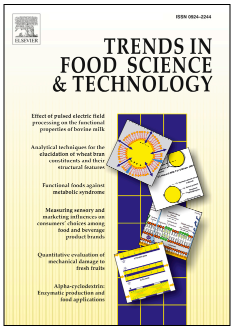
Accepted Manuscript



Innovative non-thermal technologies affecting potato tuber and fried potato quality

Cátia Dourado, Carlos Pinto, Francisco J. Barba, Jose M. Lorenzo, Ivonne Delgadillo, Jorge A. Saraiva

PII: S0924-2244(19)30083-4

DOI: https://doi.org/10.1016/j.tifs.2019.03.015

Reference: TIFS 2475

To appear in: *Trends in Food Science & Technology*

Received Date: 5 February 2019

Revised Date: 25 February 2019

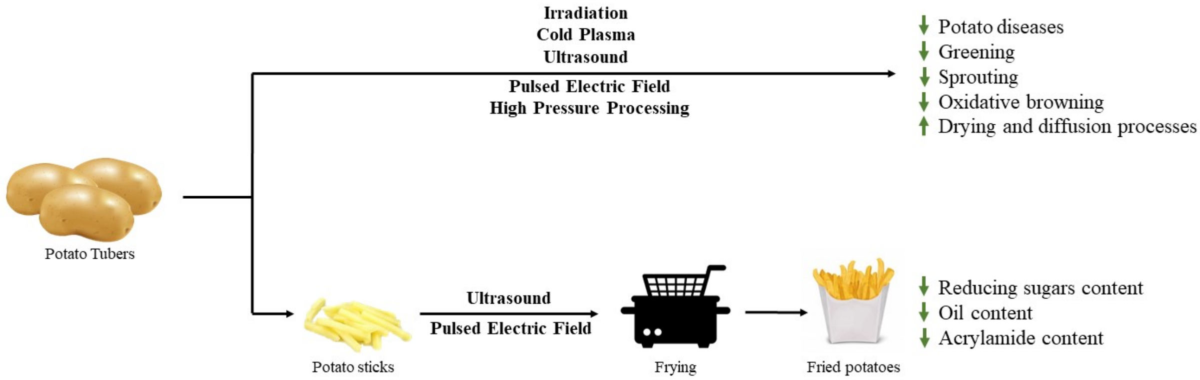
Accepted Date: 18 March 2019

Abstract

Background: Potatoes are important tubers for human consumption, providing an essential source of energy and great nutritional characteristics for human health. However, before consumption, potato tubers need to be stored and processed. As frying is the most common technique used in potato processing, fried potato is the most important processed potato product. Some food characteristics, provided by the frying process, are considered desirable, but others are harmful to human health and, thereby the main challenge is to reduce the formation of the undesirable characteristics, without compromising the sensorial attributes.

Scope and approach: In this review, the origin, economic importance, morphology and composition of potato tubers are presented. Afterwards, some factors affecting potato tuber quality, not only for human consumption, but also for further processing are addressed. Then, potato processing is discussed with a focus on the frying process, including the textural, chemical and nutritional changes induced by frying and the main characteristics affecting the quality of fried potato products. Finally, a special focus is given to the novel emerging non-thermal technologies and a brief review of their effects on potato tuber and fried potato quality is provided.

Key findings and conclusions: Irradiation, cold plasma, ultrasounds, pulsed electric fields and high pressure processing are innovative non-thermal technologies with potential to be an alternative for the traditional treatments of potato tubers and to be applied as a frying pre-treatment, improving time and energy for slicing and cooking, and creating improved and healthier fried potatoes. Further studies are needed to better understand the subjacent biochemical mechanisms.


Irradiation
Cold Plasma
Ultrasound
Pulsed Electric Field
High Pressure Processing
Potato diseases
Greening
Sprouting
Oxidative browning
Drying and diffusion processes
Potato Tubers
Potato sticks
Ultrasound
Pulsed Electric Field
Frying
Fried potatoes
Reducing sugars content
Oil content
Acrylamide content

Innovative non-thermal technologies affecting potato tuber and fried potato quality

Cátia Dourado[1], Carlos Pinto[1], Francisco J. Barba[2], Jose M. Lorenzo[3], Ivonne Delgadillo[1], Jorge A. Saraiva[1,] *

[1]QOPNA & LAQV-REQUIMTE, Department of Chemistry, University of Aveiro, 3810-193 Aveiro, Portugal

[2] Nutrition and Food Science Area, Preventive Medicine and Public Health, Food Science, Toxicology and Forensic Medicine Department, Faculty of Pharmacy, Universitat de València, Avda.Vicent Andrés Estellés, s/n, 46100 Burjassot, València, Spain

[3]Centro Tecnológico de la Carne de Galicia, rúa Galicia n° 4, Parque Tecnológico de Galicia, San Cibrao das Viñas, Ourense, Spain

*Corresponding author email address: jorgesaraiva@ua.pt (J.A.Saraiva)

Abstract

Background: Potatoes are important tubers for human consumption, providing an essential source of energy and great nutritional characteristics for human health. However, before consumption, potato tubers need to be stored and processed. As frying is the most common technique used in potato processing, fried potato is the most important processed potato product. Some food characteristics, provided by the frying process, are considered desirable, but others are harmful to human health and, thereby the main challenge is to reduce the formation of the undesirable characteristics, without compromising the sensorial attributes.

Scope and approach: In this review, the origin, economic importance, morphology and composition of potato tubers are presented. Afterwards, some factors affecting potato tuber quality, not only for human consumption, but also for further processing are addressed. Then, potato processing is discussed with a focus on the frying process, including the textural, chemical and nutritional changes induced by frying and the main characteristics affecting the quality of fried potato products. Finally, a special focus is given to the novel emerging non-thermal technologies and a brief review of their effects on potato tuber and fried potato quality is provided.

Key findings and conclusions: Irradiation, cold plasma, ultrasounds, pulsed electric fields and high pressure processing are innovative non-thermal technologies with potential to be an alternative for the traditional treatments of potato tubers and to be applied as a frying pre-treatment, improving time and energy for slicing and cooking, and creating improved and healthier fried potatoes. Further studies are needed to better understand the subjacent biochemical mechanisms.

Keywords: potato tuber; fried potatoes; quality; frying; acrylamide; oil uptake; emergent technologies; non-thermal technologies.

1. Introduction

Potato is a tuberous crop produced by a perennial herb (potato plant), which belongs to the family *Solanaceae*, species *Solanum tuberosum L.* (Singh and Kaur, 2016), being the second most important crop for human consumption in Europe and fourth on a global scale after maize, rice, and wheat (O'Connor et al., 2001). Actually, the production of starch per hectare is greater in potatoes than in any other crop and, with regard to protein production, they are the second main crop after soybeans (Oerke, 2006). Nowadays, there are more than 4,500 varieties of potatoes (differing in texture, flavour, shape, and colour) growing in more than 160 countries, with a global total production exceeding 374 million tons per year, being consumed by more than a billion people worldwide (Camire et al., 2009; Cipotato, 2018; Singh and Kaur, 2016).

The potato tubers are essentially an underground stem and, morphologically, they have several differences in size, shape and flesh/skin colour, depending on the genetics of the cultivar. Nevertheless, the potato tubers are usually oval to round in shape, with pale brown skin and white flesh (Singh and Kaur, 2016). Their outer skin consist of a layer of corky periderm, formed by dead cells without starch and protein, providing the primary barrier against physical intrusions, diseases, insects, and dehydration (Fiers et al., 2012; Miranda and Aguilera, 2006). The cortex, a thin layer of parenchyma tissue, underlies the skin and is composed by cells with multiple oval-shaped starch granules stored as a reserve material (Miranda and Aguilera, 2006). In the central zone of the potato tuber is the pith (also called medulla or water core), composed of smaller cells with lower starch content (Troncoso et al., 2009).

Potatoes are considered an excellent source of energy, carbohydrates and dietary fibre, whose nutritional characteristics (such as starch digestibility and glycaemic index) are important in human health (Camire et al., 2009). Their nutritional composition vary with potato varieties, soil type, crop practices, location, weather conditions and postharvest storage conditions (Miranda and Aguilera, 2006). **Table 1** shows the nutritional composition variability of raw potatoes. Generally, in a potato tuber about 1-2% is dietary fibre (being supplied especially by the thickened cell walls of the skin), 20% consists of dry matter, and the remaining fraction is water (Singh and Kaur, 2016). The water is contained in different compartments inside the potato cells, being 84% in the vacuoles, the nucleus, and the cytoplasm, 13% inside starch granules and 3% in the cell wall (Rutledge et al., 1994). Starch is the major component of the dry matter, accounting for approximately 70% of the total solids, and is composed by amylose and amylopectin chains (Singh and Kaur, 2016). In addition, considering the several polymorphic types of starch crystallinity, potato starch belongs to B-type (Buléon et al., 1998; Pérez et al., 2009). Moreover, potato tubers have very low fat content and supply protein of high relative biological value (90-100). Regarding the free amino acids, asparagine (Asn) is an important amino acid for plant growth, playing a central role in nitrogen storage and transport (Lea et al., 2006), and is the most abundant free amino acid in potatoes, usually accounting for 0.2-4% for dry matter and 20-60% of total free amino acids (Food Drink Europe, 2013). Lastly, potatoes are also composed by several micronutrients, namely essential minerals like potassium, phosphorus, calcium and magnesium, and bioactive compounds, such as vitamins C (the major vitamin in raw potato), E and B (folic acid, niacin, pyridoxine, riboflavin and thiamine), carotenoids and phenolic compounds (phenolic acids, flavonoids, anthocyanins) (Camire et al., 2009; Singh and Kaur, 2016).

The main objective of this review article is to show the effects of innovative processing technologies on potato tuber and fried potato quality. For this purpose, the factors affecting potato tuber quality, not only for human consumption but also for further processing are presented. Afterwards, the changes and problems induced by frying that affect the quality of fried potatoes will be addressed, and finally the novel methods for potato treatment will be introduced.

2. Potato tuber quality

The preservation of the potato tuber quality is essential for human consumption and processing, as well as to avoid/reduce economic losses, and is determined by several external, internal and nutritional aspects. The skin appearance (skin finish and greening) and sprouting are the main factors determining the external quality of potato tubers. In addition, the internal potato tuber quality may be affected by several factors, such as the susceptibility to enzymatic discoloration and the development of brown spots and hollow heart (Lisińska et al., 2009). Regarding the nutritional properties, potato tubers should have appropriate content of essential minerals and bioactive compounds (**Table 1**), low reducing sugars content, and low anti-nutrients content (Lisińska et al., 2009; Meyhuay, 2001). **Table 2** summarizes the main events that affect the potato tuber quality, as well as their causes, more conventional control strategies and novel non-thermal technologies which may be used as an alternative treatment.

2.1. Potato tuber diseases

Several potato pathogens originate potato diseases, which cause severe damages on tuber skin finish as well on its interior, resulting in marketable yield reductions and economic losses. Total losses are estimated to be about 24% in Northwest Europe and more than 50% in Central Africa, highlighting accented differences in crop protection intensity (Cerda, 2017; Oerke, 2006). Actually, 40 soil-borne diseases are known worldwide and, frequently, the favourable conditions for potato diseases development are the same as those needed for potato growth. For instance high humidity, medium pH and temperature around 10 and 25 ºC (Fiers et al., 2012). Some of the most important diseases affecting potato tubers are described below, and summarized in **Table 2**.

The fungus *Colletotrichum coccodes* causes black dots, a disease characterized by silvery lesions on the tuber surface and may be controlled by using soil fumigants, chemical fungicides and cool and dry storage conditions (Lees and Hilton, 2003). The fungus *Helminthosporium solani* induces the silver scurf disease, which is associated with moisture loss and skin discoloration and sloughing, caused by rupture of periderm integrity (Elson et al., 1997). The fungus *Polyscytalum pustulans* originates the skin spot disease, being characterized by purplish-black raised spots of about 2 mm diameter on the tuber surface which appear at least after 6 weeks of storage (Lees et al., 2009). The control of these three blemish diseases may be accomplished by using dry and cool conditions for potato tuber storage (Fiers et al., 2012). In addition to these problems, the oomycete pathogen *Phytophthora infestans* causes the late blight disease, whose associated symptoms are a darker brown area on the tuber surface and a reddish brown granular rot in the tuber interior, being controlled by using chemical fungicides (CIPC, 2015; Hijmans et al., 2000). Moreover, three Gram-negative bacteria, *Erwinia carotovora spp. carotovora* (Ecc), *E. carotovora spp. atroseptica* (Eca) and *E. chrysanthemi* (Ech) are important potato pathogenics, since under high temperature and humidity, poor ventilation and low oxygen levels, the synthesis and secretion of pectic enzymes is stimulated, causing tissue softening, water and nutrients release, and eventually cell death. Therefore, the infected tubers exhibit blackleg (stem rot) and soft rot (Nourian et al., 2002; Pérombelon, 2002). Besides, the *Potato virus Y*, currently considered the most important virus pathogen affecting potato crops, is capable of inducing superficial and internal necrosis on potato tubers and, consequently, the potato tuber necrotic ringspot disease development (Karasev and Gray, 2013; Romancer et al., 1994).

2.2. Discolouration

Enzymatic discolouration consists in the oxidation of phenolic compounds, in the presence of O_2, to *o*-quinones by the enzyme polyphenol oxidase (PPO), and in turn the *o*-quinones undergo polymerization being converted into black-brown polymers (Friedman, 1997). As PPO is located in the plastids of potato cells and phenolic compounds are stored in the vacuoles, enzymatic oxidation is prevented in undamaged living tissues by this physical separation. However, during harvesting and processing, plant tissues suffer damage due to physical processes like cutting and peeling, disrupting cellular compartments, which trigger the above-mentioned enzymatic reaction (Busch, 1999; van Eck, 2007; Yildiz, 2019). Although PPO is considered a key factor in this enzymatic process, high levels of tyrosine and free amino acids have also shown a positive influence on the discolouration of potato tubers (Corsini et al., 1992; van Eck, 2007). The inactivation or inhibition of oxidative enzymes (such as PPO and peroxidase, POD) is important in order to avoid undesirable browning reactions and detrimental effects on sensorial and nutritional quality of tubers (Bußler et al., 2017). Several strategies have been reported in the literature for the reduction or prevention of tuber discolouration, namely by using citric, acetic, malic and ascorbic acids to reduce the pH (Ali et al., 2015; Wang et al., 2011); vacuum packaging of cut food to decrease the quantity of available oxygen (Rocha et al., 2003); and using PPO inhibitors, such as 4-hexylresorcinol (Buta and Moline, 2001).

2.3. Greening

Potato tubers, as underground stems, are non-photosynthetic plant organs. However, exposure of tubers to light induces the differentiation of amyloplasts into chloroamyloplasts, resulting in chlorophyll synthesis and accumulation on the newly membrane vesicle formed between the envelope and the starch grain of the plastid (Tanios et al., 2018). This phenomenon occurs in cortical parenchyma tissue directly beneath the periderm, which is responsible for the undesirable greening. Actually, tuber greening is considered an important cause of quality loss in potato tubers, being associated with problems for human health and marketability (Grunenfelder, 2005).

Steroidal glycoalkaloids are phytochemicals that are naturally formed (parallel and independently to chlorophyll synthesis) in green tubers, being present in all parts of the plant (Petersson et al., 2013). However, the highest levels of these secondary metabolites have been found in metabolically active organs like tuber sprouts, flowers, peripheral layers of the tuber and the parenchyma of periderm cells (Friedman, 2006). In potatoes, glycoalkaloids predominantly (over 95%) exist in two main forms, α-solanine and α-chaconine (Petersson et al., 2013), whose chemical structures are shown in **Table 2**, and they are probably responsible for the protection against the tissue invasion due to their antimicrobial, insecticidal and fungicidal properties. However, these compounds also present toxicological effects in humans, being α-chaconine more toxic than α-solanine. Due to the increase production and consumption of fresh and processed potatoes, glycoalkaloids formation and toxicity are a concern for public health (Nema et al., 2008). Therefore, it is important to select potato tubers for consumption with lower glycoalkaloids levels, *i.e.* not exceeding the safe limit established of 200 mg/Kg fresh weight (FW) (van Eck, 2007).

On the other hand, the United States Department of Agriculture (USDA) established that a green potato tuber is considered as “damaging” when removal causes a loss of more than 5% of the total weight or when more than 25% of the tuber surface is affected by the green colour (USDA, 2011). Therefore, potato greening is a problem which results in economic losses and marketability reductions and according to the United Kingdom Research and Innovation (UKRI), in the United Kingdom (UK), tuber greening is responsible for an estimated loss of £37 million to the industry and 116,000 tons of household potato waste annually (UKRI, 2018).

Tuber greening may be influenced by several factors, such as potato variety, tuber physiological age, environmental oxygen levels, temperature, and lighting conditions (Tanios et al., 2018). Once potatoes turn green, it is not possible to reverse the process and thereby, there are some possible strategies for greening prevention. The simplest one consists in minimizing light exposure during potato handling and storage, although low-oxygen storage, edible oil coatings and chemical treatments (such as, herbicides, nematicides and plant growth regulators and inhibitors) have also shown potential to reduce potato tuber greening (Nema et al., 2008; Pavlista, 2001; Tanios et al., 2018). Regarding to the greening control by manipulating the storage temperature, the results present in the literature are controversial and not consistent.

2.4. Sprouting

The life cycle of a potato tuber is characterized by a set of stages, starting with tuber induction, initiation and enlargement followed by a period of dormancy and finally sprouting (Fernie and Willmitzer, 2001). Dormancy is a physiological process characterized by a temporary growth arrest of any plant structure, which contains a meristem. Upon a dormancy period, sprouts start to grow, resulting in the formation of roots at the tuber buds bases (Aksenova et al., 2013). Several factors are responsible for the regulation of tuber dormancy and sprouting, which include internal physiological and environmental factors (Mani et al., 2014). Phytohormones are endogenous regulators that play an important role in the control of these phenomena. Cytokinins, such as abscisic acid and indole acetic acid, have shown to be involved with the induction and maintenance of tuber dormancy, inhibiting sprouting, while gibberellins, such as gibberellic acid, are associated with the active stimulation of tuber sprouting (Fernie and Willmitzer, 2001; Suttle, 2004; Weiner et al., 2010). The chemical structures of abscisic acid, indole acetic acid and a gibberellin are shown in **Table 2**.

Sprouting causes softening, shrinkage, formation of toxic alkaloids, and consequently leads to changes at nutritional and texture level (Sorce et al., 2005). Actually, the United States Department of Agriculture (USDA) established that any lot of potato tubers is considered as “damaging” when more than 5% of the potatoes have a sprout with more than 0.64 cm in length or have individual and/or groups of sprouts, which affects negatively the potato appearance (USDA, 2011). Therefore, the control of sprouting during potato storage is essential to avoid or decrease potato quality and economic losses. The storage at low temperatures (<8 ºC) and the use of chemical sprouting inhibitors (such as, chlorpropham) are the primary methods used to control potato sprouting of stored tubers (Sorce et al., 2005). However, there are some problems associated with these control measures. Firstly, the storage at low temperatures increases the amount of sugars in potato tubers, which is undesirable for the potato processing industry (the reasons will be explained afterwards) (Sowokinos, 2007). Secondly, the demand for more organic and chemical-free foods is increasing (Statista, 2018) and therefore, it is necessary to develop other methods to inhibit potato sprouting.

2.5. Starch content

Starch content (also known as dry matter content) is a moderately important parameter for table use, but with high importance for the processing industry (Sowokinos, 2007), an issue that will be described in more detail in section *4. Quality of fried potato* *products*. Certain storage conditions can lead to starch-to-sugar conversion and cause sugar (glucose, fructose and sucrose) accumulation mainly due to senescence sweetening and cold temperatures (Singh and Kaur, 2016). On the one hand, senescence sweetening is a normal biological process associated with sprouting, occurring more rapidly at higher storage temperatures (> 8 ºC) (Amrein et al., 2003). During this process, the sugars released are used as an energy source for the growth of the potato plant (Blenkinsop et al., 2010). On the other hand, cold temperatures (< 8 ºC) lead to a quick accumulation of reducing sugars in stored potato tubers, a phenomenon known as cold sweetening. This process serves as a cryoprotection mechanism since the release of sugars reduces the freezing point, preventing damages in tissues that could result from the formation of large ice crystals (Blenkinsop et al., 2010). The biochemical mechanism behind cold sweetening is complex and involves a series of reactions, including for example, changes in gene expression and/or modulation of post-translational activity of key enzymes, such as sucrose phosphate synthase (Hill et al., 1996), the appearance of a new amylolytic activity, specifically a cold-induced β-amylase isoform (Hill et al., 1996; Nielsen et al., 1997), increasing sucrose synthesis and starch degradation via phosphorolytic and hydrolytic reactions (Sowokinos, 1990). Therefore, ideally, potato tubers should be stored at 8-10 ºC, since reducing sugar content is not significantly influenced and although sprouting would occur at this temperature, it can be controlled using sprout suppressants such as chloropham (De Wilde et al., 2005, 2006a; Halford et al., 2012).

3. Potato cooking

Before consumption, potatoes need to be processed mainly due to the indigestibility of their ungelatinized starch. Indeed, according to García-Alonso and Goñi (2000), potato cooking greatly improves the digestibility of potato starch due to the conversion of the natural resistant starch into highly digestible starch (**Figure 1**). The most popular cooking methods include boiling, baking, toasting, roasting, frying and microwaving (Decker and Ferruzzi, 2013; García-Alonso and Goñi, 2000), although emerging thermal technologies, such as ohmic heating, are being recently studied for potato cooking (Farahnaky et al., 2018). Considering all the products resulted from the potato cooking (**Figure 2)**, the most important one refers to French fries, with an annual consumption of approximately 7 million metric ton worldwide, and the second one refers to potato chips (Miranda and Aguilera, 2006; Mordor Intelligence, 2016; National Potato Council, 2018).

The next section of this review will focus on potato frying process, addressing the changes induced by the frying procedure and the desired and undesired characteristics of fried potato products.

3.1. Potato frying process

Deep-fat or immersion frying is the most common technique used in potato processing (Miranda and Aguilera, 2006), which involves the immersion of potato slices in hot oil or fat and creates unique sensorial qualities, namely unique flavour and textures (Gertz, 2014). In addition, recent new frying techniques have also been used, such as vacuum frying, a frying process performed under pressures below atmospheric levels, which has resulted in fried potatoes with less acrylamide levels (Belkova et al., 2018; Granda and Moreira, 2005); microwave-assisted vacuum frying, a special vacuum frying which uses the microwave as the only heating source and results in potato chips with a lower oil content and a better texture and flavour (Quan et al., 2014; Su et al., 2016, 2018a, 2018b); and air frying, a process that produces fried potatoes with low oil content due to the utilization of oil droplets dispersed in a hot air stream, within a closed chamber (Santos et al., 2017, 2018).

Frying is mainly a drying procedure based on heat transfer by convection from the surrounding oil of the surface and afterwards, by conduction within the potato core (interior). In addition, mass transfer also takes place resulting in water removal and oil uptake by the potato strips (Aguilera and Gloria-Hernandez, 2000). As a result, several physical, structural, chemical and nutritional changes are induced by the potato frying process (Miranda and Aguilera, 2006), which are represented schematically in **Figure 3.**

3.1.1. Physical and structural changes induced by frying

During frying, the crust and the core of fried products suffer different changes at microstructural level. When the potato pieces are placed into the hot oil (160-180 ºC), the temperature of the surface layers rises rapidly, the surface water boils and evaporates, starch granules undergo gelatinization and the tissues quickly dehydrate. Consequently, the surface porosity increases, as well as the shrinkage and roughness (Aguilera et al., 2001; Arslan et al., 2018; Bouchon and Aguilera, 2001; Gertz, 2014). As frying proceeds, the dehydrated crust develops and increases, a temperature gradient is formed in the interior (not exceeding 100 ºC), as a result of heat transfer by conduction from the crust into the core, and the core is cooked. More specifically, starch granules inside cells undergo hydration by the water surrounding them, causing the starch swelling (Aguilera et al., 2001), and the middle lamellae between cells becomes softened and disintegrates, resulting in the so-called mealy texture (Bouchon and Aguilera, 2001). Oil uptake also occurs during potato frying and according to Aguilera and Gloria (1997), it is mainly a surface phenomenon and French fries have almost six times as much oil in the crust than in the inner part.

Besides, Bouchon et al. (2001) have studied the oil distribution in fried potato cylinders of 1 cm diameter and reported that the maximum penetration of oil in the crust was about 300 μm. In addition, several studies have noted that a small amount of oil is absorbed during frying since the majority of absorption occurs at the end of frying and on cooling, involving a balance between adhesion and drainage of oil after the removal of the fried products from the fryer (Costa and Oliveira, 1999; Ufheil and Escher, 1996; Ziaiifar et al., 2008). When the chips or fries are removed from the frying medium, their temperature immediately starts to decrease. Below 100 ºC, water vapour condenses and the internal pressure drops on the surface, resulting in the creation of a positive pressure vacuum, which favours the oil placed in the surface to be absorbed (Miranda and Aguilera, 2006).

3.1.2. Chemical and nutritional changes induced by frying

During frying, food products suffer changes in their surface colour as well as in their aroma profile. At higher temperatures (>120 ºC), the Maillard reaction between amino acids (or free amino groups of proteins and peptides) and reducing sugars occurs, which is responsible either for the colouring of fried products, changing their colour to golden yellow and later to brown, or for their aromatization due to the formation of volatile compounds as secondary products (Miranda and Aguilera, 2006; Moreira et al., 1999). However, toxic compounds are also formed during the Maillard reaction, namely acrylamide, hydroxymethylfurfural (HMF), furan, heterocyclic amines, and polycyclic aromatic hydrocarbons (Anese et al., 2013; Balagiannis et al., 2019; Camire et al., 2009; Pedreschi et al., 2008; Qi et al., 2018).

Acrylamide is classified by the World Health Organization and the International Agency for Research on Cancer as a Group 2A carcinogen ("probably carcinogenic to humans") due to its implication in cancer in rats (Food et al., 2002; IARC, 1994). This compound has not been detected in unheated or boiled foods (< 5-50 μg/Kg) and therefore it was considered to be formed during heating at high temperatures (>120 ºC), as result of the Maillard reaction between the amino acid asparagine and reducing sugars (fructose and glucose) found in foods (Capuano and Fogliano, 2011; Miranda and Aguilera, 2006; Novozymes, 2017; Pedreschi et al., 2008; Powers et al., 2013). Furan and HMF are also by-products resulting from the Maillard reaction, involving several precursors, intermediates, and different reactions (Anese et al., 2013).

In addition, during frying some thermo labile compounds (such as ascorbic acid and other vitamins, flavonoids and essential amino acids) are lost by evaporation, leaching or degradation (Camire et al., 2009). Tian et al. (2016) have reported that frying caused losses of 83.35% in vitamin C content, 14.08% of total phenolics, 57.06% of total anthocyanins, 75.66% of total carotenoids and 33.84% of phenolic acids. Furthermore, prolonged use of oil at high temperature and in the presence of air leads to several reactions such as hydrolysis, oxidation and polymerization, resulting in the formation of volatile and non-volatile compounds within the oil, and some of which have been reported to pose risks to health (Miranda and Aguilera, 2006). The undesirable volatile products formed include peroxides, monoglycerides, diglycerides, aldehydes, ketones and carboxylic acids. The undesirable non-volatile compounds include free fatty acids, formed by the hydrolysis of oil, and trans-fatty acids, formed by hydrogenation (Yee and Bussell, 2007). The loss of healthy compounds and the formation of unhealthy ones, which can be absorbed by the product, leads to a reduction of the nutritional value of fried foods (Ziaiifar et al., 2008). Moreover, when starch is gelatinized, it can interact with polar and non-polar compounds, like fatty acids. The hydrocarbon portion of the lipid locates within the helical cavity of amylose, forming helical inclusion complexes (De Pilli et al., 2008), which modify some properties of starch, decreasing its solubility in water, retarding retrogradation and reducing the viscosity of gelatinized starch (Meng et al., 2014).

4. Quality of fried potato products

The overall quality of foods is a combination of the sensorial perception of appearance, texture, taste and consumer acceptability (Miranda and Aguilera, 2006; Yee and Bussell, 2007). In the specific case of fried products, their quality is a result of the quality of the tubers used in the manufacture and the manufacturing process applied. The fried products manufacturing process improves the palatability of foods and some sensorial properties (such as the range of colours, tastes, aromas and textures) (Capuano and Fogliano, 2011), but it may also bring about some undesirable effects. It includes (i) the loss of thermo labile compounds (such as vitamins and essential amino acids), reducing the nutritional value of heated foods; (ii) the formation of undesired tastes and off-flavours, reducing the sensorial quality; and (iii) the formation of harmful compounds with mutagenic, carcinogenic and cytotoxic effects (Decker and Ferruzzi, 2013), as it is the case of acrylamide and hydroxymethylfurfural.

Given the large consumption of French fries worldwide, a main challenge is to reduce the formation of the undesirable characteristics, without compromising the sensorial qualities. Thus, texture, colour and nutritional composition of fried potato products are the main properties that should be monitored (Yee and Bussell, 2007). Table 1 shows the nutritional composition of French fries produced by McDonald's company (USDA, 2018). French fries exhibit a unique texture composed by two regions: (i) an external dehydrated, crispy and oily crust and (ii) a humid, cooked and tender moist core free of oil (Miranda and Aguilera, 2006), while chips are a crispy and dehydrated product infiltrated by oil (Moreira et al., 1999). Fried potatoes with high-oil content are associated with an higher incidence of obesity, cholesterol level and high blood pressure, and thereby fat uptake is a major health concern for the potato processing industry (Arslan et al., 2018; Yee and Bussell, 2007). For French fries, the final oil and moisture content is around 15 g/100 g and 38 g/100 g (total weight basis), respectively (Aguilera and Gloria-Hernandez, 2000) and for potato chips the final oil and moisture content is around 33-38% and 1-2% (weight basis), respectively (Moreira et al., 1999). In addition, fried potato products are strongly susceptible to acrylamide formation due to asparagine and reducing sugars content as well as the high temperatures applied during the frying process. In French fries and chips, acrylamide formation occurs predominantly at the surface, where the (oil) temperature is high and the moisture content low (Parker et al., 2012). Regarding the acrylamide levels, the U.S. Environmental Protection Agency (EPA) requires the limit content in water to be less than 0.5 ppb (CSPI, 2003). However, starch rich products, like those produced from potato tubers, have a much higher content of acrylamide (170-3700 ppb) than the level identified as safe by EPA (Becalski et al., 2003). For this reason, controlling the acrylamide precursors levels in potato tubers, either during potato cultivar and storage or applying a pre-treatment, is an essential strategy to prevent acrylamide formation in potato fried products (Amrein et al., 2003; O'Connor et al., 2001; Singh and Kaur, 2016). On the other hand, the light golden colour and desirable flavours of fried potato products result from compounds produced by the Maillard reaction. However, excessive browning and the development of off-flavours have a negative impact on the quality of fried potatoes, being considered undesired by consumers and associated with burnt potato fries (Blenkinsop et al., 2010; van Eck, 2007; Yee and Bussell, 2007).

5. Effect of processing by emergent technologies on the quality of potato tuber and fried potato products

The more restrict legislation and new consumptions habits are leading to the innovation of alternative or complementary treatments in order to improve the changes that occur during potato storage and to control potato diseases (Alamar et al., 2017). In addition, several novel food processing technologies have been developed for food non-thermal pasteurization, as well for structural modification, allowing to reduce heat induced changes (nutritional and sensorial properties) in product quality (Jaeger et al., 2010). Irradiation, cold plasma, ultrasounds, pulsed electric fields (PEF), and high pressure processing (HPP) are non-thermal technologies (Fauster et al., 2018; Huang et al., 2017), which have already been applied in the treatment of potatoes. Several effects of these non-thermal emergent methods on potato quality are presented in **Table 3** and **Table 4**. Furthermore, a brief reference to a novel extraction technique, moderate electric fields (MEF), will be given later.

5.1. Irradiation

The potential application of irradiation in food processing is based mainly in the inactivation of living cells, as a result of the DNA damage caused by ionizing radiation (Arvanitoyannis et al., 2009). This non-thermal technology is quite effective for the extension of shelf life of fresh foods, but it can adversely affect their sensory properties (Soares et al., 2016). In 1964, it was approved by FDA for the application on potato tubers in order to inhibit tuber sprouting, using doses between 0.05 and 0.15 kilogray (KGy) (Andress et al., 1998; Ashley et al., 2004). Soares et al. (2016) have reported a slower sprouting in potatoes irradiated with 0.10 and 0.15 kGy and a sprouting inhibition when a dose of 2.00 kGy was applied. In addition, the effect of those gamma radiation doses on the sensory properties of potato tubers was also studied. It was found that the flavour of tubers was only slightly affected by irradiation, but potato tubers irradiated with 2.00 kGy exhibited a less desirable appearance after 35 days of storage. The authors concluded that 0.15 kGy was the most efficient radiation dose since it did not change nutritional and sensory properties and increased the shelf life of potato tubers. Moreover, Rezaee et al. (2013) treated potato tubers with gamma radiation of 50 and 100 Gy at 10th, 30th and 50th day after harvest. The authors have reported that the results obtained depend not only on the dose of radiation used but also on the potato variety and the day of treatment during potato storage.

For instance, the later the treatment was applied after harvesting, the greater radiation was required to inhibit sprouting. Similar results were obtained by Avdyukhina et al., (2018), applying an x-ray treatment of 15, 20 and 30 Gy after 2, 3 and 4 months of storage, respectively. Irradiation has also shown effects on potato greening, with reductions between 50 and 80% by applying 0.05 and 0.250 kGy doses. However, in the literature there are only two studies which were carried out in the late 50's (Gull and Isenberg, 1958; Schwimmer and Weston, 1958), and, so far, there is no documented evidence of the commercial application of irradiation for tuber greening control (Tanios et al., 2018).

Other studies have shown that irradiation treatments have also an effect on reducing sugars content. Rezaee et al. (2013) reported an increase of reducing sugar content in potato tubers, mainly when the irradiation treatment was applied at a more advanced storage time or a lower dose of radiation was used. The results obtained by Avdyukhina et al. (2018) were similar but these authors have also found that the irradiation treatment at more than 4 months after harvest was not useful since the sugar content exceeded the concentration in the non-treated tubers. The authors suggested that the increase of sucrose synthase, invertase and phosphorylase activity was probably the cause for the increase of reducing sugars content in potato tubers. The effect of irradiation technology on ascorbic acid content was also evaluated. Rezaee et al. (2013) observed that the loss of ascorbic acid increased at higher radiation doses and with earlier treatments.

Furthermore, the effect of irradiation on degradation of potato pesticides was also evaluated and Basfar et al. (2012) who found that by applying 1 kGy of irradiation, the concentration of pirimiphos-methyl residues decreased between 18 and 44.4%.

5.2. Cold plasma

Cold plasma is a novel technology, which uses reactive compounds in plasma to damage cell membranes, to denature the DNA and, consequently, to destroy or inactivate microorganisms. As cold plasma is a cold treatment, sensory and functional properties of foods have the potential to be better maintained (Dey et al., 2016). This non-thermal method has shown effects on bacterial pathogens present in potato tuber as well as on PPO and POD activity. Moreau et al. (2007) studied the effect of gliding arc (glidarc) discharge in the potato pathogen *Erwinia carotovora* subsp. *atroseptica*. The authors found that the application of this treatment caused changes in the bacterial membrane, induced the release of bacterial genomic DNA and proteins as well as protein dimerization and/or aggregation, and resulted in the effective destruction of Erwinia spp. Bußler et al. (2017) have reported that after the application of plasma processed air for 10 min, the PPO and POD activities were reduced by about 77 and 89%, respectively.

Although cold plasma has several benefits, some disadvantages have been also reported in the literature, namely the negative effect on fatty acids in several food products (Gavahian et al., 2018a). This technology induces lipid oxidation, when oxygen is present, due to the presence of reactive oxygen species in plasma, which adversely affects the sensory and nutritional quality of foods (Barden and Decker, 2016; Shahidi and Zhong, 2010), and even consumers health (Niki, 2009). Specifically in potato products, no information was found in the literature. Nevertheless, as fried potatoes have high lipids content it is possible to hypothesize that cold plasma technology may increase their lipid oxidation. However, it is only a hypothesis that should be further investigated.

5.3. Ultrasound

Ultrasound (US) may be used in food technology for non-destructive testing, by applying low intensities in the 0.1-20 kHz range. However, by applying high-power ultrasounds in the 20-100 kHz range, several physical, mechanical or chemical alterations may occur in foods (Mason et al., 2005). First of all, US influences some physicochemical properties of potato starch, namely disruption of starch granules, which results in more transparent and less viscous starch pastes (Chung et al., 2002), as well as changes in the crystal structure and formation of cavities in starch granules (Zhu et al., 2012). Furthermore, the drying rates of potato tubers are also affected by this technology.

Ozuna et al. (2011) observed that a treatment with ultrasonic power between 0 and 37 $kW.m^{-3}$ caused both an improvement of water transport mechanisms, probably due to the reduction on the boundary layer thickness, or an increase of the drying kinetics when a higher ultrasonic power was applied, reducing the drying time and the energy required for the drying process. Similar results were observed by Schössler et al. (2012), *i.e.*, the water removal was improved by the application of an US treatment at a frequency of 24 kHz, as well as a reduction in drying time of 10.3%.

In addition, the application of US associated with osmotic dehydration has shown effects on reducing oil uptake in fried potatoes since osmotic dehydration decreases the initial water content of potato strips and US increases the mass transfer rate (Dehghannya and Abedpour, 2018; Karizaki et al., 2013). US may also affect browning, firmness and cell microstructure in potato tubers, and according to Amaral et al. (2015), a sonication treatment (40 kHz, 200 W) for 5 min inhibited PPO activity in 50% for the first 4 days of potato storage, and 10 min of treatment damaged the potato cells. The majority of components and sensory properties of potato tubers were not affected by the treatment and the firmness of the potato strips after frying was found to be more uniform. In addition, Wambura and Yang (2011) showed the potential of US to remove lipids from the surface of the potato chips, improving oxidative stability during storage and eventually shelf life and sensory quality of potato chips.

Antunes-Rohling et al. (2018) studied the effect of US (with a frequency of 35 and 130 kHz and an ultrasonic power density of 9.5, 47.6 and 95.2 W/Kg, for 30 min at 30 and 42 ºC) as a frying pre-treatment to mitigate the acrylamide formation in fried potatoes and noted a decrease in the potatoes' moisture gain by applying higher ultrasonic densities. In addition, the authors noted an increase in the extraction of reducing sugars between 17 and 52%, probably due to the surface cells degradation and the chemical breakdown of starch, as well as a reduction in acrylamide content by up to 83% compared with directly fried potatoes.

5.4. Pulsed Electric Fields

The application of pulsed electric field (PEF) treatment in foods is based on the permeabilization of biological membranes. PEF processing involves the application of short pulses (µs to ms) of electric fields in the range of 100-300 V/cm to 20-80 kV/cm, resulting in the disintegration of the cell membrane and in the formation of membrane pores (temporarily or permanently), retaining or minimally modifying sensorial, nutritional and health-promoting attributes of food products (Barba et al., 2015; Jaeger et al., 2010; Puértolas et al., 2016; Puértolas and Barba, 2016; Sánchez-Vega et al., 2015). However, Ammar et al. (2011) emphasized that the plant tissue structure, cell size and electrophysical properties of cell fluids and membranes have a high influence on the PEF damage efficiency. For instance, potato tissue shows a rapid PEF-induced damage due to the large size of its cells. In addition, the potato peel has also influence on results of PEF treatment, showing a protective effect against cell lysis and death, and thus peeled potato tubers are more sensitive to electric field application than unpeeled tubers (Faridnia et al., 2015).

On the other hand, Fincan and Dejmek (2003) and Pereira et al. (2009) observed that the rapid change on the viscoelastic properties of potato tissue is another effect caused by PEF, as a result of electroporation, cell permeabilization and partial loss of turgor pressure. Moreover, other studies have proven that electric pulses induce more metabolic responses in potato tissue, which involve oxygen consuming pathways, a resealing process accompanied by oxidative stress due to the formation of reactive oxygen species (ROS), and ATP hydrolysis for the restoration of the charges gradients across cell membranes. These results were observed a few minutes after the application of PEF treatment (Galindo et al., 2008).

However, Galindo et al. (2009) studied the changes occurring in potato metabolism 24h after the treatment and found changes in the hexose pool, involving probably the degradation of starch and ascorbic acid, and changes in the amino acid pool. Furthermore, PEF has also shown to affect enzymatic browning of potato tubers, a phenomenon that has negative effects on the nutritional and sensory features of fried potatoes (Queiroz et al., 2008). Indeed, this technology favours enzymatic browning of cut potato tubers, due to the release of previously entrapped PPO, which will have an improved contact with oxidizable compounds, namely phenolic compounds (Oey et al., 2016).

In the literature, several studies have reported that diffusion processes (intra- or extracellular mass transfer) are modified after PEF application (Arevalo et al., 2004; Janositz et al., 2011; Lindgren, 2006). Researchers have presented a couple of explanations for this phenomenon, namely the formation of pores in cell membrane, the cell membrane disintegration as well as the reduction of lignin content of the cell wall, which may be caused by the breaking of inter- and intramolecular bonds between the cellulose, hemicellulose, an lignin polymers. As a consequence, PEF treated potato tubers show higher diffusion coefficients (Arevalo et al., 2004) and an enhanced release of reducing sugars (precursors of the Maillard reaction and acrylamide formation) (Janositz et al., 2011; Lindgren, 2006).

PEF technology has also shown to influence drying processes. According to May and Perré (2002) and Wang and Brennan (1995), the drying rate is both dependent on the cell liquid (water) release or tissue structure, density and porosity. Thus, a greater PEF-induced release of cell liquid and degree of tissue damage are associated with an increase in drying rate (Janositz et al., 2011; Lebovka et al., 2007). Other studies have noticed effects on potato texture (Fauster et al., 2018; Ignat et al., 2015). Fauster et al. (2018) studied, in an industrial scale production environment, the impact of PEF pre-treatment on potato texture and on process performance characteristics during the manufacturing of French fries. The researchers observed an increase in cell permeabilization and the loss of the cell turgor pressure, thus the tissues became softer and the potato surface smoother. The influence of PEF treatment on the peeling behaviour of potatoes was also evaluated, but no significant differences were observed. Ignat et al., (2015) have shown similar results regarding to softening of potato tubers. Indeed, these results have an important industrial application, the decreasing of the energy required for PEF treatment (ten-fold lower than for potato blanching) as well as the energy needed for cutting (35% less). There are already some works protected by patent, which use PEF to improve cutting, patent number US6821540B2, (Cousin et al., 2004) and to reduce the energy needed to accomplish appropriate cooking, patent number WO2016008868A1 (Oord and Roelofs, 2016).

Besides improvements in the potato texture, PEF has also provided benefits in economic aspects, namely by reducing feathering (up to 80%), starch loss (from 7.1 to 5.9 Kg/t of treated potatoes), fat uptake (from 7.5 to 6.8%) and the proportion of broken sticks (from 11.0 to 6.0%) due to the improvement in elastic properties of potato strips (Fauster et al., 2018).

Regarding fried potato products, Botero-Uribe et al. (2017) reviewed the main effects of PEF on the texture of French fries, and Kalum and Hendriksen (2016) showed a potential alternative for reducing acrylamide levels in fried potatoes by applying a PEF treatment. The authors proposed that PEF pre-processing, followed by the treatment with enzymes capable of reacting with asparagine (asparaginase) or with reducing sugars (oxidoreductase), can reduce asparagine and glucose contents in the potato products before deep frying, as well as acrylamide levels after frying. Indeed, such a possibility, it was protected by a U.S. patent (US20160100612A1) (Kalum and Hendriksen, 2016).

Moreover, Ignat et al. (2015) also observed an increase in the tubers moisture by applying 9000 pulses at 0.75 kV/cm or 810 pulses at 2.50 kV/cm electric field, as well a reduction of oil uptake and an increase in the leaching of reducing sugar, decreasing browning tendency during frying. Liu et al. (2018) have reported a reduction in drying and frying time processes when a PEF treatment of 100 pulses at 600 V/cm was applied. In addition, the researchers noted that during frying, the skin of potato strips became denser and less oil penetrable. In addition, a reduction of oil content in 38% was observed in fried potatoes using tubers that where treated by PEF, at 1.5-5.0 kV/cm and 20-40 pulses of 100-400 μs (Janositz et al., 2011).

Due to the raise of PEF-induced cell membranes permeability, the diffusion of cell liquid from the core to the surface of potato strips is increased, a greater vapour pressure difference between food moisture and oil is obtained as well as a thicker water vapour layer, which decreases dehydration on the potato surface and consequently oil uptake (Janositz et al., 2011; Thanatuksorn et al., 2005). Furthermore, PEF treated potatoes result in strips with lower roughness, leading to a better oil draining and a decreased susceptibility to oil uptake (Bouchon and Pyle, 2004).

Moreover, physicochemical properties of potato starch undergoes some changes when a PEF treatment is applied, namely (i) denaturation and damage of potato starch granules, leading to a rough surface; (ii) aggregation among granules and formation of a gel-like structure due to the increase of water absorption, starch swelling and granule size; (iii) loss of crystalline structure; and (iv) reduction of the peak and breakdown viscosity (Han et al. 2009).

5.5. Moderate Electric Fields

Moderate Electric Fields (MEF) are characterized by the application of an alternating electric current up to 100 V/cm of electric field without pulsation across food products, with or without the presence of ohmic heating effects. It induces a controlled and possibly reversible increase in cell permeability (Gavahian et al., 2018b; Sensoy and Sastry, 2004). MEF have been used as an alternative to the conventional extraction techniques in the food industry. MEF extraction have several benefits, namely the reduction of extraction energy and time, and the improvement of extraction yields and quality (Gavahian et al., 2018b). This extraction technique has been already applied in potatoes, and it resulted in an increase of the degree of potato tissue damage with the increase of the applied temperature (Lebovka et al., 2005). Furthermore, Pereira et al. (2016) found that MEF can be applied for the extraction of anthocyanins and phenolic compounds from coloured potatoes, with enhanced recovery yields, reduced treatment time and energy consumption, and no utilization of organic solvents.

5.6. High Pressure Processing

High pressure processing (HPP), also known as high hydrostatic pressure or high isostatic pressure, is an emerging technology in food processing and preservation, which uses elevated hydrostatic pressure (commercially, up to 600 MPa) for cold pasteurization, without affecting the sensory quality of foods (Basak and Ramaswamy, 1998; Oey et al., 2016), and is based on two essential principles: (i) Le Chatelier's Principle and (ii) the isostatic principle (Elamin et al., 2015). Besides its use in food preservation, this technology has also been studied for several other applications, such as for the modification of physiological processes, like potato sprouting (Alexandre et al., 2016; Saraiva and Rodrigues, 2011), to accelerate infusion processes (Sopanangkul et al., 2002) and for the modification of food biopolymers, such as starch and proteins (Balasubramaniam et al., 2015).

Although potato starch is more baroresistant than other starches, requiring a pressure about 800-900 MPa to achieve a complete gelatinization (Katopo et al., 2002; Stute et al., 1996), some researchers have shown that by applying 600 MPa for 2-5 min, the starch granule is affected, and more drastic conditions (600 MPa for 30 min) induce starch gelatinization in tubers (Błaszczak et al., 2005; Tribst et al., 2016).

Oey et al. (2016) published a review article focused on the effects of HPP on colour, texture and flavour of fruits and vegetables, the main factors affecting the sensory quality and consumer acceptance of foods. They reported that this technology has the ability of preserving nutritional and sensory properties of fruits and vegetables due to its limited effects on the covalent bonds of compounds related to their colour and flavour. The effects of HPP on fresh tubers were only evaluated in a few studies. Tribst et al. (2016) and Oliveira et al. (2015) have investigated the effect of HPP (at 600 MPa applied for 5 and 30 min), respectively on oxidative enzymes and on physical characteristics of cocoyam, Peruvian carrot and sweet potato. Tribst et al. (2016) found an increase of PPO and POD activity in sweet potato. However, this increase was dependent of the food matrix, *i.e.* in sweet potato puree and cubes, PPO activity increased by up to 468 and 221%, respectively. Considering POD activity, the only matrix where POD activity increased was in sweet potato puree (~ 20%).

On the other hand Oliveira et al. (2015) reported that HPP treatment caused physical damage in the cellular structure of the tubers, evidenced by the presence of starch outside the cells, lack of cellular definition, agglomeration of the starch granules and increase of the granule volume, possibly due to hydration of starch. In addition, water exudation and an increase in syneresis (up to 12%) were also observed, as well as the increasing of the drying rate (~30%) and the reduction of the firmness (up to 60%). The decrease of firmness and stiffness was also observed in other studies, as for instance, by applying 100 MPa for 5 or 10 min (Saraiva and Rodrigues, 2011), and 400 MPa for 15 min (Eshtiaghi and Knorr, 1993).

Furthermore, Sopanangkul et al. (2002) have studied the effect of HPP on the diffusion coefficient of sucrose in potato cylinders and reported that pressure opened up the tissue structure, increased the cell permeability and facilitated the diffusion to a certain extent. Actually, higher pressures (above 400 MPa) also induced starch gelatinization and hindered diffusion. The maximum value of diffusion coefficient was 8-fold higher than the atmospheric pressure value, and the authors highlighted that application of appropriate levels of pressure (100 to 400 MPa) can be used to accelerate mass transfer during ingredient infusion into foods and to reduce processing times.

Other studies have shown that HPP could be used as a nonthermal and chemical-free alternative to control the sprouting of potato tubers. Saraiva and Rodrigues (2011) observed a sprouting inhibition up to 6 weeks at 18 ºC after the application of 100 MPa for 5 and 10 min. Moreover, Alexandre et al. (2016) have studied the effect of short thermal treatments (60 and 65 ºC for 1 min) and low intensity high pressure treatments (15 and 30 MPa for 10 min) on potato sprouting. The most pronounced inhibitory effect on potato tuber sprouting was achieved when treatments were sequentially combined. The induction of PPO activity by pressure and the regulation of sucrose availability due to the control of the co-factor inorganic pyrophosphate (PPi) concentration are two possible explanations provided by the authors of both studies for the inhibitory effects noted on potato sprouting.

6. Final remarks

Potato is the second most important crop for human consumption in Europe and fourth at a global scale, being considered an excellent source of energy, carbohydrates, and dietary fiber. The preservation of the potato tuber quality is crucial for human consumption and processing, as well as to avoid economic losses. Potato tuber diseases, enzymatic discolouration, greening, sprouting and cold sweetening are important aspects that affect potato tuber quality. Besides, potato cooking is an indispensable process before consumption and frying is considered the most common technique used in potato processing. The frying process results in physical, textural, chemical and nutritional changes, of which some are considered desirable food characteristics like the typical texture, colour and flavour, and others are undesirable, namely the destruction of essential amino acids and vitamins, the production of carcinogenic and cytotoxic compounds (such as acrylamide and hydroxymethylfurfural) and the high oil content. Given the large consumption of fried potato products worldwide, it is important to reduce the formation of the undesirable characteristics, without compromising the sensorial qualities.

Several emerging non-thermal technologies have already been applied in the treatment of potatoes, namely irradiation, cold plasma, ultrasounds, pulsed electric field and high pressure processing. These novel non-thermal processing techniques have shown to improve several aspects associated with either the quality of potato tubers and fried potato products, or even improved their processing, such as time and energy for potato slicing and cutting. For these reasons, non-thermal technologies are considered potential alternatives for the potato tubers treatment and as frying pre-treatment to create improved and healthier fried potato products.

7. Acknowledgments

Thanks are due to the University of Aveiro and FCT/MCT for the financial support for the QOPNA research Unit (FCT UID/QUI/00062/2019) through national founds and, where applicable, co-financed by the FEDER, within the PT2020 Partnership Agreement.

8. References

Aguilera, J.M., Cadoche, L., López, C., Gutierrez, G., 2001. Microstructural changes of potato cells and starch granules heated in oil. *Food Res. Int.* 34, 939–947.

Aguilera, J.M., Gloria, H., 1997. Determination of oil in fried potato products by Differential Scanning Calorimetry. *J. Agric. Food Chem*. 45, 781–785.

Aguilera, J.M., Gloria-Hernandez, H., 2000. Oil absorption during frying of frozen parfried potatoes. *J. Food Sci.* 65, 476–479.

Aksenova et al., 2013. Regulation of potato tuber dormancy and sprouting. *Russ. J. Plant Physiol.* 60, 301–312.

Alamar, M.C., Tosetti, R., Landahl, S., Bermejo, A., Terry, L.A., 2017. Assuring potato tuber quality during storage: a future perspective. *Front. Plant Sci.* 8, 1–6.

Alexandre, E.M.C., Rodrigues, I.M., Saraiva, J.A., 2016. Influence of thermal and pressure treatments on inhibition of potato tubers sprouting. *Czech J. Food Sci.* 33, 524–530.

Ali, H.M., El-Gizawy, A.M., El-Bassiouny, R.E.I., Saleh, M.A., 2015. Browning inhibition mechanisms by cysteine, ascorbic acid and citric acid, and identifying PPO-catechol-cysteine reaction products. *J. Food Sci. Technol.* 52, 3651–3659.

Al-Khuseibi, M.K., Sablani, S.S., Perera, C.O., 2005. Comparison of water blanching and high hydrostatic pressure effects on drying kinetics and quality of potato. *Dry. Technol.* 23, 2449–2461.

Amaral, R.D.A., Benedetti, B.C., Pujola, M., Achaerandio, I., Bachelli, M.L.B., 2015. Effect of Ultrasound on quality of fresh-cut potatoes during refrigerated storage. *Food Eng. Rev.* 7, 176–184.

Ammar, J.B., Lanoisellé, J.-L., Lebovka, N.I., Hecke, E.V., Vorobiev, E., 2011. Impact of a Pulsed Electric Field on damage of plant tissues: effects of cell size and tissue electrical conductivity. *J. Food Sci.* 76, E90–E97.

Amrein et al., 2003. Potential of Acrylamide Formation, Sugars, and Free Asparagine in Potatoes: A Comparison of Cultivars and Farming Systems. *J. Agric. Food Chem.* 51, 5556–5560.

Andress, E.L., Delaplane, K.S., Schuler, G.A., 1998. Food irradiation. pp. 1-11.

Anese, M., Manzocco, L., Calligaris, S., Nicoli, M.C., 2013. Industrially applicable strategies for mitigating acrylamide, furan, and 5-hydroxymethylfurfural in Food. *J. Agric. Food Chem*. 61, 10209–10214.

Antunes-Rohling, A., Ciudad-Hidalgo, S., Mir-Bel, J., Raso, J., Cebrián, G., Álvarez, I., 2018. Ultrasound as a pretreatment to reduce acrylamide formation in fried potatoes. *Innov. Food Sci. Emerg. Technol.* 49, 158–169.

Arevalo, P., Ngadi, M.O., Bazhal, M.I., Raghavan, G.S.V., 2004. Impact of Pulsed Electric Fields on the dehydration and physical properties of apple and potato slices. *Dry. Technol*. 22, 1233–1246.

Arslan, M., Xiaobo, Z., Shi, J., Rakha, A., 2018. Oil uptake by potato chips or French fries: a review. *Eur. J. Lipid Sci. Technol.* 120, 1–17.

Arvanitoyannis, I.S., Stratakos, A.C., Tsarouhas, P., 2009. Irradiation applications in vegetables and fruits: a review. *Crit. Rev. Food Sci. Nutr.* 49, 427–462.

Ashley et al., 2004. Health concerns regarding consumption of irradiated food. *Int. J. Hyg. Environ. Health* 207, 493–504.

Avdyukhina et al., 2018. An investigation of the effects of X-Ray treatment on the concentration of reducing sugars in potatos and their sprouting. *Mosc. Univ. Phys. Bull*. 73, 334–338.

Balagiannis et al., 2019. Kinetic modelling of acrylamide formation during the finish-frying of french fries with variable maltose content. *Food Chem*. 284, 236–244.

Balasubramaniam, V.M. (Bala), Martínez-Monteagudo, S.I., Gupta, R., 2015. Principles and application of High Pressure–based technologies in the food industry. *Annu. Rev. Food Sci. Technol*. 6, 435–462.

Barba et al., 2015. Current applications and new opportunities for the use of pulsed electric fields in food science and industry. *Food Res. Int*. 77, 773–798.

Barden, L., Decker, E.A., 2016. Lipid oxidation in low-moisture food: a review. Crit. *Rev. Food Sci. Nutr*. 56, 2467–2482.

Basak, S., Ramaswamy, H.S., 1998. Effect of high pressure processing on the texture of selected fruits and vegetables. *J. Texture Stud*. 29, 587–601.

Basfar, A.A., Mohamed, K.A., Al-Saqer, O.A., 2012. De-contamination of pesticide residues in food by ionizing radiation. *Radiat. Phys. Chem*. 81, 473–478.

Becalski, A., Lau, B.P.-Y., Lewis, D., Seaman, S.W., 2003. Acrylamide in Foods: Occurrence, Sources, and Modeling. *J. Agric. Food Chem*. 51, 802–808.

Belkova et al., 2018. Impact of vacuum frying on quality of potato crisps and frying oil. *Food Chem*. 241, 51–59.

Błaszczak, W., Valverde, S., Fornal, J., 2005. Effect of high pressure on the structure of potato starch. *Carbohydr. Polym*. 59, 377–383.

Blenkinsop, R.W., Yada, R.Y., Marangoni, A.G., 2010. Metabolic control of low-temperature sweetening in potato tubers during postharvest storage, in: Janick, J. (Ed.), Horticultural Reviews. John Wiley & Sons, Inc., Oxford, UK, 317–354.

Botero-Uribe, M., Fitzgerald, M., Gilbert, R.G., Midgley, J., 2017. Effect of pulsed electrical fields on the structural properties that affect french fry texture during processing. *Trends Food Sci. Technol*. 67, 1–11.

Bouchon, P., Aguilera, J.M., 2001. Microstructural analysis of frying potatoes. *Int. J. Food Sci. Technol*. 36, 669–676.

Bouchon, P., Hollins, P., Pearson, M., Pyle, D.L., Tobin, M.J., 2001. Oil Distribution in Fried Potatoes Monitored by Infrared Microspectroscopy. *J. Food Sci*. 66, 918–923.

Bouchon, P.B., Pyle, D.L., 2004. Studying oil absorption in restructured potato chips. *J. Food Sci*. 69, 115–122.

Buléon, A., Colonna, P., Planchot, V., Ball, S., 1998. Starch granules: structure and biosynthesis. *Int. J. Biol. Macromol*. 23, 85–112.

Busch, J.M., 1999. Enzymic browning in potatoes: a simple assay for a polyphenol oxidase catalysed reaction. *Biochem. Educ*. 27, 171–173.

Bußler, S., Ehlbeck, J., Schlüter, O.K., 2017. Pre-drying treatment of plant related tissues using plasma processed air: Impact on enzyme activity and quality attributes of cut apple and potato. *Innov. Food Sci. Emerg. Technol*. 40, 78–86.

Buta, J.G., Moline, H.E., 2001. Prevention of browning of potato slices using polyphenoloxidase inhibitors and organic acids. *J. Food Qual*. 24, 271–282.

Camire, M.E., Kubow, S., Donnelly, D.J., 2009. Potatoes and Human Health. *Crit. Rev. Food Sci. Nutr*. 49, 823–840.

Capuano, E., Fogliano, V., 2011. Acrylamide and 5-hydroxymethylfurfural (HMF): A review on metabolism, toxicity, occurrence in food and mitigation strategies. *LWT - Food Sci. Technol*. 44, 793–810.

Cerda, R., 2017. Assessment of yield and economic losses caused by pests and diseases in a range of management strategies and production situations in coffee agroecosystems. *Agric. Sci. Montpellier SupAgro*, pp. 151.

Chung, K.M., Moon, T.W., Kim, H., Chun, J.K., 2002. Physicochemical properties of sonicated mung bean, potato, and rice starches. *Cereal Chem. J*. 79, 631–633.

CIPC, 2015. Late Blight | AHDB Potatoes [WWW Document]. URL https://potatoes.ahdb.org.uk/media-gallery/detail/13214/2634 (accessed 01.22.2019).

Cipotato, 2018. Potato [WWW Document]. Int. Potato Cent. CIP Potato Facts. URL https://cipotato.org/crops/potato/ (accessed 10.22.2019).

Corsini, D.L., Pavek, J.J., Dean, B., 1992. Differences in free and protein-bound tyrosine among potato genotypes and the relationship to internal blackspot resistance. *Am. Potato J*. 69, 423–435.

Costa, R.M., Oliveira, F.A.R., 1999. Modelling the kinetics of water loss during potato frying with a compartmental dynamic model. *J. Food Eng*. 41, 177–185.

Cousin, J.-F., Desailly, F., Goullieux, A., Pain, J.-P., 2004. Process for treating vegetables and fruit before cooking. US6821540B2.

CSPI, 2003. FDA Urged to Limit Acrylamide in Food [WWW Document]. Cent. Sci. Public Interest. URL https://cspinet.org/new/200306041.html (accessed 01.18.2019).

De Pilli, T., Jouppila, K., Ikonen, J., Kansikas, J., Derossi, A., Severini, C., 2008. Study on formation of starch–lipid complexes during extrusion-cooking of almond flour. *J. Food Eng*. 87, 495–504.

De Wilde et al., 2006. Selection criteria for potato tubers to minimize acrylamide formation during frying. *J. Agric. Food Chem*. 54, 2199–2205.

De Wilde et al., 2005. Influence of storage practices on acrylamide formation during potato frying. *J. Agric. Food Chem*. 53, 6550–6557.

Decker, E.A., Ferruzzi, M.G., 2013. Innovations in food chemistry and processing to enhance the nutrient profile of the white potato in all forms. *Adv. Nutr*. 4, 345S-350S.

Dehghannya, J., Abedpour, L., 2018. Influence of a three stage hybrid ultrasound-osmotic-frying process on production of low-fat fried potato strips: Hybrid process for fried potato strips. *J. Sci. Food Agric*. 98, 1485–1491.

Dey et al., 2016. Cold Plasma Processing: A review. *J. Chem. Pharm. Res*. 9, 1-6.

Elamin, W.M., Endan, J.B., Yosuf, Y.A., Shamsudin, R., Ahmedov, A., 2015. High Pressure Processing technology and equipment evolution: a review. *J. Eng. Sci. Technol. Rev*. 10.

Elson, M.K., Schisler, D.A., Bothast, R.J., 1997. Selection of microorganisms for biological control of silver scurf (*Helminthosporium solani*) of potato tubers. *Plant Dis*. 81, 647–652.

Eshtiaghi, M.N., Knorr, D., 1993. Potato cubes response to water blanching and high hydrostatic pressure. *J. Food Sci*. 58, 1371–1374.

Farahnaky et al., 2018. Effect of ohmic and microwave cooking on some bioactive compounds of kohlrabi, turnip, potato, and radish. *J. Food Meas. Charact*. 12, 2561–2569.

Faridnia, F., Burritt, D.J., Bremer, P.J., Oey, I., 2015. Innovative approach to determine the effect of pulsed electric fields on the microstructure of whole potato tubers: Use of cell viability, microscopic images and ionic leakage measurements. *Food Res. Int*. 77, 556–564.

Fauster et al., 2018. Impact of pulsed electric field (PEF) pretreatment on process performance of industrial French fries production. *J. Food Eng*. 235, 16–22.
Fernie, A.R., Willmitzer, L., 2001. Molecular and biochemical triggers of potato tuber development. *Plant Physiol*. 127, 1459–1465.
Fiers et al., 2012. Potato soil-borne diseases. A review. *Agron. Sustain. Dev*. 32, 93–132.
Fincan, M., Dejmek, P., 2003. Effect of osmotic pretreatment and pulsed electric field on the viscoelastic properties of potato tissue. *J. Food Eng*. 59, 169–175.
Food Drink Europe, 2013. Acrylamide Toolbox. pp. 25-31.
Food, F.C. on H.I. of A. in, Programme, W.H.O.F.S., Organization, W.H., Staff, W.H.O., FAO., WHO, Programme, F.S., 2002. Health Implications of Acrylamide in Food: Report of a Joint FAO/WHO Consultation, WHO Headquarters, Geneva, Switzerland, 25-27 June 2002. World Health Organization.
Friedman, M., 2006. Potato glycoalkaloids and metabolites: roles in the plant and in the diet. *J. Agric. Food Chem*. 54, 8655–8681.
Friedman, M., 1997. Chemistry, biochemistry, and dietary role of potato polyphenols. A review. *J. Agric. Food Chem*. 45, 1523–1540.
Galindo, F.G., Dejmek, P., Lundgren, K., Rasmusson, A.G., Vicente, A., Moritz, T., 2009. Metabolomic evaluation of pulsed electric field-induced stress on potato tissue. *Planta* 230, 469–479.
Galindo, F.G., Wadsö, L., Vicente, A., Dejmek, P., 2008. Exploring Metabolic Responses of Potato Tissue Induced by Electric Pulses. *Food Biophys*. 3, 352–360.
García-Alonso, A., Goñi, I., 2000. Effect of processing on potato starch: In vitro availability and glycaemic index. *Nahrung/Food* 44, 19–22.
Gavahian, M., Chu, Y.-H., Mousavi Khaneghah, A., Barba, F.J., Misra, N.N., 2018a. A critical analysis of the cold plasma induced lipid oxidation in foods. *Trends Food Sci. Technol*. 77, 32–41.
Gavahian, M., Chu, Y.-H., Sastry, S., 2018b. Extraction from Food and Natural Products by Moderate Electric Field: Mechanisms, Benefits, and Potential Industrial Applications. *Compr. Rev. Food Sci. Food Saf*. 17, 1040–1052.

Gertz, C., 2014. Fundamentals of the frying process. *Eur. J. Lipid Sci. Technol*. 116, 669–674.
Granda, C., Moreira, R.G., 2005. Kinetics of acrylamide formation during traditional and vacuum frying of potato chips. *J. Food Process Eng*. 28, 478–493.
Grunenfelder, L., 2005. Physiological studies of light-induced greening in fresh market potatoes (M.S. Thesis). Washington State University, Pullman. pp. 1-114.
Gull, D.D., Isenberg, F.M.R., 1958. Light burn and off-flavour development in potato tubers exposed to fluorescent lights. *Proc. Am. Soc. Hortic. Sci*. 71, 446–454.
Halford et al., 2012. Concentrations of free amino acids and sugars in nine potato varieties: effects of storage and relationship with acrylamide formation. *J. Agric. Food Chem*. 60, 12044–12055.

Han, Z., Zeng, X.A., Yu, S.J., Zhang, B.S., Chen, X.D., 2009. Effects of pulsed electric fields (PEF) treatment on physicochemical properties of potato starch. *Innov. Food Sci. Emerg. Technol*. 10, 481–485.

Hijmans, R.J., Forbes, G.A., Walker, T.S., 2000. Estimating the global severity of potato late blight with GIS-linked disease forecast models. *Plant Pathol*. 49, 697–705.

Hill, L.M., Reimholz, R., Schroder, R., Nielsen, T.H., Stitt, M., 1996. The onset of sucrose accumulation in cold-stored potato tubers is caused by an increased rate of sucrose synthesis and coincides with low levels of hexose-phosphates, an activation of sucrose phosphate synthase and the appearance of a new form of amylase. *Plant Cell Environ*. 19, 1223–1237.

Huang, H.-W., Wu, S.-J., Lu, J.-K., Shyu, Y.-T., Wang, C.-Y., 2017. Current status and future trends of high-pressure processing in food industry. *Food Control* 72, 1–8.

IARC, 1994. Monographs on the evaluation of carcinogenic risks to humans: some industrial chemicals. *Int. Agency Res. Cancer Lyon Fr*. 60, 389–433.

Ignat, A., Manzocco, L., Brunton, N.P., Nicoli, M.C., Lyng, J.G., 2015. The effect of pulsed electric field pre-treatments prior to deep-fat frying on quality aspects of potato fries. *Innov. Food Sci. Emerg. Technol*. 29, 65–69.

Jaeger, H., Janositz, A., Knorr, D., 2010. The Maillard reaction and its control during food processing. The potential of emerging technologies. *Pathol. Biol*. 58, 207–213.

Janositz, A., Noack, A.-K., Knorr, D., 2011. Pulsed electric fields and their impact on the diffusion characteristics of potato slices. *LWT - Food Sci. Technol*. 44, 1939–1945.

Kalum, L., Hendriksen, H.V., 2016. Process for treating vegetable material with an Enzyme. US20160100612A1.

Karasev, A.V., Gray, S.M., 2013. Continuous and emerging challenges of *Potato virus Y* in potato. *Annu. Rev. Phytopathol*. 51, 571–586.

Karizaki, V.M., Sahin, S., Sumnu, G., Mosavian, M.T.H., Luca, A., 2013. Effect of ultrasound-assisted osmotic dehydration as a pretreatment on deep fat frying of potatoes. *Food Bioprocess Technol*. 6, 3554–3563.

Katopo, H., Song, Y., Jane, J., 2002. Effect and mechanism of ultrahigh hydrostatic pressure on the structure and properties of starches. *Carbohydr. Polym*. 47, 233–244.

Lea, P.J., Sodek, L., Parry, M.A.J., Shewry, P.R., Halford, N.G., 2006. Asparagine in plants. *Ann. Appl. Biol*. 150, 1–26.

Lebovka, N.I., Praporscic, I., Ghnimi, S., Vorobiev, E., 2005. Does electroporation occur during the ohmic heating of food? *J. Food Sci.* 70, E308–E311.

Lebovka, N.I., Shynkaryk, N.V., Vorobiev, E., 2007. Pulsed electric field enhanced drying of potato tissue. *J. Food Eng*. 78, 606–613.

Lees, A.K., Hilton, A.J., 2003. Black dot (*Colletotrichum coccodes*): an increasingly important disease of potato. *Plant Pathol*. 52, 3–12.

Lees, A.K., Sullivan, L., Cullen, D.W., 2009. A quantitative Polymerase Chain Reaction assay for the detection of *Polyscytalum pustulans*, the cause of skin spot disease of potato. *J. Phytopathol*. 157, 154–158.

Lindgren, M., 2006. Device for electroporation of potatoes and potato products. EP2941968A1.

Lisińska, G., Peksa, A., Kita, A., Rytel, E., Tajner-Czopek, A., 2009. The quality of potato for processing and consumption. *Glob. Sci. Books Food* 3, 99–104.

Liu, C., Grimi, N., Lebovka, N., Vorobiev, E., 2018. Effects of preliminary treatment by pulsed electric fields and convective air-drying on characteristics of fried potato. *Innov. Food Sci. Emerg. Technol*. 47, 454–460.

Mani, F., Bettaieb, T., Doudech, N., Hannachi, C., 2014. Physiological mechanisms for potato dormancy release and sprouting: a review. *Afr. Crop Sci. J*. 22, 155–174.

Mason, T.J., Riera, E., Vercet, A., Lopez-Buesa, P., 2005. Application of Ultrasound, in: Emerging Technologies for Food Processing. Elsevier, pp. 323–351.

May, B.K., Perré, P., 2002. The importance of considering exchange surface area reduction to exhibit a constant drying flux period in foodstuffs. *J. Food Eng*. 54, 271–282.

Meng, S., Ma, Y., Cui, J., Sun, D.-W., 2014. Preparation of corn starch–fatty acid complexes by high-pressure homogenization. *Starch - Stärke* 66, 809–817.

Meyhuay, M., 2001. POTATO: Post-harvest Operations. Post-harvest Compendium.

Miranda, M.L., Aguilera, J.M., 2006. Structure and texture properties of fried potato products. *Food Rev. Int*. 22, 173–201.

Mordor Intelligence, 2016. Potato Market Outlook | Analysis | Report (2018 - 2023) [WWW Document]. URL https://www.mordorintelligence.com/industry-reports/potato-market (accessed 12.19.18).

Moreau, M., Feuilloley, M.G.J., Veron, W., Meylheuc, T., Chevalier, S., Brisset, J.-L., Orange, N., 2007. Gliding arc discharge in the potato pathogen Erwinia carotovora subsp. atroseptica: mechanism of lethal action and effect on membrane-associated molecules. *Appl. Environ. Microbiol*. 73, 5904–5910.

Moreira, R.G., Castell-Perez, M.E., Barrufet, M., 1999. Deep fat frying: fundamentals and applications, 1st ed. Springer US, 1-350.

National Potato Council, 2018. National Potato Council: Potato Facts [WWW Document]. Statistics. URL https://www.nationalpotatocouncil.org/potato-facts/ (accessed 02.01.2019).

Nema, P.K., Ramayya, N., Duncan, E., Niranjan, K., 2008. Potato glycoalkaloids: formation and strategies for mitigation. *J. Sci. Food Agric*. 88, 1869–1881.

Nielsen, T.H., Deiting, U., Stitt, M., 1997. A β-amylase in potato tubers is induced by storage at low temperature. *Plant Physiol*. 113, 503–510.

Niki, E., 2009. Lipid peroxidation: Physiological levels and dual biological effects. *Free Radic. Biol. Med*. 47, 469–484.

Nourian, F., Kushalappa, A.C., Ramaswamy, H.S., 2002. Physical, physiological and chemical changes in potato as influenced by *Erwinia carotovora* infection. *J. Food Process. Preserv*. 26, 339–359.

Novozymes, 2017. Reduce acrylamide by up to 95% | Novozymes Acrylaway® [WWW Document]. URL http://www.novozymes.com/en/advance-your-business/food-and-beverage/baking/acrylaway (accessed 10.12.18).

O'Connor, C.J., Fisk, K.J., Smith, B.G., Melton, L.D., 2001. Fat uptake in French fries as affected by different potato varieties and processing. J. Food Sci. 66, 903–908.

Oerke, E.-C., 2006. Crop losses to pests. *J. Agric. Sci*. 144, 31–43.

Oey, I., Faridnia, F., Leong, S.Y., Burritt, D.J., Liu, T., 2016. Determination of Pulsed Electric Fields effects on the structure of potato tubers, in: Miklavcic, D. (Ed.), Handbook of Electroporation. Springer International Publishing, Cham, pp. 1–19.

Oliveira, M.M. de, Tribst, A.A.L., Leite Júnior, B.R. de C., Oliveira, R.A. de, Cristianini, M., 2015. Effects of high pressure processing on cocoyam, Peruvian carrot, and sweet potato: changes in microstructure, physical characteristics, starch, and drying rate. *Innov. Food Sci. Emerg. Technol*. 31, 45–53.
Oord, G.V., Roelofs, J.T.M., 2016. Low field strength PEF cooking. WO2016008868A1.
Ozuna, C., Cárcel, J.A., García‐Pérez, J.V., Mulet, A., 2011. Improvement of water transport mechanisms during potato drying by applying ultrasound. *J. Sci. Food Agric*. 91, 2511–2517.
Parker, J.K., Balagiannis, D.P., Higley, J., Smith, G., Wedzicha, B.L., Mottram, D.S., 2012. Kinetic model for the formation of acrylamide during the finish-frying of commercial French fries. *J. Agric. Food Chem*. 60, 9321–9331.
Pavlista, A.D., 2001. Green Potatoes: the problems and the solution. pp. 1-5.
Pedreschi, F., Kaack, K., Granby, K., 2008. The effect of asparaginase on acrylamide formation in French fries. *Food Chem*. 109, 386–392.
Pereira, R.N., Galindo, F.G., Vicente, A.A., Dejmek, P., 2009. Effects of Pulsed Electric Field on the viscoelastic properties of potato tissue. *Food Biophys*. 4, 229–239.
Pereira et al., 2016. Effects of ohmic heating on extraction of food-grade phytochemicals from colored potato. *LWT* 74, 493–503.
Pérez, S., Baldwin, P.M., Gallant, D.J., 2009. Structural Features of Starch Granules I, in: Starch: Chemistry and Technology. Roy Whistler Editor, pp. 149–192.
Pérombelon, M.C.M., 2002. Potato diseases caused by soft rot erwinias: an overview of pathogenesis. *Plant Pathol*. 1–12.
Petersson, E.V., Arif, U., Schulzova, V., Krtková, V., Hajšlová, J., 2013. Glycoalkaloid and Calystegine levels in table potato cultivars subjected to wounding, light, and heat treatments. *J. Agric. Food Chem*. 61, 5893–5902.
Powers, S.J., Mottram, D.S., Curtis, A., Halford, N.G., 2013. Acrylamide concentrations in potato crisps in Europe from 2002 to 2011. *Food Addit. Contam*. Part A 30, 1493–1500.
Puértolas, E., Barba, F.J., 2016. Electrotechnologies applied to valorization of by-products from food industry: main findings, energy and economic cost of their industrialization. *Food Bioprod. Process*. 100, 172–184.
Puértolas, E., Koubaa, M., Barba, F.J., 2016. An overview of the impact of electrotechnologies for the recovery of oil and high-value compounds from vegetable oil industry: energy and economic cost implications. *Food Res. Int*. 80, 19–26.
Qi et al., 2018. Reduction of 5-hydroxymethylfurfural formation by flavan-3-ols in Maillard reaction models and fried potato chips. *J. Sci. Food Agric*. 98, 5294–5301.
Quan, X., Zhang, M., Zhang, W., Adhikari, B., 2014. Effect of Microwave-Assisted Vacuum Frying on the Quality of Potato Chips. *Dry. Technol*. 32, 1812–1819.
Queiroz, C., Mendes Lopes, M.L., Fialho, E., Valente-Mesquita, V.L., 2008. Polyphenol oxidase: characteristics and mechanisms of browning control. *Food Rev. Int*. 24, 361–375.
Rezaee, M., Almassi, M., Minaei, S., Paknejad, F., 2013. Impact of post-harvest radiation treatment timing on shelf life and quality characteristics of potatoes. *J. Food Sci. Technol*. 50, 339–345.

Rocha, A.M.C.N., Coulon, E.C., Morais, A.M.M.B., 2003. Effects of vacuum packaging on the physical quality of minimally processed potatoes. *Food Serv. Technol*. 3, 81–88.

Romancer, M.L., Kerlan, C., Nedellec†, M., 1994. Biological characterisation of various geographical isolates of *potato virus Y* inducing superficial necrosis on potato tubers. *Plant Pathol*. 43, 138–144.

Rutledge, D.N., Rene, F., Hills, B.P., Foucat, L., 1994. Magnetic resonance imaging studies of the freeze-drying kinetics of potato. *J. Food Process Eng*. 17, 325–352.

Sánchez-Vega, R., Elez-Martínez, P., Martín-Belloso, O., 2015. Influence of high-intensity pulsed electric field processing parameters on antioxidant compounds of broccoli juice. *Innov. Food Sci. Emerg*. Technol. 29, 70–77.

Santos, C.S.P., Cunha, S.C., Casal, S., 2018. Domestic low-fat “frying” alternatives: Impact on potatoes composition. *Food Sci. Nutr*. 6, 1519–1526.

Santos, C.S.P., Cunha, S.C., Casal, S., 2017. Deep or air frying? A comparative study with different vegetable oils. *Eur. J. Lipid Sci. Technol*. 119, 1600375.

Saraiva, J.A., Rodrigues, I.M., 2011. Inhibition of potato tuber sprouting by pressure treatments: Potato sprouting inhibition by pressure. *Int. J. Food Sci*. Technol. 46, 61–66.

Schössler, K., Thomas, T., Knorr, D., 2012. Modification of cell structure and mass transfer in potato tissue by contact ultrasound. *Food Res. Int*. 49, 425–431.

Schwimmer, S., Weston, W.J., 1958. Chlorophyll formation in potato tubers as influenced by gamma irradiation and by chemicals. *Am. Potato J*. 35, 534–542.

Sensoy, I., Sastry, S.K., 2004. Extraction using Moderate Electric Fields. *J. Food Sci*. 69, FEP7–FEP13.

Shahidi, F., Zhong, Y., 2010. Lipid oxidation and improving the oxidative stability. *Chem. Soc. Rev*. 39, 4067.

Singh, J., Kaur, L., 2016. Advances in Potato Chemistry and Technology, 2nd ed. Elsevier. pp. 1-740.

Soares, I.G.M., Silva, E.B., Amaral, A.J., Machado, E.C.L., Silva, J.M., 2016. Physico-chemical and sensory evaluation of potato (*Solanum tuberosum L.*) after irradiation. A*n. Acad. Bras. Ciênc*. 88, 941–950.

Sopanangkul, A., Ledward, D.A., Niranjan, K., 2002. Mass transfer during sucrose infusion into potatoes under high pressure. *J. Food Sci*. 67, 2217–2220.

Sorce, C., Lorenzi, R., Parisi, B., Ranalli, P., 2005. Physiological mechanisms involved in potato (*Solanum tuberosum*) tuber dormancy and the control of sprouting by chemical suppressants. *Acta Hortic*. 177–186.

Sowokinos, J., 1990. Stress-induced alterations in carbohydrate metabolism. *Mol. Cell*. Biol. Potato 137–158.

Sowokinos, J.R., 2007. Chapter 23: Internal physiological disorders, nutritional and compositional factors., in: Potato Biology and Biotechnology: Advances and Perspectives. Elsevier, Amsterdam, pp. 501–523.

Statista, 2018. Organic food sales growth in the U.S., 2017 [WWW Document]. Stat. Portal. URL https://www.statista.com/statistics/196962/organic-food-sales-growth-in-the-us-since-2000/ (accessed 01.23.2019).

Stute, R., Heilbronn, Klingler, R.W., Boguslawski, S., Eshtiaghi, M.N., Knorr, D., 1996. Effects of High Pressures treatment on starches. *Starch - Starke* 48, 399–408.

Su, Y., Zhang, M., Zhang, W., 2016. Effect of low temperature on the microwave-assisted vacuum frying of potato chips. *Dry. Technol*. 34, 227–234.

Su, Y., Zhang, M., Zhang, W., Liu, C., Adhikari, B., 2018b. Ultrasonic microwave-assisted vacuum frying technique as a novel frying method for potato chips at low frying temperature. *Food Bioprod. Process*. 108, 95–104.

Su, Y., Zhang, M., Zhang, W., Liu, C., Bhandari, B., 2018a. Low oil content potato chips produced by infrared vacuum pre-drying and microwave-assisted vacuum frying. *Dry. Technol*. 36, 294–306.

Suttle, J.C., 2004. Physiological regulation of potato tuber dormancy. *Am. J. Potato Res*. 81, 253–262.

Tanios, S., Eyles, A., Tegg, R., Wilson, C., 2018. Potato tuber greening: a review of predisposing factors, management and future challenges. *Am. J. Potato Res*. 95, 248–257.

Thanatuksorn, P., Pradistsuwana, C., Jantawat, P., Suzuki, T., 2005. Oil absorption and drying in the deep-fat frying process of wheat flour-water misture, from batter to dough. *Jpn. J. Food Engeneering* 143–148.

Tian at al., 2016. Domestic cooking methods affect the phytochemical composition and antioxidant activity of purple-fleshed potatoes. *Food Chem*. 197, 1264–1270.

Tribst, A.A.L., Leite Júnior, B.R. de C., de Oliveira, M.M., Cristianini, M., 2016. High pressure processing of cocoyam, Peruvian carrot and sweet potato: effect on oxidative enzymes and impact in the tuber color. *Innov. Food Sci. Emerg. Technol*. 34, 302–309.

Troncoso, E., Zúñiga, R., Ramírez, C., Parada, J., Germain, J.C., 2009. Microstructure of potato products: effect on physico-chemical properties and nutrient bioavailability. *Glob. Sci. Books* 3, 41–54.

Ufheil, G., Escher, F., 1996. Dynamics of oil uptake during deep-fat frying of potato slices. *LWT - Food Sci. Technol*. 29, 640–644.

UKRI, 2018. 16AGRITECHCAT5: Strategies to reduce waste due to greening in potato tubers [WWW Document]. URL https://gtr.ukri.org/projects?ref=BB%2FP004903%2F1 (accessed 01.22.2019).

USDA, 2011. United States Standards for Grades of Potatoes. pp. 1-14.

USDA, 2018. Food Composition Databases Show Foods -- McDONALD'S, french fries [WWW Document]. Natl. Nutr. Database Stand. Ref. Leg. Release. URL https://ndb.nal.usda.gov/ndb/foods/show?ndbno=21249&fg=21&man=&lfacet=&format=Abridged&count=&max=25&offset=0&sort=f&qlookup=&rptfrm=nl&nutrient1=213&nutrient2=&nutrient3=&subset=0&totCount=236&measureby=m (accessed 11.9.18).

USDA, ARS, 2018. Food Composition Databases - Potatoes, flesh and skin, raw [WWW Document]. Natl. Nutr. Database Stand. Ref. Leg. Release. URL https://ndb.nal.usda.gov/ndb/foods/show/11352 (accessed 02.01.2019).

van Eck, H.J., 2007. 6.5 Tuber Quality Traits, in: Potato Biology and Biotechnology - Advances and Perspectives. Dick Vreugdenhil, Netherlands, pp. 104–115.

Wambura, P., Yang, W., 2011. Influence of power ultrasound on oxidative rancidity of potato chips: oxidative rancidity of potato chips. *J. Food Process Eng*. 34, 1046–1052.

Wang, N., Brennan, J.G., 1995. Changes in structure, density and porosity of potato during dehydration. *J. Food Eng*. 24, 61–76.

Wang, Y., Zhao, P., Zhou, S., Li, J., He, H., Song, Q., 2011. Enzymatic browning and its control during potato pulp powder processing. Presented at *the 2011 International Conference on New Technology of Agricultural Engineering (ICAE)*, IEEE, Zibo, China, pp. 869–873.

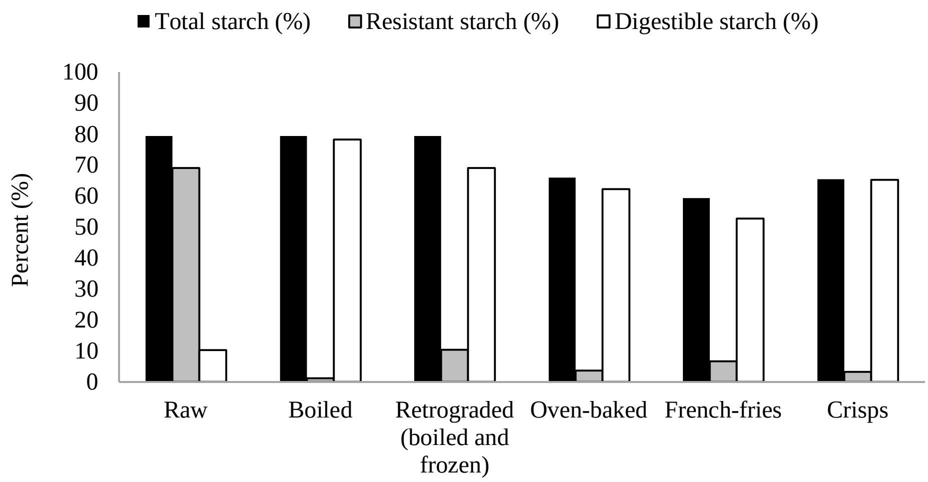
Weiner, J.J., Peterson, F.C., Volkman, B.F., Cutler, S.R., 2010. Structural and functional insights into core ABA signaling. *Curr. Opin. Plant Biol*. 13, 495–502.

Yee, N.G., Bussell, W.T., 2007. Good potatoes for good potato crisps, a review of current potato crisp quality control and manufacture. *Glob. Sci. Books* 1, 271–286.

Yildiz, G., 2019. Control of enzymatic browning in potato with calcium chloride and ascorbic acid coatings. *Food Health* 5, 121–127.

Zhu, J., Li, L., Chen, L., Li, X., 2012. Study on supramolecular structural changes of ultrasonic treated potato starch granules. *Food Hydrocoll*. 29, 116–122.

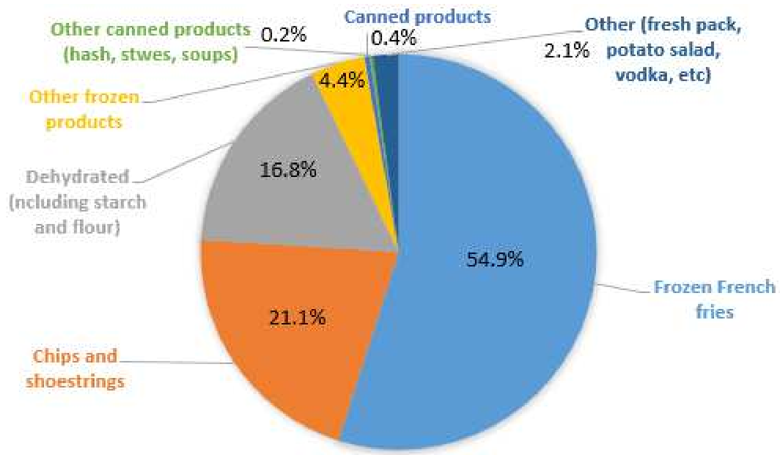
Ziaiifar, A.M., Achir, N., Courtois, F., Trezzani, I., Trystram, G., 2008. Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process. *Int. J. Food Sci. Technol*. 43, 1410–1423.



1185

1186 Figure 1 - Impact of processing on total, resistant and digestible starch in potatoes. Values taken from
1187 García-Alonso and Goñi (2000).

1188



1189

1190 Figure 2 - Different products and applications of processed potatoes. Values taken from National Potato
1191 Council (2018).

1192

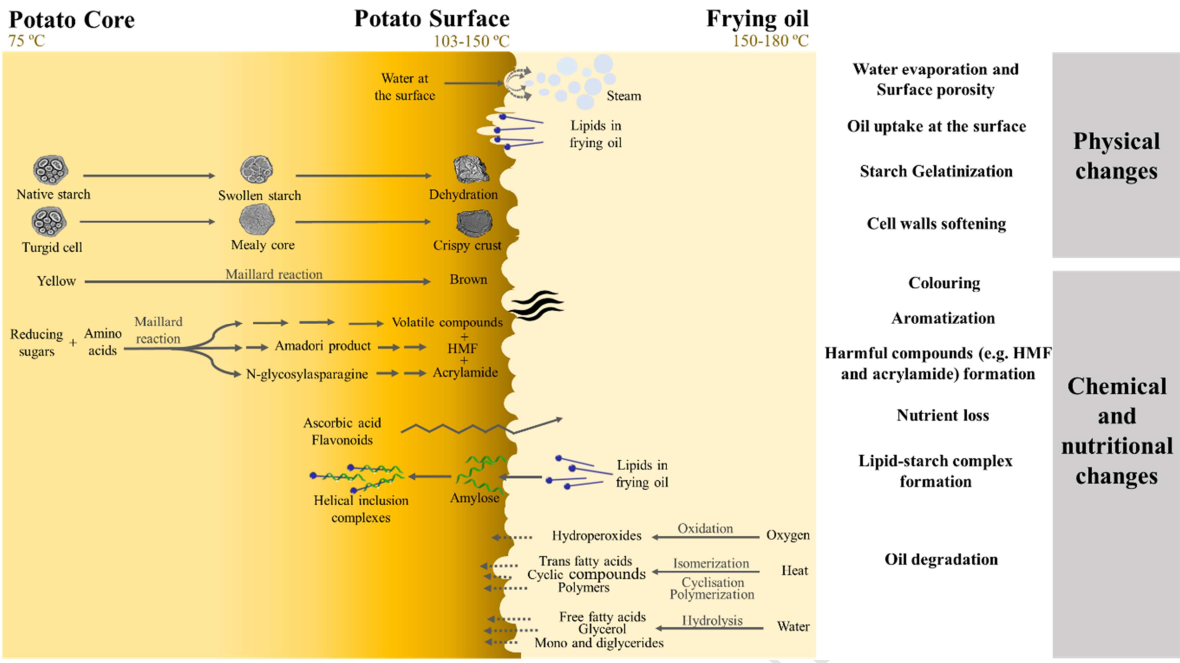


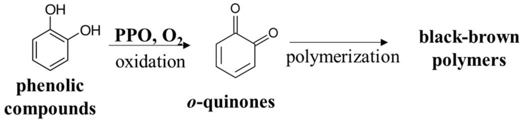
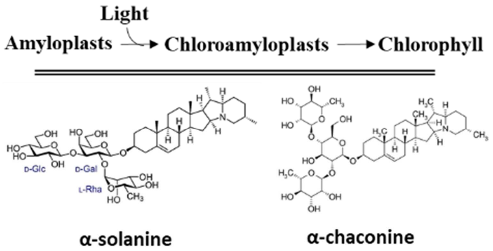
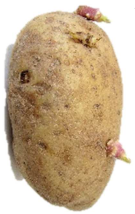
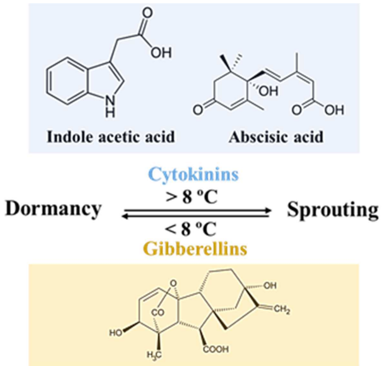
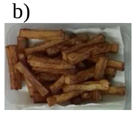
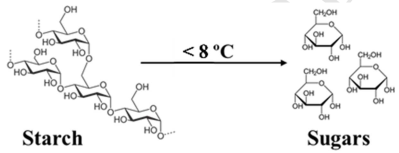
Figure 3 - Physical, chemical and nutritional changes induced by potato frying.

Table 1 - Nutritional composition of raw potato tubers and French fries produced by McDonald's company, per 100g of edible portion. Values taken from USDA and ARS (2018) and USDA (2018), respectively.

Nutrient	**Raw potato tuber (value per 100g)**	**French fries (value per 100g)**
Water (g)	79.25	36.63
Carbohydrates (g)	17.46	323
Sugars, total (g)	0.82	3.41
Fibre, total dietary (g)	2.1	15.47
Protein (g)	2.05	42.58
Lipid (g)	0.09	3.9
Sugars, total (g)	0.82	0.21
Minerals		
Potassium (mg)	425	19
Phosphorus (mg)	57	0.80
Magnesium (mg)	23	37
Calcium (mg)	12	127
Iron (mg)	0.81	596
Sodium (mg)	6	189
Zinc (mg)	0.30	0.51
Vitamins		
Vitamin C, total ascorbic acid (mg)	19.7	5.6
Thiamin (mg)	0.081	0.180
Riboflavin (mg)	0.032	0.037
Niacin (mg)	1.061	3.220
Vitamin B-6 (mg)	0.298	0.380
Folate (µg)	15	-
Vitamin A (IU)	2	0
Vitamin E (α-tocopherol)	0.01	1.38
Vitamin K (µg)	2.0	16.0
Lipids		
Fatty acids, total saturated (g)	0.025	2.271
Fatty acids, total monounsaturated (g)	0.002	7.379
Fatty acids, total polyunsaturated (g)	0.042	4.727
Fatty acids, total trans (g)	0.000	0.064

Table 2 - Some events affecting the potato tuber quality (potato diseases, enzymatic discolouration, greening, sprouting and cold sweetening), their biological or biochemical causes, and the traditional control strategies applied and novel non-thermal technologies that may be used as alternative treatment.

	Events affecting potato tuber quality (Lisińska et al., 2009; Meyhuay, 2001)	**Biological/ biochemical causes**	**Traditional control strategies**	**Novel non-thermal technologies alternatives**
Potato diseases	**Black dot**	The fungus *Colletotrichum coccodes*		-
	 [1] **Silver scurf**	The fungus *Helminthosporium solani*	Dry and cool conditions during potato tuber storage (Fiers et al., 2012)	-
	 [2] **Skin spot**	The fungus *Polyscytalum pustulans*		-
	 [1] **Late blight**	The oomycete pathogen *Phytophthora infestans*	Chemical fungicides (CIPC, 2015; Hijmans et al., 2000)	-
	 [1] **Blackleg (stem rot) and soft rot**	Gram-negative bacteria, *Erwinia carotovora spp. carotovora* (Ecc), *E. carotovora spp. atroseptica* (Eca) and *E. chrysanthemi* (Ech)	-	Cold plasma (Moreau et al., 2007)
	 [1] **Potato tuber necrotic ringspot**	The *Potato virus Y*	-	-

Enzymatic discolouration	 1		Use of citric, acetic, malic and ascorbic acids; Vacuum packaging of cut food; PPO inhibitors (Ali et al., 2015; Buta and Moline, 2001; Rocha et al., 2003; Wang et al., 2011).	Cold Plasma (Bußler et al., 2017); Ultrasound (Amaral et al., 2015).
Greening	 1		Minimizing light exposure during potato handling and storage; Low-oxygen storage; Edible oil coatings; Chemical treatments (Nema et al., 2008; Pavlista, 2001; Tanios et al., 2018).	Irradiation (Gull and Isenberg, 1958; Schwimmer and Weston, 1958).
Sprouting	 1		Storage at low temperatures (<8 ºC); Chemical sprouting inhibitors (such as, chlorpropham) (Sorce et al., 2005).	Irradiation (Avdyukhina et al., 2018; Rezaee et al., 2013; Soares et al., 2016); High Pressure Processing (Alexandre et al., 2016; Saraiva and Rodrigues, 2011).
Cold Sweetening	a)  b)  Fried potatoes using potato tubers stored at: a) ~20 ºC b) 4 ºC		Potato storage at 8-10 ºC (De Wilde et al., 2005; Halford et al., 2012)	Irradiation (Avdyukhina et al., 2018; Rezaee et al., 2013); Ultrasound (Antunes-Rohling et al., 2018); Pulsed Electric Field (Ignat et al., 2015).

- No information available.
1 - Images taken from Wikipedia, accessed 01.02.2019
2 - Images taken from WikiGardener, accessed 01.02.2019

Table 3 - Effect of non-thermal technologies on several quality parameters important for potato tuber quality.

Method	Experimental conditions	Evaluated parameters of potato tuber quality										Reference
		Potato diseases	Greening	Potato Sprouting	Weight loss	Reducing sugar content	Ascorbic acid content	Oxidative browning	Drying process	Texture	Diffusion process	
Irradiation	0.05 kGy dose	-	↓ 62%	-	-	-	-	-	-	-	-	Schwimmer and Weston (1958)
	0.15 kGy dose		↓ 67%									
	0.50 kGy dose		↓ 75%									
	0.250 kGy dose		↓ 80%									
	0.4 kGy dose	-	↓ 50%	-	-	-	-	-	-	-	-	Gull and Isenberg (1958)
	50 Gy at 10^{th}, 30^{th} and 50^{th} day after harvest	-	-	Inhibition (earlier treatment, higher inhibition)	↓ 7.6% at 10^{th} day ↓ 9.5% at 30^{th} day ↓ 12.5% at 50^{th} day	↑ 57.1% at 10^{th} day ↑ 40.6% at 50^{th} day	↓	-	-	-	-	Rezaee et al. (2013)
	100 Gy at 10^{th}, 30^{th} and 50^{th} day after harvest					↑ 10.2% at 10^{th} day ↑ 28.5% at 50^{th} day	↓ 24.8% at 10^{th} day ↓ 8.5% at 50^{th} day					
	0.10 and 0.15 kGy doses	-	-	↓	-	-	-	-	-	-	-	Soares et al. (2016)
	0.20 kGy dose			inhibition								
	X-ray treatment with 15, 20 and 30 Gy after 2, 3 and 4 months of storage, respectively	-	-	inhibition	-	↑	-	-	-	-	-	Avdyukhina et al. (2018)
Cold plasma	Pre-drying treatment with plasma processed air for 10 min	-	-	-	-	-	-	↓ 77% of PPO activity ↓ 89% of POD activity	-	-	-	Bußler et al. (2017)

	Plasma treatment generated by gliding arc discharge	*Erwinia* spp. inactivation	-	-	-	-	-	-	-	-	-	Moreau et al. (2007)
Ultrasound	Treatment with ultrasonic power of 0-37 kW.m-3	-	-	-	-	-	-	-	↑ water transport mechanisms ↑ Drying kinetics	-	-	Ozuna et al. (2011)
	Sonication treatment of 40kHz, 200 W for 5 min	-	-	-	-	-	-	↓ 50% of PPO activity	-	-	-	Amaral et al. (2015)
	US at 28-40 kHz	-	-	-	-	-	-	-	↑ water removal ↓ 10.3% drying time	-	-	Schössler et al. (2012)
Pulsed Electric Field	1-500 pulses for 2-500 µs at 0.2-10 kV/cm of electric field (European patent)	-	-	-	-	-	-	-	-	-	↑ rate of mass transfer	Lindgren (2015)
	1.5 – 5.0 kV/cm of electric field and 20-40 pulses of 100-400 µs	-	-	-	-	-	-	-	↑ water loss during drying	-	-	Janositz et al. (2011)
	0.75-1.5 kV/cm of electric field and up to 120 pulses of 100 and 300 µs	-	-	-	-	-	-	-	-	-	↑ 40% of diffusion coefficients	Arevalo et al. (2004)
High Pressure Processing	400 MPa applied for 15 min	-	-	-	-	-	-	-	↑ drying rate	-	-	Al-Khuseibi et al. (2005)

	600 MPa applied for 5 and 30 min	-	-	-	-	-	-	-	↑ 30% of drying rate	↑ water exudation ↑ 12% of syneresis ↓ 60% of firmness Damage in the cellular structure	-	Oliveira et al. (2015)
	600 MPa applied for 5 and 30 min	-	-	-	-	-	-	↑ 148% - 468% of PPO activity ↑ 20% of POD activity	-	-	-	Tribst et al. (2016)
	400 MPa applied for 15 min	-	-	-	-	-	-	-	-	Changes in tissue structure ↑ cell permeability	↑ mass transfer ↑ 8-fold of diffusion coefficient	Eshtiaghi and Knorr (1993)
	100 MPa applied for 5 and 10 min	-	-	Inhibition up to 6 weeks	-	-	-	-	-	-	-	Saraiva and Rodrigues (2011)
	Short thermal treatment (60 and 65 ºC for 1 min) + Low intensity HP treatment (15 and 30 MPa for 10 min)	-	-	Inhibition	-	-	-	-	-	-	-	Alexandre et al. (2016)

- No information available.

Table 4 - Effect of non-thermal technologies, as a frying pre-treatment, on several quality parameters important for the quality of fried potato products.

Method	Experimental conditions	Effects on processing		Effects on parameters related to the quality of fried potato products							Reference
		Frying or cooking process	Cutting process	Changes in cell microstructure	Moisture of potato strips	Texture of potato strips	Asparagine and reducing sugars content in raw potato	Extraction of reducing sugars from raw potato	Oil content of fries	Acrylamide content in fries	
Ultrasound	40kHz, 200 W for 1, 5 and 10 min	-	-	Cell damage with 10 min of treatment	-	More uniform firmness	-	-	-	-	Amaral et al. (2015)
	Pre-frying treatment in water (30 and 42 ºC) for 30 min; 35 and 130 kHz of frequency; 9.5, 47.6 and 95.2 W/Kg of ultrasonic power density	-	-	-	↑ ultrasonic power density → ↓ Moisture gain	-	-	↑ 17-52%	-	↓ 83%	Antunes-Rohling et al. (2018)
	US at 28-40 kHz for 15 min + Osmotic dehydration using osmotic solutions with 2-4% NaCl concentration for 180 min	-	-	-	-	-	-	-	↓ 40-50%	-	Dehghannya and Abedpour (2018)
	US at 20 kHz for 10-30 min + Osmotic dehydration using osmotic solutions with 15% salt and 15% salt/50% sugar *w/w* concentration for 10-90 min	-	-	-	-	-	-	-	↓ 12.5%	-	Karizaki et al. (2013)

Pulsed Electric Fields (PEF)	18.9 kJ/Kg, 9000 pulses at 0.75 kV/cm or 810 pulses at 2.50 kV/cm of electric field	-	-	-	↑	↓ firmness ↓ 35% energy for cutting	-	↑	↓	-	Ignat et al. (2015)
	100 pulses at 600 V/cm of electric field	↓ frying time	-	-	-	-	-	-	↓	-	Liu et al. (2018)
	1.0 kV/cm of electric field	↓ energy for processing	↓ energy for cutting	↑ cell permeabilization ↓ cell turgor pressure	-	↓ firmness ↑ smoothing of surface ↓ feathering	-	-	↓	-	Fauster et al. (2018)
	0.2 – 10 kV/cm of electric field + treatment with asparaginase and oxireductase (U.S. patent number US20160100612A1)	-	-	-	-	-	↓	-	-	↓	Kalum and Hendriksen (2016)
	PEF treatment of 45-65 V/cm of electric field for 3-5 s (U.S. patent)	-	↓ energy for cutting	-	-	-	-	-	-	-	Cousin et al. (2004)
	PEF treatment of 1-2000000 pulses at 10-180 V/cm of electric field (international patent)	↓ energy for cooking	-	-	-	-	-	-	-	-	Oord and Roelofs (2016)
	PEF treatment of 1.5 – 5.0 kV/cm and 20-40 pulses of 100-400 µs						↓ ~ 1/3 fructose ↓ ~ 1/2 glucose	↑	↓ 38% oil		Janositz et al. (2011)

- No information available.

Highlights

- Factors affecting the potato tuber quality for consumption and processing are presented.
- Potato tuber quality is affected by diseases, greening, sprouting, oxidative browning, and cold sweetening.
- Irradiation, cold plasma, ultrasound, PEF and HPP can improve potato tuber quality.
- The textural, chemical and nutritional changes induced by frying are described.
- Ultrasound and PEF (prior to frying) decrease reducing sugars, oil and acrylamide content in fried potatoes.