

# A Review of Cooking of Potatoes (*Solanum tuberosum* L.) Served in Large-Scale Food-Service Systems, Including Industrial Pre-Treatments

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**Abstract:** Potatoes (*Solanum tuberosum* L.) often constitute a meal's main carbohydrate source. When consumed outside the home, dishes are often prepared in large-scale food service systems, like school canteens and hospitals. To manage the logistics of serving the required quantities of potatoes, raw tubers must be prepared by washing, industrial peeling, preservative actions, and packaging to stand transportation and storage before cooking. There are several steps of pre-treatment, packaging, transportation, and cooking techniques that differ from traditional preparation at home, and each of these steps— or more likely a combination of several steps— might contribute to reduced quality in terms of enzymatic discoloration, microbiological failure, and subsurface hardening. In this review, the effect of each of these steps on the potato tuber; from industrial peeling to steam-cooking in the large-scale food service system, has been studied to understand where the most significant quality changes occur, and to understand the combined impact of different actions.

**Keywords:** Potato (*Solanum tuberosum* L.); Tubers; Industrial pre-treatment; Eating quality; Large-scale food service system subsurface hardening; Texture; Pectin.

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## 1. Introduction

Potato plants (*Solanum tuberosum* L.) were brought to Sweden in the middle of the 17th century as decorative plants. It was not until 1749 that active cultivation of the tubers for consumption was encouraged by the Swedish government due to starvation, who provided information about boiling potatoes, mashing them for bread baking, and using them for alcohol production [1]. At this point, peeling was already described as an important preparation step to increase product quality. Potato cultivation kept increasing until after the first world war, as the stability of tuber production compared to other crops was a big advantage. In 1892, an abrasive peeler adapted for peeling vegetables and potatoes on a larger scale was patented, and the first industrial peeling facility was housed in Boston in 1931 [2]. The high efficiency of the peeling process resulted in economic benefits, but also problems with discoloration and high waste levels (40–50%), that were not observed to the same extent for tubers peeled by hand [3,4]. Even though a general and fundamental understanding of the problem has developed during the past century, modern industrial peeling facilities still experience quality issues due to discoloration and large amounts of waste. Today potatoes are considered a staple food in many parts of the world, and Sweden is no exception. One of the big advantages of potatoes is the possibility of storing the tubers after entering dormancy; a state of low activity enabling storage up to 11 months [5].

The wish to increase efficiency has also resulted in negative side-effects in terms of quality issues. In this review, a short physiological overview will be followed by the different steps for industrial pre-treatment for tubers cooked in large-scale food service systems (Figure 1), after which we will discuss the impact of different steps on the eating quality of boiled and steam-cooked potatoes.

## 2. Tuber physiology and its impact on quality during industrial pre-peeling

### 2.1 Tuber anatomy

A potato tuber can be divided into tissue zones with different functions and cellular composition, see Figure 2 [6,7]. The outer layer, the periderm, consists of dead cells that protect the tuber. Beneath the periderm is the cortex, where cells with the highest amount of starch within the tuber are located. At the edge of the cortex is the vascular area with the vascular ring, where nutrients and water are transported to other parts of the tuber. About 75% of the tuber's volume consists of parenchyma cells, which store starch. The pith is the core of the tuber, where most water transport occurs.



each other to a higher extent after cooking compared to waxy varieties. In addition, mealy potatoes are perceived drier and crumblier during consumption, compared to waxy potatoes. [14,15].

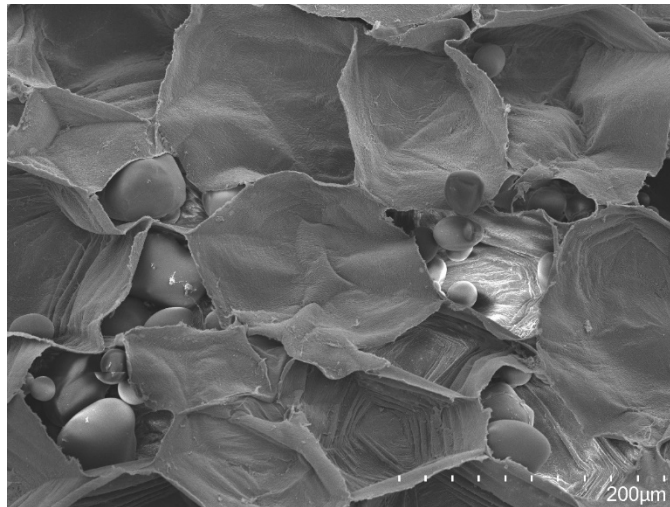


Figure 3. SEM picture of cell wall structure, with starch granules of various sizes captured in the cells of a raw potato, Fakse variety. Photo: Klara Sjölin

The composition of individual cells differs depending on the location in the tuber. Bush and McCann [16] showed that pectin is present in the middle lamella and cell walls surrounding the cells. The pith is a region with a higher amount of low-methylated pectin at the junction between cells. The calcium content also differs, depending on location within the tuber: the closer to the core, the lower the calcium content [17]. Levels of other minerals, such as magnesium, sulfur, and zinc, are constant throughout the entire tuber [16].

### 2.3 Intercellular adhesion

The cells in the tubers are connected by an intercellular network referred to as intercellular adhesion, linking the cells to each other. The intercellular network consists mainly of pectin, but also complexes where proteins and suberin-like molecules (forming a protective layer in the cell walls of the periderm) are involved [18]. During industrial pre-treatment, intercellular adhesion (further referred to as subsurface hardening) might be strengthened, contributing to an unpleasantly tough surface after cooking.

During cooking, intercellular adhesion strength is reduced, which can be evaluated by texture analysis. Histological analysis showed a correlation between texture and intercellular adhesion [19]. Parker, *et al.* [20] found that intercellular adhesion during heating remains the longest at the corners of the cells, where the degree of pectin methylation is the lowest. The presence of divalent cations, especially  $\text{Ca}^{2+}$ , enables cross-linking between pectin chains as illustrated in Figure 4 [21,22]. For cross-linking to occur, methyl groups must be removed. Pectin gelation occurs faster and becomes more rigid if the reaction occurs at a relatively high pH since it is unfavorable for  $\beta$ -elimination (an enzymatic degradation shortening the pectin chain).

Interestingly, pectin chains at the cell corners have a lower degree of methylation compared to other regions around the cells. This coincides with higher calcium content in those regions [16]. Since calcium assists in cross-linking low-methylated pectin chains to form a network, this may explain the phenomena of delayed cell separation at cell corners during cooking.

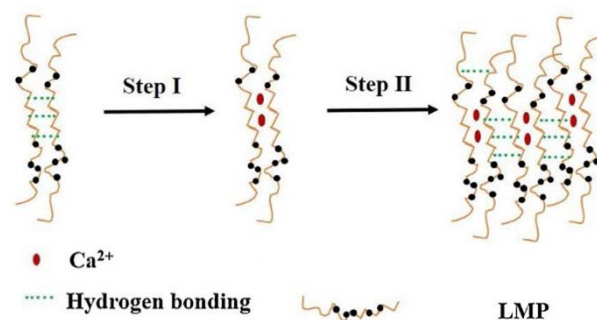


Figure 4. Illustration on  $\text{Ca}^{2+}$ -assisted cross-linking of low methylated pectin (LMP). The figure is a modified version from Cao, Lu, Mata, Nishinari and Fang [22].

### 3. Enzymatic activity related to reduced quality

Potatoes contain several different enzymes, with different functionality and activity at different stages of the tuber's life. The enzymes affecting eating quality in industrial pre-treatment are polyphenol oxidase (PPO) and pectin methylesterase (PME). An overview summarizing how each of the enzymes is affected by external factors is presented in Table 1.

Table 1. Optimal extrinsic factors for PPO and PME.

	PPO	PME
Optimal temperature	40°C [23,24]	50–80°C [25-27].
Inactivation temperature	60 s at 75°C [28]	Approximately 80°C [29]
Optimal pH	4.5-6.5 [23,24]	7 [30] Increasing from 3.5-8.5 [22]

#### 3.1 Polyphenol oxidase

PPO oxidizes phenolic compounds into quinones, which can be further depolymerized resulting in a dark pigment [31]. The absence of oxygen or alternative oxidative compounds, like organic acids, prevents the formation of quinones. PPO is present in cell liposomes, separated from phenolic compounds which mainly appear in the vacuole [32]. When mechanical stress is applied to the potato and its cells, membranes might break, causing the enzyme and substrate to react. Depending on the type of mechanical stress, the level of cellular rupture differs with more damage and enzymatic browning caused by rougher treatment. Cantos, Tudela, Gil and Espín [24] showed that there were enzymes bound to membranes in the cell. Those findings were confirmed for pears by Gomes, *et al.* [33], where the phenomena that prevented the reaction from occurring in healthy tubers is described by structural differences, such as sterically hindering membranes. Other findings confirm that the degree of mealiness, as well as phenolic content, only show a weak correlation with enzymatic browning, but a stronger relation with tyrosine content (one of the amino acids possibly oxidized by PPO) and tyrosine turnover. [34,35].

#### 3.2 Pectin methylesterase

PME catalyzes the removal of methyl groups from pectin chains by hydrolysis, lowering the degree of methylation. Temperature for PME activation and inactivation varies. Several studies show that PME inactivation follows a biphasic behavior, indicating the presence of several forms of PME with differing heat stability. PME activity has been detected from 8°C to 100°C [25-28,36]. Gomez, *et al.* [37] suggest that the different kinetics discovered for PME depend on stress response, and PME is activated to protect the tuber.

PME activity is often related to subsurface hardening. Since the degree of methylation is reduced by PME, cross-linking of the pectin chains by divalent cations such as Ca<sup>2+</sup> is simplified. Kaaber, Kriznik, Bråthen, Knutsen and Kaack [27] quantified non-soluble polysaccharides, such as pectin, and analyzed the hardness of half tubers stored at 4–20°C. They found a positive correlation between higher levels of free methyl groups and increased hardness for tubers stored at 8°C and warmer, leading to the conclusion that PME activity was already initiated at 8°C and contributed to increased hardness. Shomer and Kaaber [18], on the other hand, concluded that PME was not involved in subsurface hardening for tubers treated with organic acids.

The general opinion is that PME activity increases at lower pH since an increase of methyl groups and subsurface hardening has been observed. However, optimum pH for PME is higher (see Table 1), as well as the level of several pectinases, catalyzing  $\beta$ -elimination [38]. High pectinase activity leads to shorter pectin chains, which are unable to form rigid cross-linked systems as longer pectin chains.

Subsurface hardening by increased PME activity has been used to design an optimal cooking procedure depending on desired texture; for example, French fries preferably become hard and crispy and increased adhesion is considered preferable, while boiled potatoes preferably remain as soft as possible.

### 4. Industrial pre-peeling

Potatoes are generally consumed with the peel removed. Traditionally, potatoes are peeled by hand, but that would be too time-consuming in large-scale food service systems. To save time, there are several available techniques for industrial pre-peeling. This review will cover abrasive peeling (AP), knife peeling (KP), steam peeling (SP), chemical peeling (CP), and enzymatic peeling (EP). Each method is suitable for different situations, with different advantages and disadvantages. A disadvantage common to all peeling techniques is a large amount of waste. Table 2 shows comparisons in weight losses reported from different peeling techniques. Due to lack of data, knife peeling and enzymatic peeling are excluded.

Table 2. Potato weight loss for different industrial peeling processes.

Reference	Information	Abrasion peeling	Steam peeling	Chemical peeling
Sapers and Miller [39]	Russet Burbank	38.8%	16.0%	6.8%
	Round-white potato	29.4%	15.8%	4.6%
Gray and Ludwig [9]	Optimized storing properties and variety choice lowers waste	12-30%	n.d.	n.d.
Sandra, et al. [40]	Optimized conditions	n.d.	n.d.	14.96%

#### 4.1 Abrasion peeling

Abrasion peeling is a technique where the peel is scraped off the tuber by friction caused by a rough surface in a rotating drum, and simultaneously washed with water [41]. Abrasion peeling is relatively cheap, in terms of both material investment and processing, but it generates more waste compared to other methods, see Table 2. For tubers of irregular shape or with deep eyes, the waste will be even bigger if the process aims to completely remove the peel [42,43]. Since waste when removing all the peel becomes unreasonably high, the degree of peeling could be measured in terms of peel loss and peeling efficiency. Peel loss refers to %(w/w) of the tuber that has been removed in relation to initial tuber weight, and peeling efficiency refers to %(w/w) of the total amount of peel that has been removed in relation to the total peel content of the untreated tuber [41,44]. Peeling efficiency and peel loss are affected by both operational factors like drum speed, peeling time and potato load [41], but also intrinsic factors such as variety and tuber hardness [44]. A positive correlation between high peeling efficiency, high peel losses, high drum speed and long peeling time can be seen [41,44,45]. However, results vary. Singh and Shukla [41] found peel losses of 6% with a peeling efficiency of 78%, while Fouda, Darwesh and Elkhodarey [44] found peel losses as low as 1.4–2.2% for peeling efficiency at 77–93%. Since the peeling efficiency is below 100%, some peel residues must be acceptable, or an additional peeling method is required.

Abrasion peeling is a rough peeling method, contributing to quality losses like enzymatic browning and subsurface hardening as tuber cells are torn apart during the peeling process [39,46,47]. Outer cell layers are transformed into dense, brick-like cells and stimulated to produce suberin to create a new, protective periderm. The suberized, bricklike cells can be observed 1–15 cell layers below the surface [46]. The shelf-life of abrasion-peeled tubers is about half as long compared to chemically peeled tubers, with discoloration being the main factor limiting shelf-life [47].

#### 4.2 Knife peeling

Knife peeling is performed by letting the tuber pass over rotating disks with knives attached, where the knives remove the outer layer. Knife peeling is a more gentle method, compared with abrasion peeling, and the physical impact on the tuber can be compared to hand peeling [46]. Knife peeling also stimulates suberization, but not as many cell layers are affected compared to abrasion peeling [48]. Kaack, et al. [49] compared subsurface hardening of boiled tubers peeled with sharp versus blunt knives, which resulted in significantly harder tubers when peeled with blunt knives [49].

#### 4.3 Steam peeling

Steam peeling is performed by exposing tubers to hot steam, which loosens the peel. The tubers are then cooled and the peel is removed by cold water jets [42]. Steam peeling has a lower waste yield compared to abrasion peeling. Steam peeling is considered a more gentle process than abrasion peeling, yet discoloration is comparable to abrasion peeling [35]. Since heat treatment during steam peeling initiates subsurface hardening, tubers peeled by this process are not suited for further storage or mashing [42].

#### 4.4 Chemical peeling

Chemical peeling is performed by soaking the tuber in an alkaline solution. Sodium hydroxide (NaOH) is most common, but potassium hydroxide (KOH) has also proven to be efficient [50]. Removal of the outer part of the tuber occurs due to a combination of increased temperature, NaOH concentration, and time, with an optional pre-step of hot water treatment [40]. Several studies for different food items have been conducted with various set-ups for the flexible parameters. For potatoes, Garrote, et al. [51] studied temperature at the interval 55–95°C, NaOH concentrations of 40–200 g/kg and time in the interval 1–7 min. At the higher temperatures, concentrations, and times, diffusion distance increased and caused a deeper region of subsurface hardening. Depending on further processing of the tuber, the severity of the structural changes differs. Fried products might benefit from a firmer texture, while lumps in mashed potatoes are considered unpleasant [42,52]. The advantages of chemical peeling are low cost and low waste, while waste handling is a disadvantage [50].

#### 4.5 Enzymatic peeling

Peel removal by enzymatic treatment is a novel peeling technique, and studies have been conducted for several fruits and vegetables [53,54]. Enzymatic peeling is efficient as a pre-step to traditional peeling, as the peel is dissolved. This helps remove the peel faster and with less impact due to irregularities on the tuber surface [53].

Most fruits or vegetables are successfully peeled by polygalacturonase, cellulase, xylanase, or amylase, but potato peel composition, which has a relatively high content of suberin, complicates the peel degradation [54,55]. Bishai, et al. [56] evaluated the efficiency of a mixture of cellulase, xylanase, and amylase and found it efficient for potato tubers. The enzymatic mixture, consisting of 50% cellulase–xylanase and 50% amylase worked optimally at pH 6 and increased temperature favored the process until 60°C, where it stagnated. Incubation time and enzyme concentration seem to have a linear correlation with peel removal. Barati, Latif and Müller [53] found that enzymatic peeling of cassava with a mixture of xylanase, cellulase, and hemicellulase was mainly affected by enzymatic concentration, but also pH, incubation time, and temperature. Temperature and pH reached their optimums at 45°C and 4.5 respectively, while peeling efficiency improved with increased concentration and time [53]. Suutarinen, Mustranta, Autio, Salmenkallio-Marttila, Ahvenainen and Buchert [54] studied the effects of cellulase and pectinase and varied enzymatic concentration at a constant temperature (40°C) and incubation time (2 h). Both temperature and incubation time were lower than reported as optimal conditions, and the enzymatic set-up differed compared to other studies, which might explain why Suutarinen, Mustranta, Autio, Salmenkallio-Marttila, Ahvenainen and Buchert [54] saw hardly any peeling effect on the potatoes.

Efficient enzymatic removal of potato peels requires operation at temperatures where several internal enzymes are active, such as PPO and PME [26,27,57]. Due to the risk of increased enzymatic discoloration and subsurface hardening, enzymatic peeling is usually applied for peeling products aimed for frying.

#### 4.6 Combined peeling methods

When optimizing industrial peeling, different peeling methods are usually combined to reduce each method's disadvantages. Sapers and Miller [39] reported that abrasion peeling followed by lye peeling increased shelf life when compared to abrasion peeling alone, since lye diffused faster through damaged cell layers, making it possible to remove them but keep most of the unaffected structures. A combination of abrasion peeling and knife peeling showed that the depth of affected cells, as well as the hardness of cooked tubers, was lower compared to abrasion peeling alone, but higher compared to knife peeling alone [46]. Since abrasion peeling is considered a cheaper method than knife peeling, a combination of these peeling methods might be a step toward optimization.

### 5. Preservative actions

Minimally processed potatoes have a very limited shelf-life due to enzymatic browning and microbiological spoilage [58]. There are several methods of increasing shelf-life. The most common method is chemical treatment by immersion in organic acids, sulfites, or a combination of both.

#### 5.1 Organic acids

Organic acids are efficient against enzymatic browning since they combine an antioxidative effect with lowering pH below the optimum for PPO [59]. However, quality issues in terms of a sour off-flavor and subsurface hardening have been reported in some cases when heat was applied during the peeling step [52], while others do not see any or only slight significant side effects [58,60]. Sapers, Cooke, Miller, Heidel and Martin [52] concluded that potato cell walls treated with ascorbic acid became more rigid, with a denser layer in the middle. Ascorbic acid occurs naturally in potatoes, and a positive correlation between reduced enzymatic browning of peeled and cut potatoes stored for six days for varieties with high ascorbic acid contents have been observed [61].

#### 5.2 Sulfite

Sulfite is commonly used as a preservative agent for industrially pre-treated potatoes. It acts by inhibiting PPO as well as a reducing agent. Sulfite also has a bleaching effect on anthocyanins [59]. The use of sulfite is problematic as it produces an off flavor, can result in severe allergic reactions among oversensitive persons, and contributes to subsurface hardening. Parameters affecting side effects include sulfite concentration, immersion time, and post-treatment temperature [62-64]. Sulfite uptake increases if the immersion dip consists of sulfite and organic acid, compared to only sulfite [64]. Svensson [62] reported that immersion time is the parameter with the least impact, while increased temperature and sulfite concentration contributes to a significant increase in the thickness of the tough surface layer.

Ceponis and Friedman [63] found that microbiological growth was the shelf-life limiting factor after lye peeling and sulfite immersion, with a shelf-life of 1 day at 20°C, 3–5 days at 7°C, and 4–10 days at 2°C. The sulfite levels at the tuber surface are reduced during storage, which shows that the anti-browning effect appears to be due to reactions that occur inside the potato, and not from the sulfite itself [64].

### 5.3 Stress caused by preservative actions

General stress on tubers caused by chemical pre-treatment has been evaluated. Rocculi, et al. [65] monitored the heat production in parenchyma tissue as a measurement of metabolic potato activity after immersion in ascorbic acid, citric acid, and L-cysteine respectively. It was concluded that the heat production of the potato was significantly higher for all treatments during the first five hours following chemical treatment, with L-cysteine showing the highest heat production. Contradictive results have been reported by Petri, et al. [66], where decreased respiration rates after chemical pre-treatment of potato slices was reported, especially when treated with sulfite. The authors also found this to be unexpected and explained the phenomena as inhibition of not only PPO but also other organelles responsible for cellular respiration. However, it is of great interest that Petri, Arroqui, Angos and Virseda [66] monitored the respiration rate every 12 h for 5 days, while Rocculi, Galindo, Mendoza, Wadsö, Romani, Dalla Rosa and Sjöholm [65] monitored the heat production continuously for 30 h. The results from Rocculi, Galindo, Mendoza, Wadsö, Romani, Dalla Rosa and Sjöholm [65] show the maximum heat production after 6–14 h, as a result of chemical pre-treatment, and the higher the peak of heat production, the larger is the following reduction in heat production. If the respiration rates monitored by Petri, Arroqui, Angos and Virseda [66] follow the same pattern, the respiration peaks had already passed after 12 h, when the first measurement was taken. Since higher peaks were followed by lower heat production, the low respiration rates could be an indication of extra stress at initial stages following chemical pre-treatment.

## 6. Packaging and storage

Modification of packaging properties is another method of reducing PPO activity and increasing shelf-life. Most common is vacuum packaging, which has proven to be very efficient. However, the technique is relatively expensive and sensitive since the product is destroyed rapidly if the package is broken. The presence of anaerobic bacteria or spores is a potential hazard for vacuum packaging, especially since vacuum packaging often replaces sulfite treatment [67,68]. Modified atmosphere packaging (MAP) has also been tested by replacing O<sub>2</sub> with different ratios of CO<sub>2</sub> and N<sub>2</sub>. The results show that enzymatic browning is reduced, which increases shelf life to 2–3 weeks [47,69,70]. The best effect was achieved when chemical preservation was combined with MAP [71]. Kaaber, Martinsen, Bråthen and Shomer [69] found that MAP contributed to subsurface hardening, but those results contradicted Dite Hunjek, et al. [72] and Angós, Virseda and Fernández [70]. Evaluation of different gas compositions showed the possibility of increasing shelf-life without increasing hardness when gas pressure ratios (kPa/kPa) of 10/0, 10/10, and 80/20 (O<sub>2</sub>/CO<sub>2</sub>, N<sub>2</sub> as void) were applied [70].

Storage temperature after chemical treatment influences both the appearance and thickness of subsurface hardening. Kaaber, Martinsen, Bråthen and Shomer [69] found that peeled, vacuum-packed potatoes stored at 20°C became significantly harder after cooking compared to peeled, vacuum-packed potatoes stored at 4°C. Svensson [62] reported that storage at 25°C compared to 5°C for 24 h after abrasion peeling and immersion in 2% sodium metabisulphite gave rise to a tough layer approximately twice as thick. However, significant differences have also been found based on external factors such as year of cultivation [27]. A fast temperature reduction of the cooling rate of 10°C before placing in the cooling room generally increased shelf-life by 1 day [63].

Treatment by dipping in water or brine has been proven efficient since the 1950s [42]. The method has developed, and immersion of CO<sub>2</sub> and N<sub>2</sub> in the water for 10 min per day during the storage period has been studied by Kaaber, Martinsen, Bråthen and Shomer [69]. CO<sub>2</sub> showed a significant decrease in enzymatic discoloration while N<sub>2</sub> had no effect, probably due to the reduced pH of the solution.

## 7. Cooking of potatoes in large-scale food service systems

Traditionally, boiled potatoes are prepared in boiling water until they feel soft when poked with a fork. In large-scale food service systems, boiling occurs in combination ovens, which is more efficient with respect to time.

### 7.1 Phenomena during cooking

During cooking, the potato undergoes physical processes contributing to softening and textural changes, mainly due to loosening of cell wall structures. The cell walls of potato varieties with bigger cells tend to break more easily than those of smaller cells [73]. van Marle, et al. [74] reported that cell walls of mealy varieties, which usually have larger cells, were not as tightly connected as those of waxy varieties, causing more cell separation during cooking. The effect of cooking on cell wall structure might also affect post-cooking sensorial parameters: cellular separation appears to a larger extent than cell wall cleavage in mealy varieties [75]. As the potato is cooked, increased temperature in combination with the presence of water will induce swelling and gelatinization of starch in the tuber. Starch gelatinization and swelling occur at 55–83°C, with a peak at 66–71°C when present in potato tissue [76,77]. Alvarez, et al. [78] showed histologically that starch granules are still intact after 5 min heat

treatment at 80°C, but gelatinization and swelling were initiated after 5 min at 90°C. Starch gelatinization may also create increased internal pressure on cells, contributing to cell wall loosening [79]. Keijbets [80] found that  $\text{Ca}^{2+}$  is released from starch during gelatinization, enabling pectin cross-linking. Pectin chains are loosened from the cell walls during cooking, contributing to tissue softening. The presence of cations, especially  $\text{Ca}^{2+}$ , reduces softening in combination with a low degree of methylation of the pectin chains. However, Murayama, et al. [81] investigated the cross-linking effect of the addition of  $\text{Ca}^{2+}$  and confirmed that increased  $\text{Ca}^{2+}$  reduced softening, but did so independently of PME activity and degree of methylation.

The cell membrane, responsible for regulating cellular compound transportation, is also affected by cooking. During cooking, structural proteins lose their functionality, increasing membrane permeability. Increased permeability by heating with forced convection by steam has been reported to occur at 60–70°C [82]. However, the membranes' ability to resist heat also depends on the holding time. At 60°C, a partial collapse of the cell membrane is seen after a 5 min heat treatment, but no complete collapse was observed during the entire test run (40 min). When the temperature is increased, the required time for complete collapse decreases and is achieved within 5 min at 90°C. [83].

## 7.2 Optimal cooking time

In large-scale food service systems, potatoes are considered cooked after a certain time or when a certain core temperature is reached. Finding a standardized method to determine when a batch of potatoes is ready is challenging. In Sweden, the recommendation is to cook the potatoes until their core temperature is 96°C, based on results by Andersson, et al. [84]. However, this recommendation was set based on boiling in water, while most large-scale food service systems use steam cooking. There were also very high temperature fluctuations in the study, extrapolation to reach the recommended temperature, and only one variety was tested. For steam cooking, 94°C has been recommended as core temperature to achieve a good eating quality, but with some variation based on variety [85]. Potatoes have been studied by hyperspectral imaging, an imaging technique based on electromagnetic properties, and boiled tubers were considered cooked after 21 min [86]. It has been shown that conventional boiling contributes to softer tubers when cooked to the same core temperature, compared with steam cooking, and that the softening kinetics for different cooking methods differ [85,87].

## 7.3 Cooking kinetics

During the cooking of potatoes, heat is transferred from the surrounding media (water during boiling and air saturated with steam during steam-cooking) to the tuber. Since temperature changes with both time and tuber location, heat transfer can be described by Equation 1 [88].

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (1)$$

Where  $\alpha$ , thermal diffusivity, is described by Equation 2.

$$\alpha = \frac{k}{\rho c_p} \quad (2)$$

In Equation 1 and Equation 2, T: temperature at the core of the tuber, t: heating time,  $\alpha$ : thermal diffusivity, x: position in the tuber, k: thermal conductivity,  $\rho$ : density,  $C_p$ : specific heat capacity.

Partial differential equations, like Equation 1, are usually solved using finite element methods. However, approximate solutions have been developed for certain situations. Biot number, Bi, is a dimensionless number showing the ratio of external and internal resistance to heat transfer (see Equation 3). If Bi is low, heating rate is limited by the rate of heat transfer to the object being heated from the heating medium. If, on the other hand,  $\text{Bi} > 40$ , internal resistance of heat transfer is the limiting factor, and a constant surface temperature can be assumed. In this case the temperature at any position in the potato over time is determined by  $\alpha$ .

$$\text{Bi} = \frac{hx}{k} \quad (3)$$

In Equation 3, h: convective heat transfer coefficient.

Based on the thermal properties of the tuber determined by Lamberg and Hallström [89] in combination with an estimated convective heat transfer coefficient for boiling water specified by Singh and Heldman [88]  $\text{Bi} \gg 40$ . Thermal diffusivity describes the ability of heat to travel through an object; with conductivity describing the ability of heat to transfer from warm to cold regions, density is the amount of material that has to change temperature and specific heat capacity is enthalpy required for the temperature change.



Assuming that the surface temperature is constant and heat transfer within the tuber is homogenous through all tissue zones enables simplification of Equation 1 into Equation 4.

$$\frac{T_a - T_t}{T_a - T_{t=0}} = a e^{-(b F_o)} \quad (4)$$

where

$$F_o = \frac{\alpha t}{x^2} \quad (5)$$

Where  $T_a$ : temperature of heating media,  $T_t$ : temperature at a certain time,  $T_{t=0}$ : initial temperature, and  $a$  and  $b$ : geometric and integration constants for an approximation of  $Bi \gg 40$ , describing temperature and thermal properties for different geometrical shapes. When studying whole potatoes, a sphere should be considered where  $x = 0$  is the geometrical center. However, most studies focus on uniform samples formed as either a cylinder or a cube [89-91]. Table 3 compares studies where thermal diffusivity has been determined and compares thermal properties as well as calculated cooking times based on Equation 4.

Table 3. Calculation of cooking time. Numbers written in italics are calculated based on temperature and thermal properties specified by Singh and Heldman [88].

	Lamberg and Hallström [89]	Derbyshire and Owen [91]
$\rho$ (kg/m <sup>3</sup> )	1085	<i>1126</i>
$C_p$ (J/kg°C)	3600	<i>3299</i>
$k$ (W/m°C)	0.684	0.631
$\alpha$ (m <sup>2</sup> /s)	<i>1.75*10<sup>-7</sup></i>	<i>1.70*10<sup>-7</sup></i>
$h$ (W/m <sup>2</sup> °C)	<i>100000</i>	<i>100000</i>
Bi	4389	3191
Shape	cylinder	sphere
Height (m)	0.009	n.d.
Radius (m)	<i>3.00*10<sup>-2</sup></i>	<i>2.02*10<sup>-2</sup></i>
$T_a$	75	100
$T_i$	20	15
T	70	94 [85]
Cooking time (min)	42.5	13.5

In addition to the heat required to change the temperature, the cooking kinetics of potatoes differ from that of other vegetables due to the enthalpy required for starch gelatinization,  $\Delta H_{gel}$ . Since  $\Delta H_{gel}$  is a phase transition occurring at a certain temperature, the additional enthalpy is added like latent heat. Based on the thermal properties of a potato tuber and the starch in the tuber,  $\Delta H_{gel}$  is approximated to be 20% of the total enthalpy required to heat the potato from 15 to 94°C [88,92]. Derbyshire and Owen [91] and Lamberg and Hallström [89] included  $\Delta H_{gel}$  by determining the thermal diffusivity experimentally covering the gelatinization temperature, which was 10.6% and 13.8% higher, respectively, compared to estimations based on composition.

When evaluating cooking kinetics, most studies refer to texture kinetics during cooking to improve eating quality since there is a clear correlation between texture and eating quality [85,87,93-96]. Tuber softening starts in the temperature region where starch gelatinizes and cell wall loosening is initiated, which could be mathematically described as a first-order equation [93]. If the analysis starts around 60–70°C, just before softening is initiated, the Arrhenius equation generally fits the texture kinetic during cooking. The initiation of cell wall loosening, causing softening, is described as activation energy in the model [90,95]. Starch gelatinization has also been mathematically described as activation energy [78,94]. Since gelatinization requires additional enthalpy for phase transition, which is independent of continuous heating, the phenomena should be considered a type of latent heat instead of activation energy when describing the cooking kinetics of potatoes.

## 8. Warm-holding

Warm-holding (WH) is added after cooking due to logistical reasons, like transportation after cooking or delays before serving, and is prolonged heat treatment after completion of cooking, usually at a lower temperature than that occurs during cooking. WH is generally known to cause quality reductions in terms of vitamin C loss and reduced eating quality. A significant loss of vitamin C has been reported after only 30 min WH in a combination oven, compared to storage at room temperature [97]. The eating quality, in terms of sensorial evaluated texture, flavor and total impression of organoleptic properties, of steam-cooked potatoes warm-held in a closed tin was reduced with increased WH time. At 60°C, the reduction of eating quality was slower compared to 75°C and 90°C [98].

## 9. Conclusion

When introducing and developing industrial pre-treatment of potatoes, side-effects in terms of enzymatic discoloration occurred. The need to scale up production to increase efficiency outran the understanding of phenomena underlying the rough peeling methods causing enzymatic discoloration. Instead, new treatments were added, including the addition of preservatives and the creation of more complicated packaging systems, which has given rise to new problems like subsurface hardening, microbial growth, and off-flavor. Most research conducted in the field investigates the effect on boiled, geometrically standardized samples, even though reality mostly deals with whole, steam-cooked tubers. To meet increasing demands on quality, as well as environmental and health sustainability, a step back is required to understand the problems at hand and use current experience and knowledge, a century after the invention of the abrasion peeler, to identify and eliminate the real cause of quality issues related to industrially pre-treated potatoes. There is a big gap in research when it comes to finding the best methods to hide the side-effects and understanding the complex, but still fundamental, reactions that occur while cooking potatoes, and preventing side-effects from occurring.

## 10. References

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