes, which cause an oxidative and enzymatic attack on inherent lipids. This obviously results in a vast amount of unsaturated and saturated aldehydes and alcohols, several of which have extremely low odour thresholds and therefore probably a negative impact on flavour (Petersen et al., 1998). Analyses by Schormüller and Weder (1966b), as well as by Khan et al. (1977), detected primarily short-chain alcohols, aldehyde, ketone, thiazoles and sulphur compounds are discovered in raw potatoes. Buttery and Ling (1973) hypothesized that raw potato volatiles are derived from biosynthetic processes in the tuber or associated microorganisms rather than from thermally catalyzed reactions. Lipid oxidation products of unsaturated fatty acids are the major source of volatiles in raw potatoes, because the lipoxygenase content is relatively high (Josephson and Lindsay, 1987; Petersen et al., 1998; Fischer and Müller, 1991). These dominated the constituent's 2-octenal, hexanal, heptanal, pentanol, 2-pentylfuran as well as 2-methyl- and 3-methylbutanol. The high amount of 2-methyl- and 3-methylbutanol is a sign of intensive amino acids metabolism in the tuber, because both compounds arise from the enzymatic degradation of leucine rather isoleucine (Drawert, 1975). When slicing or shredding potato tubers, there is a large increase in hexanal, octenal and isomeric forms of 2,4-decadienal, all products of lipoxygenase-initiated reactions of unsaturated fatty acids, taking place soon after the disruption of cells (Josephson and Lindsay, 1987; Petersen et al., 1998). The following volatiles, which were also found in raw potatoes, belonging to the products of lipoxygenase-initiated reactions: heptanal, 1-penten-3-one, 1-pentanol, 2,4-heptadienal, 2,6-nonadienal and 2-pentyl furan (Gardner et al., 1996; Ho and Chen, 1994; Josephson and Lindsay, 1987; Schieberle and Grosch, 1981; Sok and Kim, 1994; Petersen et al., 1998). This could explain the observation of Self et al. (1963b; Petersen et al., 1998), who noted that the aroma of fresh-cut potatoes was different from that of whole potatoes, but made no attempt to identify responsible compounds. Buttery and Ling (1973) as well as Murray and Whitfield (1975) found compounds such as methoxy-pyrazines in raw potatoes. They assumed that they were derived from biosynthetic processes. Morgan et al. (1972) reported that 2-methoxy-3-isopropylpyrazine occurs in relatively large concentrations in the cultures of the microorganism *Pseudomonas taetrolens*. They guessed that the small concen-

tration that occurs in potatoes might first be formed in the soil or on tuber surface (by this or some related microorganism) and then be absorbed into the potato. However, the potato plant is botanically related to the bell pepper plant which produces relatively large amounts of 2-isobutyl-3-methoxypyrazine and probably is quite capable of producing the compound itself. The occurrence of relatively high amounts of methoxypyrazines in peeled tubers may argue against the synthesization of this compound by soil microflora associated with the tuber, and indicate that a biosynthetic route for their production is present in the potato tuber. The most identified methoxypyrazine present in raw potato volatiles was 2-methoxy-3-isopropylpyrazine (Murray and Whitfield, 1975). Methoxypyrazines have very low odour thresholds and have characteristic vegetable-like odours, including potato-like odours. In contrast to this analysis by Murray and Whitfield (1975), Fischer and

Müller (1991) did not find any pyrazines in the analysis of raw potatoes.

Desjardins et al. (1995) were the only researchers who also find the hydrocarbon sesquiterpenes in raw potatoes and detected them at higher levels after tuber damage or microbial attack. It could be demonstrated that fungal and bacterial infections (*Erwinia carotovora* ssp. *atroseptica*, *Phytophthora infestans*) lead to an increase of the potato stress metabolite solavetivone, a sesquiterpene (Zacharius and Kalan, 1984). This observation by Desjardins et al. (1995) showed that the raw potatoes tested were stressed or infected.

Individually, raw potatoes include many potent flavours which represent juicy, earthy, oily as well as nutty- and roast-like flavour notes. For the description of the typical raw potato flavour, no single component would even suggest the familiar aroma.

Table 2:

Volatiles identified in Raw, Boiled and Baked Potatoes with their odour description

Compound	Raw	Boiled	Baked	Odour description
<b>Aldehydes</b>				
Acetaldehyde	1-9, 24, 25	1, 3, 14, 16, 26, 27		
Isobutyraldehyde		1, 3, 14, 18, 26, 27		
Propanal	1, 2, 5-9, 24, 25	1, 6, 16, 26, 27		
Acrolein (= Propenal)		1, 3, 16, 27		
2-Propenal	1, 3, 6, 7, 9			
Methylpropanal		33, 36		malty
2-Methylpropanal	1, 3, 5-10		7, 37, 38, 44	
2-Methyl-2-propanal			38	
Butanal	3, 6, 9, 24, 25	3		
2-Butenal	6, 9	31		
2-Methylbutanal	1, 6, 7, 10	16, 33, 36	7, 37, 43-45	sweet, chocolate, sometimes roasted/toasted, malty
3-Methylbutanal	1, 3, 5-9	1, 3, 16, 26, 27, 33, 36	7, 37, 43-45	sweet, chocolate, sometimes roasted/toasted, malty
3-Methyl-1-butenal			38	
2-Methyl-2-butenal			38, 47	
3-Methyl-2-butenal			38	
Pentanal	2, 5, 6, 8, 9, 23		38, 43-45, 47	green, almond, marzipan
Pentenal	29, 30, 40	31, 34, 35	47	roasty, rubber, unpleasant
2-Pentenal	6, 7	35	38, 45, 47	
4-Methyl-2-phenyl-2-pentenal			38	
Hexanal	2, 5-9, 11-14, 23	6, 14, 28, 31-36	7, 37, 38, 43-47	green, grass, fatty
2-Ethylhexanal			38	
5-Methyl-2-phenylhexanal			38	
2-Hexenal	2, 5-14	6, 12, 34, 35	7, 37, 47	
3-Hexenal			37, 38	green, bitter-almond-like
Heptanal	2, 6, 7, 9, 11, 13-15, 23	6, 12, 14, 23, 34	7, 37, 38, 43-47	soapy-fruity, resinous
Heptenal			7, 37	

Compound	Raw	Boiled	Baked	Odour description
2-Heptenal	23	6, 14, 23, 31, 34, 35	45-47	cardboard-like
4-Heptenal		12, 23		earthy, prepared food, potato-like
Octanal	2, 9, 11, 13	12, 31, 34-36	43, 45, 47	fatty, soapy-fruity, citrus-like
Octenal		6, 12	7, 37	
2-Octenal	2, 6, 7, 9, 12-14, 23	23, 34-36	45, 47	fatty, nutty, baked potato, chips
2,4-Octadienal		31		
Nonanal		6, 12, 34, 35	7, 37, 38, 43-47	rancid, boiled potato
2-Nonenal	6, 7, 9, 13, 14, 23	6, 12, 14, 32-34, 36	7, 37, 43, 45, 47	sweet, green, cucumber
3-Nonenal		36		green, tallowy
Decanal	6	6, 12, 18, 32, 34	7, 37, 43-46	
Undecanal			38, 43, 45, 46	metallic
2-Undecanal			46	
Dodecanal			43, 45	
2-Dodecanal			46	
Hexadecanal			46	
Octadecanal			38	
Decenal			7, 37	
2-Decenal		36		fatty
2,4-Decadienal	6, 7, 12-15, 23	6, 12, 14, 30, 32-36	7, 37, 46	fatty, green, onions, chips, chip fat, hot potato, liquorice, roasty
2,4-Heptadienal	6, 13, 23	6, 12, 34, 35	7, 37, 46, 47	oily, rancid nuts, mushroom
Nonadienal			7, 37	
2,4-Nonadienal	13, 23	12, 32, 34-36	46, 47	fatty-soapy/oily, old, rancid, nutty, almond, marzipan
2,6-Nonadienal	23	12, 23, 30, 32, 35, 36		fatty, green, cucumber, grass, peas, paint, vinegar-dressed
Benzaldehyde	6, 7, 14	6, 12, 14, 35	7, 37-39, 43-47	flowery
Phenylacetaldehyde	6, 7, 14, 23	30, 36	37-39, 43-47	earthy, flower, roses, sweet, honey-like
Ethylbenzaldehyde			38	
2,5-Dimethylbenzaldehyde			38	
Methoxycinnamaldehyde			38	
Salicaldehyde			38	
Methional (=3-(Methylthio)propanal)	6, 7, 14	5, 14, 23, 28, 30, 32-36	43, 44, 46, 47	boiled potato
<i>trans</i> -4,5-Epoxy-(E)-2-decenal		32, 33, 36		metallic
<i>trans</i> -4,5-Epoxy-(E)-2-nonenal		36		metallic
Furfural	6, 7, 14	12, 14	47	
2-Furfural			43-46	
5-Methylfurfural			46	
5-Methyl-2-furfural			46	
5-Methyl-2-thiophenecarbox-aldehyde			46	
Vanillin		32, 33, 36		sweet, vanilla-like
<b>Alcohols</b>				
Methanol	1, 6, 7, 16, 21, 24, 25	16, 26, 27	38	
Ethanol	1, 6, 7, 21, 23-25	27	38	
2-Methyl-1-propanol	6, 24, 25			
1-Butanol	6, 21, 24, 25	28		
2-Butanol	24, 25		38	
2-Buten-1-ol	6	6		



Compound	Raw	Boiled	Baked	Odour description
Propanol	11, 24, 25			
2-Propanol	24			
1-Butoxy-2-propanol		35		
2-Methylbutanol	3, 6, 7, 13, 14, 21, 23	14, 30	43, 44, 47	malty
3-Methylbutanol	3, 6, 7, 13, 14, 21	6, 14	43, 44, 46, 47	malty
Pentanol	6, 7, 13-15, 21, 23	6, 12, 14, 28, 34, 35		malty
2-Pentanol			38	
2-Methyl-2-pentanol			38	
3-Methyl-1-pentanol		35	38	
4-Methyl-1-pentanol	21			
2,4-Dimethyl-3-pentanol			38	
4-Methyl-4-pentanol			38	
2-Methyl-3-penten-2-ol			38	
2-Methyl-1-penten-3-ol			38	
Hexanol	6, 13, 21	6, 12, 34, 35	43, 47	green, flowery
2-Ethyl-1-hexanol			47	
Hexenol	6			
2-Hexen-1-ol	6	28		
3-Hexen-1-ol			47	
3-Methyl-2-hexanol	6	6		
Nananol		35		
Heptanol	17, 21	6	38	
2-Heptanol		23		popcorn
Octanol	17	6, 30, 31		
3,6-Dimethyl-3-octanol			38	
2-Isobutyloctanol			38	
Octenol	6, 7, 14			
2-Octen-1-ol		12, 14		
1-Octen-3-ol	6, 7, 13, 14, 17	6, 12, 14, 34, 35	37, 38, 43-47	fungus, mushroom
Non-3-enol	17			
Geraniol	6, 7, 14			
Nerol	6, 7, 14	6, 14		
Nerolidol		31		
Linalool	6, 7, 14	14, 34	43, 47	
Benzyl alcohol	6, 7, 14, 23	14, 28, 35	38	flower, citrus, fruit
2-Phenylethanol	6	28, 35		
Terpineol	6, 7, 14	14		
Terpenol		37		
Furfuryl alcohol		31		
cis-Farnesol		31		
Menthadienol		31		unpleasant, sweet
1,2-Ethanediol		35		
2-(2-Butoxyethoxy)-ethanol		35		
Dodecanol			38	
Hexadecanol			38, 46	
Cyclohexanol			38	
2-Tetradecyloxyethanol			38	
Hexahydrofarnesol			38	
Trimethylbenzyl alcohol			38	

Compound	Raw	Boiled	Baked	Odour description
3-Methoxy-4-isopropylbenzyl alcohol			38	
Naphthol			38	
2-Methoxyphenol			46	
Eugenol			46	
4-Vinyl-2-methoxyphenol			46	
2-Methoxy-4-vinylphenol			46	
<b>Ketones</b>				
Acetone	1, 3, 6, 7, 9, 24	1, 3, 16, 26, 27	38	
3-Methyl-2-butanone	3, 6, 9	3		
3-Hydroxybutanone	24			
3-Hydroxy-2-butanone	25			
Butanedione			43, 44	
2,3-Butanedione (= Diacetyl)	6, 11	31, 36		buttery
2,3-Pentanedione	6	12	43, 44, 47	
Propanone	11			
2-Propanone	25			
1-Phenyl-1,2-propanedione			38	
Butanone	11		43	
2-Butanone	24, 25	31	45	
3-Pentanone			43	
4-Methyl-2-pentanone			38	
5-Methoxy-2-pentanone			38	
3-Ethylcyclopentanone			46	
Cyclopentanone			38	
2,5-Dimethyl-1-cyclopentanone			38	
2-Pentadecanone			46	
4-Methyl-3-penten-2-one			38	
2,6-Dimethyl-3-penten-2-one			38	
Hexanone	11		38	
3-Hexanone			43	
2-Acetyl-3,3-dimethylcyclohexanone			38	
3,5, 5-Trimethyl-3-cyclohexene-1-one			45, 46	
Heptanone	2, 6, 7, 11, 14		7, 38	
2-Heptanone		6, 14	37, 38, 44, 47	
4-Heptanone			7, 37, 38	
2-Methyl-4-heptanone			38	
2-Methyl-2-hepten-6-one			38	
6-Methyl-5-hepten-2-one			43, 45, 47	
Octanone	2, 11			
1-Octen-3-one	6, 7, 14	12, 14, 32, 36		mushroom-like
3-Octen-2-one			38	
4-Octen-3-one			47	
1-Penten-3-one	23	31		
Nonanone	2, 11			
2-Nonen-4-one	6, 7, 14	14, 31		
2-Decanone	6, 7, 14	14		
4-Decanone			38	
2-Undecanone		12		

Compound	Raw	Boiled	Baked	Odour description
2,3-Octanedione			46, 47	
3,5-Octadien-2-one		12, 30, 31	46	
1,5-Octadien-3-one		12, 32, 36		geranium-like
2-Methyl-3-octanone		31		
1-Methyl-2-pyrrolidinone	23			
Furyl methyl ketone		28		
1-Furyl-2-propanone		28		
1,2-Cyclohexanedione		31		
Farnesyl acetone		31		
Geranylacetone		31	43	
(E)- -Damascenone		32, 36	43	fruity, sweet
Decalactone		32, 36		sweet, peach-like
Octalactone		36		sweet, coconut-like
Nonalactone		36		sweet, coconut-like
Acetophenone			45	
-Methyl acetophene			38	
Solavetivone			46	
Isophorone			43	
Camphor			45	
<b>Acids</b>				
Acetic acid	7, 23	23, 28, 35	38	
Propanoic acid	23		38	
Butanoic acid		36	38	
Decanoic acid	5, 8			
Tetradecanoic acid	5, 8			
Pentanoic acid		36	38	
Pentadecanoic acid	5, 8			
Hexanoic acid	23	12, 35	38	prepared food, soup, cake, raw potato
Hexadecanoic acid	5, 8			
9-Hexadecanoic acid	5, 8			
Heptanoic acid			38	
Heptadecanoic acid	5, 8			
Octanoic acid		35, 36		
Octadecanoic acid	5, 8			
cis-9-Octadecanoic acid	5, 8			
9,12-Octadecanoic acid	5, 8			
9,12,15-Octadecatrienoic acid	5, 8			
Eicosanoic acid	5, 8			
Phenylacetic acid	7	28		
2-Methylhexanoic acid			38	
2-Methylpentanoic acid			38	
2-Methylpropanoic acid			38	
2-Phenylcrotonic acid			39	
3-Methylbutanoic acid			36, 38	
3-Methylpentanoic acid			38	
4-Methylpentanoic acid			38	
2-Ketoadipic acid			38	

Compound	Raw	Boiled	Baked	Odour description
<b>Esters</b>				
1-Methylpropyl acetate			38	
2-Methylbutyl acetate			38	
2-Methylbutyl pentanoate			38	
Allyl hexanoate			38	
Butyl acetate			38, 45	
Butyl butyrate		34		
Diethyl phthalate			38	
Di-isobutyl isophthalate			38	
Di-isobutyl phthalate			38	
Ethyl acetate			38, 43	
Ethyl benzaldehyde		12		
Ethyl heptanoate		12		
Hept-1-enyl 2 acetate			38	
Methyl 2-hydroxybenzoate	6, 7, 14			
Methyl 2-methylbutanoate			38, 45, 47	
Methyl 2-methylpentanoate			38	
Methyl 2-methylpropanoate			43	
Methyl hexadecanoate			46	
Methyl hexanoate			38	
Methyl nonanoate			38	
Methyl octadecanoate			46	
Methyl octanoate			38	
Methyl pentanoate			38	
Methyl salicylate		14		
Methyl tetradecanoate			46	
Methylbutanoate			43, 45, 47	
Octadecyl acetate			46	
Pentyl acetate			38	
Phthalic anhydride			38	
<b>Lactones</b>				
4-Pyridoxic acid lactone			38	
<b>Hydrocarbons</b>				
Octane		18	45	
Hexane			45	
Nonane			45	
Decane	6	18	45	
Tridecane			45	
Tetradecane	6	31	45	
2-Methyldecane			45	
4-Methyldecane			45	
2-Methyltetradecane			38	
Pentadecane		31	45	
2,6,10,14-Tetramethylpentadecane			38	
Hexadecane			45	
5,7-Dimethylhexadecane			38	
7,9-Dimethylhexadecane			38	
2,6,11,15-Tetramethylhexadecane			38	

Compound	Raw	Boiled	Baked	Odour description
Heptane		18	45	
Cycloheptane			46	
2,4-Dimethylheptane			38	
9-Octylheptadecane			38	
2,2,4,6,6-Pentamethylheptane			45, 47	
Cyclodecane			38	
Undecane	6		45, 46	
2,6,9-Trimethylundecane			38	
2,6,10-Trimethylundecane			38	
Dodecane	6		45	
1-Dodecane			45	
4,6-di- <i>n</i> -Propyldodecane			38	
1-Cyclopentyl-4-octyldodecane			38	
(E)-9-Octadecene	23			
Copaene			43-45, 47	
1,1-Diethoxyethane			39	
3,5,5-Trimethyl-1-hexene			38	
2-Ethyl-3-octene			38	
4-Ethyl-3-octene			38	
1-Octadiene			38	
1,4-Dimethyl-4-vinylcyclohexene			38	
1,1-Dichloroheptane			38, 42	
1-Chlorohexadecane			38, 42	
<i>o</i> -Chloroaniline			38, 42	
<i>p</i> -Chloroaniline			38, 42	
2-Chlorobiphenyl			38, 42	
Trichloroacetic acid			38, 42	
20-Bromo-5-ethylnonane			38, 42	
1-Iodo-octadecane			38, 42	
Diphenylmethane			38	
1-Methylindan			38	
4,5,7-Trimethylindan			38	
$\alpha$ -Aromadendrene			43, 45	
Guaiene			43	
Cyclosativene			45	
Longicyclene			45	
Gurjunene			45	
Limonene	6	6	38, 43-47	
$\alpha$ -Pinene	6	6	38, 43-45, 47	
$\beta$ -Pinene	6	6		
3-Carene	6	6	38, 43-45, 47	
Benzene	6	18	38, 43, 47	
Methylbenzene (=Toluene)	6	18	38, 43, 45, 47	
Ethylbenzene	6	6	43, 45-47	
Dimethylbenzene (= Xylene)		6, 18		
1,2-Dimethylbenzene	6		38, 43, 45, 47	
1,3-Dimethylbenzene	6		38, 43, 45, 47	
1,4-Dimethylbenzene	6		38, 43, 45, 47	

Compound	Raw	Boiled	Baked	Odour description
Isopropylbenzene			38	
1-Ethyl-2-methylbenzene	6	6		
1-Ethyl-4-methylbenzene	6	6		
2-Ethyl-6-propylpyrazine			38, 40	
2-Ethyl-3,5,6-trimethylpyrazine			38, 40	
Trimethylbenzene			38, 47	
1,2,3-Trimethylbenzene	6	6		
1,2,4-Trimethylbenzene	6			
1,3,5-Trimethylbenzene	6	6		
2,3,6-Trimethyl-5-hydroxy-cyclopentapyrazine			38, 40	
Pentylbenzene			45	
Propylbenzene			45-47	
Alkylbenzene			45	
Vinylbenzene (=Styrene)			43	
2-Methylvinylbenzene			47	
3-Ethylstyrene			38	
<i>tert</i> -Butylbenzene			38	
<i>sec</i> -Butylbenzene			38	
1,2,3,5-Tetramethylbenzene			38	
Hexamethylbenzene			38	
1-Methyl-4-ethylbenzene			38	
Methylpropylbenzene			45, 47	
Ethylmethylbenzene			45	
Nonylbenzene			38	
Biphenyl	6, 7, 14	14	38	
Diphenylmethane			38	
Naphthalene	6, 7, 14	14, 18	43, 45, 47	earthy
2,6-Naphthalene	18			
1-Methylnaphthalene	18	14, 18		
2-Methylnaphthalene	6, 14		46	
Dimethylnaphthalene	6	6		
1,2-Dimethylnaphthalene			38	earthy
1,3-Dimethylnaphthalene			38	earthy
1,4-Dimethylnaphthalene	18			
1,6-Dimethylnaphthalene	18			
2,7-Dimethylnaphthalene			38	earthy
2,5-Diethyl-3-methylpyrazine			7, 37	
2,6-Diethyl-3-methylpyrazine			37	
Trimethylnaphthalene	18			
1,3,8-Trimethylnaphthalene			38	earthy
1,4,5-Trimethylnaphthalene			38	earthy
1,4,6-Trimethyl-1,2,3,4-tetrahydronaphthalene			38	
Decahydronaphthalene			45	
2-Isopropylnaphthalene			38	earthy
3-Methyleicosane			38	
Methylcyclopentane			38, 43	
Sesquiterpene	22			

Compound	Raw	Boiled	Baked	Odour description
$\gamma$ -Humulene			38	
Myrcene			38, 43, 47	
Ocimene			43	
Cymene		34	38, 44, 47	
Curcumene			45	
Terpinolene			44	
<i>trans, trans</i> -Farnesene			38	
Phellandrene			38, 44	
<b>Pyrazines</b>				
2,3,5-Trimethyl-6-(3-methylbutyl)pyrazine			46	
2,3,5-Trimethylpyrazine			37, 38, 40	
2,3,6-Trimethyl-5-hydroxy-cyclopentapyrazine			38, 40	
2,3-Diethyl-5-methylpyrazine	19	32, 33, 36	7, 37-40, 43, 46	earthy, roasty
2,3-Diethylpyrazine			38, 40	
2,3-Dimethyl-5-butylpyrazine			38, 40	
2,3-Dimethylpyrazine			7, 37, 38, 40	
2,5-Diethyl-3-methylpyrazine			7, 37	
2,5-Dimethyl-3-(2-methylpropyl)pyrazine			46	
2,5-Dimethyl-3-(3-methylbutyl)pyrazine			46	
2,5-Dimethyl-3-butylpyrazine			38, 40	
2,5-Dimethyl-3-propenylpyrazine			46	
2,5-Dimethylpyrazine			7, 37-40, 43, 44, 46, 47	
2,6-Diethyl-3-methylpyrazine			37	
2,6-Dimethyl-3-(2-methylbutyl)pyrazine			46	
2,6-Dimethyl-3-butylpyrazine			38, 40	
2,6-Dimethylpyrazine		30	7, 37-40, 43, 44, 46, 47	nutty, warm
2-Butyl-3-methoxypyrazine	19			potato-like odour
2-Butyl-3-methylpyrazine			38, 40	
2-Butyl-6-methylpyrazine			38, 40	
2-Ethenyl-5-methylpyrazine			46	
2-Ethenyl-6-methylpyrazine			46	
2-Ethoxy-3-ethylpyrazine		6		not distinctive
2-Ethoxy-3-methylpyrazine		6		not distinctive
2-Ethyl-3,5,6-trimethylpyrazine			38, 40	
2-Ethyl-3,5-dimethylpyrazine			38, 40	roasty, coffee-like
2-Ethyl-3,6-dimethylpyrazine			37-40, 43, 46	earthy, buttery, baked, potato-like
2-Ethyl-3-methoxypyrazine		6		
2-Ethyl-3-methylpyrazine			7, 37-40, 43, 46	earthy, nutty
2-Ethyl-5-methylpyrazine			7, 37-40, 43, 46	
2-Ethyl-6-methylpyrazine		30	7, 37-40, 43, 46	nutty, warm, chemical
2-Ethyl-6-propylpyrazine			38, 40	
2-Ethyl-6-vinylpyrazine			38, 40	buttery, baked, potato-like
2-Isobutyl-2,5-dimethylpyrazine			40	
2-Isobutyl-3,6-dimethylpyrazine			39	
2-Isobutyl-3-methoxypyrazine	19	23, 33, 36	43-45	potato-like, pepper-like, green
2-Isobutyl-3-methylpyrazine			7, 37-40	

Compound	Raw	Boiled	Baked	Odour description
2-Isobutyl-5-methylpyrazine			39	
2-Isopropyl-3-methoxypyrazine	6, 7, 14, 17, 19, 20	6, 17, 32, 36	40, 43, 44, 46, 47	earthy/green, pea-like
2-Methoxy-3,5-dimethylpyrazine		6		bready
2-Methoxy-3-ethylpyrazine		6		raw potato
2-Methoxy-3-isopropylpyrazine		12, 17, 18		earthy, green, peas, raw potato, dry
2-Methoxy-3-methylpyrazine		6		nutty
2-Methoxy-5,6-dimethylpyrazine		6		caraway seed
2-Methoxy-5-ethylpyrazine		6		bready/mousy
2-Methoxy-5-methylpyrazine		6		not distinctive
2-Methoxy-6-ethylpyrazine		6		bready/mousy
2-Methoxy-6-methylpyrazine		6		fruit squash note
2-Methyl-3-isopropylpyrazine	6	12, 17, 18		nutty, warm, chemical
2-Methyl-5-isopropylpyrazine		30		
2-Methyl-5-propenylpyrazine			46	
2-Methyl-5-vinylpyrazine			7, 37	
2-Methyl-6,7-dihydro-5 <i>H</i> -cyclopentapyrazine			38, 40	earthy, baked- potato-like
3,5-Diethyl-2-methylpyrazine			7, 37-40, 43, 46	
3,5-Dimethyl-2-(2-methylpropyl)pyrazine			44, 46	
3,5-Dimethyl-6,7-dihydro-5 <i>H</i> -cyclopentapyrazine			38, 40	earthy, baked- potato-like
3-Butyl-2,5-dimethylpyrazine			38, 40	
3-Ethyl-2,5-dimethylpyrazine		30	37, 38, 40, 43, 46	nutty, earthy, herbaceous
3-Ethyl-2-methoxypyrazine		6		earthy/green
3-Ethyl-2,5-dimethylpyrazine			47	
3-Isoamyl-2,5-dimethylpyrazine			40	
3-Isobutyl-2,5-dimethylpyrazine			7, 37, 39, 40	
3-Isopropyl-2-methoxypyrazine		23, 29, 32	43	earthy, green, peas, raw potato, dry
5,7-Dimethyl-1,2,3,4,7,8-hexahydroquinoxaline			38, 40	earthy, baked- potato-like
5-Butyl-2,3-dimethylpyrazine			38, 40	
5-Methyl-6,7-dihydro-5 <i>H</i> -cyclopentapyrazine			38, 40	earthy, baked- potato-like
Amylmethylpyrazine			37	
Diethylpropylpyrazine			37	
Dimethylpropylpyrazine			37	
Ethylmethylvinylpyrazine			37	
Ethylpyrazine			7, 37, 38, 40, 43, 46	
Ethylvinylpyrazine			37	
Isoamylmethylpyrazine			37	
Isoampyrazine			37	
Isobutylmethylpyrazine			37	
Isobutylethylmethylpyrazine			37	
Methylpyrazine		30	7, 37, 38, 40, 43, 44, 46, 47	nutty, strong
Trimethylpyrazine			46	
<b>Pyridines</b>				
Pyridine	6, 7, 14	14, 18	7, 37, 43, 44, 46	
2-Pyridine methanol		31		



Compound	Raw	Boiled	Baked	Odour description
2-Aminopyridine			38	
2-Acetylpyridine			38	
<b>Pyrroles</b>				
2-Acetylpyrrole			38, 41, 46	
2-Acetyl-1-pyrroline		32, 36	38, 41, 46	roasty, popcorn
N-Methyl-2-formylpyrrole			38, 41	
1-Methyl-1( <i>H</i> )-pyrrole			43, 45, 46	
1-(2-furanylmethyl)-(1 <i>H</i> )-pyrrole			46	
<b>Furans</b>				
Furan	6			
2-Furaldehyde			38, 39, 41	
2-Ethylfuran	6, 23	31, 34, 35	43-45, 47	sweet, burnt
2-Pentylfuran	6, 7, 13, 14, 23	6, 12, 14, 23, 30, 34, 35	7, 37, 38, 41, 43-47	unpleasant, green, beany, grassy, cooked
2-Acetylfuran	6		7, 37, 38, 41	
2-Methylfuran		18	43-45	
3-Methylfuran		18		
2-Butylfuran		18		
2-Hexylfuran		18		
2-Propionylfuran			38, 41	
1-(2-Furyl)-2-propanone	6			
5-Methylfurfural		31	7, 38, 39, 41	
4-Hydroxy-2,5-dimethyl-3(2 <i>H</i> )-furanone		32, 33, 36		caramel-like
3-Hydroxy-4,5-dimethyl-2(5 <i>H</i> )-furanone		32, 33, 36		spicy, seasoning-like
<i>trans</i> -2-(2-Pentenyl)furan			38, 41	
Methyl furoate			38, 41	
2,5-Dimethyltetrahydrofuran			38, 41	
2-Methyltetrahydrofuran-3-one			38, 41	
2-Methyl-3-(2 <i>H</i> )-furanone			38, 41, 47	
2,5-Dihydrofuran			46	
<b>Amines</b>				
Methylamine	21			
Propylamine	21			
Isobutylamine	21			
Diethylamine	21			
<b>Ethers</b>				
Methyl ether			38	
Diethyl ether	6			
Ethyl isopropyl ether			38	
Ethyl pentyl ether			38	
Methyl nonyl ether			38	
Diethylene glycol diethyl ether			38	
1-Ethoxy-1-propoxyethane			38	
1,1-Diethoxyisopentane			38	

Compound	Raw	Boiled	Baked	Odour description
<b>Halogens</b>				
Bromodichloromethane	6			
2-Bromo-5-ethylnonane			38, 42	
Chloroform			38, 42	
1,1,1-Trichloroethane			38, 42	
Tetrachloroethylene			38, 42	
2-Chloropropane			38, 42	
1-Chloro-2-methylbutane			38, 42	
1-Chloroheptane			38, 42	
2-Chlorobiphenyl			38, 42	
1-Chlorohexadecane			38, 42	
1,1-Dichloroheptane			38, 42	
<i>o</i> -Chloroaniline			38, 42	
<i>p</i> -Chloroaniline			38, 42	
1-Iodo-octadecane			38, 42	
<b>Thiazoles</b>				
Dipropylthiazole	20	20		
2,4,5-Trimethylthiazole	20	20		
Ethyl-dimethylthiazole	20	20		
2-Isopropyl-4,5-dimethylthiazole	20	20		
2-Isobutyl-4,5-dimethylthiazole	20	20		
2-Isopropyl-4-methyl-5-ethylthiazole	20	20		
Benzothiazole	6, 10, 14	14		
2-Acetylthiazole	20	20		
2,5-Dimethyl-4-ethylthiazole			38, 40	earthy, nutty
2,5-Dimethyl-4-butylthiazole			38, 40	earthy, nutty
2,5-Diethyl-4-methylthiazole			38, 40	sweet, earthy
<b>Thiophenes</b>				
Thiophene			38, 41	
Benzothiophene		18		
2-Formylthiophene			38, 41	
2-Butyl-6-ethylthiophene			38, 41	
<b>Oxazoles</b>				
2,4,5-Trimethyloxazole			38, 41	earthy, nutty
5-Acetyl-2,4-dimethyloxazole			38, 41	earthy, nutty
<b>Sulphur compounds</b>				
Methanethiol	1, 3, 5-7,16	1, 3, 5, 16, 26, 27, 32, 33, 36		cabbage-like, sulfury
Ethanethiol	1, 3, 5-7,16	1, 3, 5, 16, 26, 27		
Butanethiol		5		
1-Propanethiol	1, 5-7	1, 5		
2-Propanethiol	1, 5-7	5		
2-Methyl-2-propanethiol	1, 5, 6			
Hydrogen sulphide	1, 3, 6, 7,16	1, 3, 5, 16		
Methylpropyl sulphide	1, 5, 6	5		
Methylpropyl disulphide			46	
Methyl <i>N</i> -pentyl disulphide			46, 47	

Compound	Raw	Boiled	Baked	Odour description
Ethylmethyl sulphide	1, 5-7	5		
Ethylmethyl disulphide	1, 5-7	5		
Dimethyl sulphide	1, 3, 5, 16	1, 3, 5, 16, 26, 27, 32, 33, 36	45	sulfury
Dimethyl disulphide	1, 5-7		43-47	
Dimethyl trisulphide		31-33, 36	43-47	cabbage-like
Dimethyl tetrasulphide		31	43-47	cabbage-like
3,5-Dimethyl-1,2,4-trithiolane	6, 7, 14	14		
Dimethyl sulphoxide		34		
Diethyl sulphide	1, 5-7	5		
Isopropylmethyl disulphide	1, 5-7	5		
2-Ethylhexyl mercaptan			38	
Ethyl pentyl disulphide			46	
2-Isopropylbenzimidazole			38	
Benzyl methyl sulphide			46	
Benzyl methyl disulphide			46	
Dipentyl disulphide			46	
<b>Nitrogen compounds</b>				
Diethylformamide			38	
Diethylacetamide			38	
Diphenylamine			38	
Thymine			38	
Cyanobenzene			38	
2-Amino-4-nitrotoluene			38	
2-Aminopentane			38	
<b>Miscellaneous compounds</b>				
Benzaldehyde diethylacetal	6	28		
Pentyl oxirane		12		
2-Propyl-1,3-dioxolane			38	
2,4,6-Trimethyl-1,3,5-trioxane			38	
1= Self (1967); 6= Nursten and Sheen (1974); 11= Khan (1971); 16= Self et al. (1963a); 21= Schormüller and Weder (1966a); 26= Self and Swain (1963); 31= Salinas et al. (1994); 36= Mutti and Grosch (1999); 41= Ho and Coleman (1980); 46= Oruna-Concha et al. (2001);	2= Khan et al. (1977); 7= Sapers (1975); 12= Josephson and Lindsay (1987); 17= Buttery and Ling (1973); 22= Desjardins et al. (1995); 27= Swain and Self (1964) 32= Mutti (2000); 37= Buttery et al. (1973); 42= Ho and Coleman (1981); 47= Oruna-Concha et al. (2002b)	3= Self et al. (1963b); 8= Buttery et al. (1961); 13= Fischer and Müller (1991); 18= Meigh et al. (1973); 23= Petersen et al. (1998); 28= Ryder (1966); 33= Grosch (1999); 38= Coleman et al. (1981); 43= Duckham et al. (2001);	4= Dumelin and Solms (1976); 9= Schormüller and Weder (1966b); 14= Buttery et al. (1970); 19= Murray and Whitfield (1975); 24= Waterer and Pritchard (1984b); 29= Mazza and Pietrzak (1990); 34= Thybo et al. (2006); 39= Pareles and Chang (1974); 44= Duckham (2002);	5= Gumbmann and Burr (1964); 10= Buttery and Teranishi (1963); 15= Fischer (1991); 20= Buttery and Ling (1974); 25= Waterer and Pritchard (1985); 30= Ulrich et al. (2000); 35= Petersen et al. (1999); 40= Coleman and Ho (1980); 45= Oruna-Concha et al. (2002a);

### 3.3 Boiled potatoes

The volatile profile obtained from boiled potatoes contains many process-derived compounds that contribute to the overall potato flavour (Buttery et al., 1970; Maarse, 1991). Important reactions for the flavour formation are the Maillard reaction, Strecker degradation and the thermal and enzymatic degradation of fatty acids (Figure 2). The Maillard reaction results in the formation of methional (Lindsay, 1996), which is a key compound of boiled potato flavour (Petersen et al., 1998). Autooxidation (Frankel, 1998) and enzymic (hydroperoxide lyase) action on hydroperoxides derived from linoleic and  $\alpha$ -linolenic acids (Gardner, 1995) produce a range of flavour-active volatile aldehydes, ketones, alcohols and alkyl furans. Pyrazines, pyridines, pyrroles, thiophenes, thiazoles and terpenes present the other major classes of cooked potato volatiles (Taylor et al., 2007; Coleman and Ho, 1980).

Ulrich et al. (2000) have identified in total more than 140 volatiles which contribute, more or less, to the aroma impression. Maga (1994) and Salinas et al. (1994) have identified approximately 150 volatile compounds in boiled potatoes. The amount of volatiles varies and depends on analysis methods, cooking time, temperature of water, cooking conditions (vacuum or atmospheric system), holding time after cooking, and if analysing, peeled, unpeeled or mashed potatoes. Table 2 displays all volatiles specified in the literature with their odour description. A total of 182 compounds were compiled.

Buttery et al. (1970) analysed the volatile oil fraction from potatoes distilled under vacuum conditions at 40 to 50 °C versus a 3-h distillation under atmospheric conditions at 100 °C. The results showed that under vacuum conditions, the major identified component was 1-octen-3-ol, while in the atmospheric system, the compound 2-pentylfuran was predominant. This shows that the air and the temperature play an important role in the formation of cooked potato volatiles. Nursten und Sheen (1974) had results similar to the findings of Buttery et al. (1970), as far as the major components are concerned. They compared the volatiles associated with the steam distillation of peeled and unpeeled potatoes. Over 30 components were characterised, showing that the essence from unpeeled potatoes generally contained more aromatic compounds and a greater proportion of terpenes in comparison to peeled potatoes. Josephson and Lindsay (1987) identified c4-heptenal in freshly boiled potatoes at high concentrations, which provided a boiled potato-like characterizing aroma and flavour note in the potatoes. C4-Heptenal was formed by a double-bond hydration, retro-aldol degradation of t2, c6-nonadienal, which was also identified in boiled potatoes. Although these compounds occurred at very low concentrations in fresh boiled potatoes, the extremely low recog-

nition thresholds exhibited by these volatiles should allow each of them to influence the overall flavour and aroma of boiled potatoes. The addition of very low levels of c4-heptenal (0.1 to 0.4 ppb) enhanced the overall earthy potato-like flavour in freshly boiled mashed potatoes. However, addition of c4-heptenal at higher levels, more than 0.7 ppb, resulted in a distinct stale-type flavour.

In addition, several specific compounds have been directly related to desirable flavour and aroma characteristics with methional (Lindsay, 1996), methoxypyrazines (Murray and Whitfield, 1975) and the lipid degradation product, *cis*-4-heptenal (Josephson and Lindsay, 1987), all reported to exhibit "a cooked potato odour." According to Ulrich et al. (1998) the characteristic impact compounds of the boiled potato aroma are methional, diacetyl and alkyl pyrazines. The compounds 2,4-nonadienal, 2,4-decadienal and 2-pentyl furan are among the off-flavour compounds in boiled potatoes.

Mutti and Grosch (1999) screened the potent odorants of boiled potatoes of the cultivar Sieglinde with three different sensory analyses. In addition to the aroma extract dilution analysis (AEDA) and aroma extract concentration analyses (AECA), which both detect only the medium and low volatile odorants, gas chromatography/olfactometry of static headspace samples (GCO-H) was used for the identification of the highly volatile odorants. Altogether 45 compounds were found of which 42 were identified. After boiling under conditions usual for domestic consumption, the volatiles were isolated from the potato sample and then separated into the neutral/basic and acidic fractions. In the neutral-basic fraction, 29 odorants were found in the flavour dilution (FD)-factor range of 8 to 512. The FD-factor for a compound is defined as the ratio of its concentration in the initial extract to its concentration in the most dilute extract, in which odour was detected by High Resolution gas chromatography (HRGCO) (Milo and Grosch, 1995). The most odour-active compounds with the highest FD-factor were methional (FD-factor 256) and *trans*-4,5-epoxy-(E)-2-decenal (FD-factor 512) (Mutti and Grosch, 1999). Further important flavour compounds with an FD-factor of 64 were 2-acetyl-1-pyrroline, dimethyltrisulphide and 2,3-diethyl-5-methylpyrazine. The next FD-factor level of 32 appeared with 1-octen-3-one, 1,5-octadien-3-one, 2-nonenal, 2,6-nonadienal, 2-nonenal, 2,4-nonadienal and 2,4-decadienal, which were formed by peroxidation of linoleic acid or linolenic acid. After the AECA method methional and epoxydecenal were revealed as the most potent odorants of boiled potatoes. This result was in agreement with that of AEDA. In the GCOH analysis, the odorants methanethiol and 2-isopropyl-3-methoxypyrazine were additionally detected.

The comparison of the aroma of the original potato and the imitation resulted in satisfying agreement. This suc-

cessful imitation of the boiled potato aroma shows that this aroma is mainly created by these five compounds. The rest of identified compounds serve to round or rather to intensify the boiled potato flavour. The results demonstrate that only odorous substances are involved in boiled potato flavour, the intensity of which can be enhanced by adding table salt (Grosch, 1999; Mutti, 2000).

According to the analysis of Mutti (2000) and Grosch (1999), the compounds methanethiol, 2,3-diethyl-5-methylpyrazine, 2-isopropyl-3-methoxypyrazine as well as methional showed high FD-factors and contributed to the typical boiled potato flavour.

### 3.4 Baked potatoes

Traditionally the potato is intact before baking at a relatively high temperature for approximately one hour, which results in subtle but pleasant flavour changes in a potato. A potato with higher solids content is used for baking, and the outer layer and skin of the potato are retained during preparation (Coleman and Ho, 1980). The potato is in this case the only source of thermally generated flavour precursors. In other processed potatoes (boiled potato, chips, French fries) some of the flavour precursors and compounds are derived from the cooking medium (oil, fat, water with table salt) or through enzymatic and oxidative attack by the peeling or slicing of potatoes (Deck et al., 1973; Maga, 1994). Nevertheless, the baked potato flavour has a very mild but extremely complex flavour (Coleman and Ho, 1980).

Since potatoes are usually baked intact, one could suggest that the potato skin serves as a trap to hold the resulting thermally-produced volatiles within the potato. Certainly, it is evident that during baking some of the volatiles produced do escape into the atmosphere, but this proportion has not been reported in the literature. That is also the reason why some consumers prefer to wrap aluminium foil around potatoes before baking. Maybe the foil wrap retains a greater portion of the volatiles generated, so that they can be absorbed into the potato instead of being lost to the atmosphere (Maga, 1994). However, in the literature there are no findings concerning the use of foil during the baking process. Mostly, after baking, the potatoes were removed from the oven, then wrapped in foil, and left to stand for some minutes (Oruna-Concha et al., 2002a; Oruna-Concha et al., 2002b).

Up until 2000, only few papers dealt with the flavour of baked potato (Buttery et al., 1973; Coleman and Ho, 1980; Coleman et al., 1981; Ho and Coleman, 1980; Ho and Coleman, 1981; Pareles and Chang, 1974; Mazza and Pietrzak, 1990). All volatiles of baked potato are listed in Table 2. The compiled references identify 392 compounds in baked potatoes.

One of the earliest studies, reported by Buttery et al. (1973), commented that the skins from baked potatoes had a greater ratio of pyrazines to aldehydes than the whole baked potato. In contrast, the volatiles from inside of the potato had a greater ratio of aldehydes to pyrazines. They held that both temperature and moisture conditions were more appropriate for pyrazine formation in the skin fraction compared to the potato interior. From their point of view, the most important compounds were 2-ethyl-3,6-dimethylpyrazine, methional, 2,4-dienal and 2-ethyl-3,5-dimethylpyrazine. In their opinion, of the pyrazines, 2-ethyl-3,6-dimethylpyrazine is one of the major contributors to baked potato aroma.

This is in accordance with the results of Pareles and Chang (1974) (s. Table 2). They separated the volatile flavour compounds in baked potatoes into acidic, neutral, and basic fractions and found that the basic and neutral fractions had the most characteristic baked potato aroma. They concluded that 2-ethyl-3,6-dimethylpyrazine was one of the most important compounds contributing to baked potato aroma. However, it was deduced that a combination of 2-isobutyl-3-methylpyrazine, 2,3-diethyl-5-methylpyrazine, and 3,5-diethyl-2-methylpyrazine had a much more characteristic baked potato aroma than did any single compound. Beside the pyrazines, the compound 5-methyl-2-furaldehyde was identified in their investigation, which might also contribute to the total flavour of baked potatoes.

Coleman, Ho and Chang (Coleman and Ho, 1980; Coleman et al., 1981) also pointed out that in addition to pyrazines, thiazoles contribute to the baked potato flavour. Around thirty pyrazines and three thiazoles were identified, whereof many of them have never been reported as volatile flavour components of baked potato or potato products before. The results of their research indicated that a natural baked potato flavour is not due to a single compound, but is the result of the mixture of a number of components. The compounds are considered as important contributions to the earthy, nutty, baked, sweet earthy potato, and baked potato-like aromas. 2-Ethyl-6-vinylpyrazine was described as buttery, baked, and potato-like. 2-Ethyl-3-methylpyrazine produces a pleasant earthy and nutty note to the total flavour (Coleman and Ho, 1980; Coleman et al., 1981). 2-Ethyl-3,6-dimethylpyrazine possesses an earthy, baked potato-like aroma, and is according to the scientists a very important compound to influence the flavour. Furthermore they found out that there are more pyrazines in baked potatoes than in other forms of cooked potatoes because of the presence of baked potato skins (Coleman and Ho, 1980). In a study by Koehler et al. (1969) it was shown that for an appreciable rate of pyrazine formation temperatures greater than 100 °C are needed.

On the basis of these thus-far mentioned studies, it would appear that the most important flavour compounds of baked potato are pyrazines, special 2-ethyl-3,6-dimethylpyrazine, methional, oxazoles, thiazoles and furanone.

As of 2000, other studies followed. These were engaged mainly in effects of cultivars (Duckham et al., 2001; Duckham et al., 2002; Oruna-Concha et al., 2001; Oruna-Concha et al., 2002a), storage times (Duckham et al., 2002) and preparation possibilities (Oruna-Concha et al., 2002b) on the volatile flavour components in baked potatoes.

Oruna-Concha et al. (2001) were the first who compared the volatile flavour components of different potato cultivars after baking. They analysed the volatile compounds from the skin and flesh of baked potatoes and compared the levels isolated from four potato cultivars growing at different sites. The potatoes were baked in their skins prior to separating the skin and flesh. The volatile composition of the skin and flesh of baked potatoes varies quantitatively and qualitatively among cultivars grown at different sites. Sugar degradation and/or the Maillard reaction is the major source of volatiles in skin, due largely to pyrazine while, in the flesh, lipid degradation products were also important (more in chapter 4.3.3).

Duckham et al. (2001) analysed the volatile flavour components of the flesh of potatoes following baking. For this study, a wider range of cultivars was used than has been ever reported so far. Their research revealed that lipid oxidation and the Maillard reaction are the major sources of flavour compounds of baked potato flesh, and that other components like sulfur compounds, methoxypyrazines and terpenes are also present at lower levels. According to their analysis, compounds like 2-isobutyl-3-methoxypyrazine, 2-isopropyl-3-methoxypyrazine,  $\beta$ -damascenone, dimethyl trisulfide, decanal and 3-methylbutanal contribute most to baked potato flavour.

#### **4 The effects of variety, agronomic and preparation measures on the volatile compounds and quality of raw, boiled and baked potatoes**

The flavour of food plants is variety-specific, defined genetically, but the natural habitat determinants, the cultivation (including fertilization) and the stage of maturation could also have an influence on the forming of flavour components (Doms and Timmermann, 1982). Furthermore, the storage conditions have an effect on the chemical composition of raw potatoes and on the sensory quality and aroma composition of boiled potatoes (Thybo et al., 2006). Even preparation methods like boiling, conventional baking or microwave baking have an impact on the volatile compounds and ultimately on the sensory quality.

The specific effects and their interference with the volatiles are specified in the following.

#### *4.1 Raw potatoes*

##### *4.1.1 Potato variety*

It is clear that plant genetics influence flavour (Paillard, 1981). The genetic composition determines enzyme systems and their activity in flavour formation (Heath and Reineccius, 1986). It is also known that varietal differences in flavour are due to quantitative differences in flavour composition rather than qualitative differences. But there are no comparable analyses about raw potatoes concerning differences of volatile compounds.

##### *4.1.2 Fertilization*

In how far a different nutrient supply can influence the flavour of potatoes has so far attracted only little interest. Hunnius et al. (1978) and Nitsch and Klein (1983) reported the negative changes of taste value of table potatoes (low mealiness, high moisture, poor taste) as a result of a high fertilization with nitrogen. Khan et al. (1977) showed via a pot experiment the influence of nutrient combinations on the spectrum of volatiles in raw potatoes. Both analyzed varieties, Grata and Saturna, include the following compounds: acetaldehyde, propanal, 2-butanone, pentanal, hexanal, heptanone, heptanal, 2-hexenal, octanal and nonanal. Differences in fertilization with nitrogen, phosphoric acid, potassic and magnesium cause a deferment in the spectrum of identified volatiles. High fertilization with nitrogen resulted in a decrease of acetaldehyde and propanal. In contrast, quantities of hexanal, heptanone, 2-butanone, 2-hexenal and octanal increased. Neither a positive nor a negative influence of different nitrogen fertilization levels on pentanal and nonanal could be detected. Higher addition of potassium benefit the volatiles of tubers with the exception of 2-hexenal and nonanal. An elevated fertilization with phosphate had a positive effect of acetaldehyde, pentanal, hexanal, heptanone, 2-butanone and octanal. No differences were observed after different phosphate applications by propanal, heptanal and nonanal, but a higher phosphate application caused a decrease of 2-hexenal. An increase in magnesium application induced a higher content of heptanone in both cultivars. No other effects of magnesium fertilization were assessed. The results were partially confirmed by Fischer (1991). He used a pot experiment to analyze the effect of various amounts of nitrogen and potassium on the composition of the aroma of native potatoes. Fischer (1991) found an increase of 2-hexenal, heptanal and 2,4-decadienal due a higher nitrogen application. A rising potassium application resulted in an increase of pentanol and 2-hexenal. He postulated that fertilization influenced the amount and type of lipid in the tuber, which in turn was the precu-

sor for the compounds identified. How far climate factors can also contribute to differences in volatile compounds is under discussion.

#### 4.1.3 Storage conditions

Under proper conditions, potato tubers can be stored for long periods of time before they are processed or consumed. Waterer and Prichard (1985) compared the volatiles produced by healthy tubers versus tubers that had been intentionally punched with needles. Volatiles were analyzed daily for six days. Wounded tubers produced 2-3 times more volatiles in total than the non-damaged control. Especially an increase of 15 compounds like methanol, ethanal, 1-propanal, 2-propanone, 1-propanol, 2-butanol, 2-butanone, 1-butanal, 2-methyl-1-propanal, 1-butanol, and 3-hydroxy-2-butanone were measured. All compounds except 3-hydroxy-2-butanone were found in normal tubers. Water and Prichard (1985) explained this with a higher metabolic activity associated with the wounds.

The content of volatile compounds increases and the quantitative ratios change when potato tubers are infected with pathogens. Waterer and Prichard (1984a) compared the volatiles produced by non-infected and infected tubers stored in plastic bags. They inoculated potato tubers with the bacterium *Erwinia carotovora* var. *carotovora*. Healthy tubers produced volatiles at a relatively low and constant rate. In the volatile profiles of the infected tubers a wide range of short chain alcohols and carbonyls were identified. During the development of the *E. carotovora* infection there was a general increase in the concentration of the individual volatiles, but certain compounds increased more than others. Lowering the temperature slowed disease development, resulting in decreased volatile production and changes in the pattern of volatile output. Wounding of potato tubers caused a general increase in volatile production by the tubers. In total, 14 volatile compounds (5 unidentified) were detected in the infected tubers. These included amongst others ethanol, methanol, ethanal, propanal, 1-propanol, 1-butanol, 2-butanol, 2-methyl-1-propanol, 2-propanone (acetone) and 3-hydroxy-2-butanone.

## 4.2 Boiled Potato

### 4.2.1 Potato variety

Only little information is available concerning the typical cooking flavour influenced by varieties. Ulrich et al. (1998) analysed the aromatic compounds of two varieties, the genotype "St1.365" and cv. "Adretta". The isolated volatiles were identified by GC-olfactometry-method. The obtained aromagrammes, including the aroma key compounds, were compared with the results of the sensory

evaluation. The sensory evaluation was carried out by a trained panel consisting of 15 members. Methional (3-methylthio-propanal), with the typical potato smell, was the compound with the highest peak in both varieties. The results showed that Adretta has an increased buttery or sweet caramel-like impression caused by 2,3-butanedione (diacetyl). The genotype St. 1.365 is characterized by high boiling volatiles, some identified as dienals with fatty and rancid odour impressions. The sensory profiles corresponded very closely to the analytical results. Adretta emits an increased sweet impression caused by diacetyl. The St 1.365 is evident in off-flavour note impressions like metallic and musty notes produced by dienals.

Thybo et al. (2006) proved the effect of cultivars on the aroma composition of cooked pre-peeled potatoes. The cultivars Berber, Arkula, Marabel, Sava, Folva and Agria were grown in three replicates on a fine sandy soil. A PCA (Principal Component Analysis) of the aroma components indicated that the variation of most of the aroma components was caused mainly by the effects of cultivar. In Sava, Folva and Agria higher intensities of methional, linalool and cymene and lower intensities of nonanal and decanal were detected. In contrast, higher intensities of nonanal and decanal was found in the cultivars Marabel and Berber, with a high intensity of rancidness and low intensity in potato flavour. This result showed that the cultivars Sava, Folva and Agria performed better with methional, described with a distinct boiled potato odour, than Marabel and Berber with their identified compounds contributing with a rancid and fatty odour.

### 4.2.2 Fertilization

It is known that fertiliser and method of application generally influence the basic nutrients of the boiled potatoes (Ceylan et al., 2006; Haase et al., 2005; Neuheff et al., 1999; Peine, 2005; Sandbrink and Grocholl, 2006; Singh et al., 2008; Stühling, 2004). Because the volatile aroma compounds derive from the basic nutrients, it could be assumed that the flavouring compounds would be affected by fertilization, too. However, there are hardly any findings in this area.

Thybo et al. (2002) analysed the effect of six different organic treatments of the sensory quality of potatoes. The cultivar Sava was grown under six organic treatments with three field replicates (18 samples) in sandy loam. Cattle slurry or cattle deep litter was applied corresponding to an equal supply of total nitrogen. The manure was applied 7-8 days before planting. The slurry was either placed under the seed potatoes, ploughed in with the straw of the preceding rye crop left in the field or ploughed in alone. The results showed no significant effects of the flavour of boiled potatoes manuring with different organic fertilizers.

#### 4.2.3 Storage time after boiling

When potatoes are boiled and then chill-stored, they rapidly (i.e., within hours) change their flavour. This rather undesirable flavour can be described as cardboard-like (Petersen et al., 2003). It is a result of lipoxygenase activity released from disrupted cells during the peeling process and the first part of the boiling process (Petersen et al., 1999). Petersen et al. (2003) determined the lipoxygenase activity in raw and fresh boiled potatoes and in boiled potatoes refrigerated until the next day. All potatoes underwent a long-term storage at 4° to 5 °C at 90 to 95 % relative humidity. All potatoes were peeled manually before boiling. Each month (from November until May) potatoes were analyzed for lipoxygenase activity and their aroma profile was measured in raw freshly boiled potatoes and in potatoes that were refrigerated for 24 h/5 °C after boiling. The most off-flavour compounds in all three versions were pentanal, hexanal, 2-octenal, 2-nonenal, 2,4-nonadienal and 2,4-decadienal and two typical potato aromas, methional and 2,6-nonadienal. Except 2-nonenal, all compound concentrations were significantly higher in the boiled/24 h-stored potatoes than in raw or the freshly boiled. The two 2,4-alkadienals were in fact only detected in the boiled/24 h-stored potatoes. Petersen et al. (2003) could not detect nonanal, and 2-nonenal did not change significantly during 24 h storage of boiled potatoes. However, they found out that the typical potato aroma compound 2,6-nonadienal disappeared during 24 h storage of boiled potatoes and the concentration of methional showed a tendency to decrease. On the other hand, Grosch (1999) realised an increase of the concentration of methional with its typical boiled potato flavour and 2,4-decadienal with fatty notes about 320 % and 283 % within 2 hours. However the compounds with an earthy note 2,3-diethyl-5-methylpyrazine and 3-isobutyl-2-methoxypyrazine decreased. The warm-holding induced a negative modification of the boiled potato flavour.

De Fiellietaz Goethart et al. (1985) studied the influence of keeping potatoes warm on their organoleptic quality. One or two temperatures and three or four different times, up to 3 h, were applied. It appeared that the decrease in quality as the result of keeping warm is, in most cases, the result of an increase in off-flavours and a decrease in positive flavour aspects. The panel concluded that boiled potatoes should not be kept warm for longer than half an hour, and certainly not longer than 1 h.

#### 4.3 Baked potatoes

##### 4.3.1 Potato variety

Oruna-Concha et al. (2001) reported the volatile flavour compounds of the skin and the flesh (analysed separately) from four potato cultivars after baking. The varieties Cara, Nadine, Fianna and Marfona were selected. The concentrated extracts were analyzed by GC-MS. The volatiles were identified and classified according to their origin, that is, lipid, sugar degradation (SD) and/or Maillard reaction (MR) not involving sulphur amino acids, sulphur compounds, methoxypyrazines, and other compounds. They observed quantitative and qualitative differences between samples isolated from flesh and skins, and among cultivars grown at different sites in the U.K., SD and/or MR was by far the main source in skin of all cultivars (71 to 78 % of the total amount) except Nadine (28 %), with pyrazines contributing from 56 % (Nadine) to 73 % (Cara) of amounts in this group. In every cultivar 2,5- and/or 2,6-dimethyl-pyrazine was the most abundant representative compound. The amino acid asparagine comprised the largest component in pyrazine formation (Hwang et al., 1995). Nadine possessed the lowest level of asparagines, and this may account, partially, for the low levels of pyrazines observed. Methional with its typical cooked potato aroma could not be identified. Maybe it was masked by 2,5- and/or 2,6-dimethylpyrazine (Oruna-Concha et al., 2001). The methoxypyrazine 2-isopropyl-3-methoxypyrazine was only present in Marfona. This compound is of particular interest due to its very low odour threshold value of 2 ng/L and because it was previously identified in raw, boiled and baked potatoes. Buttery and Ling (1973) have suggested that it stems from bacteria formed in the soil and can be absorbed into the tuber. But they discovered that the similar compound 2-isobutyl-3-methoxypyrazine is synthesized by bell peppers, to which the potato is closely related. Because 2-isopropyl-3-methoxypyrazine was only found in one cultivar, it would appear that there may be differences among the cultivars examined in their ability to synthesize this compound. In the opinion of Oruna-Concha et al. (2001), another reason for the synthesis could be the differences in cultural conditions. Solavetivone, a sesquiterpene, was identified in all four cultivars. Compared to the other cultivars, a relatively high level was analysed in the skin of the cultivar Nadine. Because solavetivone is a marker of stress metabolite (Zacharius and Kalan, 1984), Oruna-Concha et al. (2001) suggested that Nadine tubers were under stress during storage, although they and all the tubers of the other three cultivars appeared to be in good condition. One could argue that Nadine may have been biochemically less stable than other cultivars.



The lipid and SD and/or the MR were responsible for the volatile formation in the flesh. The lipid degradation was the prevalent source of volatiles in Cara (93 %), in Fianna (75 %), but only 15 and 19 % of the volatiles in Nadine and Marfona. Especially levels of pyrazines were much lower in the flesh, and those compounds that were identified, according to Buttery et al. (1973), migrated from the skin, where the higher temperature and lower water activity (compared to the interior of the tuber) located during baking would favour their formation. Furthermore, the compounds 2,4-decadienal, 2-nonenal and methional appear to be the most important contributors to flesh aroma. Oruna-Concha et al. (2002a) compared the volatiles in the flesh of eight cultivars of potatoes after microwave baking. The cultivars Marfona, Desiree, King Edward, Fianna, Nadine, Pentland Squire, Saxon and Cara were grown in the same field in the U.K.. Sixty of the 80 volatile compounds identified in this study were lipid-derived. Prominent compounds present in all cultivars included hexanal, nonanal, decanal, benzaldehyde and 2-pentyl-furan. 2-Isobutyl-3-methoxypyrazine was presented in identifiable amounts in only the cultivar Desiree. Alkylpyrazines followed from the MR were not identified in the microwave-baked potatoes. Duckham et al. (2001) came to similar conclusions. They analysed the baked potato flesh of eleven cultivars which were grown on the same field and were baked in a conventional oven. The cultivars were partially equal to those of Oruna-Concha et al. (2002a): Nadine, Golden Wonder, Fianna, Estima, Cara, Saxon, Kerr's Pink, Maris Piper, Desiree, Marfona and Pentland squire. Marfona gave the highest absolute yield and relative yield (77 %) of compounds formed by the MR and/or SD while yields were lowest for Cara (25 %). These results agree with those of Oruna-Concha et al. (2002a), who also found the highest yield of compounds by the MR and/or SD in Marfona and the lowest in Cara. The most abundant representatives in both studies were the Strecker aldehydes 2- and 3-methylbutanal, which were identified in every cultivar and contributed 75 to 96 % of the volatiles in this category. However, statistically significant differences were observed in the levels of both aldehydes between the cultivars. Furthermore, only one or more pyrazines were identified in only six of the eleven cultivars, most representatives Golden Wonder (Duckham et al., 2001). The formation of pyrazines is facilitated by high temperature and intermediate moisture; conditions that concerned in the outer layer of the potato tuber during baking. The analysed pyrazines may have migrated from the outer layers of the potato towards the centre during baking (Buttery et al., 1973). Also methional was detected in only five cultivars with the highest level in the cultivar Nadine. In contrast, dimethyl disulphide, which can form from methional, was present in all cultivars and dimethyl trisulphide were found in all except Golden Wonder (Duckham et al., 2001).

In summary, it could be retained that the lipid and the MR and/or SD are the major sources of compounds in all cultivars. However, each potato cultivar possessed a unique profile of volatile compounds.

#### 4.3.2 Storage conditions

A study of Duckham et al. (2002) examined the effects of cultivar and storage time on amounts of selected volatile flavour components of the flesh of potatoes following baking. They chose the five cultivars Estima, Saxon, Golden Wonder, Kerr's Pink and Desiree, which were grown on different sites in the U.K.. Tubers were stored at 4 °C for 2, 3, and 8 months and baked in a conventional oven. The flavour compounds were isolated by headspace method and analyzed by GC-MS. More than 150 compounds were detected. There was a significant increase in total amounts of compounds between 2 and 3 months, and between 3 and 8 months storage. With storage time, the total amounts of compounds derived primarily from lipid increased, and there were differences for each storage time interval. The amounts of the lipid-derived aldehyde hexanal, heptanal, nonanal and decanal all increased significantly between 3 and 8 months. By contrast, 2-heptanone, 1-octen-3-ol and butanedione, which are also originated from lipids, were significantly lower after 8 months of storage compared the other storage times. The levels of Maillard/sugar-derived compounds were significantly higher after 8 months as compared to 2 and 3 months of storage. Between 2 and 3 months, methylpropanal, 2-methylbutanal and 3-methylbutanal showed no significant increase, followed by a significant increase between 3 and 8 months. Methional was the only compound in this study that showed a significant storage time effect, the amounts decreased between 3 and 8 months.

#### 4.3.3 Preparation methods (conventional baking, microwave baking, boiling)

Heat and mass transfer characteristics of foods cooked by microwave radiation are different from those associated with conventional baking (Van Eijk, 1994). Potatoes are more rapidly baked in a microwave oven (e.g., ~10 min) than in a conventional oven (~1 h) (Wilson et al., 2002b). There are some studies compared the flavour of conventionally and microwave baked potatoes (Bowman et al., 1971; Brittin and Trevino, 1980; Eheart and Gott, 1964; Maga and Twomey, 1977; Oruna-Concha et al., 2002b). In a study by Maga and Twomey (1977), a trained panel ranked four potato cultivars (respectively baked conventionally and baked by microwave) from the best to worst on the basis of external and internal appearance, aroma and flavour. It could be shown that in all cases microwave

baking came off badly, and the trained panel preferred the conventionally baked potatoes. Brittin and Trevino (1980) evaluated the flavour of conventionally and microwave-baked potatoes using both a 10-member trained panel and a 120-member consumer panel. The trained sensory panel ranked the microwave-baked tubers lower while a consumer panel showed no significant differences for preferences or acceptability. Using GC-MS, Oruna-Concha et al. (2002b) determined the effects of boiling, conventional baking and microwave baking on the profiles of flavour compounds of two potato cultivars (Estima and Maris Piper). Peeled and sliced tubers were boiled, while intact potatoes were baked in their skins. Regardless of cooking procedure, main sources of flavour compounds resulted in lipid degradation and from the MR and/or SD. The proportion of lipid-derived compounds to the proportion of sugar- and/or Maillard-derived compounds decreased from 8.5-9.1 (boiling) to 2.7-3.4 (microwave baking) and to 0.4-1.1 (conventional baking). The total levels of lipid-derived compounds in boiled potatoes were 1.2-2.1-fold higher than those that had been prepared in the microwave and 1.5-3.2-fold higher than those that had been conventionally baked. Hexanal, 2-heptenal and 2-pentylfuran were higher after boiling, but 2-nonenal and decanal were the highest following microwave baking. Higher amount of hexanal and 1-octen-3-ol were found after baking conventionally than in the microwave oven. The levels of the lipid-derived 2-methylfuran, 2-pentylfuran, 3-hexanone and 1-octen-3-ol were significantly higher after boiling. The total number of compounds derived from SD and/or the MR was always highest for conventionally baked potatoes and lowest for those that had been boiled. The potato flesh of microwave-baked potatoes gave the weakest isolates of volatile compounds.

These quantitative and qualitative differences for the flavour compounds created by the three cooking procedures may be partially attributed to the variations in heat and mass transfer processes that occur.

During baking in a conventional oven, heat is transferred into the potato at its surface and the surface temperature increases to 100 °C. The rate of the heat transfer is limited by heat loss through water evaporation and by the reduced thermal conductivity of the dried skin layer (Wilson et al., 2002a). Finally, the surface temperature increases above 100 °C, a crust develops, further evaporation of water takes place and the 100 °C isotherm moves towards the centre of the tuber. Water loss during baking amounts for ~200 g kg<sup>-1</sup> of the original mass of the tuber and increases linearly with cooking time. From the outer 3 mm of the tuber is the most of moisture lost (~57 %) and the crust rapidly becomes a low-moisture zone. During boiling, the water loss from the tuber is marginal and the 100 °C isotherm migrates more rapidly towards the cen-

tre of the tuber than during conventional baking (Oruna-Concha et al., 2002b).

The heating method during microwave baking is quite different from those for other cooking procedures; short baking time and the outer surface, which, owing to evaporative cooling, remains at a lower temperature, and, in contrast to conventional baking, forms no crust (Oruna-Concha et al., 2002b). Baking in the microwave resembles oven baking in that there is substantial evaporative loss of water, but the conversion of microwave energy into heat is dispersed (Wilson et al., 2002b). The input of energy is not spatially uniform, but the degree of non-uniformity varies with the shape and dimensions of food material (Zhou et al., 1995). Oruna-Concha et al. (2002b) could show that the amount of moisture lost during microwave and conventional baking were about the same, but in the tubers prepared in microwave oven the loss of water was uniformly throughout the tuber. This mechanism of water loss, which in their opinion could result in losses of flavour compounds through co-distillation, plus evaporative cooling at the tuber surface could account for the lowest of total volatiles in the isolates prepared from microwave-baked potatoes. The moisture is an important factor influencing the MR, and the reduced moisture levels in potatoes baked by both methods most likely played a key role in the observed levels of components formed via this pathway. In the conventionally baked tubers, an outer crust was formed, an area of low moisture content with a temperature between 100 °C and the set oven temperature (190 °C). Such a crust was not noticed in the microwave-baked potatoes, but the levels of the Maillard products were higher than in boiling and this must be the consequence of the reduced moisture level in the tuber caused by microwave baking. In an investigation by Van Eijk (1994), the low moisture content and the high temperature of the crust that develops at the surface of the tuber during conventional baking, together with the relatively long cooking time, affect the MR in comparison to microwave baking.

Both baking methods, which had lower amounts of lipid degradation products than boiling, led to a more rapid temperature increase in potato tissue, compared to boiling, and lipoxygenase is expected to make a smaller contribution to flavour development in intact tubers. Thus it is presumed that, the majority of the lipid-derived components in baking potatoes resulted by thermal degradation of lipid rather than enzymatic oxidation.

## 5 Conclusions

Large numbers of volatile compounds were identified in raw, boiled and baked potatoes. These can be considered as products of lipid or sugar degradation and/or Maillard reaction/lipid interactions.

Lipid oxidation products of unsaturated fatty acids are the major source of volatiles in raw potatoes due to the relatively high lipoxygenase content. Important reactions for the flavour formation in boiled potatoes are the Maillard reaction, the Strecker degradation and the thermal and enzymatic degradation of fatty acids. The volatile composition of the skin and flesh of baked potatoes varies quantitatively. Sugar degradation and/or the Maillard reaction is the major source of volatiles in skin, due largely to pyrazine while, in the flesh, lipid degradation products were also important.

The desirable heated potato flavour in boiled and baked potatoes seems to center around pyrazines in various combinations that result in a typical earthy, potato-like flavour.

Because potato tubers are only consumed after cooking or baking, there are only few results on the volatiles in raw potatoes. The small number of studies deals with volatiles after tuber damage or microbial attack. However, there would be an advantage to identifying the volatiles in the raw product. By comparing these with those of processed potatoes, positive or negative impacts by the raw product on the final product-flavour could be determined. This information could serve for breeding new varieties with certain properties which eventually comply with consumer demand.

The impact of agronomic measures on the volatile compounds in raw, boiled and baked potatoes was not taken into intensive consideration thus far. Especially in view of the volatiles in different varieties and in different agricultural systems (ecological, conventional), fertilization and storage there are hardly findings.

This stresses the future need for research, in particular regarding the effects of agronomic measures on the volatile compounds and their influence on the sensory quality of raw as well as processed potatoes.

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