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Good Potatoes for Good Potato Crisps, a Review of Current Potato Crisp Quality Control and Manufacture

Nigel G. Yee* • **William T. Bussell****

School of Natural Sciences, Unitec New Zealand, Private Bag 92025, Auckland, New Zealand

***Corresponding author*: * nyee@unitec.ac.nz, ** wbussell@unitec.ac.nz**

ABSTRACT

Potato crisps are commercially manufactured by frying thin slices of potato tuber in oil/fat using automated production machinery. During the manufacturing process, the properties of the tuber are transformed to produce a potato crisp that is of a light golden complexion, mechanically crisp and palatable to consumers. This paper reviews the manufacturing process used to produce potato crisps, legislative regimes governing the production of potato crisps, and sensory methods used to determine the quality properties of the potato crisp. Measurement methods used to determine potato crisp quality and identify unsatisfactory potato crisps produced within the manufacturing process are discussed. The review concludes with a case study using near infrared spectroscopy for determination of moisture levels in potato crisps and future perspectives.

Keywords: HACCP, moisture level, NIR spectroscopy, tuber quality

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INTRODUCTION

Potato (*Solanum tuberosum* L.) is currently one of the world's most important food crops, being the fourth largest in tonnage. Fried potato products are one third of the end use of the potato crop. Frying is desirable to human beings because of the texture and taste provided by the fried product. Processors have a vested interest in ensuring that food which is palatable and safe reach consumers, so a large number of methods to measure product quality have been developed.

A thinly sliced fried potato tuber is known as a potato crisp and was invented by a cook named George Crum in 1853 at Saratoga Springs, New York State. The first potato

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crisps labelled 'potato crunches' were prepared in restaurants and sold in baskets. Crum later marketed the fried thin potato slices as Saratoga chips. William Tappendon of Cleveland, OH, in 1895, is credited with constructing and running one of the first potato crisp factories in the USA (Snack Food Association 1987). Potato crisps are now widely consumed and a multi-billion dollar industry.

The quality of a potato crisp (appearance, texture, taste, consumer acceptability) is a product of the quality of the tubers used in the manufacture of the potato crisp and the manufacturing process used. The potato tuber is non-homogeneous and varies in physical shape and chemical composition so when tubers are processed in a modern manufacturing line variations in potato crisp quality occur. Manufacturers prefer to have consistent potato crisp quality and try to reduce the manufacturing variability. The potato crisp manufacturing process produces hazardous substances of chemical, physical or microbiological origin, such as acrylamide, *trans*-fatty acids and moisture-dependent micro-organisms that are considered harmful to consumers if present in levels exceeding tolerance limits. To reduce variability in potato crisp quality from the manufacturing process and prevent hazardous substances from reaching consumers, points within the manufacturing process are identified where quality variations can occur. These points are termed Critical Control Points (CCPs). Tolerance limits at the CCPs are identified and then monitored using appropriate measurement techniques with the results analyzed and archived. If the tolerance levels are exceeded at a CCP, corrective actions need to be performed and causes for non-compliance at the CCP identified and documented. The process of identifying manufacturing hazards and monitoring the CCPs (where hazards can occur) is known as Hazard And Critical Control Point (HACCP) analysis.

Current regulatory regimes encourage the production of healthy foods. Potato crisps are manufactured in many countries and over 50 countries have adopted the HACCP regulatory procedures into current legislation, for the purpose of ensuring that consumers receive food that is safe for consumption. For example, the HACCP regulatory regime is explicitly used in EC regulatory directive (Dir. 93/43 EC 1993) to ensure food safety (Anonymous 1993a; Coutrelis 2000).

This paper presents a review of current manufacturing methods used for potato crisp production and potato crisp quality parameters. The review firstly discusses the HACCP legislative regimes governing the manufacture of food. A description of the manufacturing process is presented, common processes used in the manufacturing of potato crisps are described and points where manufacturing variation occur are discussed. Quality control systems, automatic inspection systems and measurement systems are described in relation to determining product quality at points in the manufacturing process. The changes that tubers undergo within the production process are presented. These are physical, chemical, textural and visual changes during the processing from tuber to potato crisp. A description of how the manufacturing process can cause variability in the processed tuber's properties is presented and different manufacturing processes that reduce the variability are discussed. Measurement techniques for determining potato crisp quality are reviewed. The review finishes with a case study in which near infrared spectral analysis is used to measure moisture level in potato crisps and considers future perspectives for crisp processing.

HAZARD AND CRITICAL CONTROL POINT ANALYSIS

Many countries have different regulations governing food manufacture; however most of the regulations are based on the principles of HACCP analysis. Some countries and trading blocks explicitly stipulate the use of HACCP in their food manufacture regulations while others use HACCP implicitly within the regulatory regime.

Regulation 178/2002 EC (Anonymous 2002) of the European Parliament and Council stipulates that all aspects should be focused on in the food chain, starting from primary production and finishing with consumption of the food product by the consumer. The implication of this directive is that traceability should be present in the food production system; increasing traceability allows regulators and producers to issue product recalls if food safety problems arise.

The HACCP regime focuses on CCPs within the food production chain and uses monitoring of the performance at the CCPs and also rigorous attention to hygiene at the control point to enhance food safety. HACCP is considered to be a cost-effective method that reduces the risk of production and sale of unsafe food products. It requires the identification of potential risks (microbiological, chemical and physical) in the food production chain and identifying critical parameters that must be monitored and recorded to obtain a safe food product. **Appendix A** contains a list of principles used in the HACCP processes.

A HACCP flow chart outlines preventative measures and mitigation strategies for hazard prevention and a list of CCPs that require monitoring in order to prevent unsafe food from reaching consumers. Presented in **Appendix B** is a HACCP flow chart containing steps that mitigate hazards involved with crisp production. The flow chart is adapted from the HACCP chart by Vorria *et al.* (2004) for potato crisp and potato chip production. It outlines preventative measures and mitigation strategies for hazard prevention and a list of CCPs that require monitoring in order to prevent unsafe potato crisps from reaching consumers.

Factors that affect crisp quality and safety

People purchase food that is texturally and colour appealing, flavoursome and inexpensive. General attributes considered desirable in potato crisps and used as indicators of quality are light colouring, amount of crunch that the crisp has and palatability. However the production of potato crisps also produces micro-biological and chemical compounds that require monitoring because they are considered undesirable to human beings and pose a health risk if present in large quantities. These compounds are:

- Acrylamide;
- Those produced by moisture-dependent micro-organisms;
- Those resulting from differences in oil/fat content.

Measurable physio-chemical properties of potato crisps which affect consumer perception and are related to their sensory properties are also monitored. Some physio-chemical properties are directly related to the presence of the undesirable compounds listed above. They are monitored to determine both the levels of these undesirable compounds and the sensory quality of the potato crisp that consumers find desirable. These properties are:

- Texture/mechanical properties;
- Acoustic properties;
- Colour properties;
- Near infrared spectral properties.

Acrylamide in potato crisps during frying

Acrylamide is classified by the International Agency for Research on Cancer (IARC) as probably carcinogenic to humans and carcinogenic in animals (IARC 1994). It is also considered by this same agency as neurotoxic to humans.

The U.S. Environmental Protection Agency (EPA) requires the limit for acrylamide content in water to be less than 0.5 ppb (EPA 2004). Starch-rich products, such as those produced from potato tubers (7.80-25.43% starch), have a much higher content of acrylamide (170-3700 ppb) than the level identified as safe by the EPA (Becalski *et al.* 2003).

Moderate levels of acrylamide (5-50 ppb) have been found in heated protein-rich foods, while higher levels

(150-4000 ppb) originate from carbohydrate-rich foods (Tareke *et al.* 2002). No acrylamide has yet been found in raw or unheated foods. This suggests that a reaction during cooking of carbohydrate-rich foods is responsible for the formation of acrylamide. Currently the most accepted theory for the formation of acrylamide is that it is a by-product of Maillard browning (Stadler *et al.* 2002). The chemical pathway for acrylamide formation from amino acids and reducing sugars is shown in **Appendix C**.

Moisture-dependent micro-organisms

The water activity level (a_w)[1] of potato crisps is determined by taking measurements of their moisture levels. It must be low enough to inhibit micro-organism growth.

Section 110.80 of the USFDA (Anonymous 2006a) regulations requires that foods relying on the control of a_w for preventing the growth of undesirable micro-organisms shall be processed to and maintained at a safe moisture level. Compliance with this requirement may be accomplished by any effective means, including employment of one or more of the following practices:

(i) Monitoring the a_w of food.
(ii) Controlling the soluble solids-water ratio in the finished food.
(iii) Protecting finished food from moisture pickup by use of a moisture barrier or by other means, so that the a_w of the food does not increase to an unsafe level.

The frying process producing potato crisps is a dehydration process. A potato crisp moisture level exceeding 12% when packaged will sustain micro-organism growth and pose a health risk, thus it is important that preventative measures are implemented to prevent potato crisps with unacceptable moisture levels reaching consumers.

Compounds resulting from the use of oil/fat during frying

The frying of tuber slices in heated oil creates compounds within the oil that are absorbed into the potato crisp and eventually eaten by consumers. Strategies should be put in place during manufacture to monitor the oil/fat content of the potato crisp to ensure thresholds are not exceeded. Polymerization of oil/fats occurs when the oil/fat is heated in the fryer which causes the oil/fat to decompose into volatile and non-volatile products. The volatile products formed considered undesirable for human consumption include peroxides, monoglycerides, diglycerides, aldehydes, ketones and carboxylic acids. The undesirable non-volatile products are primarily monomers and other high-molecular-weight compounds. Free fatty acids are created within the oil by the hydrolysis process, when food products containing water are heated in oil and are considered undesirable for human consumption. *Trans*-fatty acids are created by hydrogenation of oil/fat in the frying process and are considered harmful to human beings because they increase cholesterol levels in human blood (Hayakawa *et al.* 2000).

Texture/mechanical properties

Texture is one of the most significant quality attributes in food products since it makes a dominant contribution to overall quality and acceptability (Kayacier and Singh 2003). It plays an important role in the quality of potato crisps; consumers desire crisps that are crisp in texture (crispness), and a crisp that is soggy and lacks firmness is considered to be undesirable to consumers. Sogginess in a potato crisp is an indicator of an unacceptable moisture level, and is monitored to prevent crisps that are both potential health risks and unacceptable to the human senses from reaching consumers.

Acoustic properties

Humans perceive acoustic sound by the sense of hearing. Audio sound are vibrations (of frequencies 20 Hz to 20 kHz) that travel through air and can be heard by humans. The sensory perception of the potato crisp quality is influenced by the sound that is emitted from a potato crisp when it is crunched or broken in the mouth by the person consuming the potato crisp; the sound emitted is referred to as the potato crisp's crunch (Szczesniak 1988). Consumers prefer crisps that are crunchy and emit a sound characteristic of a crunchy potato crisp. Crisps that do not sound crunchy when crushed are considered undesirable by crisp manufacturers because they are undesirable to consumers. One of the parameters that influences the amount of crunch in a potato crisp is the moisture level, soggy crisps do not sound crunchy when they are consumed thus the crunchiness of a potato crisp is also an indicator of the moisture levels in potato crisps.

Colour properties

Food colour derives from the spectrum of light (distribution of light energy versus wavelength) interacting in the eye with the spectral sensitivities of the light receptors. The only features of light that are detectable by humans are within the visible spectum (of λ ~400 nm to 750 nm wavelength). This part of the spectrum is related to the psychological phenomenon of colour and to its physical specification (Smithson 2005). The colour of a potato crisp is an important attribute that affects the perception of the potato crisps' quality by a consumer. Potato crisps that are of a light golden colour are considered desirable by consumers whereas potato crisps that are of a dark complexion are considered undesirable and are associated with burnt potato crisps (Maga 1973). Colour development in potato crisps is produced by the Maillard reaction and the colour of a potato crisp is an indicator of the levels of compounds such as acrylamide. Studies have shown that the most influential parameters affecting colour development during tuber frying are temperature, tuber slice thickness, tuber variety, and frying temperature. Oil type is not considered an influential parameter in the colour development process (Krokida *et al* 2001; Weber and Putz 2003).

Monitoring the colour of potato crisps and only passing onto consumers potato crisps of a light golden colour is a means of satisfying consumer sensory expectations of

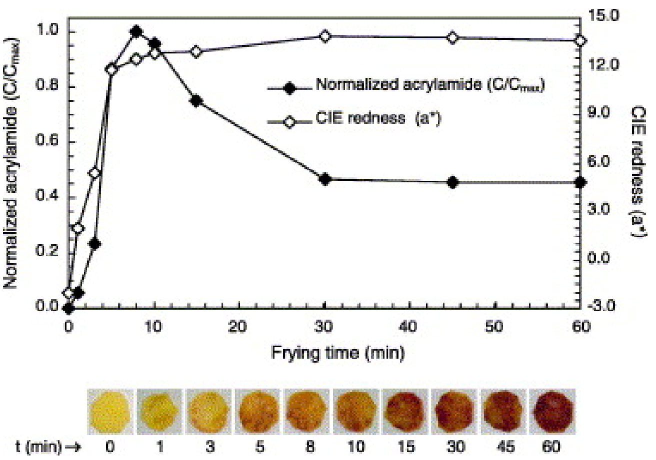

Fig. 1 Change of acrylamide concentration and CIE redness parameter a* in potato chips during frying at 170 °C. Reprinted from **Gokman V, Senyuva H, Dulek B, Cetin A** (2007) Computer vision-based image analysis for the estimation of acrylamide concentrations of potato chips and French fries. *Food Chemistry* **101**, 791-798, ©2006, with kind permission from Elsevier.

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[1] **Water activity** or a_w is the relative availability of water in a substance. It is defined as the vapor pressure of water divided by that of pure water at the same temperature. Water activity or a_w is a measure of the vapour pressure generated by the moisture present in a hygroscopic product.

potato crisp colour and preventing crisps with high levels of acrylamide being consumed. **Fig. 1** shows the picture of colour changes in potato crisps with corresponding changes in acrylamide level and CIE redness parameter (a*).

Near infrared spectral properties

Near infrared (NIR) spectroscopy is the collection and analysis of information from within the NIR region of the electromagnetic spectrum with wavelength of 750 nm to 2500 nm (Osborne and Fearn 1986). NIR spectroscopic analysis is an alternative method to colour analysis. NIR's advantage over colorimetry and conventional image processing is that it is not limited to three wavelengths but uses many wavelengths compiled from the NIR spectrum. NIR spectroscopy has the ability to make inferences about the chemical composition of materials. This is based on molecular overtone and overtone combination vibrations from chemical components present within the NIR spectrum. When light at the same frequency of a molecular overtone or combination of overtone's vibrational frequency is presented to the subject under study, the light at this frequency is absorbed by the subject under study. The amount of light absorbed at this frequency is related to the amount of chemical compounds present in the object under study (Wilson 1994).

The NIR spectrum contains more information than the visual spectrum because this part of the spectrum is directly related to the chemical structure of the potato crisp. By analysing the NIR spectral properties of a potato crisp, measurements of the chemical structure can be made. Levels of chemical compounds such as acrylamide, moisture, protein, carbohydrates and oil/fat can be made. Because some of these compounds are considered harmful to consumers and others influence the sensory properties of the potato crisp, NIR spectral properties are used as a means of monitoring chemical composition and sensory quality of a potato crisp. **Table 1** lists constituent components present in an acceptable potato crisp (source USDA Nutrient Database for Standard Reference, Anonymous 2006b).

Table 1 Composition of potato crisps, nutrient values and weights are for edible portion of 100 grams (source USDA Nutrient Database for Standard Reference, Anonymous 2006b).

Nutrient	Units	Value per 100 grams	Number of Data Points	Std. Error
Proximates				
Water	g	1.90	191	0.053
Energy	kcal	536	0	
Energy	kj	2243	0	
Protein	g	7.00	145	0.122
Total lipid (fat)	g	34.60	158	0.248
Ash	g	3.60	157	0.068
Carbohydrate, by difference	g	52.90	0	
Fiber, total dietary	g	4.8	0	
Sugars, total	g	0.22	0	
Minerals				
Calcium, Ca	mg	24	223	0.518
Iron, Fe	mg	1.63	248	0.028
Magnesium, Mg	mg	67	240	0.605
Phosphorus, P	mg	165	237	2.256
Potassium, K	mg	1275	234	11.564
Sodium, Na	mg	8	0	
Zinc, Zn	mg	1.09	88	0.048
Copper, Cu	mg	0.306	218	0.009
Manganese, Mn	mg	0.440	210	0.01
Selenium, Se	mcg	8.1	0	
Vitamins				
Vitamin C, total ascorbic acid	mg	31.1	93	1.498
Thiamin	mg	0.167	125	0.008
Riboflavin	mg	0.197	122	0.013
Niacin	mg	3.827	129	0.133
Pantothenic acid	mg	0.402	24	0.031
Vitamin B-6	mg	0.660	73	0.029
Folate, total	mcg	45	24	0.735
Folic acid	mcg	0	0	
Folate, food	mcg	45	24	0.735
Folate, DFE	mcg_DFE	45	0	
Vitamin B-12	mcg	0.00	1	
Vitamin B-12, added	mcg	0.00	0	
Vitamin A, IU	IU	0	0	
Vitamin A, RAE	mcg_RAE	0	0	
Retinol	mcg	0	0	
Vitamin E (alpha-tocopherol)	mg	9.11	0	
Vitamin E, added	mg	0.00	0	
Vitamin K (phylloquinone)	mcg	22.1	0	
Lipids				
Fatty acids, total saturated	g	10.960	0	
4:0	g	0.000	0	
6:0	g	0.000	0	
8:0	g	0.000	0	
10:0	g	0.000	31	
12:0	g	0.080	31	
14:0	g	0.300	31	
16:0	g	9.320	31	
18:0	g	1.110	31	
Fatty acids, total monounsaturated	g	9.840	0	
16:1 undifferentiated	g	0.180	31	
18:1 undifferentiated	g	9.510	31	
20:1	g	0.150	31	
22:1 undifferentiated	g	0.000	0	
Fatty acids, total polyunsaturated	g	12.170	0	
18:2 undifferentiated	g	11.980	31	
18:3 undifferentiated	g	0.190	31	
18:4	g	0.000	0	
20:4 undifferentiated	g	0.000	0	
20:5 n-3	g	0.000	0	
22:5 n-3	g	0.000	0	
22:6 n-3	g	0.000	0	
Cholesterol	mg	0	24	0

THE MANUFACTURE AND QUALITY OF POTATO CRISPS

The many steps in the manufacturing process are summarised diagrammatically in **Appendix D**. The process starts with planting tubers of a selected cultivar. Soil, growth conditions and tuber development is monitored during crop growth so that mature tubers suitable for production of good quality potato crisps are harvested. At harvest, maturity indicators of sugar level, soluble solids, moisture levels, specific gravity and size are determined.

The mature tubers are then transported from the field to the factory. Upon entry to the factory they are stored in a storage area where they are conditioned prior to cooking; storage factors monitored that affect tuber quality for crisping are temperature, humidity, light intensity, additives for the prevention of rot, period held in storage and tuber quality prior to storage. **Table 2** lists conditions commonly used in commercial potato crisp manufacture. Tubers considered being of suitable quality for crisping are selected by tuber examination and tuber tests. Tuber properties tested include levels of reducing sugars, starch, soluble solids, moisture, specific gravity, dry matter and amino acids. However in general tubers preferred for crisping should have specific gravity in the range 1.08-1.09, dry matter in the range 20-22%, high amylase to amylpectin ratio, small cell size, and low sugars content (Adams 2004).

The cooking process begins with the washing and cleaning of the tuber to remove stones, debris, dirt and contaminants. Dirty tubers that are processed into potato crisps are undesirable to consumers and are considered a health risk, thus the washing and cleaning process is monitored to ensure that only clean tubers are processed into potato crisps. One quality control method for monitoring the cleanliness of tubers is the implementation of automatic inspec-

Table 1 (Cont.)

Nutrient	Units	Value per 100 grams	Number of Data Points	Std. Error
Amino acids				
Tryptophan	g	0.108	0	
Threonine	g	0.253	0	
Isoleucine	g	0.283	0	
Leucine	g	0.419	0	
Lysine	g	0.424	0	
Methionine	g	0.110	0	
Cystine	g	0.089	0	
Phenylalanine	g	0.310	0	
Tyrosine	g	0.259	0	
Valine	g	0.392	0	
Arginine	g	0.321	0	
Histidine	g	0.153	0	
Alanine	g	0.214	0	
Aspartic acid	g	1.706	0	
Glutamic acid	g	1.170	0	
Glycine	g	0.207	0	
Proline	g	0.251	0	
Serine	g	0.303	0	
Other				
Alcohol, ethyl	g	0.0	0	
Caffeine	mg	0	0	
Theobromine	mg	0	0	
Carotene, beta	mcg	0	0	
Carotene, alpha	mcg	0	0	
Cryptoxanthin, beta	mcg	0	0	
Lycopene	mcg	0	0	
Lutein + zeaxanthin	mcg	0	0	

Table 2 Tuber storage conditions commonly used in commercial manufacture of potato crisps.

Additives	Chlorophām
Storage relative humidity	60%
Light intensity level	as dark as possible
Temperature	8-12ºC

tion systems at the end of the washing and cleaning process. Tubers identified as unclean, by inspection, are either removed from the process or are rewashed.

In the next step, tubers are cut into thin slices 1.3-2.5 mm thick using a slicing machine; the tuber slices are washed to remove excess starch. Excess starch on tuber slices causes slices to stick together during the frying stage, producing a crisp that is only partially fried. Partially fried crisps are considered a health risk because high moisture levels facilitate the presence of water-dependent micro-organisms which are likely to include *Aspergillus flavus*, *A. glaucus*, *A. nidulans*, *A. niger*, *A. ochraceous*, *A. tamarii*, *A. candidus*, *Bacillus cereus*, *B. subtilis*, *Botryodiplodia theobromae*, *Cylindrocarpon radicicola*, *Erwinia carotovora*, *Neurospora crassa*, *Penicillium oxalicum*, *Rhizopus nigricans*, *Serratia marcescens* and *Trichoderma longibrachyatum*, which have been isolated from dried yam chips (Adeyanju and Ikotun 2006).

The slices are blanched by submersion in hot liquid solution for a preset time prior to frying to partially cook the tubers; this is the first stage of colour development. The blanching process is optional but has been shown to produce crisps of a lighter complexion and lower oil content which is considered to be more desirable by consumers. After blanching, excess water on the surface of the tuber slices is removed using a dryer, to produce a tuber slice weighing 60% of its initial wet weight. The crisps are then fried by immersion in oil (palmolene, cotton, olive, canola, sunflower or soy are common) using either a batch or continuous fryer at a temperature of 120-190ºC (at atmospheric conditions). This is where most of the cooking takes place and where most of the crisp's texture and colour are developed. During frying physical and chemical changes take place in tuber cell structure. The potato crisp exits this process with an oil content of 33-38% and a moisture level reduced from 75-85% to 1-2%. The oil/fat used in the frying process is monitored to ensure that the oil absorbed into the crisp during frying is safe for human consumption. The fry time (dwell time) is also monitored and carefully selected to produce the optimal quality potato crisps. The crisps are then inspected for colour defects, excessive oil content; flavourings are added and they are then packaged. These steps are described by Miranda and Aguilera (2006) in a review on potato crisps and French fries. The exact production configurations and processes vary slightly between different crisp manufacturers because crisp manufacturers tend to have small customisations made to the plant to produce crisps with a unique product signature specific to the manufacturer. For example, some manufacturers produce crisps that are fried with the skin present, while others specifically remove the skin from the tuber by abrasive washing prior to frying. For this reason only the processes common to most manufacturers have been described above.

Tuber structure, composition, growth cycle and influence on crisp quality

Structurally, the mature tuber has an apical (bud) end and a stem end which connects to the rest of the plant by a degenerated stolon. The apical end has an apical bud (eye) and more lateral buds (eyes) than the stem end. The tissues found from the outside to the centre of a mature tuber are periderm, cortex, vascular (xylem and phloem in a ring configuration), parenchyma surrounding the vascular tissue and pith. Periderm is protective, vascular is conducting and cortex, vascular parenchyma and pith are storage tissues. More starch and protein are stored in cortex and vascular parenchyma than in pith and there is no starch or protein in periderm. The mature tuber structure is fully described in more detail by Artschwager (1924), Schwimmer and Burr (1967) and Kadam *et al.* (1991) and shown diagrammatically in **Fig. 2**.

The chemical composition of the tuber varies according to cultivar, location, soil conditions, growing method, and maturity at harvest. The main chemical components are presented in **Table 3**.

Tuber quality is important for production of good quality potato crisps. Tuber attributes that influence potato crisp quality are nitrogen levels, soil fertility, dry matter content, specific gravity, amount of starch present, and sugars present. These attributes are measured in the developing tuber

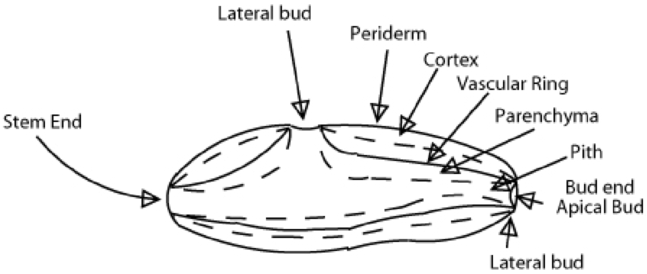

Fig. 2 Diagrammatic representation of a potato tuber.

Table 3 Main chemical components of a mature potato tuber (source Smith (1977), with kind permission of Springer Science and Business Media).

Constituent	Average (%)	Range (%)
Water	77.5	63.2 - 86.9
Total solids	22.5	13.1 - 36.8
Protein	2.0	0.7 - 4.6
Fat	0.1	0.02 - 0.96
Carbohydrates total	19.4	13.3 - 30.53
Crude fibre	0.6	0.17 - 3.48
Ash	1.0	0.44 - 1.9

and used as harvest indicators for the purpose of producing good potato crisp quality.

The quality of the tuber at harvest time is affected by cropping conditions. Factors to take into consideration when growing crisping tubers are nitrogen levels and soil fertility, both of these parameters are known to effect starch levels which in turn affects crisp quality (Hope *et al.* 1960). Dry matter content and specific gravity reflect the amount of starch present. In general, tubers with high dry matter content (20-22%) and specific gravity (1.08-1.09), high amylase-to-amylopectin ratio, small cell size, and low sugar content are preferred for frying (Smith 1961). Specific gravity (total solids) of the cultivar is widely known to influence crisp quality and is used as the principal selection criteria when identifying suitable tubers for crisp production (Lawson 2005; Sinha *et al.* 1992).

Moisture in raw tubers is related to their specific gravity; the higher the moisture, the lower the total solids and the lower the specific gravity (Lusas and Rooney 2001). The potato tuber hydrometer method is used to determine the solids content and is available from the Snack Food Association (Anonymous 1983). Specific gravity sorting machinery has been used to sort and process tubers based on specific gravity. This has been shown to improve crispness and colour development of the potato crisp (Rogers *et al.* 1937).

A number of studies have focused on the relationships between sugar and colour. As the tuber sugar level increases the colour of the crisp darkens and the crispness/texture becomes softer (Smith 1961). Lower levels of crispness are assumed to be result of high sugar content and low starch content. Studies investigating tuber maturity and crisping quality have shown a relationship between tuber maturity, harvest time, reducing sugars and tuber quality for crisping (Kushman *et al.* 1959; Clegg and Chapman 1962). Sugar level has been identified as an important parameter in crisp colour development. Measurement of sugar levels in tubers is performed using sugar level testing tape, i.e. Lilly Glucose Enzymatic Test Strip (TES) and Snack Food Association (SFA) tape tests (Anonymous 1983; Brash and Shingleton 2001). Measurement and monitoring of sugar levels should be performed prior to processing and at harvest time to ensure that good quality tubers are processed into potato crisps. Starch is another measurable parameter that can be used to determine the texture of the potato crisp. A relationship exists between starch and sugar, increased starch levels in tubers corresponds to reduced sugar levels which produces crisper and less browned potato crisps (Hoover and Xander 1963).

Storage and conditioning of tubers prior to processing into crisps

Potato crisp manufacturers need to have a readily available supply of tubers throughout the year, however maturity and harvesting of optimal crisping tubers is restricted by the growth cycle of the tuber. To overcome the misalignment between tuber harvest maturity and the demands of the crisp manufacturer, tubers from different cultivars are harvested throughout the year and put into storage by the crisp manufacturer. Storage conditions of tubers are important considerations in the manufacture of good quality potato crisps because the properties of tubers change while they are in storage affecting the quality of the crisps. A number of parameters are used to monitor the crisping quality of tubers in storage and storage methods have been devised to improve stored tuber crisping quality.

Reducing sugar content is used to predict tuber suitability for crisp processing because it is an indicator of colour development (Marquez and Añon 1986). Increased sugar content results in increased browning when the tubers are processed (Smith and Treadway 1960; David and Smith 1965; Schippers 1971). One of the parameters that influences sugar level in storage is the sugar level of the tuber before it goes into storage and this is dependent on maturity of the tuber at harvest (Clegg and Chapman 1962; Massa 1983).

Tubers accumulate high levels of reducing sugars when conditioned in sub-zero storage temperatures, in a process known as "low-temperature sweetening" (ApRees *et al.* 1981). A demonstration of decreasing the amount of tuber reducing sugars before frying by using pre-selected storage times and temperature conditioning methods and achieving a reduction in browning (Timm *et al.* 1968) has been followed by many other studies (e.g. Miller *et al.* 1975; Schippers 1975; Brown *et al.* 1990; Mackay *et al.* 1990; Williams and Cobb 1992; Brierly *et al.* 1996; Harvey *et al.* 1998) of the effect on sugar levels when different cultivars and clones are stored at pre-selected temperatures (e.g. 0ºC, 4ºC, 10ºC) for pre-selected periods of time ranging from 2 to 30 weeks and then reconditioned for times up to 4 weeks at 18-21ºC. These studies show the amount of tuber reducing sugar after conditioning varies between cultivar. The process of non-enzymic browning increases with increasing reducing sugar levels. Non-enzymic browning is related to acrylamide formation in potato crisps. A recent study has shown that tubers stored at 2°C and 20°C for two weeks prior to processing had reduced acrylamide content from 20 ppm to 2 ppm in potato crisps, suggesting an inverse relationship between potato crisp acrylamide content and tuber storage temperature (Chuda *et al.* 2003).

If tubers are stressed in storage, the reducing sugar levels increase causing non-enzymic browning (Ewing *et al.* 1981). The storage climate parameters of relative humidity and storage atmosphere composition should be considered when storing tubers because they can stress the tuber (Miyamoto *et al.* 1958; Stevenson and Cunningham 1961; Gould *et al.* 1979). Transportation to the processing facility results in stressing the tuber, thus increasing reducing sugar levels; some cultivars show more resistance to transportation stress than other cultivars (David and Smith 1965), thus cultivar should be considered in respect to transportation to the storage area.

When tubers are in storage they are often treated with chlorpropham to reduce sprouting and fungal attack by spraying a 1% active ingredient emulsion at a rate of 1 qt per 2000 pounds of tuber (Kalt *et al.* 1999). Thus methods have been devised to determine the amount of chlorpropham residue in the final potato crisp (Ritchie *et al.* 1983). Ideally chemical treatment of tubers in storage should be monitored to prevent residues being consumed by consumers. An alternative to chemical treatments is ozone treatment of tubers; this treatment has been demonstrated to reduce sprouting and fungal on tubers when applied in levels up to 100 ppm[2] (Daniels-lake *et al.* 1996).

Cleaning of tubers prior to frying

Tubers are washed prior to blanching/frying to remove dirt from them. Dirt and debris can harbour micro-organisms and bacteria that are harmful to consumers. Washing also removes harmful herbicides used to prevent sprouting during storage (Schwimmer *et al.* 1957; Prange *et al.* 2005).

To improve the effectiveness of washing, the washing equipment should be cleaned with sterilizing compounds frequently. The washing water should not be continuously recycled but be replaced at frequent intervals. The quality of washing water should be monitored regularly. Potential monitoring methods include bacterial counts and NIR spectroscopy. An examination of the tubers should be performed after washing to validate that the washing process has removed dirt, debris and that the tubers are clean (Vorria *et al.* 2004). The data from the monitoring and validation examinations should be compiled and stored for future referencing.

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[2] **ppm** is parts per million

Cutting of the tubers into thin slices

The accuracy and precision of the cutting process is an important parameter in producing potato crisps that have similar moisture levels upon exiting the frying process. The amount of time taken to cook a potato crisp is dependent on the thickness of the tuber slice and one study demonstrated that large variations in tuber slice thickness are caused by an Urshel slicer with the mean thickness value being 10% smaller than the set value. This study also reported discrepancies in moisture level with thick crisps and shorter fry times (Gamble and Rice 1988).

The final moisture level of the potato crisp is also affected by the position within the tuber that the slice has originated from. It has been demonstrated that uneven spatial distribution of water exists between slices obtained from different positions in a tuber, confirming tuber position as a parameter affecting moisture distribution (Ruan *et al.* 1991; Thybo *et al.* 2004). Tuber slice position also affects the puncture force of the potato crisp. This suggests a relationship between tuber slice position and potato crisp texture (Segnini *et al.* 1999).

Blanching and predrying

Blanching is a process that is used in some fry lines to partially cook the tuber slices prior to frying. The blanching process requires submersion of the tuber slices in a vessel containing hot water for a preset period of time. On exiting the blancher the tuber slices are partially cooked.

The use of blanching prior to frying has been shown to improve texture, oil/fat content and crispness of the potato crisp (Ng and Waldron 1997). Blanching prior to frying reduces oil absorption in the tuber slice by two mechanisms; firstly a film is created between the tuber slice and the oil that acts as a barrier to oil penetration into the tuber slice. Secondly, when tuber slices undergo the blanching process, sealing of intercellular pores takes place using the mechanism of cell expansion (Pedreschi and Moyano 2005a). The sealing of intercellular pores reduces oil absorption because once the pores are sealed they are no longer available for oil absorption. Predrying has also been shown to further reduce oil absorption into potato crisps (Pedreschi and Moyano 2005b).

Some studies have investigated the effect of additions of compounds to the water in the blancher as a means to improve crisp quality by reduction of oil content and acrylamide level. Blanching in water solutions containing calcium chloride or citric acid and by immersion in carboxymethyl cellulose solutions has been shown to reduce oil content (Rimac-Brncic *et al.* 2004). Citric acid immersion before frying has also been shown to reduce acrylamide content by 70% (Jung *et al.* 2003). Blanching tuber slices in acetic acid has been reported to achieve a 90% decrease in acrylamide content (Kita *et al.* 2004). Blanching temperature and blanch time have been shown to be related to acrylamide content in potato crisps, in one study tuber slices were blanched in hot water at six different time and temperature combinations prior to frying to illustrate that certain blanch water temperatures reduce acrylamide content in potato crisps (Pedreschi *et al.* 2004).

The frying process in potato crisp manufacture

There are two types of fryer configurations, the continuous fryer and the batch fryer. Both configurations require submerging of the tuber slices in hot oil. In respect to temperature changes that take place within the oil of the batch fryer when the tuber slices are added, the oil will drop in temperature and then rise back to a predetermined temperature. For a continuous fryer, the temperature drop is described by a temperature differential between the entry and exit points of the fryer. When the crisp exits the fryer, the crisp crust attains the temperature of the oil. This temperature is consistent through the crisp (Talburt and Smith 1975).

When the tuber slices are placed in hot oil, surface temperature increases. When it reaches 100°C, water at the surface boils. At the onset of boiling, convection in the oil is increased by the turbulent water vapour. Explosive evaporation leads to the creation of large pores on the crisp surface. Water inside the tuber slice will be heated and the slice will be cooked (Mellema 2003). Water from the tuber slice is lost in the process while the tuber slice oil content is increased. Conductive heat transfer mechanisms cook the interior of the tuber slice. The frying process is effectively a drying process, reducing the moisture content of the tuber slice to 1-2% largely by replacement of water with oil.

In respect to the changes that take place within the tuber parenchyma cell structure, the frying process is described in terms of changes taking place to starch. When tuber slices are fried to produce potato crisps, the water inside the tuber slice is heated to 100°C and this causes changes in starch grains similar to those observed in cooking of tubers by boiling. The water that is resident within parenchyma cells of the tuber slice heat starch granules in them and they consequently swell in size. The first change in tuber starch structure is gelatinization occurring when starch is 60-70°C. Next steam bubbles start to leave the interior of the cell through pores and move to the oil/crisp interface. Enlarged starch granules behave as a solid mass that pressurize the outer cell walls until the starch becomes dehydrated and reduces in size. The starch granules in the crisp crust dehydrate corresponding to the starch being heated above 100°C. Oil then can enter into cracks in the crust (Miranda and Aguilera 2006).

There has been considerable work done on understanding the process of oil absorption in the potato crisp with the intention of finding ways of reducing oil uptake and thus reduce the oil/fat content in the finished potato crisp. Generally oil content of potato crisps is around 35%, however this figure varies between different manufacturers depending on the fry line configuration and oil type used (Ndjouenkeu and Ngassoum 2002). Oil absorption in the crisp takes place on its surface and the amount of oil absorbed depends on the crisp surface area available. Oil absorption takes place in the potato crisp by capillary action in thin pores in the crisp that form after most of the steam has been released. Studies of oil uptake and location inside potato crisps have been able to precisely determine the maximum penetration distance of oil in the crust (Bouchon *et al.* 2001).

Since the surface area of the product is important for oil uptake, some studies have investigated the use of coatings to reduce oil uptake (Ang *et al.* 1991; Feeney *et al.* 1992; Mellema 2003; Tran *et al.* 2007). One study demonstrated that tuber strips coated with methylcellulose and hydroxypropylmethylcellulose had up to 40% reduction in oil uptake (Garcia *et al.* 2002).

An alternative fry line configuration known as vacuum frying has been shown to reduce oil content in crisps (Garayo and Moreira 2002). The main industrial limitation of vacuum frying is that it is not a continuous production method but is a batch production frying method.

Colour changes that occur during the frying process

Colour changes (the first yellow/gold, then the darkening brown) occur during frying. The main (yellow to gold) change in colour results from the Maillard reaction between amino acids or free amino groups, peptides and reducing sugars, mainly glucose and fructose (Hart and Smith 1963; Fitzpatrick and Porter 1966). Reducing sugars and amino acids have been investigated for their participation in the colour development of the potato crisp. Reducing sugars have been identified as the limiting factor in colour development during tuber frying (Marquez and Añon 1986). In another study, tuber slices spiked were with predetermined amounts of sucrose, reducing sugars, ascorbic, chlorogenic and amino acids indicated that reducing sugars had the greatest influence on colour (Rodriguez-Saona and Wrolstad 1997).

Post frying machinery

The other mechanism that determines oil content in the potato crisp is oil remaining on its surface entering after it has left the fryer. The amount of oil uptake during post-frying depends on the amount of residual oil on the surface and the rate at which this oil drains off in the post-frying period. Methods to reduce the oil absorption in potato crisps during the post-fry period have largely involved the development of machinery to remove oil resident on the crisp surface when they exit the fryer. One method has been the development of mechanical processes that apply hot air to the potato crisp to remove the residual oil. Another involves the application post-frying of superheated steam to the crisp's surface to remove residual oil. This method is reported to produce a 25% reduction in oil/fat content (Kochhar 1999). A third is using vibratory conveyance systems to shake the oil off. These are sometimes used with fans to blow the oil off (Bernard 1985; Lee *et al.* 1988). Lastly, some manufacturers have designed conveyance systems inclined in such a way that the angle at which the crisps are located on the conveyor assists in draining residual oil off the crisp.

Pre-packaging and packaging

Before packaging, potato crisps are cooled on a cooling conveyor. They absorb water from the surrounding atmosphere during the equilibration process, thus softening starts to take place. The amount of softening depends on the period of time that crisps are exposed to atmospheric conditions. Potato crisps exit the fryer with less than 2% moisture level. The main method to eliminate atmospheric moisture absorption is by sealing the potato crisps in foil and/or plastic packaging layers that act as a moisture barrier.

The shelf life of the crisp in the package should be modelled and monitored to ensure that potato crisps are not sold to consumers when the crisps become rancid. To prolong the shelf life of the packaged potato crisp, modified atmosphere packages are commonly used. Mathematical models relating the amount of head space in the package to the shelf life of the packaged potato crisp has been developed (del Nobile 2001). One proposed measure of the quality of the crisp for determination of shelf life is peroxide value that indicates the amount of rancidity of the crisp. Peroxide value has been evaluated with sensory perception of crisp acceptability using a sensory panel (Jonnalagadda *et al.* 2001). A model has also been proposed correlating peroxide value with potato crisp storage period $C=C_0+[AC_{0I}+B]t_{storage}$, where $t_{storage}$ is the time the crisps are held in storage, C_0 and C are the peroxide levels of the crisps during frying and after being held in storage, C_{0I} is the oxidation parameter of the frying oil, A and B are constants (Dimitra and Oreopoulou 2004).

MEASUREMENT OF POTATO CRISP PROPERTIES

Measurements of potato crisp properties can be performed by two means, sensory methods and instrumentation methods. Sensory methods serve as the primary method for determination of crisp quality; however instrumentation techniques are more convenient in the factory setting and are able to produce large numbers of reliable measurements without the variability of the human sense of perception.

Texture

Texture in a food product can be determined by instrumental analysis and by sensory evaluation (Steffe 1996a). Sensory methods are the primary tool for determination of texture; however the development of advanced instrumentation has led to the implementation of highly sophisticated sensors and instrumentation techniques. Instrumentation techniques providing force deformation curves are used as a measure of textural properties of foods. Texture measurement by instrumentation is widely used for the reasons of low cost, easy implementation, simple to reproduce and it is less time consuming than sensory analysis (McCormick 1988). Texture profile analysis consists of generating and interpreting texture profile information with instrumental and sensory means (Steffe 1996a).

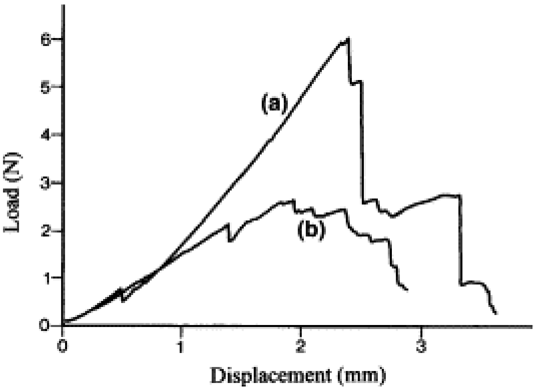

Fig. 3 Texture profile, force–deflection curve of a hard "Gourmet" potato crisp (a) and a softer "Ordinary" one (b). Reprinted from **Vincent JFV** (2004) Application of fracture mechanics to the texture of food. *Engineering Failure Analysis* **11**, 695-704, ©2004, with kind permission from Elsevier.

Crispness in the potato crisp is a characteristic produced by having low moisture levels throughout the crisp. Crispness is a property of brittle materials that fracture rapidly. The phenomenon has been studied using both instrumental and sensory methods. When the moisture content of crisps increases due to absorption of water, a loss of crispness occurs and mechanical work to break the crisp increases. An inverse relationship exists between degree of crispness and mechanical work needed to break a crisp (Seymour and Hamman 1998).

Hardness of crisps, defined as the maximum force at compression (Steffe 1996b; Vincent 1998), is another parameter that can be identified from a texture profile curve. It indicates the maximum force from the act of breaking the crisp, that is required to cause the crisp undergo fast global cracking (Lima and Singh 2001). Presented in **Fig. 3** is a texture profile curve of two potato crisps, the maximum force (hardness) required to break a potato crisp is indicated by a maximum peak in the texture profile for each potato crisp.

Sound characteristics

The properties of sound waves (e.g. jaggedness) produced in brittle solids such as potato crisps can be measured. The sound signal becomes weaker as moisture in potato crisps increases. Some studies have correlated sensory perceptions of the panellists to crispness/crunchiness in potato crisps (Seymour and Hamman 1988; Duizer 2001). A low audible noise is perceived as the undesirable softening of the product, suggesting poor quality potato crisps.

Both acoustic and mechanical information can be obtained together using a shear/compression measurement unit housed in an acoustically-insulated environment. Positive correlations between crispness and mechanical acoustical parameters have been quantified for potato crisps. An acoustic mechanical model relating crispness with the work required to cause facture, the mean sound pressure and peak force to cause facture has been produced (Vickers 1987). Moisture levels influence the acoustic signature of the potato crisp, increases in moisture levels result in less acoustic sound being generated on puncture. The decrease in brittleness and crunchiness that occurs as moisture level increases cause the removal of high frequency components from the acoustic signal's power spectrum (Alchakra *et al.* 1997).

Visual analysis by colorimetry

Laboratory measurements of potato crisp colour are usually performed using a colorimeter because of its high level of accuracy. In the area of tuber growing conditions, the effect of nitrogen fertilizer upon crisp colour has been assessed using a colorimeter (Eastwood and Watts 1956; Kunkel and Holstad 1972). During storage, tubers are treated for sprouting using ethylene. The application of ethylene to tubers has also been evaluated in terms of its effect on crisp colour by colorimetry (Prange *et al.* 2005). Irradiation with gamma rays, sometimes used to reduce fungal growth on tubers in storage, increases sugar levels producing darker colour crisps and its effect has been measured by colorimetry (Schwimmer *et al.* 1957). Tuber respiration levels and storage conditions have been correlated with crisp colour using colorimetry (Copp *et al.* 2000).

Prior to the frying process, sugar levels are directly measured because sugar level is an important indicator of crisp colour. Quantitative relationships have been developed correlating sugar level to crisp colour using colorimetery (Pritchard and Adam 1994). Starch levels in tubers prior to processing have been correlated with crisp colour by colorimetry (O'Donoghue *et al.* 1996). Other studies which have examined correlations of tuber sugar levels and soluble solids and crisp cooking time against crisp colour have also used colorimetery (Iritani and Weller 1974; Khanbari and Thomas 1993; Rodriguez-Saona and Wrolstad 1997).

Colorimetry studies have shown that potato crisp acrylamide levels are strongly correlated with colour. Thus colour has been proposed as a method for identification of crisps with high acrylamide levels and which need to be removed from a production line (Kita 2002).

Colour determination in the processing factory

Colorimeters are a scientific tool and are not used on the production floor for measurement of potato crisp colour; the device that is used on the production floor for measurement of colour is the optical colour sorter/scanner. The optical sorter/scanner uses either a line scanning camera, or a digital imaging camera. The digital image camera directly captures data as a pixel image for analysis whereas the data from the line scanning camera is compiled and then assembled in pixel image format for analysis. As the pixel image format is different from the format of a colorimeter and studies have been undertaken to calibrate image data with colorimeter data (Orr and Janardan 1990; Pedreschi *et al.* 2006).

Image analysis has now become the preferred method of determining colour in automated production lines (Pritchard and Adam 1994) because of the greater spatial resolution provided by image analysis. Image analysis has been successfully used for measurement of the darkening caused by excess free sugar during crisping of tubers (Coles *et al.* 1993). Relationships between colour and acrylamide levels determined by computer image analysis, offer a promising tool for screening of crisps with large amounts of acrylamide (Gokman *et al.* 2007).

NIR spectral analysis to determine tuber and crisp quality

NIR spectral analysis can be divided into two forms of analysis. The first kind of NIR analysis, qualitative analysis, separates objects under analysis into different sets based on an object's spectral properties. Mathematically this problem is termed a classification problem. The second kind of NIR analysis, quantitative analysis, involves predicting the amounts of the chemical components within objects under analysis; mathematically this problem is termed function approximation. The quality of NIR results are evaluated by statistical measures such as the correlation coefficient (R^2)[3] and the standard error of prediction (SEP)[4].

Table 4 SEP and R^2 values for NIR measurement of tuber and potato crisp properties from published works.

Author(s)	Attribute being determined	SEP	R^2
(a) Uncooked tubers prior to processing			
Chen *et al.* 2004	Carbohydrates	-	0.93
Kang *et al.* 2003	Dry matter	-	0.85
Haase 2003	Starch and dry matter	-	0.94
Dull *et al.* 1989	Dry matter	-	0.88
Chen *et al.* 2005	Specific gravity	0.0044g/cm^3	0.94
(b) Potato crisps			
Yee and Coghill 2003	Moisture content	2.3345%	-
Swarbrick 2002	Moisture content	-	0.83
	Oil content	-	0.85

Presented in **Table 4** is a list of works correlating parameters in tubers and potato crisps to NIR spectral properties. The table provides either the R^2 correlations value or the SEP as an indicator of the strength of the correlation. In the area of growing conditions NIR has been used to determine the amount of leaf nitrogen which is closely correlated to tuber nitrogen (MacKerron *et al.* 1995; Young *et al.* 1995). NIR spectral analysis has been used to determine the carbohydrate content (Chen *et al.* 2004) and the dry matter content in tubers (Kang *et al.* 2003). NIR spectral analysis has produced good correlations with starch and dry matter in unprocessed tubers (Dull *et al.* 1989; Haase 2003). Other attributes of tuber identified using NIR spectral analysis include specific gravity of tubers (Chen *et al.* 2005) and the presence of diseases prior to processing (Porteous *et al.* 1981). The quality of the results for determining these attributes suggests sufficient accuracy for automatic inspection and sorting systems to be implemented prior to frying.

In the area of processed tubers, function approximation methods have been used to determine the amount of moisture in potato crisps (Yee and Coghill 2003), oil content and moisture content (Swarbrick 2002). Processed potato crisps have also been classified based on the cultivar used to manufacture potato crisps (Yee *et al.* 2006). NIR analysis has also been evaluated as a tool for identification of potato crisps with excessively high acrylamide content. This particular application of NIR technology showed much promise (Segtnan *et al.* 2006).

NIR spectral measurement of moisture in potato crisps – a case study

Moisture is an important property to measure in potato crisps. Potato crisps that have moisture levels exceeding 12% when packaged become soiled.

Some of the causes of uncooked crisps passing through the production line are:

- Tuber slices sticking together upon entry to the fry line and exiting the fry line partially cooked;
- Excessively thick slices entering the fry line process (produced by variability in the tuber shape and variability of cutter performance);
- The internal variability of moisture within the tuber resulting from the position on the tuber where the tuber slice is extracted from;

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[3] The correlation coefficient is equivalent to dividing the covariance between the two variables by the product of their standard deviations. In general the correlation coefficient is one of the two square roots (either positive or negative) of the coefficient of determination (r^2), which is the ratio of explained variation to total variation: $r^2=\Sigma(Y'-Y)^2/\Sigma(Y-Y)^2$, where Y= a score on a random variable, Y′= corresponding predicted value of Y, given the correlation of X and Y and the value of X, Y = **sample** mean of *Y* (i.e., the mean of a finite number of independent observed realizations of *Y*, ***not*** to be confused with the expected value of *Y*)

[4] SEP is an approximation of standard deviation of the prediction set which give an indication of the predictive ability of the multi-variate model.

- Mixing cultivars when processing potato crisps, causing incorrect process settings for the cultivar and condition of the tubers being processed.

NIR spectral analysis is a promising tool for determination of moisture levels in potato crisps. In order to form quantitative calibration models for samples of crisps at different moisture levels, the usual process involves spiking crisps with water and equilibration for 24 hours (Anonymous 1993b). Presented in **Fig. 4** are some NIR spectral curves for potato crisps with spiked moisture levels between 12 and 35%. NIR quantitative models are formed using partial least squares regression modelling (PLS) (Wold 1966). The method of full spectrum modelling (a model in which all the available wavelength predictors are used) is used to generate a relationship between potato crisp spectral response and moisture level. **Fig. 5** shows a plot of the cross validated standard error (SE_{cv}) vs. the number of PLS factors in a full spectrum model. Using this plot, the optimal number of PLS factors is selected by identifying where there appears a levelling off in SE_{cv} value, this occurs at 10 PLS factors.

The plot of predicted vs. actual moisture level, shown in **Fig. 6**. The SEP value relating to this plot is 2.3345%. This illustrates that sufficient information is present in potato crisp NIR spectra to make predictions of moisture levels. NIR technology has been used to determine moisture level of the tubers before frying and at the end of processing for the purpose of process control (Swarbrick 2002). Moisture level measurement automatic inspection applications post frying have been investigated by Yee and Coghill (2003).

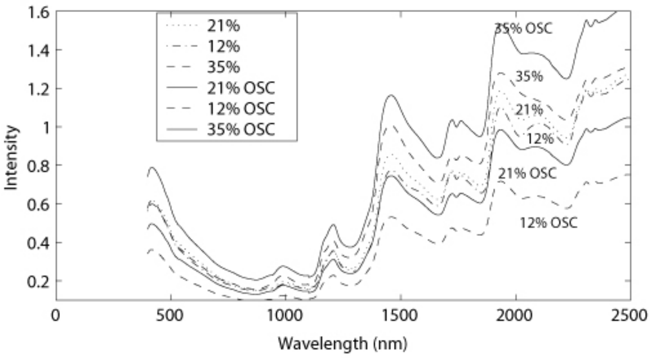

Fig. 4 Three sample NIR spectra (spectral intensity vs. wavelength) corresponding to 12%, 21% and 35% moisture content in the potato crisp samples. The spectra are displayed prior to Orthogonal Signal Correction (OSC) with no form of data pre-treatment applied to the spectra and after 2 *OSC* factors have been removed. Reprinted from **Yee N, Coghill GG** (2003) Factor selection strategies for orthogonal signal correction applied to calibration of near-infrared spectra. *Chemometrics and Intelligent Laboratory Systems* **67**, 145-156, ©2003, with kind permission from Elsevier.

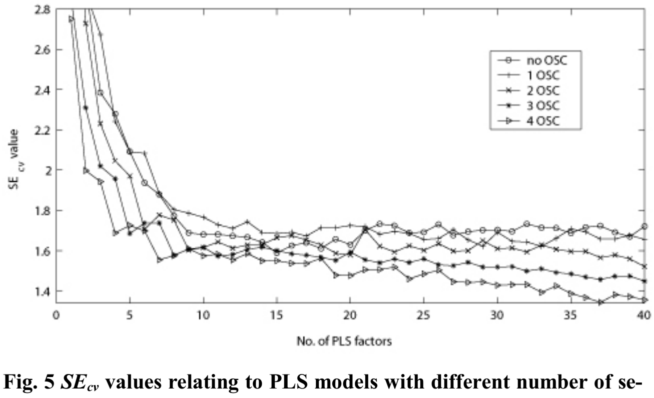

Fig. 5 SE_{cv} values relating to PLS models with different number of sequentially selected OSC factors removed. This plot is used to determine the optimal number of PLS factors used in the full spectrum PLS model. Reprinted from **Yee N, Coghill GG** (2003) Factor selection strategies for orthogonal signal correction applied to calibration of near-infrared spectra. *Chemometrics and Intelligent Laboratory Systems* **67**, 145-156, ©2003, with kind permission from Elsevier.

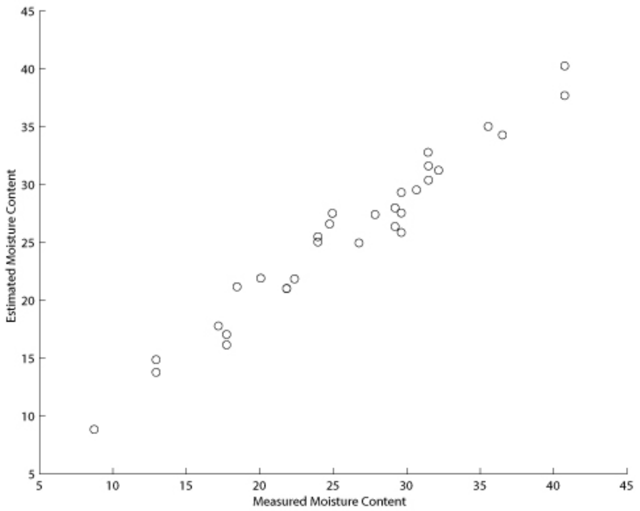

Fig. 6 Plot of predicted moisture level vs estimated moisture level (adapted from Yee and Coghill 2003).

FUTURE PERSPECTIVES

Future research in the area of potato crisp manufacture will be driven by three main forces, firstly future regulatory changes or the prospect of future regulatory changes will require research and development for compliance reasons. Increasing knowledge about the effect of potato crisp constituent components on the human physiology will redefine regulations regarding potato crisp constituent levels considered safe for human consumption. Currently much research focus is on constituent levels directly related to oil/fat content, acrylamide level and moisture-dependent microorganisms, future research will continue to focus on developing strategies to produce potato crisps with safe levels of these constituents but will also include other constituent levels.

The second area of future research is the development of manufacturing systems and processes that increase the efficiency of potato crisp manufacture. Financial objectives of commercial manufacturers will continue to require ways of improved production efficiency.

The third area of future research is the continued research into improved potato crisp quality for increased levels of consumer satisfaction.

The first key future research focus is the use of pathogen measurement technologies with the objective of pathogen level measurement in the manufacturing environment and the development of automated sanitization processes to ensure a sanitized manufacturing environment with acceptable levels of pathogens. Non-invasive measurements of sanitization levels has the potential to quickly identify areas within the manufacturing process where pathogens can enter into the potato crisp, sanitization levels in plants could be the subject of revised and improved regulations and research effort will be required to improve the framework specifying acceptable levels of pathogens, viable ways of measuring pathogens and a manufacturing environment that has acceptable levels of pathogens. The development of newer and improved technologies for monitoring pathogens and financially viable methods for controlling pathogen levels will require considerable research effort.

The second key research focus will be plant varieties with the primary objective of improving potato crisp quality and producing potato crisps with safe constituent levels.

The third key research focus will involve the potato crisp cooking process and the manufacturing process with the objective of developing new processes that produce potato crisps with acceptable constituent levels. An increased understanding of the cooking process will enable new cooking methods capable of producing potato crisps with safe constituent levels and improved quality. Electromagnetic processing methods (use of Gamma rays, X rays, UV rays, Microwave rays, and Infrared rays) adapted from cooking processes for other food products and applied to potato crisps or further refinement of methods from completed electromagnetic potato crisp research efforts may provide a commercially viable cooking method that improves product quality and produces safe constituent levels. Increased understanding of the effect of electromagnetic radiation profiles on tuber constituent levels and pathogens during processing will be required for implementation of electromagnetic radiation cooking technologies. Continued concurrent research into frying and into blanching using innovative blanching solutions will assist in improving future potato crisp product quality and producing potato crisps with safe constituent levels.

The last key focus is research into automatic inspection technologies with the objective of screening out crisps considered undesirable and improving product quality, currently visual based image processing systems are used widely in commercial manufacture of potato crisps. The area of automatic inspection technologies will continue developing in the future with hyper-spectral imaging technologies being used to provide greater information on the chemical composition of the tuber and potato crisp. Hyperspectral imagery has the potential to detect chemical components not detectable or not easily detectable using visual spectrum image processing.

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Appendix A: The HACCP principles

1. Perform a hazard analysis of the food production system by identifying a list of steps in the process where hazards could occur and identify mitigating strategies to minimize the risk of unsafe food production from the hazards.

2. Identify Critical Control Points (CCPs); A critical control point (CCP) is a step in food processing which control decisions can be applied to. Food safety hazards are eliminated or reduced by the application of the control decision at the CCP.

3. Establish Limits for CCPs; a critical limit is the maximum or minimum value to which a part of the process must remain within at a critical control point to reduce the hazard/risk to an acceptable level.

4. Establish CCP monitoring requirements. Monitor activities at the critical control points to ensure that the process is under control at the CCPs. In the United States, the United States Department of Agriculture's (USDA) Food Safety Inspection Service (FSIS) requires that the monitoring procedure and frequency of monitoring is listed in the HACCP plan.

5. Establish corrective actions; these are actions that are taken when monitoring indicates a significant deviation from the critical limits. The plants HACCP plan should contain corrective decisions to be made if this event occurs. The intention of the corrective action is to ensure that products that are unsafe for human consumption as a result of deviations within the process are not passed onto consumers.

6. Establish record-keeping procedures; the HACCP regulations requires that plants maintain documents including a HACCP plan, HACCP analysis and documentation of monitoring of CCPs, control limits verification data and documentation of handling of deviations.

7. Establish procedures for verifying that the HACCP system is working as intended; the aim of the validation plan is to make sure that the plans achieve what they intend to achieve, thus ensuring safe food is produced from the system and passed onto consumers. Verification activities include testing calibrations of sensors at regular intervals, reviews of HACCP systems, plans and procedures. In the case of the USDA, FSIS, microbial counts are performed as one of the verification activities.

Appendix B HACCP flow chart - adapted from Vorria *et al.* (2004).

Stage	**Hazards/reasons**	**Preventative measures**	**Critical factors/limits/controls**
1. RAW MATERIALS RECEIPTS / TUBERS	MICROBIOLOGICAL Fungi, molds, bacteria. CHEMICAL Fungicides and pesticides. PHYSICAL Foreign materials from soil, harvesting. Tubers ill-suited for crisping.	Suppliers of tubers (SQA) inspection of suppliers for hygiene. Measurements of Specific gravity, sugar content, starch content and dry matter. Use of automated sorting machinery to identify diseased tubers for removal.	Control of safety specifications. Limits of fungicide and pesticide residues (MRLs - EC directives). Control for foreign materials. Controls for starch content, sugars, specific gravity and dry matter because these parameters affect crisp quality.
oil/fat	CHEMICAL Residues of fungicides and pesticides, additives, heavy metals.	Suppliers of oil/fat (SQA) Inspection of suppliers for hygiene, measurements made for peroxide level, free fatty acids, *trans*-fatty acids.	Control of specifications. Limit of antifoams: 0.04 mg/Kg. Limit of heavy metals: 2%.
flavoring materials, salt, additives and preservatives	CHEMICAL Residues of chemicals. PHYSICAL Foreign materials.	Suppliers of materials (SQA)	Control of safety specifications. Limits for chemical residues (according to EC legislation).
water	MICROBIOLOGICAL Pathogens: *Salmonella*, *Shighella*, *Leptospira*, *E. coli*, *Pasturella*, *Vibrio*, *Cholerae*, *Yersinia enterocolica*, *Mycobacterium tuberculosi* Molds and Bacteria CHEMICAL Organic compounds Radioisotopes Heavy metal PHYSICAL Foreign materials from soil.	Cleaning and disinfection of water, analysis of water using NIR analysis to determine water quality.	Control of specifications (according to Dir. 98/83/EC). Limits for pathogens and chemical contaminants (according to Dir. 98/83/EC).

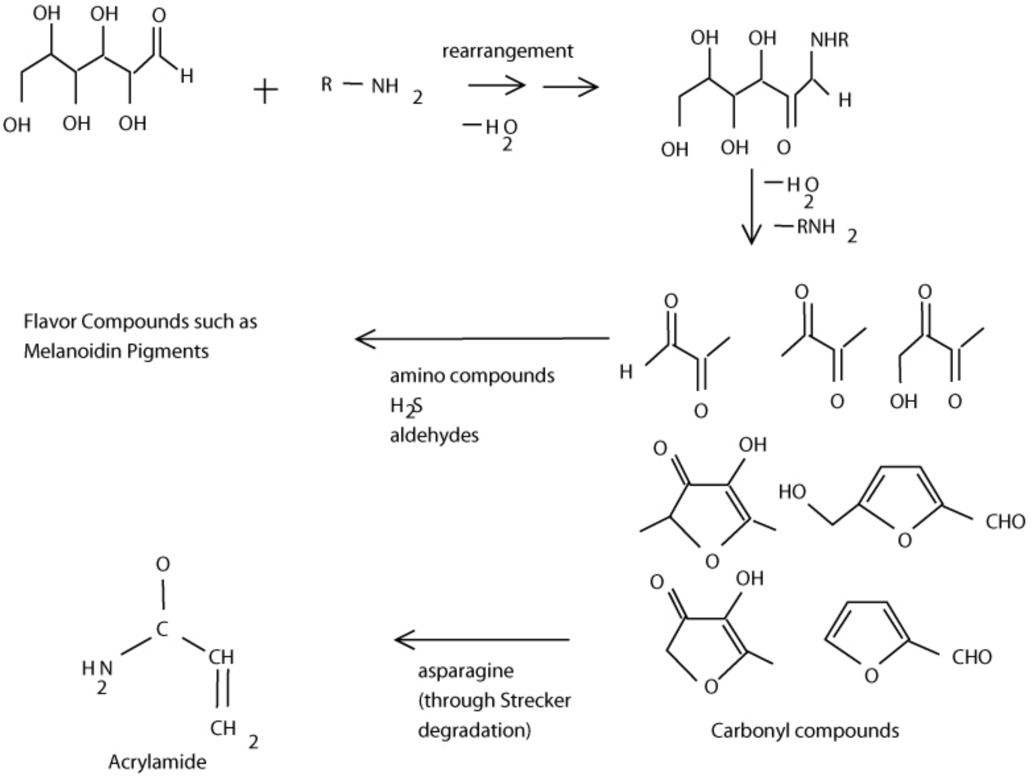
Appendix B (Cont.)

Stage	**Hazards/reasons**	**Preventative measures**	**Critical factors/limits/controls**
2. STORAGE OF RAW MATERIALS TUBERS	MICROBIOLOGICAL Fungi: *Phytopthora infestans*, *Altenaria solani*, *Fusarium sambucinum*, *Fusarium coeruleum*, *Verticillium alboatrum*, *V. dahliae*, *Heliminthosporium solani*, *Spongospora subterranean f. Sp. subterranean*. Viruses: Annulus dubius Holmes, Marnor solani Holmes, Solanum virus 14, 16, X, M, Y, S. Bacteria: *Pseudomonas solanacearum*, *Streptomyces scabies*, *Erwinia carotovora* ssp. *carotovora*, *E. carotovora* ssp. *atroseptica*, *Pseudonomas marginalis*, *Clostidium* sp., *Corynebacterium sepedonicum*. CHEMICAL Chemicals used to control vegetation.	GMP -GHP Hygienic conditions during storage. Cleaning and disinfection of storage area. Use of pallets to allow ventilation. Ventilation system. Pest control programs. Personnel hygiene, measurement of soluble solids, dry matter, starch and sugar levels.	Control of storage conditions RH: 90-100%, T=3-10°C Concentration of: O_2< 18%, CO_2 < 5%. Inspection of hygiene during storage. Inspection of programs: pest control, cleaning and disinfection of storage area. Solanine: max 0.555% dry matter of tuber-increase during storage: 20 mg/100 g. Control for residues of chemicals used to control vegetation. Control for soluble solids, dry matter, starch and sugar levels.
oil/fats	CHEMICAL Oxidation components in oil/fat (in order to be more stable in oxidation during frying). PHYSICAL Foreign materials.	GMP-GHP Cleaning and disinfection of oil silo. Pest control programs. Prevention of oil from air and light.	Control of storage conditions: T≤0°C. Control of oils/fats deterioration. Peroxide and p-Anisidine Value < 3-5 meq/Kg.
flavoring materials, salt, additives and preservatives	PHYSICAL Foreign materials.	GMP-GHP Conditions during storage. Pest control programs. Cleaning of storage area.	Control of storage conditions. Inspection of programs: pest control, cleaning of storage area.
3. CONVEYING OF RAW MATERIALS	MICROBIOLOGICAL Microorganisms from surfaces. PHYSICAL Foreign materials.	GMP-GHP Cleaning and disinfection of equipment. Cleaning agents approved for foods.	Control of cleaning and disinfection programs for surfaces and equipment.
4. TUBER WASHING	MICROBIOLOGICAL Microorganisms from equipment, water. CHEMICAL Residues of cleaning agents in the equipment. PHYSICAL Foreign materials.	GMP-GHP Assurance of hygienic conditions. Cleaning and disinfection of equipment. Renewal of water, analysis of water used for washing using NIR.	Microbiological control of water. Control of washing efficiency. Control of cleaning and disinfection programs. Control of reuse of water. Control of sensory and instrumental measurements to determine water quality.
5. PEELING AND TRIMMING	MICROBIOLOGICAL Microorganisms from equipment, surfaces. CHEMICAL Residues of cleaning agents in the equipment and lubricants. PHYSICAL Foreign materials (from metallic surfaces).	GMP-GHP Assurance of hygienic conditions. Cleaning and disinfection of equipment. Maintenance of equipment. Lubricant approved for foods.	Control of cleaning and disinfection programs. Control for foreign materials and draw away.
6. SELECTING AND SLICING	MICROBIOLOGICAL Microorganisms from equipment, personnel. CHEMICAL Residues of cleaning agents in the equipment. PHYSICAL Foreign materials (from metallic surfaces).	GMP-GHP Assurance of hygienic conditions. Cleaning and disinfection of equipment. Lubricant approved for foods. Maintenance of equipment. Personnel training.	Microbiological control. Control of cleaning and disinfection programs. Control for foreign material. Removal of tubers with defects.
7. TUBER WASHING AND 8. BLANCHING	MICROBIOLOGICAL Microorganisms from water, equipment. CHEMICAL Residues of cleaning agents. PHYSICAL Foreign materials.	GMP-GHP Assurance of hygienic conditions. Cleaning and disinfection of equipment. Renewal of water, analysis of water used for washing using NIR.	Microbiological control of water Control of cleaning and disinfection programs Control of sensory and instrumental measurements to determine water quality
9. PARTIAL DRYING OF SLICES BEFORE DEEP FRYING	MICROBIOLOGICAL Microorganisms from equipment, environment (tuber slices remain for a short time before frying). PHYSICAL Foreign materials.	GMP-GHP Assurance of hygienic conditions. Protection of the product from the environment. Cleaning and disinfection of equipment. Personnel training, process control measurements of moisture (NIR).	Control of cleaning and disinfection programs Control of environment hygiene Max removal of moisture: 4% Draw away of foreign material. Control of sensory and instrumental measurements (calibration checking) to determine moisture level for process control.
10. DEEP FRYING	MICROBIOLOGICAL The majority of microorganisms are destroyed. CHEMICAL Residues of cleaning agents and lubricant. Oxidation and polymerization products of oil. PHYSICAL Foreign materials. Contamination of fresh oil/fat with used oil/fat.	GMP-GHP Assurance of hygienic conditions. Cleaning and disinfection of equipment. Antifoam and antioxidants and their percent in oil/fat approved for foods. Use lubricant and cleaning agents approved for foods. Personnel training. Maintenance of equipment.. Replace oil/fat regularly. Monitor condition of oil using NIR. Measurement of FFA.	Temperature: 165-185°C (opt. T: 177°C). Turn-over time of oil/fat 5-10 h. Control of correct use of antifoams and antioxidants. Replace oil/fat according to specifications (country's legislation). Max consumption of trans fatty acid: 2.7-12.8 g/day. Max consume of acrylamide: 0.5 mg/Kg. Control for foreign materials. Control of sensory and instrumental measurements (calibration checking) to determine oil condition.
11. REMOVAL OF EXTRA (NOT WANTED) QUANTITY OF OIL/FAT	MICROBIOLOGICAL Contamination (air, equipment, personnel). CHEMICAL Residues of chemicals in the materials. PHYSICAL Foreign materials.	GMP-GHP Assurance of hygienic conditions. Cleaning and disinfection of equipment. Hygiene handling of materials. Maintenance of equipment. Personnel training.	Control of cleaning and disinfection programs. Microbiological control of equipment and surfaces. Control for foreign materials.
12. SALTING CHIPS AND ADDING FLAVORING MATERIAL	MICROBIOLOGICAL Contamination (air, equipment, personnel). CHEMICAL Residues of chemicals in the materials. PHYSICAL Foreign materials.	GMP-GHP Assurance of hygienic conditions. Cleaning and disinfection of equipment. Hygiene handling of materials. Maintenance of equipment. Personnel training.	Control of cleaning and disinfection programs. Control for foreign materials. Inspection of material handling by the personnel.

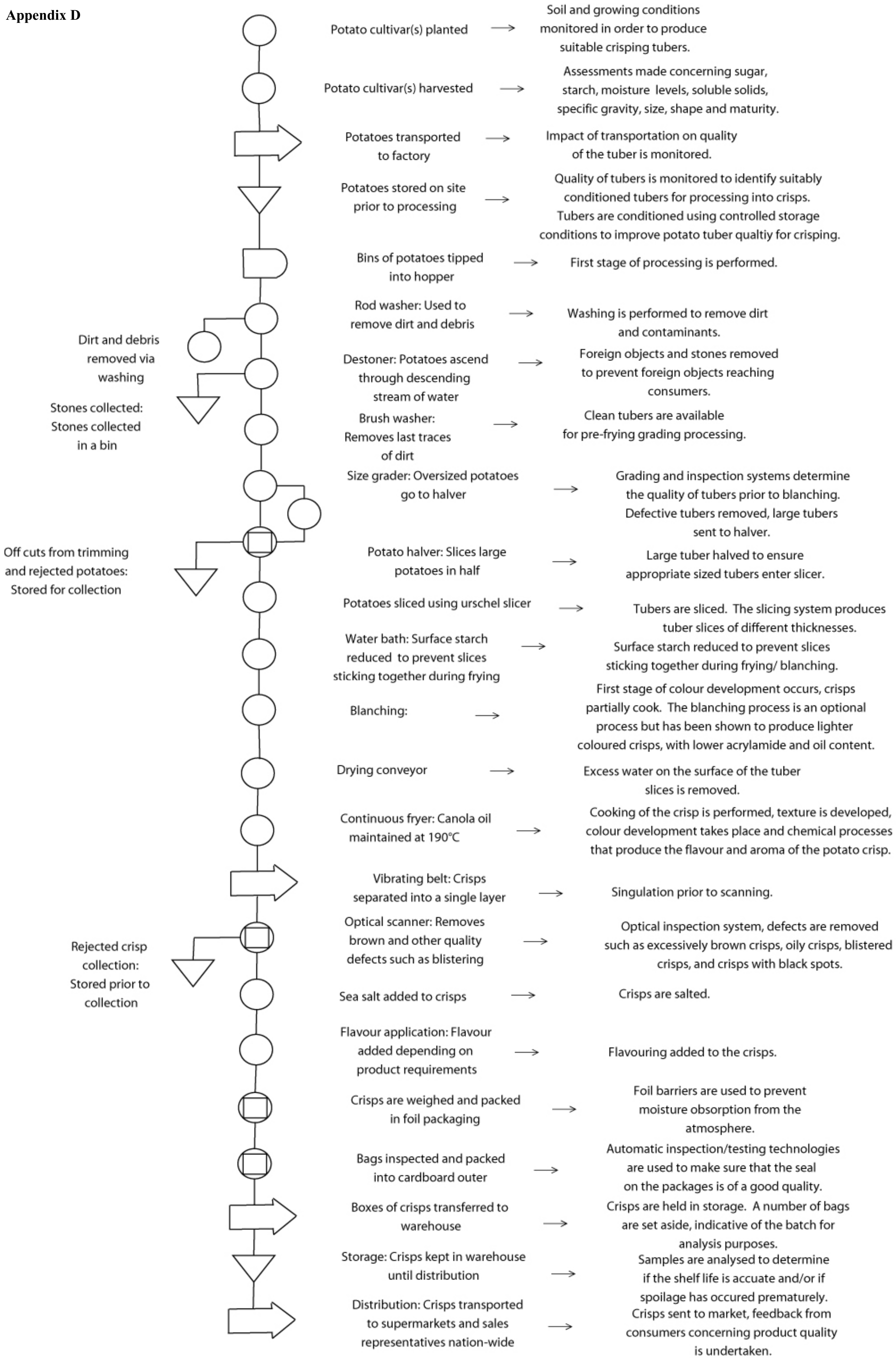
Appendix B (Cont.)

Stage	Hazards/reasons	Preventative measures	Critical factors/limits/controls
13. INSPECTION AND COOLING	MICROBIOLOGICAL Contamination (air, equipment, personnel) (the final product remains for a short time for cooling before its packaging). PHYSICAL Foreign materials.	GMP-GHP Protection the product from the environment. Assurance of hygienic conditions. Cleaning and disinfection of equipment. Ventilation for good cooling. Personnel training. Measurement of the crisp moisture, oil content using NIR.	Control of cleaning and disinfection programs. Control for foreign materials and draw away. Control for chips with defects or undesirable characteristics and direct reject. Control of hygiene in the environment during cooling. Control of sensory and instrumental measurements (calibration checking) to determine oil/moisture content.
14. PACKAGING	MICROBIOLOGICAL Contamination (air, equipment, personnel, packaging material). CHEMICAL Contaminants from the packaging materials. PHYSICAL Foreign materials.	Suppliers of packaging material (SQA). Packaging material approved for foods. Protection of the packaging area away from the production area. Metal detector after packaging. Coding of product.	Check the specifications of packaging materials. Control for foreign materials. Check for the correct closing of the package. Check for the correct coding. Removal of products with defects. Control of cleaning and disinfection programs. Control of metal detector.
15. STORAGE OF FINISHED PRODUCT	MICROBIOLOGICAL Contamination (moisture, pests) in case of not correctly closed packaged products. CHEMICAL Residues of chemicals and pesticides in case of not correctly closed packaged products.	GMP-GHP Assurance of hygienic conditions in storage area. Control of cleaning and disinfection programs. Pests control programs. Hygiene storage of final products. Monitoring samples from the batch produced for spoilage.	Control of programs: Cleaning and disinfection, pest control. Control of hygiene in storage area. Control for foreign materials. Check for the correct closing of the package.

Appendix C: Formation of Acrylamide. The Maillard reaction (also known as non enzymatic browning) is responsible for most of the flavour and aroma in the cooked potato crisp. It consists of the chemical reaction between reducing sugars (mainly D-glucose) and a free amino acid. An associated process is the Strecker degradation of amino acids by intermediates of the Maillard reaction. During the Strecker degradation, the amino acid is decarboxylated and deaminated to form an aldehyde, which is a pathway for acrylamide formation: the amino acids asparagine and methionine go through Strecker degradation in the presence of dicarbonyl products from the Maillard reaction resulting in the formation of acrylamide shown below.



Appendix D



	Potato cultivar(s) planted	Soil and growing conditions monitored in order to produce suitable crisping tubers.
	Potato cultivar(s) harvested	Assessments made concerning sugar, starch, moisture levels, soluble solids, specific gravity, size, shape and maturity.
	Potatoes transported to factory	Impact of transportation on quality of the tuber is monitored.
	Potatoes stored on site prior to processing	Quality of tubers is monitored to identify suitably conditioned tubers for processing into crisps. Tubers are conditioned using controlled storage conditions to improve potato tuber qualtiy for crisping.
	Bins of potatoes tipped into hopper	First stage of processing is performed.
Dirt and debris removed via washing	Rod washer: Used to remove dirt and debris	Washing is performed to remove dirt and contaminants.
Stones collected: Stones collected in a bin	Destoner: Potatoes ascend through descending stream of water	Foreign objects and stones removed to prevent foreign objects reaching consumers.
	Brush washer: Removes last traces of dirt	Clean tubers are available for pre-frying grading processing.
	Size grader: Oversized potatoes go to halver	Grading and inspection systems determine the quality of tubers prior to blanching. Defective tubers removed, large tubers sent to halver.
Off cuts from trimming and rejected potatoes: Stored for collection	Potato halver: Slices large potatoes in half	Large tuber halved to ensure appropriate sized tubers enter slicer.
	Potatoes sliced using urschel slicer	Tubers are sliced. The slicing system produces tuber slices of different thicknesses.
	Water bath: Surface starch reduced to prevent slices sticking together during frying	Surface starch reduced to prevent slices sticking together during frying/ blanching.
	Blanching:	First stage of colour development occurs, crisps partially cook. The blanching process is an optional process but has been shown to produce lighter coloured crisps, with lower acrylamide and oil content.
	Drying conveyor	Excess water on the surface of the tuber slices is removed.
	Continuous fryer: Canola oil maintained at 190°C	Cooking of the crisp is performed, texture is developed, colour development takes place and chemical processes that produce the flavour and aroma of the potato crisp.
	Vibrating belt: Crisps separated into a single layer	Singulation prior to scanning.
Rejected crisp collection: Stored prior to collection	Optical scanner: Removes brown and other quality defects such as blistering	Optical inspection system, defects are removed such as excessively brown crisps, oily crisps, blistered crisps, and crisps with black spots.
	Sea salt added to crisps	Crisps are salted.
	Flavour application: Flavour added depending on product requirements	Flavouring added to the crisps.
	Crisps are weighed and packed in foil packaging	Foil barriers are used to prevent moisture obsorption from the atmosphere.
	Bags inspected and packed into cardboard outer	Automatic inspection/testing technologies are used to make sure that the seal on the packages is of a good quality.
	Boxes of crisps transferred to warehouse	Crisps are held in storage. A number of bags are set aside, indicative of the batch for analysis purposes.
	Storage: Crisps kept in warehouse until distribution	Samples are analysed to determine if the shelf life is accuate and/or if spoilage has occured prematurely.
	Distribution: Crisps transported to supermarkets and sales representatives nation-wide	Crisps sent to market, feedback from consumers concerning product quality is undertaken.