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Sjölin, Klara

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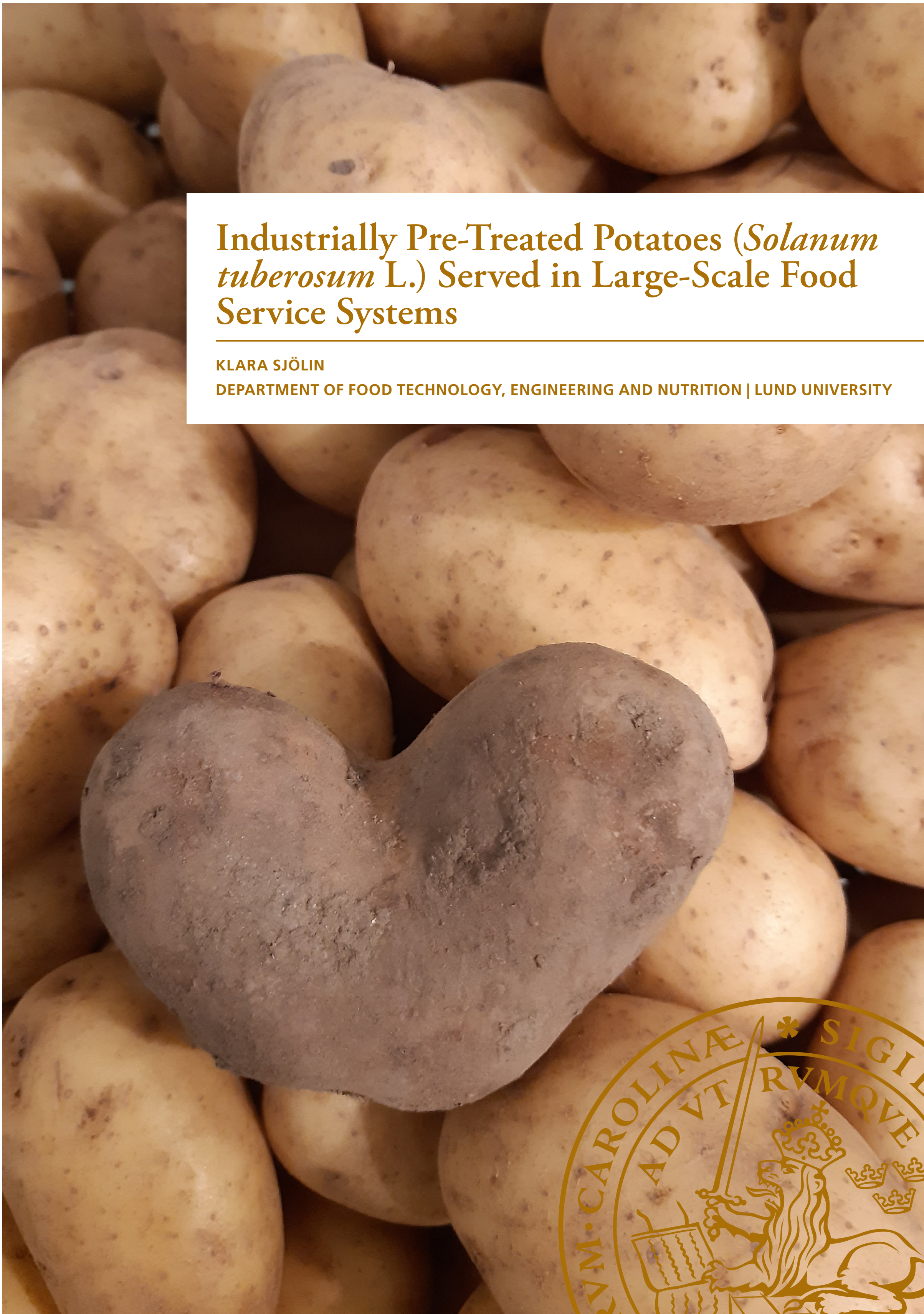

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KLARA SJÖLIN
DEPARTMENT OF FOOD TECHNOLOGY, ENGINEERING AND NUTRITION | LUND UNIVERSITY

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Served in Large-Scale Food Service Systems

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Klara Sjölin

DOCTORAL DISSERTATION

by due permission of the Faculty of Engineering, Lund University, Sweden.
To be defended 11th of November at 10.15 in lecture hall A
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*Faculty opponent*
Professor Marc Hendrickx
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**Abstract** In Swedish schools, a warm lunch is served every day. The lunch is prepared in a large-scale food service system and includes steam-cooked potatoes several times per week. The potatoes are often industrially pre-treated to facilitate the handling and logistics required to cook hundreds of meals in a couple of hours. During the industrial pre-treatment, the potato tubers are usually peeled by abrasion, knife peeling, or a combination of both, followed by preservative actions and packaging. When arriving at the large-scale food service systems, the tubers are usually cooked by steam-cooking (SC) in a combi-steamer (an oven with saturated steam as the medium for heat transfer). To manage logistical issues, the potato tubers might have to be held warm until serving. These processing steps are often very rough, causing stress and mechanical damage to the tubers, followed by a poorly controlled and understood cooking process. Unfortunately, this contributes to an unpleasant product being served with reduced eating quality.

Preservative actions are required to prolong the shelf-life and include reduction of enzymatic browning and reduction of microbiological growth. These actions can be performed by chemical treatment with organic acids (OA) and/or sodium metabisulfite (SMS). Textural analyses by puncture of the samples show that tubers treated with OA, SMS, and OA+SMS might develop a tough surface compared to untreated samples, referred to as Ref. Preservation with both OA and SMS prolongs the shelf-life but has shown to reduce the eating quality by contributing to the creation of an unpleasant, tough surface. Textural analysis revealed that the hardness of the surface depends on the chemical pre-treatment, with hardness order of Ref<OA<SMS<OA+SMS. Visual inspection showed that SMS and OA+SMS contributed to the most pronounced tough surface, while analysis by light microscopy revealed that OA developed brick-like cells at the surface, indicating that the different preservative treatments contribute to a tough surface by two different mechanisms.

SC is used to cook the samples due to decreased cooking time and easier handling compared to conventional boiling (CB) in a cooking vessel. The cooking degree has shown to mainly depend on the core temperature of the tuber at the end of the cooking process, but differences were also found depending on the cooking method (CB compared to SC) and potato variety.

Warm-holding (WH) is often conducted in the combi-steamer with a relative humidity (RH) of 100% at a minimum temperature of 72°C for a maximum of 2 h since this used to be the recommendation in Sweden. During WH, the cooking process continues, where temperature has a larger impact than time. WH can easily cause overcooking, with an unpleasant watery core as a result. However, if tubers that will be warm-held are slightly undercooked, the continuation of the cooking process can easily be adapted to achieve a good eating quality. Control of relative humidity (RH) has shown to be crucial, where too low RH contributes to a tough surface due to evaporation of water, which is a third mechanism causing a tough surface.

Keywords: Potatoes (*Solanum tuberosum* L.), large-scale food service systems, industrial pre-treatment, subsurface hardening

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Faculty of Engineering
Department of Food Technology, Engineering, and Nutrition

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*“Jag vet ingenting om tur, bara att ju mer*
*jag tränar, desto mer tur har jag.”*

*- Ingemar Stenmark*

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# Abstract

In Swedish schools, a warm lunch is served every day. The lunch is prepared in a large-scale food service system and includes steam-cooked potatoes several times per week. The potatoes are often industrially pre-treated to facilitate the handling and logistics required to cook hundreds of meals in a couple of hours. During the industrial pre-treatment, the potato tubers are usually peeled by abrasion, knife peeling, or a combination of both, followed by preservative actions and packaging. When arriving at the large-scale food service systems, the tubers are usually cooked by steam-cooking (SC) in a combi-steamer (an oven with saturated steam as the medium for heat transfer). To manage logistical issues, the potato tubers might have to be held warm until serving. These processing steps are often very rough, causing stress and mechanical damage to the tubers, followed by a poorly controlled and understood cooking process. Unfortunately, this contributes to an unpleasant product being served with reduced eating quality.

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# Populärvetenskaplig sammanfattning

”Ångpotatisen som de får är också otäck. Fast de har skalat den en gång, är det precis som ett skal till som måste skalas bort.” Denna målande beskrivning av skolmatspotatis kommer från Anders Jacobssons bok Sagan om Sune, och detta är en beskrivning som de flesta svenskar, oavsett ålder, kan relatera till. Förutom den sega, otrevliga ytan är det även vanligt med en väldigt mjuk och vattnig kärna. Det primära syftet med forskningen bakom den här avhandlingen har varit att förstå och kunna förebygga uppkomsten av den sega ytan och den vattniga kärnan på potatis som serveras i storkök.

Tillagning av potatis i storkök jämfört med traditionell tillagning i hemmet skiljer sig främst genom volymen, då det inte är ovanligt att det är flera hundra portioner som ska tillagas under enbart ett par timmar. För att detta ska vara möjligt har processen behövt effektiviseras, bland annat genom att förskala potatisarna på ett skaleri, tillaga i ångugn istället för kokande vatten i en gryta och varmhålla potatisarna från att de är tillagade tills de ska serveras. Alla dessa steg påverkar potatisen, och dess kvalitet, på olika sätt. När en potatis skalas i ett skaleri finns olika tekniker för att effektivisera skalningen. Karborundum- och knivskalning hör till de vanligaste, där karborundum avlägsnar skalet genom att låta potatisarna skrapas mot en skrovlig, sandpapper-liknande yta medan knivskalning sker genom att knölarna transporteras över roterande knivar som avlägsnar skalet. Båda dessa skalmetoder påverkar strukturen på cellerna vid potatisens yta, och framförallt karborundumskalning sliter sönder celler betydligt djupare i potatisen än skalning för hand. För att undvika att potatisarna missfärgas genom enzymatisk missfärgning, där enzymet polyfenoloxidas katalyserar bildandet av bruna ämnen, krävs en konserverande behandling för att sänka pH värdet eller en förpackningsteknik som minimerar tillgängligheten på syre. Den konserverande behandlingen sker ofta genom att potatisarna doppas i lösningar med organisk syra och/eller natriummetabisulfit. Det har dock visat sig att både skalning och konserverande behandling kan gynna bildandet av den sega ytan. För att avgöra hur tydlig den sega ytan och vattnigheten i kärnan är har texturen analyserats på hela, skalade potatisar med en texturmätare. Då har en cylinder eller trubbig kniv tryckts ner i potatisen med konstant hastighet, samtidigt som kraften för att det ska ske har noterats. Dessa texturmätningar är en av teknikerna som ligger till grund för att jämföra strukturen och hur den påverkas av olika steg i processen. Resultaten i avhandlingen visar att förbehandling med såväl organiska syror som natriummetabisulfit bidrar till den sega ytan, men att de uppvisas olika såväl visuellt som vid strukturellt. Analyser med ljusmikroskop påvisade att behandling med syra bidrar till kollapsade, brickliknande celler vid potatisens yta. Potatis behandlad med natriummetabisulfit ser däremot ut att behålla cellstrukturerna vid ytan vid analys med ljusmikroskop, medan en visuell bedömning tydligt visar att cellerna i den sega ytan är starkt sammanlänkade, och ofta separeras från eller faller av resten av knölen. Enligt tidigare vetenskapliga studier beror sammanlänkningen mellan cellerna troligen på att nätverket med pektin, som finns för att hålla samman cellerna, har blivit förstärkt.

Idag tillagas potatis i storkök främst i ångugn, där potatisen kokas liggande på bleck omgiven av het ånga. Detta förkortar den totala koktiden då uppvärmning av vatten i kokgrytor är ett tidskrävande moment, samtidigt som det underlättar hanteringen. Potatisens förmåga att värmas upp gör att påverkan från det omgivande mediet (ånga i en ångugn respektive kokande vatten i en gryta) är relativt liten i jämförelse med påverkan från potatisens egna egenskaper (som till exempel storlek och vattenhalt), men faktorer såsom relativ luftfuktighet, konvektion i ångugnen och temperatur gör att tillagningsprocesserna skiljer sig åt. Väl kontrollerad och anpassad tillagning i ångugn ger lika bra kvalitet på potatisen som kokning i vattnet, men potatisen anses vara färdigkokt vid olika kärntemperaturer. Då potatisen kan behöva transporteras till en annan lokal innan servering eller inte ska serveras direkt, behöver den ofta varmhållas. Även detta görs i ångugn, men vid lägre temperatur. Varmhållning enligt de tidigare svenska rekommendationerna (72°C i max 2 h) bidrar till att tillagningsprocessen fortlöper till viss grad, men inte påverkar strukturen på potatisen i tillräckligt stor omfattning för att kunna tillaga en rå eller kraftigt underkokt potatis. I denna avhandling visas det att varmhållning ofta är orsaken till den vattniga kärnan av potatisen, och att potatis som avses varmhållas bör vara lätt underkokt för att sedan nå optimal kokningsgrad under varmhållningen. Om varmhållning sker vid för låg relativ luftfuktighet bidrar det till uttorkning av potatisens yta, vilket även det kan ge upphov till en seg yta. För att avgöra kokningsgrad på en potatis har olika analystekniker använts, tex textur som har beskrivits ovan, eller sensorisk analys. En sensorisk analys innebär att en panel får utvärdera produkten enligt specificerade kriterier, och resultaten kan sedan kopplas ihop med mekaniska observationer och mätningar från till exempel texturmätningar.

Forskningen som ligger till grund för denna avhandling ger en solid bas för att förstå hur kvaliteten på potatis som tillagas i storkök påverkas av olika faktorer kopplade till tillagningen och förskalningen, med fokus på tillämpbar och verklighetsanknuten forskning. Nästa steg är att dels undersöka ännu fler faktorer som påverkar potatisen under dess resa, som tex temperatur under transport från skaleri, dels fortsätta kartläggningen och undersökningen av de olika molekylära fenomenen som bidrar till den sega hinnan.

# List of Papers

Paper I — Sjölin K., Rayner M., Purhagen J. and Sjöholm I. (2022) A Review of Cooking of Potatoes (*Solanum tuberosum* L.) Served in Large-Scale Food-Service Systems, Including Industrial Pre-Treatments. *Journal of Food Engineering and Technology*, **11**, 22-35, https://doi.org/10.32732/jfet.2022.11.1.22

Paper II — Sjölin K, Sjöholm I, Rayner M, Purhagen J (2022) Quality Aspects of Pre-Treated Potato Tubers (Solanum tuberosum L.) After Boiling and Warm-Holding. Food and Nutrition Journal 7: 248. DOI: 10.29011/2575-7091.100148

Paper III — Sjölin, K., Rayner, M., Sjöholm, I., and Purhagen, J. (2018). Determination of Cooking Degree of Boiled and Steam Cooked Potatoes (*Solanum tuberosum* L.) from a Physico-Chemical and Sensorial Perspective. *Advances in Food Science and Engineering* **2**, 146-146.

Paper IV — Sjölin, K., Sjöholm, I., Rayner, M., and Purhagen, J. Optimization of cooking temperature and warm-holding set-ups for potatoes (*Solanum tuberosum* L.) when prepared in large-scale food service systems. *Manucsript.*

# Author's contribution to the papers

Paper I — The author identified the knowledge gap to formulate the aim of the review together with the co-authors, reviewed scientific articles, wrote the manuscript, and revised the manuscript together with the co-authors.

Paper II — The author designed the study with a few inputs from the co-authors, performed the experiments, evaluated the data with some input from the co-authors, wrote the manuscript, and revised the manuscript together with the co-authors.

Paper III — The author designed the study together with the co-authors, performed the experiments, evaluated the data together with some of the co-authors, wrote the manuscript, and revised the manuscript together with the co-authors.

Paper IV — The author designed the study together with the co-authors, performed the experiments with support from the co-authors, evaluated the data together with one of the co-authors, wrote the manuscript, and revised the manuscript together with the co-authors.

# Abbreviations

| | |
|---|---|
| CB | Conventional boiling |
| dm | Dry matter |
| DSC | Differential scanning calorimetry |
| LM | Light microscopy |
| n.d. | Not determined |
| OA | Organic acids |
| PLS | Partial least square |
| PME | Pectin methylesterase |
| PPO | Polyphenol oxidase |
| RH | Relative humidity |
| SC | Steam cooking |
| SEM | Scanning electron microscopy |
| SMS | Sodium metabisulfite |
| WH | Warm-holding |
| WH10 | Warm-holding at 10% RH |
| WH100 | Warm-holddding at 100% RH |

# Introduction

For a long time, potatoes (*Solanum tuberosum* L.) have been considered a staple food in Sweden. Already in 1749, cultivation was promoted by the Swedish government to prevent starvation by providing information about how to boil and use potatoes for bread baking and alcohol production, where peeling was described as an important step (Sällskapet, 1772). Peeling remained an important processing step to increase the eating quality, and in 1892 the abrasion peeler was invented (Groos, 1892). However, even though the efficiency was financially beneficial, side-effects in terms of increased discoloration compared to hand peeling were reported (Garrott and Mercker, 1955; Nash, 1941). The discoloration, as well as microbiological spoilage, became more pronounced since industrial pre-peeling often requires storage for several days before consumption due to logistical reasons (Bobo-García et al., 2020; Ceponis and Friedman, 1957). To overcome these problems, treatments with preservative compounds were initiated, and are still applied today for industrial pre-treated potatoes.

Potato varieties are divided into two sub-groups: mealy and firm. Historically, the tubers were categorized based on their organoleptic properties, but research has confirmed that physiological differences explain most of the differences. Mealy varieties, like Amadine and Bintje, usually have a higher dry matter (dm) content and larger cells with thicker cell walls that tend to separate instead of break when cooked compared to firm varieties, like Asterix and Fakse (Martens and Thybo, 2000; McComber et al., 1994; Ochsenbein et al., 2010; Romano et al., 2018). For industrial pre-treatment, mostly firm varieties are chosen since they generally stand the rough treatment better compared to mealy varieties. However, mealy varieties are processed to some extent when a product suitable for i.e. mashed potatoes is required.

The structure and functionality of the cells in potato tubers differ depending on the position in the tuber (Figure 1) (Fedec et al., 1977; Reeve et al., 1969). The outer layer is called the periderm. It consists of dead, tightly packed cells whose role is to protect the tuber. Small pits, the eyes, can be seen all around the tuber, which are the spots where sprouting will be initiated. Beneath the periderm is the cortex. The cells present here have the highest ratio of starch within the tuber. Between the cortex and parenchyma cells is the vascular area with the vascular ring, which consists of channels enabling the transportation of nutrients and water to other parts of the tuber. The next section, parenchyma cells, constitute about 75% of the tuber's volume and store starch. The core of the tuber is called the pith, where the cells are responsible for water transportation.

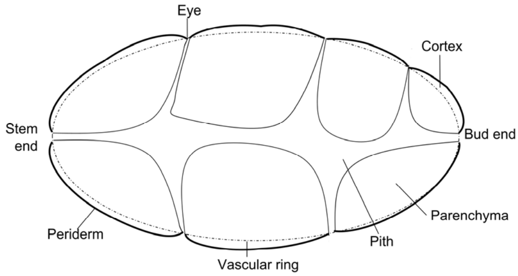



**Figure 1.** Potato tuber anatomy.

The cells within the tuber are connected by intercellular adhesion, consisting of structural proteins, suberin-like molecules, and pectin (Linehan and Hughes, 1969; Shomer and Kaaber, 2006). Pectin contributes by cross-linking at regions where the degree of methylation of the pectin chains is low (Keijbets, 1974). The unmethylated chains enable cations, especially $Ca^{2+}$ to interact and act as a bridge (Figure 2) (Bartolome and Hoff, 1972; Parker et al., 2001). The degree of methylation of pectin can be reduced by pectin methylesterase (PME). PME hydrolyzes the methyl groups, lowering the degree of methylation of the pectin chain (Kaaber et al., 2007). A lower degree of methylation reduces the steric hinder for cross-linking of pectin chains by $Ca^{2+}$-bridges, which increases the intercellular adhesion and contributes to a tough, unpleasant surface of the tubers after cooking, further referred to as subsurface hardening (Baker and Cameron, 1999; Moens et al., 2021). PME is present in lots of fruits and vegetables, including potatoes, but are physically separated from its substrate in the cells.

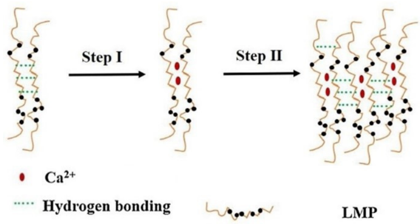



**Figure 2**. Illustration on $Ca^{2+}$ assisted cross-linking of low methylated pectin (LMP). The figure is a modified version from Cao et al. (2020).

Proximate analysis of potato composition can be seen in Table 1. The main component, except water, is carbohydrates in the form of starch. The starch content varies and is usually proportional to the dm of the tuber (Martens and Thybo, 2000).

Starch and water content vary depending on for example mealiness, fertilization, and cultivation conditions as well as storage (Schwimmer and Burr, 1959).

**Table 1.** Proximate analysis of the fresh weight wet basis of the potato (%) (Schwimmer and Burr, 1959).

| Component | Content range (%) |
| --- | --- |
| Dry matter | 13.1-36.8 |
| Total carbohydrate | 13.3-30.5 |
| Starch | 8.5-29.4 |
| Protein | 0.7-4.6 |
| Fat | 0.02-0.2 |
| Ash | 0.44-1.9 |

During the cooking of potatoes, cellular and molecular changes occur affecting the texture and appearance of the tuber (Figure 3). Intercellular adhesion is reduced during cooking. Starch gelatinization is a big, structural change during the cooking of potatoes, and occurs at 55-83°C for starch when present in the tuber, with a gelatinization peak in the range of 66-71°C (Karlsson and Eliasson, 2003a; Karlsson and Eliasson, 2003b). Starch gelatinization and the pressure it exceeds on the cell walls have been believed to contribute to softening during cooking (Jarvis et al., 1992). However, most studies agree that softening occurs due to cell wall loosening. Cell wall loosening involves denaturation of structural proteins and loosening of the structural networks consisting of pectin and suberin-like molecules. Harada et al. (1985) discovered that cell wall loosening is initiated at the same temperature interval as starch gelatinization, which probably explains why starch gelatinization was believed to cause softening.

Several different enzymes are naturally found in potatoes. Among those, polyphenol oxidase (PPO) and PME have a clear impact on tuber quality during industrial pre-treatment and preparation in large-scale food service systems. Enzymatic activity is often eliminated during the cooking process. PPO is relatively sensitive to heat and is inactivated if kept at 75°C for 60 s (Anthon and Barrett, 2002; Gomes et al., 2014). PME, on the other hand, has shown activity from 8°C up to 100°C, with an optimum around 50-80°C (Binner et al., 2000; Garcia-Segovia et al., 2008; Kaaber et al., 2007). The wide range of enzymatic activity for PME depends on the two isoforms of the enzyme, where one is more heat resistant than the other (Anthon and Barrett, 2002). Heat treatment causes losses of Vitamin C, with bigger losses for conventional boiling (CB) in water compared to steam cooking (SC) (Tian et al., 2016). The choice of variety has also shown to have a significant impact on the loss of vitamin C (Yang et al., 2016).

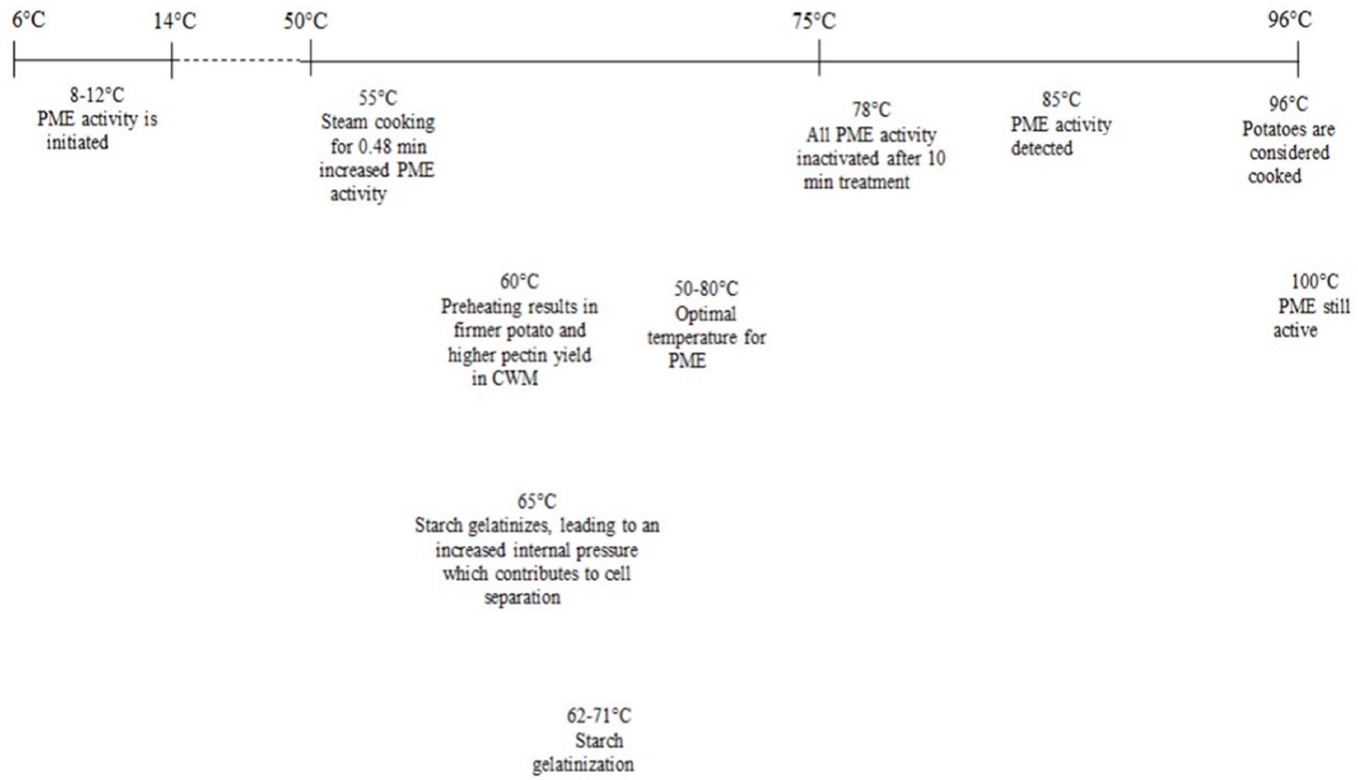



**Figure 3.** Overview of phenomena occurring during cooking of potatoes affecting the softening. CWM – cell wall material, PME – pectin methylsterase

# Background

Industrial pre-treatment contains several processing steps, like peeling, preservative actions, and packaging, which are followed by transportation and storage as well as cooking and warm-holding (WH) before consumption. An overview can be seen in Figure 4 and in Paper I. Peeling is still performed with similar techniques as it was when invented in 1892. When the efficient peeling methods showed to contribute to quality issues in terms of discoloration and subsurface hardening, additional treatment was added to mask the side effects (Alessandrini et al., 2011; Cantos et al., 2002; Jukanti, 2017). Over the past years, the awareness of quality has increased in general, including the large-scale food service systems. It has been known for a long time that industrial pre-treatment in combination with the cooking set-up applied in large-scale food service systems have contributed to subsurface hardening, but also a watery core. Since the process involves several steps that possibly affect the tuber quality along the entire process line, from entering the industrial peeler until being served to the consumer, there are several factors and their interactions to investigate to find and minimize the cause of the reduced quality.

There are several peeling techniques for industrial pre-peeling of potatoes. For potatoes aimed for SC, abrasion and knife peeling are most common. Other peeling techniques include a heating step, which would favour enzymatic activity and contribute to side effects (Garcia-Segovia et al., 2008; Robert and Fatih, 2017; Treadway and Olson, 1953). Abrasion peeling is performed by letting the tubers pass through a rotating drum with a rough surface, scraping off the peel. This method has a big mechanical impact on the tubers, where the cells close to the surface are torn apart. The peeling technique removes a relatively high degree of the peel in comparison to the amount of generated waste (Fouda et al., 2019; Sapers and Miller, 1993). Abrasion peeling and its effect on the cells has shown to contribute to subsurface hardening and discoloration to a higher extent compared to other peeling techniques (Gunes and Lee, 1997; Kaack et al., 2002b). Knife peeling is performed by letting the tubers pass over rotating discs with integrated knives. Knife peeling has a lower mechanical impact on the tubers compared to abrasion peeling, but blunt knives cause more damage compared to sharp knives (Artschwager, 1927; Kaack et al., 2002a; Kaack et al., 2002b).

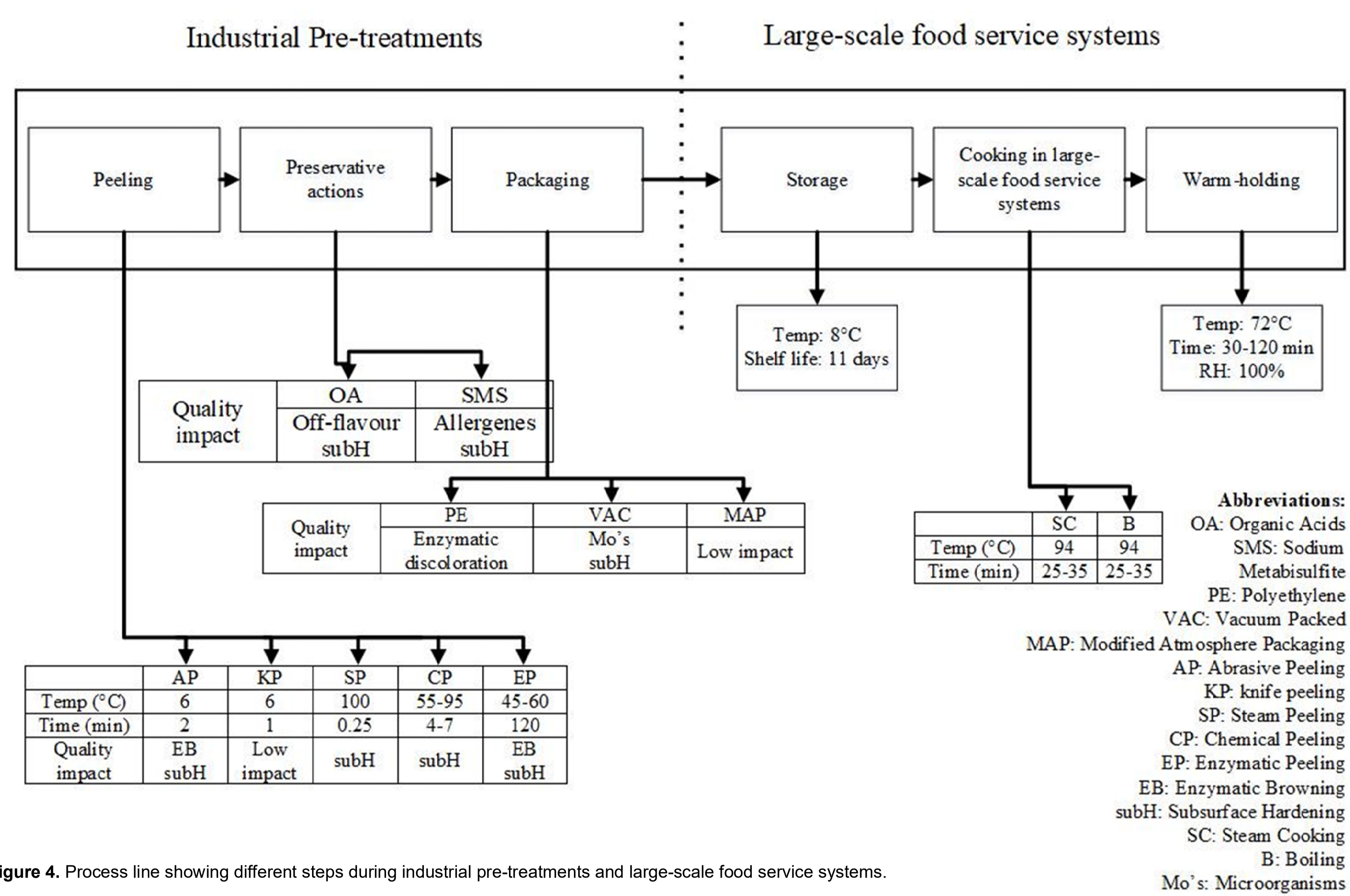



**Figure 4.** Process line showing different steps during industrial pre-treatments and large-scale food service systems.

Industrially pre-treated potatoes are consumed on average 5 days after peeling with a shelf-life of about 11 days. To ensure that the shelf-life is long enough, preservative actions are required to avoid microbiological spoilage as well as enzymatic discoloration (Santerre et al., 1991). Examples of actions prolonging the shelf-life are chemical pre-treatment, adapted packaging, and temperature control during the supply chain.

Chemical pre-treatment usually involves immersion of the peeled tubers in solutions of organic acids (OA) and/or sodium metabisulfite (SMS). Organic acids reduce the pH to a level unfavorable for PPO in combination with acting as a reducing agent, reducing enzymatic browning (Calder et al., 2012; Coultate, 2009). SMS reacts to sulfur dioxide ($SO_2$) in combination with water. Since $SO_2$ can pass the cell wall and react with the water in the cell, an antimicrobial effect is achieved (Feiner, 2006). SMS also acts as a reducing agent, preventing PPO activity from creating dark compounds, such as quinones (Coultate, 2009). Unfortunately, chemical pre-treatment has proven to have a negative impact on the quality of tubers in terms of off-flavors and contribution to subsurface hardening (Ceponis and Friedman, 1957; Ross and Treadway, 1961; Sapers et al., 1997; Svensson, 1971). The effect of chemical pre-treatment on the quality of the tubers has been reviewed in Paper I and studied in Paper II.

Different packaging techniques can also be used as a tool to decrease or completely prevent discoloration and antimicrobial growth. Vacuum packaging prevents PPO activity, preventing discoloration. The absence of oxygen also prevents the growth of aerobic bacteria. However, in some cases, anaerobic bacteria were detected and could thrive (Rajkovic et al., 2006; Solomon et al., 1994). The shelf-life of vacuum-packed tubers is also very short since enzymatic discoloration is initiated as soon as the package is broken. Controlling the atmosphere in the package, modified atmosphere packaging, is another technique to reduce enzymatic browning and increase shelf-life. By replacing the ambient air with different ratios of $O_2$ to $CO_2$ (with $N_2$ as void), the shelf-life is increased due to reduced enzymatic browning (Angós et al., 2008; Kaaber et al., 2002). Modified atmosphere packaging might contribute to surface hardening, but contradictive results have been reported (Angós et al., 2008; Dite Hunjek et al., 2020; Kaaber et al., 2002). Storage temperature has also shown to have a significant effect on the quality of tubers, where storage at higher temperatures contributed to subsurface hardening more than storage at temperatures around 4-5°C (Svensson, 1971).

After the industrial pre-treatment, the tubers are stored for several days to logistically manage transportation to and storage at the large-scale food service systems. During transportation and storage, the temperature has a high impact on the shelf-life of the tubers. Ceponis and Friedman (1957) reported that a quick cooling to refrigerated temperatures after packaging increased the shelf-life of the tuber by one day.

When industrially pre-treated tubers enter large-scale food service systems, cooking is mostly performed by SC. The impact on the cooking degree and sensorial perception by cooking technique was studied in Paper III. The sensorial analysis was performed by a semi-trained panel accustomed to handle and consume the tested product to standardize the results (except for general impression, where the individual liking and experienced eating quality were of interest). However, it is very hard to eliminate the subjective opinions. That, in combination with the high costs for sensorial analysis, increases the interest in finding a method to objectively measure parameters directly related to the cooking degree and eating quality. The softening procedure during cooking is affected by both cooking temperature and cooking time, where a longer time at a lower temperature can result in the same texture (Collison et al., 1980; Verlinden et al., 1995). Texture, and its relation to eating quality, has previously been evaluated by different techniques, for instance sensorially, textural, or by spectral imaging (Collison et al., 1980; Do Trong et al., 2011). To keep a pleasant eating temperature until serving, the tubers have to be warm-held. Warm-holding (WH) is an additional heating process after the original cooking is executed to ensure a pleasant eating temperature when the tuber reaches the consumer. A pre-study showed that a pleasant eating temperature is around 50°C -60°C (unpublished data). However, there is a risk of reduced eating quality due to continuation of the cooking process or lack of control of the temperature and relative humidity (RH), which has been studied in Paper II and IV. Previously, the national recommendation in Sweden was to keep a minimum temperature of 72°C for a maximum of 2 h. Thermal treatment of potatoes, WH being no exception, is known to be a cause of quality losses in terms of a reduction of Vitamin C and contribution to unpleasant textural properties (Ang et al., 1975; Fang et al., 2022; Karlström and Jonsson, 1977).

Several studies have been made with focus on the different processing steps, but most of them have standardized or simplified the processes in different ways, like cutting the tubers into perfect cubes or boiling them in water baths. Those adaptions simplify the experimental design and are of big importance to understand the phenomena occurring during the process. However, the methods often deviate too much from reality for implementation in large-scale food service systems. This is a big and important gap to fill within today’s knowledge field. Therefore, the research behind this thesis aims to combine scientific results and understanding with handling applicable in the everyday reality of large-scale food service systems.

# Objectives and Thesis Overview

The general objective of this thesis is to develop knowledge and tools to increase the eating quality of industrially pre-treated, steam-cooked potatoes served at large-scale food service systems. The focus has been on understanding the mechanisms contributing to subsurface hardening and the formation of a watery core, as well as investigating the cooking step in the process. The four papers have examined individual steps or combinations of steps in the process-line (Figure 5), and their impact on the eating quality.

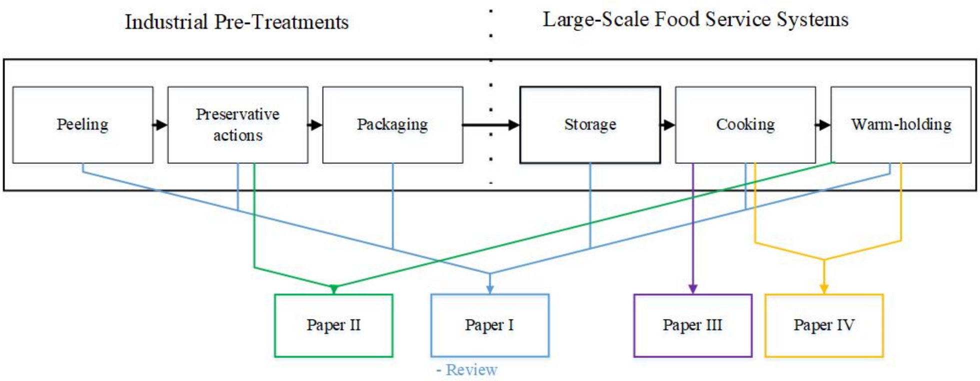



**Figure 5.** Graphical overview of the process-line, and relation to the scientific papers in this thesis.

The objectives are specified as follows:

- Identification of pre-treatment steps lowering the quality of potatoes served at large-scale food service systems (Paper I, II, and IV).
- Understanding the mechanisms causing subsurface hardening of industrially pre-treated tubers (Paper I and II).
- Evaluation of the impact of cooking and warm-holding set-ups on softening, and how to achieve a good eating quality based on textural and sensorial results (Paper II and IV).
- Understand and predict when a potato is considered cooked (Paper III).

# Methodology

## Potato properties

Different varieties of potatoes behave differently when industrially pre-treated and cooked due to physiological differences. To understand the impact of variety on the quality and appearance of potatoes served in large-scale food service systems, several varieties were included in the different studies. Some results are evaluated in the Papers, while others are presented in the thesis as parts of unpublished results (Table 2). Some tubers can be easily categorized based on character, while others vary depending on, for instance, year of cultivation, and circumstances in the cultivation area (Voisey et al., 1969). Bintje is an example of this. Even though all tubers used for the research behind this thesis were grown in southern Sweden, local variations had a significant impact on the cultivation. The Bintje tubers used for Paper III were bigger and shaped like an ellipsoid, compared to the Bintje tubers for Paper II and IV which were smaller and more spherical. These differences affect the cooking process due to differences in heat transfer through the tubers. Within each experimental setup, attention has been paid to ensure that tubers of similar size have been used, determined by radius or weight.

**Table 2.** Potato varieties evaluated in the thesis and Papers, with different internal characters and shapes.

| Variety | Character | Shape | Studied in Paper: |
|---|---|---|---|
| Asterix | Firm | Ellipsoid | Paper III |
| Bintje | Mealy/firm | Sphere/ellipsoid* | Paper II, III, and IV |
| Salome | Firm | Sphere | Paper III |
| Fakse | Firm | Sphere | Paper II and IV |

*differs due to different cultivation years and areas

The main component of potatoes is water, followed by starch. These are the two components of potatoes that might vary to any large extent. The water content of tubers might vary depending on variety, part of the tuber, cultivation, storage, etc. The water content of the pith is higher compared to regions closer to the surface. Since starch has a higher density compared to water, differences in density have been used as a quick method to determine starch content. The most common method is determination of underwater weight, where the weight under water of a certain tuber mass is determined (Simmonds, 1977; Verma et al., 1975). This method is useful for industrial pre-treatment facilities as a quick control of the tuber properties. Since mealy varieties often have a higher starch content compared to firm varieties, characteristics associated with variety type can be revealed by analyzing the starch content. In Paper II, III, and IV of this thesis, the starch content was assumed to be proportional to the dm of the tuber, and analyzed by drying the samples in an oven at 102°C until a constant weight of the sample was achieved.

# Polyphenol oxidase activity during long-term storage

During long-term storage, the tuber enters a resting state called dormancy, where cellular activities in the potato tuber are reduced. This affects the storage possibilities enabling storage for up to 11 months (with variation depending on potato variety as well as individual differences). It also affects the behavior of the tuber during industrial processing (Alamar et al., 2017; van Ittersum, 1992). In addition, the reduced cellular activity is believed to reduce the PPO activity of industrially pre-treated potatoes. This is of importance since enzymatic discoloration is one of the main factors limiting the shelf-life. By knowing the changes in PPO activity during the entire storage period, the preventative chemical treatment could be optimized to minimize side effects with a negative impact on the quality.

The activity of PPO during storage for 30 weeks was analyzed as an initial study (unpublished data). The analysis was performed according to Cornacchia et al. (2011), where an extract from the tuber was added to catechol. The oxidation level of catechol was determined spectrophotometrically and was assumed to be proportional to the enzymatic activity of the tuber.

# Chemical preservation

To avoid enzymatic browning, chemical preservation can be applied. Commonly, organic acid (OA) and sodium metabisulfite (SMS) are applied, either combined or individually. Several scientific studies as well as experiences from the industry have reported that chemical preservation contributes to subsurface hardening of the tubers. To analyze the impact of chemical preservation, the tubers were dipped in different solutions consisting of OA and/or SMS, similar to the solutions applied in industrial pre-treatments. However, since the mechanical impact on tubers pre-treated industrially is bigger compared to the tubers pre-treated on laboratory or pilot scale, and generally contributes to higher stress levels of the tubers, the chemical preservation did not seem to have any significant impact on subsurface hardening (Kaack et al., 2002a). To be able to analyze the impact and study the structural changes caused by chemical preservatives, the treatment was intensified in terms of time and concentration in Paper II, where the following treatments were applied: Ref (dipping in water), OA (0.5% ascorbic acid + 0.5% citric acid for 60 min, pH 2.4), SMS (5% Sodium metabisulfite for 20 min, pH 4.1) and OA+SMS (OA followed by SMS).

## Dimensional changes during cooking

To understand the fundamental changes during cooking on a cellular level (where several phenomena affecting the eating quality are found), mapping of physical changes on a tuber level is required as well. During cooking, water plays several roles: the tubers are surrounded by water or saturated steam as heat transfer media, water can pass collapsed cell membranes easily and water is bound to starch during gelatinization. To further understand the impact from water and its movements on the tuber eating quality, tubers were weighed at different stages of the process (raw, after cooking, and continuously during WH for Paper II). Density was determined by analysis with a volume meter (Paper IV), whereafter it could be concluded that volume and density were not affected by cooking to different core temperatures.

## Texture analysis

To determine the cooking degree or organoleptic quality-related issues of a sample, the texture is very important. Identifying the cooking degree of tubers, as well as when a good eating quality in relation to cooking degree has been achieved, is challenging (Singh et al., 2008). Texture analysis is a tool to determine the hardness objectively and has played a crucial role in Paper II, III, and IV. A method optimization was conducted in Paper IV.

There are several methods to determine the texture of a sample, and different techniques are used for different purposes (Liu et al., 2019). In this thesis, puncture by sphere and cylinder, shear by cutting, and compression methods have been evaluated (Figure 6).


**Figure 6.** Probes used for evaluation of texture by a) puncture with cylindrical probe, b) cutting, c) compression, and d) puncture with spherical probe.

Puncture by a spherical probe analyses the hardness of a certain spot, and the spherical shape helps eliminate impact from irregularities on the tuber surface (Figure 7). The probe is blunter compared to a cylindrical probe. A blunter probe requires more force to penetrate the sample, which usually also entails bigger differences in the results. In an unpublished pre-study made by the author, the bluntness of the spherical probe resulted in cracks at the surface instead of penetration as well as movement for some of the samples. Those textural results are then not reliable since the measured forces are not exclusively caused by resistance of the sample surface.

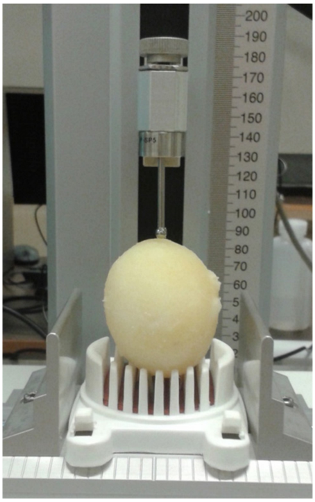


**Figure 7**. Texture analysis of a whole potato tuber by puncture with a spherical probe. The picture was taken by the author.

The force required to puncture a sample can be measured by puncturing the sample with a cylindrical probe of a significantly smaller size than the sample surface. This method also analyzes the hardness at a specific spot of the tuber, and with extra attention paid to placing the sample with a horizontal area facing the probe, the method has proven robust by a pre-study executed by the author. Some uncertainty might be explained by difficulties in detecting the watery eyes of the tubers once peeled and cooked, where the texture is assumed to differ compared to the parenchyma region. Depending on the probe size, the results differ: a smaller probe has less impact on the entire sample and requires a smaller force to penetrate the sample compared to a larger probe which reduces the risk of cracks to appearing or the sample sliding away. However, the small probe becomes sharper and is less sensitive in detecting structural differences. For Paper III, a puncture probe of 3 mm was applied to analyze the hardness at the core of the sample by puncturing half a tuber from the center, see Figure 8. For Paper II and IV, the structure of the entire tuber was of interest, and a puncture probe of 5 mm was used at the surface of the tuber, which also increased the detected differences without increasing the risk of cracking the sample.

The knife probe is semi-sharp and simulates cutting the tuber with a table knife. When evaluating eating quality, cutting is an important aspect. A knife probe is sensitive to the contact area, where a sample with a large contact area requires a larger force to be cut compared to a sample with a small contact area, even though the hardness of the samples might be the same. Due to differences in shape, depending on variety but also individual tuber characteristics, the contact area of the probe differs for different samples, which likely caused some variation in the results.

To understand the internal texture of samples, a compression test can be performed by using a cylindrical probe with a diameter larger than the sample. By compressing the tuber with the large cylindrical probe, the internal structures of the tuber are ruptured. However, a hard outer surface could still be supportive in terms of increased resistance since it holds the entire tuber together.

In Paper III, the cooking degree of the tuber was analyzed. Therefore, the texture was measured at the core of the tuber as mentioned above, see Figure 8. Each tuber was cut in half and placed in an egg holder to ensure a fixed position and analyzed with a cylindrical probe with a diameter of 3 mm. Analysis was performed in triplicates at both the pith and parenchyma zone.

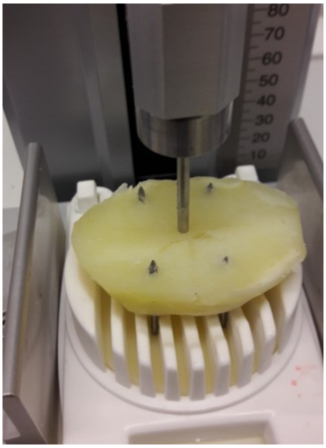



**Figure 8.** Texture analysis by puncture probe at the core of a tuber. Photo taken by the author.

# Sensorial evaluation

To find potatoes served at large-scale food service systems appealing, the appearance and organoleptic properties are of big importance. By sensorial analyses, it is possible to get a value on how the consumers experience the potatoes and their eating quality. Non-measurable values, such as general impression or perceived cooking degree, can be detected. However, sensorial analyses are often expensive, and even though training sessions aim to equalize the results, there is a risk of subjective opinions taking over. To be able to analyze the cooking degree and general impression more objectively, Paper III includes a sensorial analysis of tubers cooked to different cooking degrees, where the sensorial results are correlated to texture results. This enables repeatability of the analyses as well as objective comparisons but is still related to consumers' perceptions.

# Microscopic imaging

Most changes related to softening during the cooking of potatoes occur at a cellular level, with changes in and between cell walls involved. Several of those changes can be detected by microscopic imaging. Depending on the type of sample, the best suited type of microscope might differ. Light Microscope (LM), for instance, uses bent lenses for magnifications, where the sample is studied through oculars and analyzed based on how light is scattered when passing through it (Paper II). Another technique for visual examination is Scanning Electron Microscopy (SEM), where electron beams are shot at the sample, and the scatter of reflected electrons is detected and visually combined into an image of the sample (Paper IV).

## Differential Scanning Calorimetry

During the cooking of potatoes, several different physical changes occur during the process based on both temperature and time. Most of the physical changes are endothermic, enabling detection of the exact temperature where the change occurs. Differential scanning calorimetry (DSC) lets heat pass through a sample at a controlled rate and detects how much of the heat is transported through the sample, and how much that is absorbed. The amount of absorbed energy is assumed to contribute to structural changes of the sample, for instance in terms of starch gelatinization or retrogradation. In some rare cases, like melting of crystalline structures or hydrolysis of polymers at high temperatures, exothermic reactions can be detected in food (Bogracheva et al., 2006; Liu et al., 2002; Sievert and Wuesch, 1993).

## Respiration and packaging material

A response to industrial pre-treatment is stress and can be detected by for instance increased respiration (Hunjek et al., 2020). During respiration, $O_2$ is consumed, and $CO_2$ is released. The chosen packaging technique and material affect the gas composition surrounding the tuber, which might affect the stress level and respiration of the tuber even more (Gunes and Lee, 1997). A method to estimate the level of stress and respiration of the tubers is by determining the gas composition in the ambient top space of the package, where the characteristics and permeability of package consisting of a 5 µm thick polyethylene film affect the ambient gas composition. To understand how potato tubers respond to stress caused by the environment in the package, tubers with different pre-treatments were packed and stored at different temperatures (unpublished data). The gas composition in the top space was determined using a gas analyzer (Checkmate 9900, Dansensor, Denmark).

# Multivariate analysis

Multivariate analysis is a powerful tool to analyze complex data sets with several variables with potential interactions. It was used in Paper III and IV. In multivariate analysis, a model is created based on the existing data and this model is validated either based on included or excluded data points. Partial Least Square (PLS) Regression uses both the input variables, which are the parameters designing the experiment, and the output variables, which are the results obtained, to design a model explaining the correlation between all the variables.

# Results and Discussions

## Potato tuber

The different potato characters can partly be described by physiological differences, like starch content, dm content, cell size, or cell wall thickness. Several screenings of density and dm have been conducted to explain possible patterns and connections between fundamental physiological properties and eating quality of the cooked tuber (Table 3). No differences in density based on variety were detected. Bintje tends to have a higher dm content compared to the firmer varieties, but other factors such as cultivation area and year has a significant impact on dm as well.

**Table 3.** Fundamental characteristics of the varieties included in this thesis presented as average of n>3 ± std. Abbreviations: n.d.: not determined

| Variety | Character | Density ($kg/dm^3$) | Dm average (% w/w) | Studied in Paper: |
|---|---|---|---|---|
| Asterix | Firm | n.d. | 18.1 ± 1.0 | Paper III |
| | | | 19.8 ± 0.9 | Unpublished results |
| Bintje | Mealy/firm | 1.11 ± 0.02 | 22.7 ± 1.5 | Paper II |
| | | | 22.2 ± 1.0 | Paper III |
| | | | 20.3 ± 2.2 | Paper IV |
| Salome | Firm | 1.13 ± 0.01 | 23.3 ± 1.2 | Paper III |
| | | | 18.3 ± 0.7 | Unpublished results |
| Fakse | Firm | 1.11 ± 0.02 | 21.8 ± 0.9 | Paper II |
| | | | 19.3 ± 0.7 | Paper IV |

When preparing potatoes by industrial pre-treatment, one of the main issues is enzymatic discoloration. Figure 9 shows results indicating PPO activity for Fakse and Salome of hand-peeled tubers during storage for 30 weeks (unpublished results). The enzymatic activity is higher for Fakse than Salome. There is also a decrease in enzymatic activity between 5 and 13 weeks of storage. During this period the tubers likely entered dormancy. The dm of the samples did not differ significantly, which indicates that the internal structures or components are responsible for the differences in enzymatic activity.

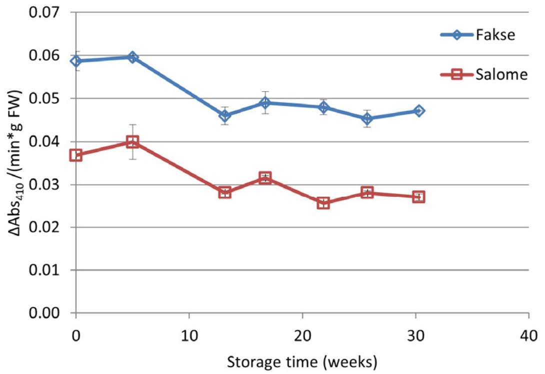



**Figure 9.** PPO activity shown as a relative value on the y-axis during storage of potato for variety Fakse and Salome respectively.

# Industrial pre-treatment

## Preservative Actions and Packaging

Today, there are several peeling techniques available for industrial pre-treatment, which are often combined with preservative actions to avoid enzymatic discoloration (Paper I). However, the preservative actions often cause stress reactions in the tubers, which previously have been shown to increase the respiration (Petri et al., 2008; Rocculi et al., 2007). Screening experiments were conducted to evaluate the effect of an industrial pre-treatment of potatoes on respiration by comparing tubers of variety Fakse being 1) unpeeled, 2) hand-peeled, and 3) pre-treated in a large-scale industrial line. This was done by monitoring the gas composition inside bags of unpeeled (Figure 10a), hand-peeled (Figure 10b), and industrially pre-treated (Figure 10c) tubers for 6 days stored at 6°C and 15°C, respectively (unpublished data). The rate of changes in gas composition differed depending on the pre-treatment, with industrially pre-treated tubers changing the fastest followed by hand peeled and lastly unpeeled tubers, pointing at an increased respiration rate caused by increased mechanical and chemical impact during pre-treatment. Both unpeeled and hand-peeled tubers seem to reach a steady-state, where the respiration rate and gas transmission rate through the package is equal within the studied storage period. Industrially peeled tubers, on the other hand, keep an intense respiration rate throughout the studied storage period, most likely since the pre-treatment induced higher stress levels. This agrees well with the results presented by Rocculi et al. (2007) and Petri et al. (2008). Storage temperature had a low impact on respiration in this experimental set up. Some data is missing due to leaking packages.

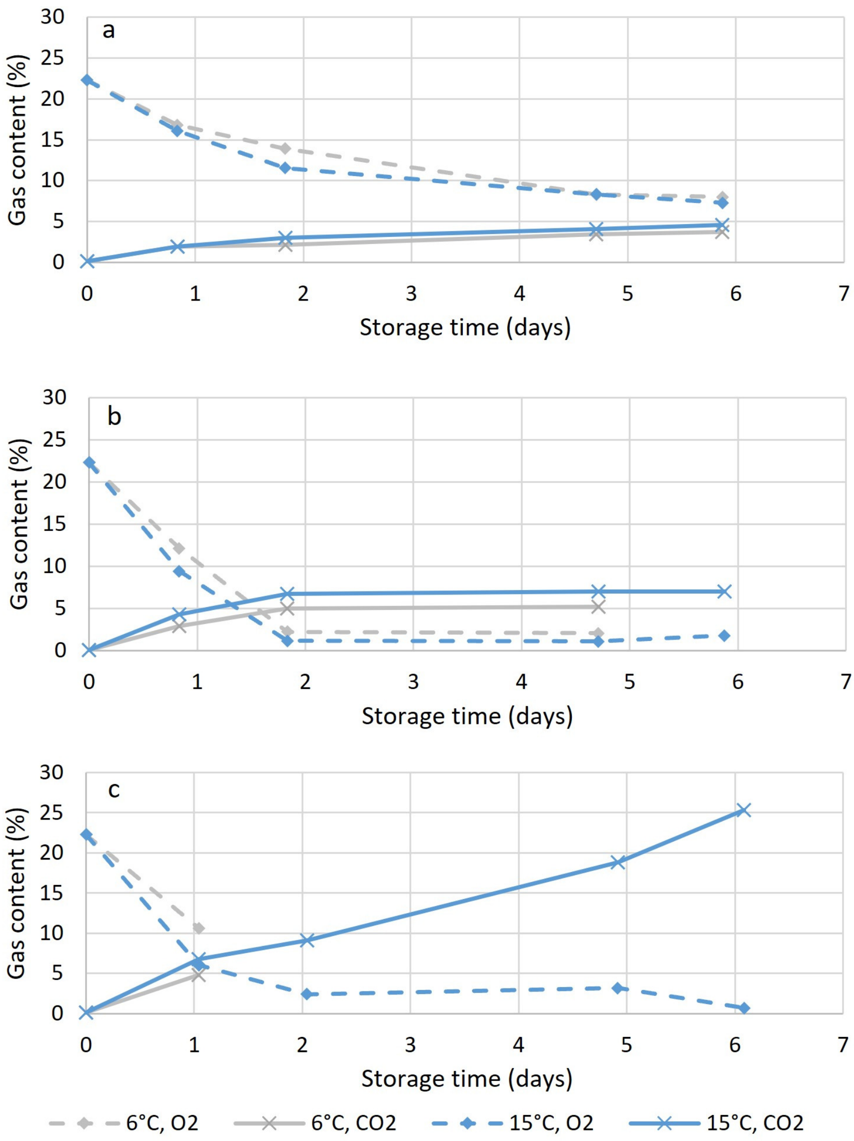



**Figure 10.** Gas composition in the void space of bags packed with a) unpeeled, b) hand-peeled, and c) industrially pre-treated potatoes of variety Fakse.

Chemical pre-treatment has also been reported to increase the stress and cellular activity, contributing to subsurface hardening (Sapers et al., 1997; Svensson, 1971). The effect of chemical pre-treatment was further studied in Paper II, where tubers were treated with OA, SMS, or OA+SMS before cooking until the core had reached

94°C. Texture analysis by puncture method of the cooked tubers showed a trend of increased hardness for tubers where chemical pre-treatment was applied (Figure 11). The biggest effect was seen for OA+SMS. For all treatments, Faske was slightly harder than Bintje.

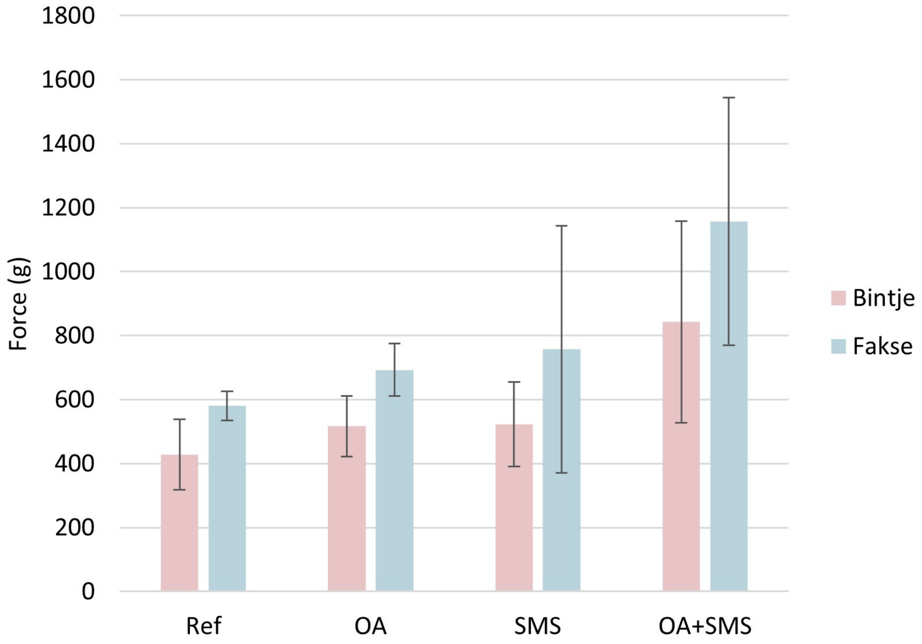



**Figure 11.** Peak force of chemically pre-treated Bintje and Fakse cooked to 94°C.

The textural differences caused by chemical pre-treatment were confirmed by visual analysis and imaging by LM of cooked potato. Visual analysis revealed that treatment with SMS or OA+SMS contributed to a thick, tough layer at the surface that tended to separate from and fall off the internal part of the tuber (Figure 12). OA did not show the same effect as SMS, but imaging by LM showed that the formation of brick-like cells consisting of 1-11 cell layers at the surface of the tuber was common for tubers treated with OA or OA+SMS, but not detected for tubers treated with SMS only (Figure 13). These two mechanisms of subsurface hardening seem to be independent of each other and, based on the texture of tubers treated with OA+SMS, exert an additive effect in terms of subsurface hardening, explaining the trend of increasing hardness for OA+SMS in Figure 11.

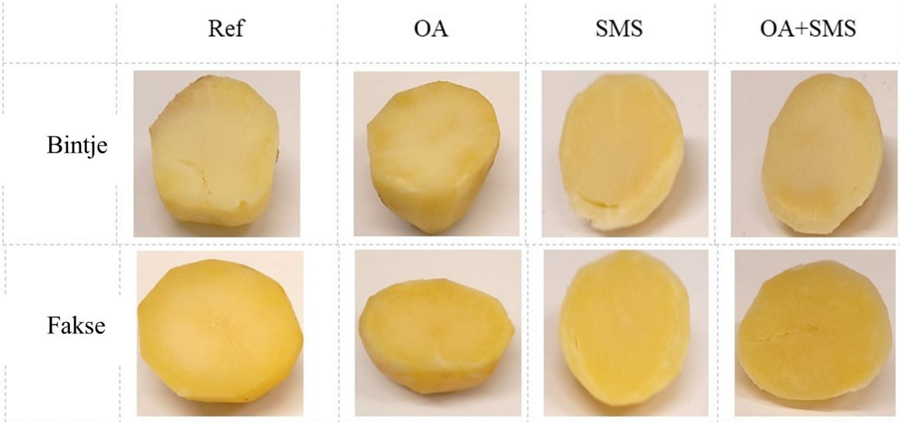



**Figure 12.** Potatoes of variety Bintje and Fakse with different pre-treatments cooked to 94°C before cut in halves. SMS contributes to the separation of the outer layer.

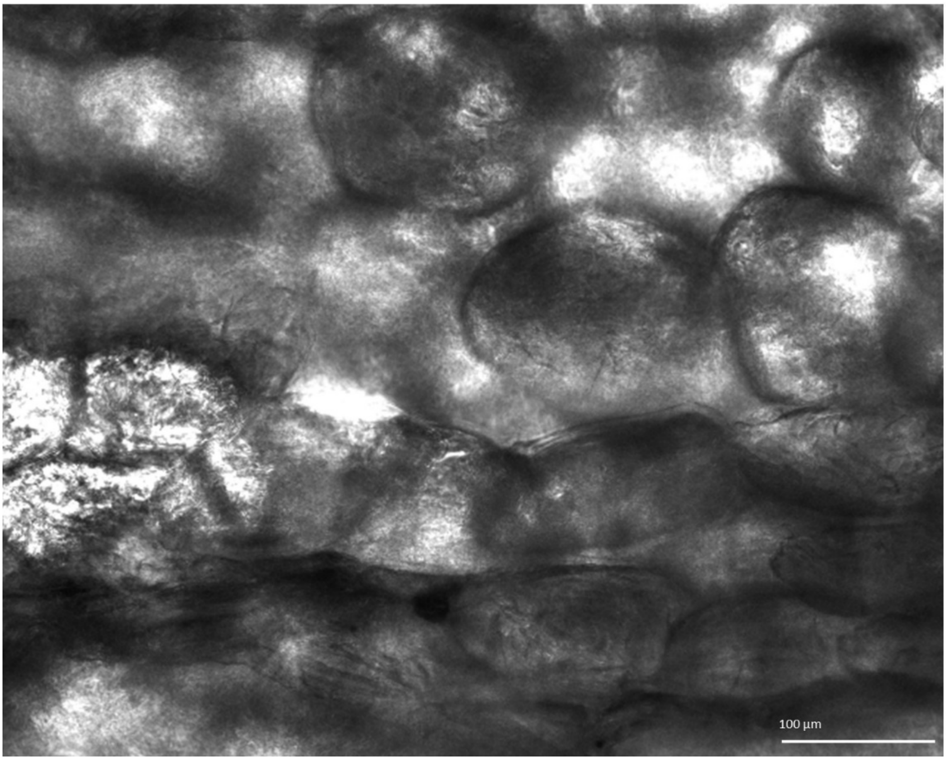



**Figure 13.** The formation of brick-like cells can be seen in the lower part of the picture, towards the surface of the sample for Bintje pre-treated with OA and WH at RH100%.

# Large-Scale Food Service Systems

## Cooking

During thermal heat treatment, like conventional boiling (CB) or steam cooking (SC), softening of the tuber tissue occurs, which was reviewed in Paper I. The intercellular structure and connections have proven to play a significant role in the softening procedure (Jobe et al., 2016). Intercellular interactions of mealy varieties seem to be weaker compared to firm varieties, resulting in a higher degree of cell separation instead of cell rupture upon cooking (Jarvis and Duncan, 1992; van Marle et al., 1997; Zdunek and Umeda, 2005). The cellular behavior of cooked tubers of variety Bintje (mealy/firm) and Fakse (firm) was studied in Paper IV by imaging with SEM (Table 4 and 5) and Paper II by imaging with LM. No differences in cell sizes or cell wall thicknesses were detected, but the characteristics of the cell walls differed. When imaged by SEM, Bintje showed fewer sharp edges of the reptured cell walls when cooked to 90°C and cell separation when cooked to 90°C with 30 min WH or cooked to 98°C, while Fakse had very sharp edges when cooked to 90°C, and rupture of cells occurred at all cooking set-ups. Imaging by LM of Fakse and Bintje in Paper II (and Amadine and Asterix, unpublished data) show that all cooked samples of those varieties tend to experience cell separation instead of cell rupture upon cooking, independent of cooking degree. This means that Fakse showed different cellular behavior after cooking at those two cooking occasions (when imaged by SEM compared to LM). Since the cutting procedure of the sample is identical, the different behavior probably depends on characteristics of the tuber caused by external factors, such as cultivation and storage, or structural differences created during cooking, since the dimensions of the samples for SEM and LM differed during cooking (cuboids and whole tubers, respectively).

**Table 4**. Scanning Electron Microscopy (SEM) pictures of Fakse with x50 and x1000 magnification, respectively.

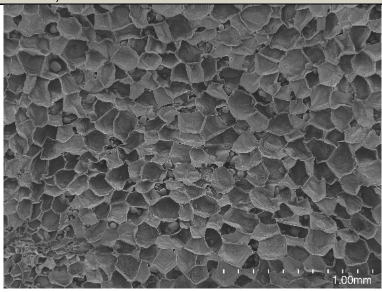
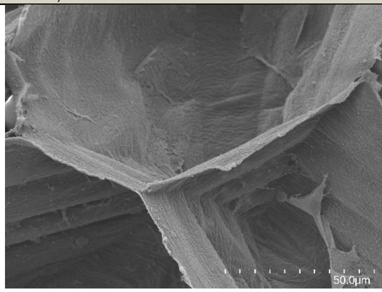
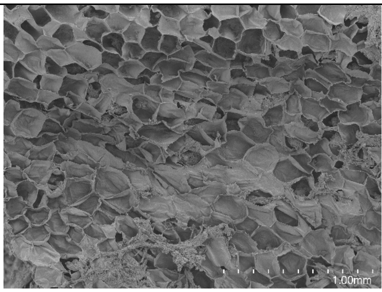
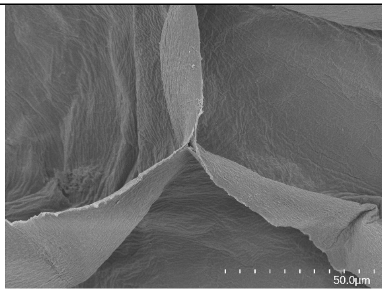
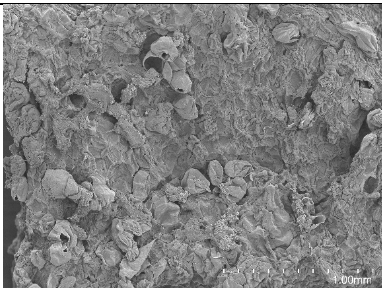
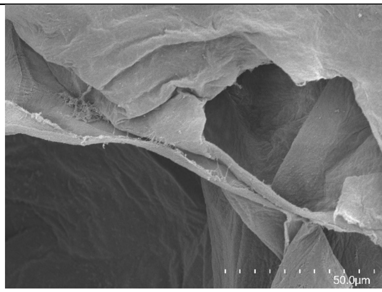
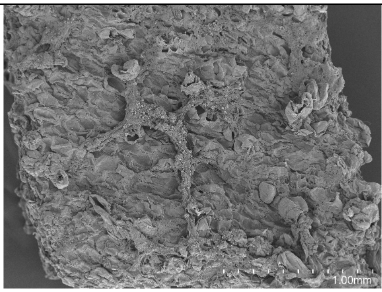
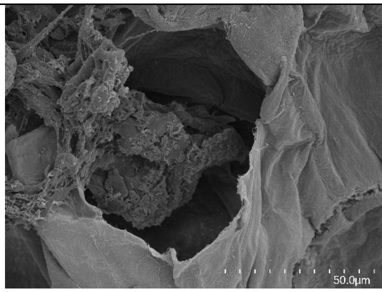
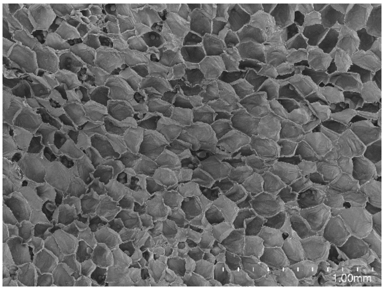
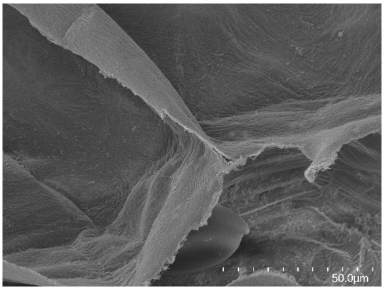
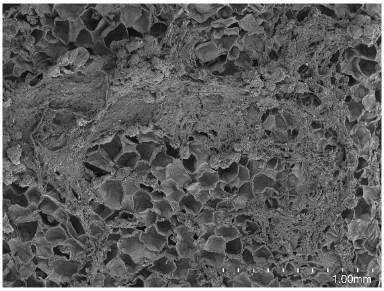
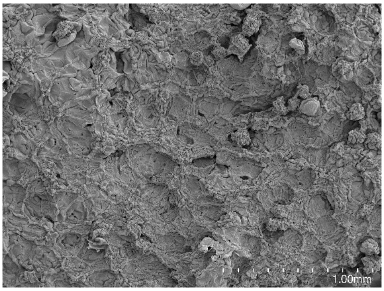
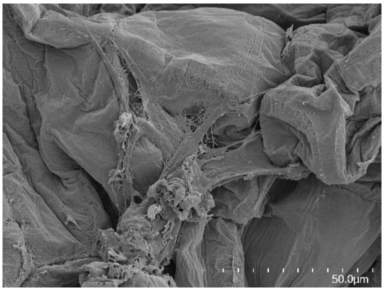
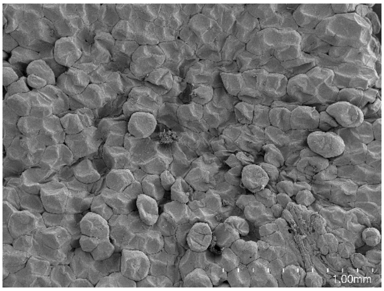
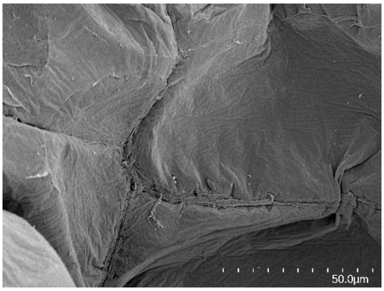
| | Fakse, x50 | Fakse, x1000 |
|---|---|---|
| Raw |  |  |
| 90°C |  |  |
| 90°C, WH72°C, 30min |  |  |
| 98°C |  |  |

**Table 5.** SEM pictures of Bintje with x50 and x1000 magnification, respectively.

| | Bintje, x50 | Bintje, x1000 |
|---|---|---|
| Raw |   |   |
| 90°C |   |   |
| 90°C, WH72°C, 30min |   |   |
| 98°C |   |   |

The degree of softening for different core temperatures during cooking can be objectively analyzed by texture analysis. In Paper III, the tubers were cut in halves and analyzed from the core to identify the optimal cooking degree among the varieties Asterix (firm), Bintje (mealy), and Salome (firm) prepared by CB and SC, respectively (Figure 14). In general, cooking to a higher temperature resulted in a softer tuber, as expected. For Bintje, CB seemed to contribute to a softer tuber compared to the same cooking temperatures at SC as well as CB of the other, firm varieties. It has previously been reported that mealy varieties are generally considered cooked at lower temperatures than firm varieties (Bordoloi et al., 2012). This agrees well with the achieved results, where Bintje tubers cooked to 94°C and 96°C, cooked with both CB and SC, are softer than the firm varieties (except Salome cooked with SC to 96°C). Texture analyses in Paper II and IV revealed only small textural differences based on variety for samples cooked by SC. SC is a gentler cooking method since the tubers are placed on a tray and remain there during the entire cooking process. During CB, the tubers are affected by turbulence and collide with other tubers. Since mealy varieties are more likely to develop cell separation as a softening mechanism, the cell separation might be increased for CB compared to SC. This would be of interest to investigate further by cooking different varieties with varying degrees of mealiness, and by studying cooking methods with different degrees of mechanical impact.

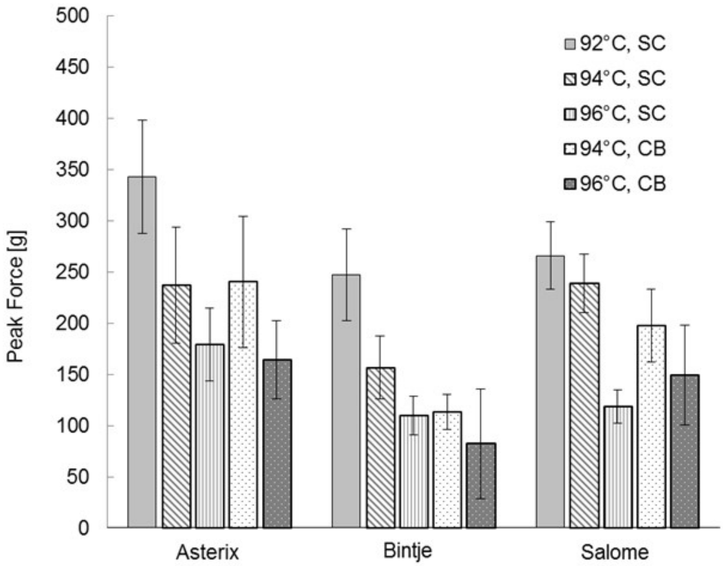



**Figure 14.** Peak force dependent on variety, cooking technique, and temperature.

The texture analysis of Asterix, Bintje, and Fakse was complemented with sensorial analyses, performed by a semi-trained panel with participants accustomed to consumption and/or preparation of products in large-scale food service systems (Figure 15). The sensorial results for softness and cooking degree correlate well with the texture results presented in Figure 14 when comparing the relationship between the different varieties for each cooking setup, but also regarding cooking temperature. However, Bintje deviates from the pattern when SC to 92°C and 96°C, where the sensorial analysis indicates a relatively harder sample than the texture analysis.

To understand the softening process of the surface and identify the occurrence of subsurface hardening, the texture of the tubers' outer part was analyzed. In Paper II and IV, differences caused by cooking temperature and chemical pre-treatment were investigated. Since cylindrical probes of different diameter have been used when analyzing the core (3 mm) compared to the surface (5 mm), the required force would have to be corrected based on the contact area of the probe to be comparable. Collison et al. (1980) previously reported that there were clear correlations between sensorially judged cooking degree and textural evaluation, which agrees with the results presented in Paper IV.

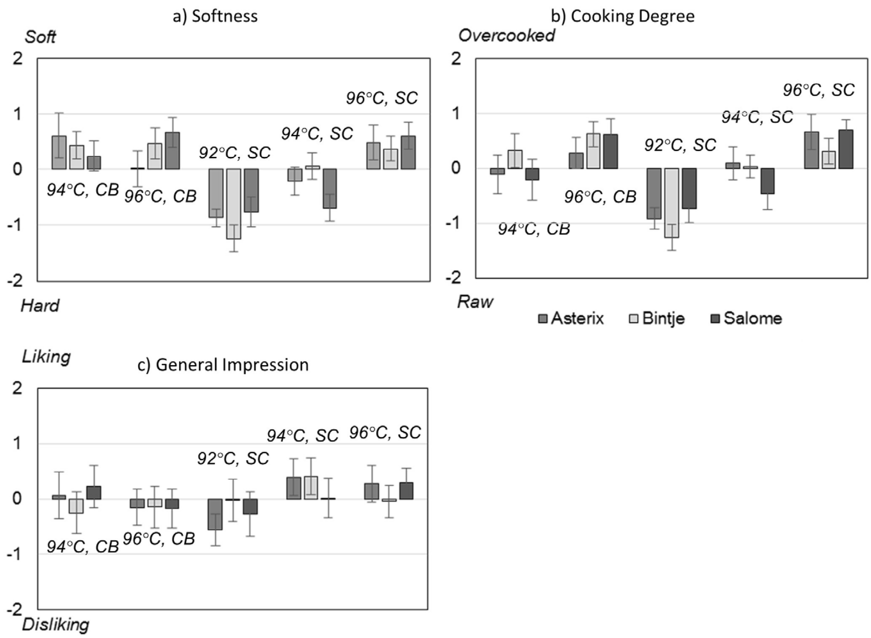



**Figure 15 a-c.** Normalized and standardized results from the sensorial analysis for a) Softness, b) Cooking Degree and c) General Impression.

Multivariate analysis is a tool to gain a better understanding of situations containing many parameters. One method within multivariate analysis is PLS, which was applied in Paper III to reveal correlations between the cooking set-up, texture analysis, and sensorial analysis (Figure 16). The different texture attributes, peak force and peak time, are located close to each other, showing that they are highly correlated. They also correlate positively with the variety Asterix, but negatively to Bintje, and are placed almost orthogonal to achieved core temperature. This shows that the textural variation between varieties has a larger impact on texture than cooking temperature based on this model. Among the sensorial parameters, general impression and textural attributes are related, showing that textural analysis can be used to estimate the overall liking of potatoes. Sensorial determined cooking degree and softness are harder to measure by texture analysis and seem to be more related to cooking methods.

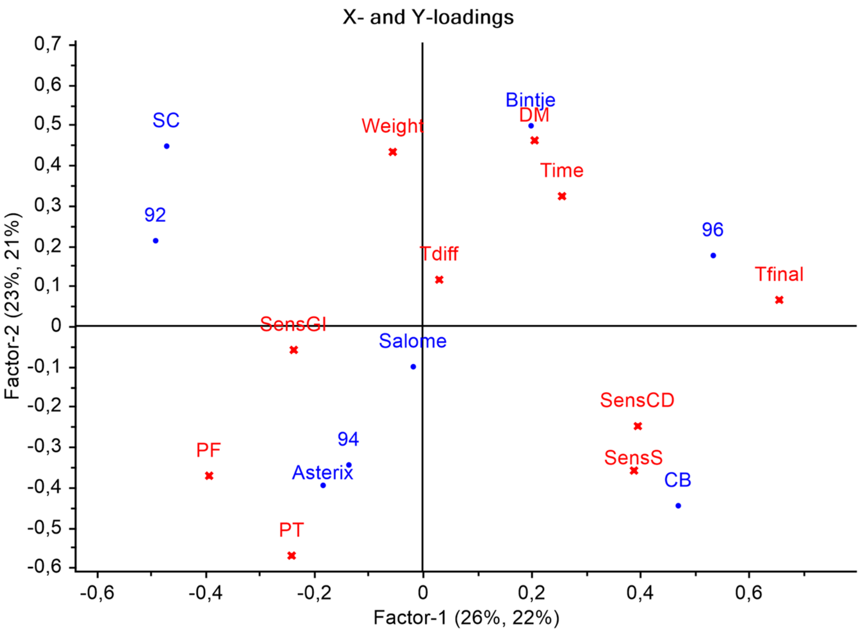



**Figure 16.** PLSR (Factor 1 and Factor 2) shows relations between the predictors (marked with blue •) and variables (marked with red x) for different attributes. The degree of explanation and validation, respectively, for each factor is presented within brackets. Abbreviations used for this graph: SC-steam cooking, CB-conventional boiling, 92, 94, 96-aimed core temperature, Tfinal-achieved core temperature, Tdiff-deviation in final temperature compared to set temperature, Time-cooking time, PF-peak force, PT-peak time, SensGI-general impression determined sensorially, SensCD-cooking degree determined sensorially, SensS-softness determined sensorially.

## Warm-holding

Warm-holding (WH) is executed in ovens with saturated steam or in a closed vessel. In Paper IV, the effect on cooking degree from WH is studied. It was concluded that WH contributes to continued cooking, and the continued softening is more pronounced for WH at 90°C compared to 72°C. Results in Paper II confirm that the tuber quality might be negatively affected by WH, both in terms of a watery core due to overcooking but also dehydration at the surface for WH at RH<100%. If RH is lower than 100%, evaporation of water occurs (Figure 17). LM images shown in Figure 18 reveal structural changes at the surface due to dehydration in terms of curly cell walls, which could be compared to the tough layer caused by the formation of brick-like cells as a result of chemical pre-treatment with OA seen in Figure 13. Dehydration contributes to increased hardness independent of chemical pre-treatment, as a third independent mechanism. A watery core is detected to a higher extent for WH at RH100%, but increased softness was also detected for tubers warm-held at 90°C. This indicates a continuation of the cooking process during WH. To compensate for this, the tubers can be slightly undercooked in the original cooking process, which enables a good eating quality after WH.

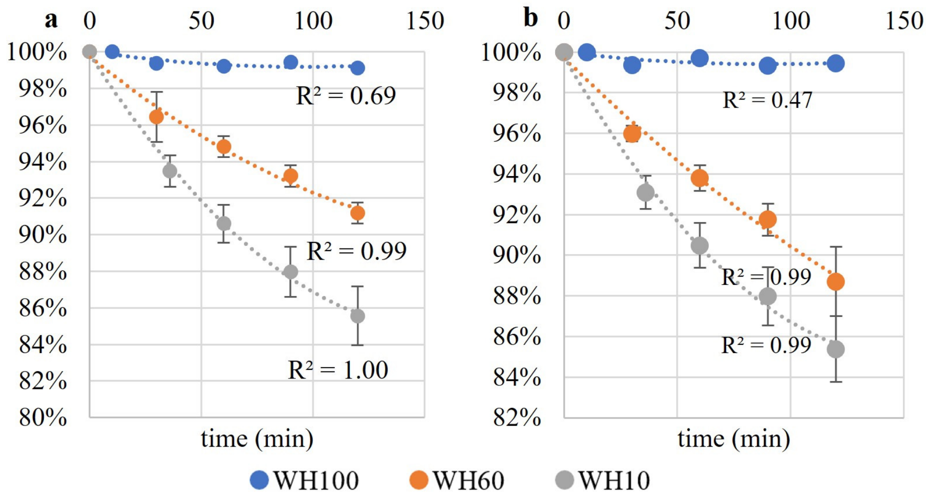



**Figure 17**. Weight loss for a) Bintje and b) Fakse during WH for 120 min at different RH, with percenutell weight loss compared to a cooked tuber without WH on the y-axis.

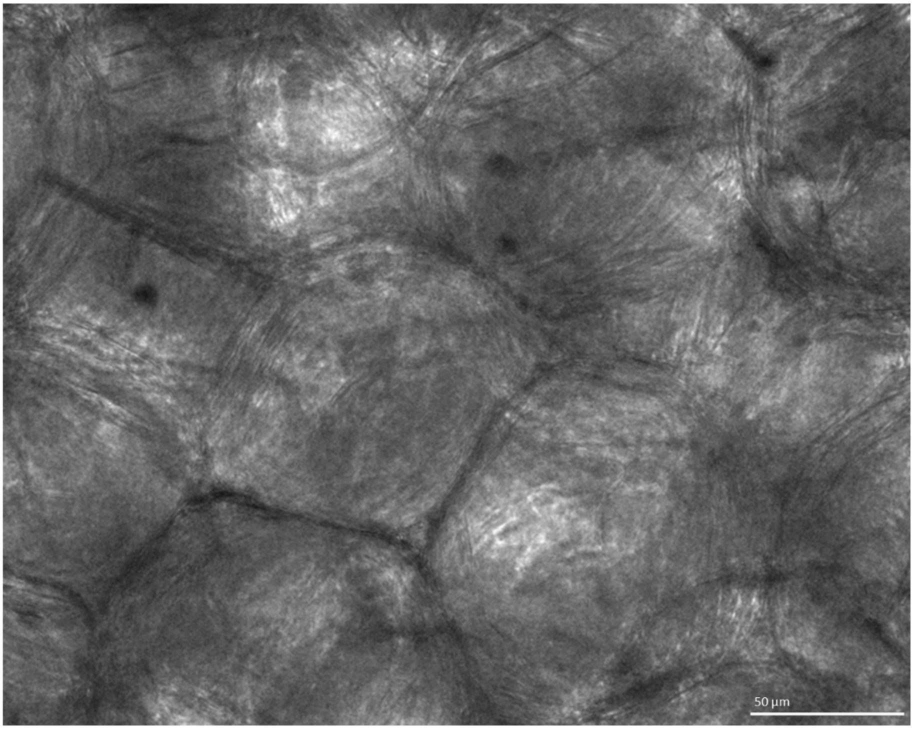



**Figure 18.** Fakse was pretreated with OA+SMS and WH at 10%. RH The cell walls show a rough pattern, probably due to dehydration.

The effect on the quality of the tuber caused by different WH setups has been analyzed by the multivariate technique PLS (Paper IV). The model can be seen in Figure 19 and reveals a strong correlation between all texture attributes and low cooking temperature. WH temperatures also correlate with texture, with a lower temperature resulting in a harder tuber. WH time does not seem to have any particular impact, where the outcomes are located closer to the center of the model. The two analyzed varieties, Bintje and Fakse, differed geometrically, where Bintje was shaped more as an ellipsoid compared to the spherical Fakse. These differences were explained by Factor 2 but had relatively low impact on the texture.

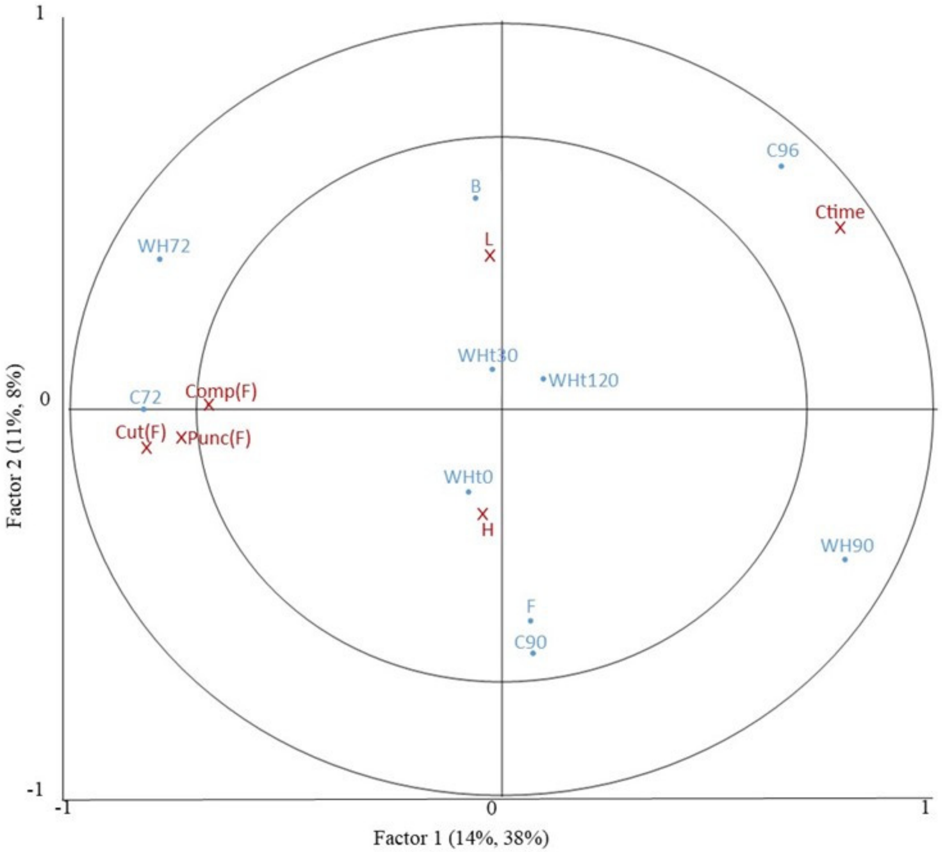



**Figure 19.** PLS presents relations between textural parameters and cooking/WH setup.

Comparing the PLS models describing the relation between cooking setup parameters and texture in Paper III (Figure 16) and Paper IV (Figure 19) shows some fundamental differences. The model seen in Figure 16 has a higher explanation and validation degree (seen in the brackets along the axis of the graphs) as well as more scattered parameters in the model, indicating a more complex model. The objectives of the two studies differed, where Paper III aimed to investigate the cooking degree of a tuber, while Paper IV aimed to analyze the impact of WH on the tuber and its surface. To meet the aims, the textural analysis for Paper III was performed from the center of half tubers, at the core where softening occurs last, while textural analysis for Paper IV was performed on whole tubers, where WH was believed to have the biggest impact. Since cooking occurs at the surface before the core, the textural differences between different cooking temperatures are bigger at the core than the surface for each temperature. However, WH turned out to not contribute to subsurface hardening significantly (if RH was held at 100% according to Paper II and some of the set-ups in Paper IV), but to continue cooking with further softening (Table 6 and Figure 20). This might have caused uncertainties in the data, which were hard to explain by the model. The continued cooking was further analyzed by texture analysis in terms of compression, where a cylinder with a larger diameter than the tuber compressed it (Figure 21). The large contact area caused the internal structures of the tuber to rupture, giving information about the internal structures. For tubers without WH, the surface and internal structures were mashed but still held together, see Figure 21a. Figure 21b shows a structure where the dehydrated, outer part of the tuber is still intact and the mashed internal structure has been leaking out at the side. WH at 100% RH, on the other hand, shows a complete collapse where neither the outer nor internal parts of the tuber tend to hold together (Figure 21c) (unpublished observations). These observations were confirmed by analyzing the ratio of tubers collapsed when a force of 5 kg was applied by compression for Bintje and Fakse cooked to different temperatures and with different WH setups (Table 7). The analysis revealed an increase in the ratio of cracked tubers for increased cooking and WH temperature and WH time, except for tubers cooked to 96°C with additional WH at 90°C for 120 min, where the ratio decreased. This probably occurred due to extensive overcooking, causing the tuber to collapse without the initial resistance causing the characteristic pattern of the textural analysis.

**Table 6.** Visual appearance of tubers with different pre-treatments and WH at different RH.

| | Bintje | | | |
|---|---|---|---|---|
| | Ref | OA | SMS | OA+SMS |
| No WH |  |  |  |  |
| WH100 |  |  |  |  |
| WH10 |  |  |  |  |
| | Fakse | | | |
| No WH |  |  |  |  |
| WH100 |  |  |  |  |
| WH10 |  |  |  |  |

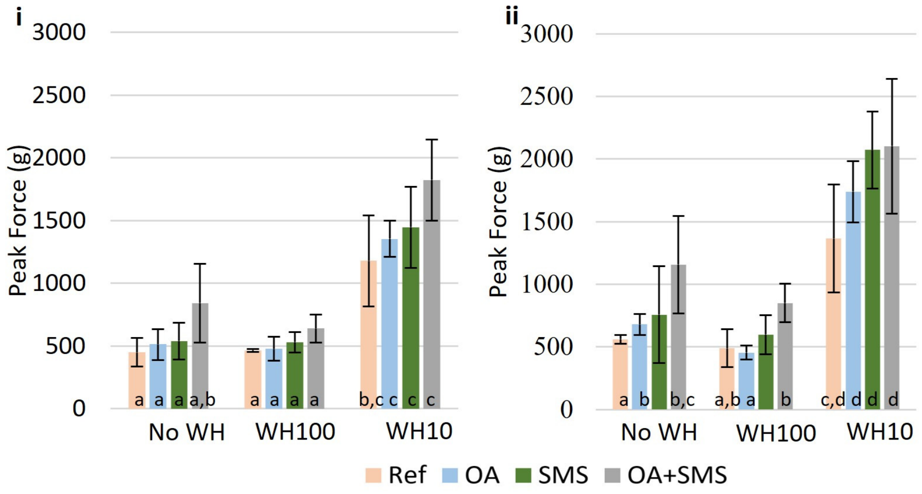



**Figure 20.** Peak force of i) Bintje and ii) Fakse for different pre-treatments and RH

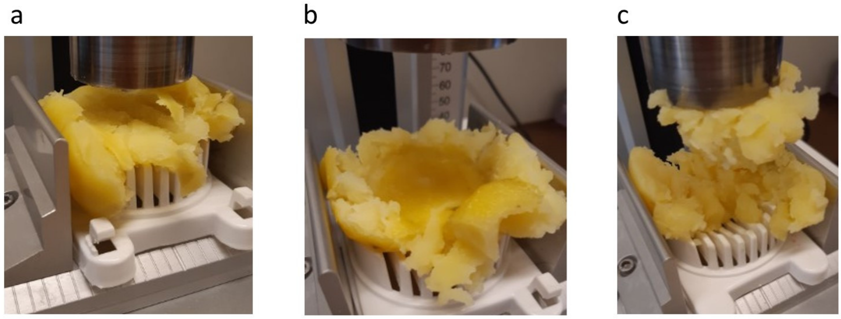



**Figure 21**. Texture analysis by compression of sample cooked to 94°C with a) no WH, b) WH at 72°C for 2 h, RH 10%, and c) WH at 72°C for 2 h, RH 100%.

**Table 7.** The ratio of cracked tubers Bintje and Fakse respectively warm-held at RH 100% at 5 kg by compression method. Abbreviations: WH:warm-holding, n.d.: not determined

| | Cooked 72°C | | Cooked 90°C | | Cooked 96°C | |
|---|---|---|---|---|---|---|
| | Bintje | Fakse | Bintje | Fakse | Bintje | Fakse |
| No WH | 0% | 0% | 0% | 0% | 0% | 67% |
| WH 72°C 30min | 0% | 0% | 0% | 0% | 67% | 100% |
| WH 72°C 120min | 0% | 0% | 67% | 33% | 67% | 100% |
| WH 90°C 30min | n.d. | n.d. | 100% | 67% | 100% | 100% |
| WH 90°C 120min | n.d. | n.d. | 100% | 67% | 0% | 67% |

# Interactive effects

The different processing steps during industrial pre-treatment contribute to different side effects of the potato tuber. When the processing steps are combined, synergetic effects or combinations strengthening each other occur.

It was previously concluded that chemical pre-treatment with SMS contributes to a tough surface that separates from the internal parts of the tuber (Table 5). In Paper II, the chemical pre-treatments were studied in combination with WH showing that WH contributes to continued cooking with a collapsed core. A combination of these phenomena was studied in Paper II, where tubers with different chemical pre-treatments were exposed to WH at different RH. A visual analysis revealed that Bintje in general shows more separation between the outer layer and the internal tuber. Bintje pre-treated with SMS or OA+SMS followed by SC and WH at RH100% show a distinct separation between the outer layer and the internal core. The internal softening seems to have a larger impact on the texture than the surface (Figure 20). However, the perceived texture when eating the potato might be different. The tougher outer part might become more pronounced with a softer internal core since the texture differences become larger.

Starch transformation is often analyzed by DSC. In Paper II, DSC was applied to identify the occurrence of retrogradation of starch after WH as a potential contributor to subsurface hardening. No results indicating retrogradation appeared. However, for most of the samples, exothermic peaks were observed in the temperature range of 17-60°C. No correlation to other parameters and variables included in the study, such as variety, chemical pre-treatment, and WH set up, were found. Previous studies where exothermic peaks have appeared at higher temperatures due to hydrolysis of polymers, such as starch or pectin, and melting of crystalline structures increase the similarities to the studied material and circumstances in this thesis (Bogracheva et al., 2006; Sievert and Wuesch, 1993). Further investigations could reveal additional explanations and circumstances explaining the behavior of the tuber during industrial pre-treatment and preparation in large-scale food service systems.

# Conclusions

The main conclusions from the studies building this thesis are:

- Subsurface hardening has shown to depend on at least three different physical mechanisms that can change the structure of the tuber, all contributing to increased hardness of the cooked tuber. The mechanisms are independent of each other and caused by preservation with organic acids, preservation with sodium metabisulfite, and too low relative humidity during warm-holding (WH) (Paper II). WH at good conditions does not contribute to subsurface hardening (Paper IV).
- Most processing steps have a (potential) negative impact on the eating quality, with synergetic effects among some of them (Paper I and II).
- Eating quality is strongly related to cooking degree, which mainly depends on core temperature, but also variety and tuber size. There are strong correlations between textural and sensorial eating quality properties (Paper III).
- WH affects the cooking process in terms of continuation of cooking with increased risk for over-cooking and development of a watery core (Paper II). However, adjustments of the cooking process in terms of time and temperatures to achieve a slightly undercooked potato before WH enables continuation of cooking during WH to reach a pleasant eating quality (Paper IV).

# Future Perspectives

In this thesis, the work to obtain potatoes prepared in large-scale food service systems starts from the end of the process, to ensure well-controlled and proper cooking. Different processing steps from the industrial pre-treatment are incorporated, but there are still questions to investigate and understand to assure a good eating quality of potatoes served in large-scale food service systems. The industrial pre-treatment contains several processing steps that affect the tuber in different ways. Two of the most important areas to investigate further are the temperature throughout the whole process and mechanical impact. In terms of temperature, it is important that critical points during handling and logistics are identified since it is known that the cold chain tends to be interrupted and this negatively affects the microbiological and eating quality.

Several studies indicate that pectin plays a crucial role in the formation of subsurface hardening, however, it is not clear in which way, and which additional parameters, like PME, degree of methylation, mechanical impact, etc., have an impact. Studies within this thesis reveal that chemical preservation contributes to the formation of a tough layer but this is caused by two different phenomena. The underlying reasons for these phenomena (brick-like cells and visual separation of a tough layer from the internal tuber), in combination with other parts of the industrial pre-treatment, like mechanical impact and temperature fluctuation, should be investigated further to see if there is any correlation to pectin.

The tubers have shown to increase their respiration level upon stress. To ensure a good environment, the packages should be adapted to minimize the stress by i.e., modified atmosphere packaging and regulating the gas composition during storage.

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