SUS Organic

Processing and Quality Guidelines for Organic Food Processing

Supported by

Authors and Affiliations

Meridian Fruchthandelsgesellschaft mbH
Dr. Albert Esper, info@meridian-frucht.de
Altdorf, Germany

Swedish University of Agricultural Sciences
Prof. Dr. Girma Gebresenbet, girma.gebresenbet@slu.se
Dr. Techane Bosona, techane.bosona@slu.se
Uppsala, Sweden

SINTEF Energy Research
Dr. Michael Bantle1), michael.bantle@sintef.no
Dr. Ingrid Camilla Claußen1), IngridCamilla.C.Claussen@sintef.no
Dr. Ignat Tolstorebrov2), ignat.tolstorebrov@ntnu.no
1)Trondheim, Norway
2)Norwegian University of Science and Technology, Trondheim, Norway

University of Kassel, Department for Agricultural and Biosystems Engineering
Dr. habil. Barbara Sturm, barbara.sturm@uni-kassel.de
MSc. Gardis von Gersdorff, g.gersdorff@uni-kassel.de
MSc. Luna Shrestha, sthaluna@gmail.com
MSc. Rosalizan Md. Saleh, rosalizansaleh@gmail.com
Witzenhausen, Germany

University of Teramo, Department of Food Science and Technology
Prof. Dr. Paola Pittia, ppittia@unite.it
Teramo, Italy

University of Tuscia, Department for Innovation in Biological, Agro-food and Forest System
Prof. Dr. Riccardo Massantini, massanti@unitus.it
Dr. Roberto Moscetti, rmoscetti@unitus.it
Tuscia, Italy

Foreword

These guidelines on quality and processing of organic foods have been prepared as part of the Core Organic Plus funded project "SusOrganic - Development of quality standards and optimised processing methods for organic produce". They intend to support actors in the organic food processing sector to simultaneously increase resource efficiency and product quality of their produce by providing deeper insights in raw material, process and product relevant aspects.
The main focus of the presented work lies on the preservation of fruits, herbs, vegetables, fish and meat by the means of drying and chilling/freezing.
In conjunction with these guidelines and to support the practical implementation an e-learning course was developed which is available here:

THE AIMS OF THESE GUIDELINES ARE TO PROVIDE THE PROCESSORS WITH:

- Drying related aspects
- A deeper understanding for naturally occurring heterogeneities in raw materials and their impact on drying characteristics
- Information on the impact of pre-treatment and holding time between preparation and drying on the resulting product quality
- Information on the impact of drying and the related process settings on product quality
- Information on improved drying strategies and process control concepts
- Best practice examples for processing
- Best practice based on LCA and LCCA
- Food drying and related food logistics
- Chilling and Freezing related aspects:
    - General aspects of superchilling
    - Superchilling for organic meat and fish
    - Effects of freezing and freezing rate on organic fruits

An opportunity for self-training is further given via the ISEKI food association:

https://moodle.iseki-food.net/course/view.php?id=59

The SusOrganic consortium wants to thank the Core Organic Plus EraNet and the involved National Contact Points for their financial and advisory support throughout the project.
We also would like to advise the readers that we are currently working on the second phase of the technological and product development in the framework of the SusOrgPlus project. Further information will shortly be available through the dedicated SusOrgPlus website.
In case of any questions regarding these guidelines or how you could participate in SusOrgPlus, please do not hesitate contacting us via: susorganic@uni-kassel.de

We hope you find these guidelines helpful and are looking forward to your feedback.

Barbara Sturm

CHAPTER I DRYING

1. Drying

I.1 IMPACT OF PROCESSING ON FRUIT AND VEGETABLE QUALITY

1. Heterogeneity of raw material

University of Kassel, Department for Agricultural and Biosystems Engineering
In the following, the apple is chosen as an example in terms of raw material heterogeneity; however, in general, these observations are also valid for other fruits and vegetables.

1.1. Morphology of an apple

Apples consists of ca. 85 % water, 14 % carbohydrates, 2.4 % dietary fibres, 0.3 % proteins and 0.2 % lipids. Due to the variety, the degree of maturity, the cultivation area and agriculturally and environmental influences, fluctuations regarding the different components occur (Ackermann et al., 1992). The usual fluctuations in terms of moisture content in ready to harvest apples for example is between 80.4 and 90 %, or 4.1 and 9.0 gw/gdm (gwater/gdry matter) (Kröll and Kast, 1989).
Ca. 75 % of all carbohydrates contained in an apple are sugars: fructose (ca. 6.0 %), glucose (ca. 2.4 %) and sucrose (ca. 2.0 %). Apple acid is the main organic acid (0.3-1.0 %). The acid content depends on the variety, the degree of maturity and environmental influences during growth and storage of apples (Ackermann et al., 1992).

1.1.1. Relation between fruit and cell growth

The size of fruits depends on the number of cells and their volume. During growth, the volume fraction of the cortex (flesh) increases to ca. 73 %, while the fraction of the core decreases to 24 % (Bain and Robertson, 1951).
In general, cells of bigger fruits show longer and more voluminous sizes and bigger surfaces than of smaller fruits. The fruit size and degree of ripeness can vary significantly at harvest (Krüger, 1986).
The relation between fruit and cell size depends on the variety and varies due to environmental influences. Primarily, the cell size depends on the supply of assimilates which was documented in thinning, cutting, shadowing and fertilization experiments. For this reason, the growing position of the fruit on the frutescence, the shoot and the tree influences the growth (Hund and Stösser, 1984). Therefore, the supply with nutrients and the weather conditions during cell division and enlargement are significant factors regarding cell size dependent fruit size.

1.1.2. Fruit firmness

The firmness of the fruit constantly decreases as progressing maturation due to the reduction of the middle lamella and the reconstruction of cells (Prasanna et al., 2007). This reduction continues during storage. The fruit firmness is a parameter to simply quantify the texture characteristics of a fruit. The firmness of ready to harvest fruits is a parameter, which is very useful to describe the quality of a fruit as it correlates very good with subjective characteristics like crunchiness (Brennan et al., 1977; Wills et al., 1980).

1.1.3 Moisture distribution

To show the moisture distribution within an apple, it was sliced into slices of 3.8 mm thickness. As shown in the following Figure 1.1, the core was removed and the outer diameter of the slices was cut to 72 mm. The slices were cut into Quarters, weighed and dried at 70 °C for 48 hours.

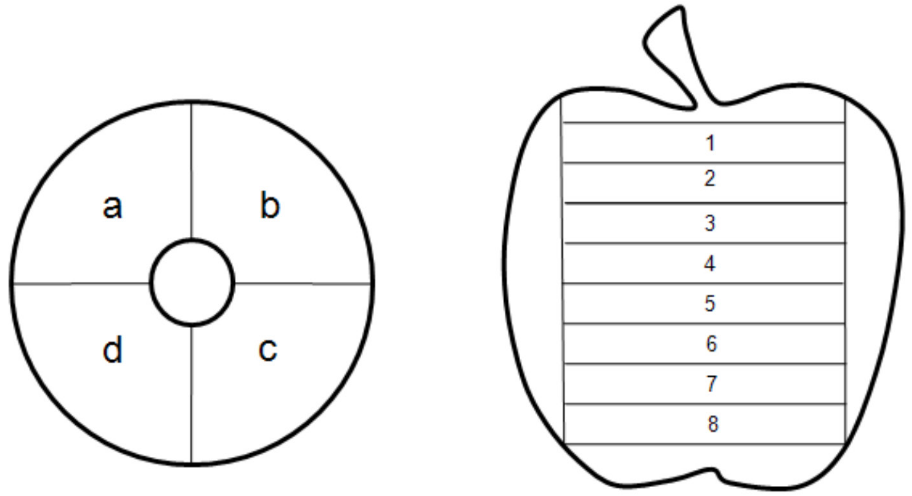

Figure 1.1.1: Division of apple slices in sectors and arrangement within an apple, left side horizontal, right vertical

The samples were weighted again and the moisture of each slice as well as the moisture alongside the middle axes was calculated. Moisture content fluctuates which depends on the natural structure of apples and is not avoidable. Further, the fluctuations within the apple remains in very narrow limits and the average values are almost the same (x0=86.7 % ± 0.8 %), which allows the calculation of the final moisture content from only a few slices.

1.1.4. Influence of the thickness of the slices

The thickness of the raw material has a significant influence on the drying time (Rahmann and Kumar, 2007). The following Figure 1.2 shows the reduction of the thickness of apples slices from 3.8 mm to 2.8 mm under two different drying conditions. For both temperatures, this reduction leads to a reduced drying time of ca. 50 %. The results are comparable for garlic and papaya slices (Fernando et al., 2008). Dissa et al. (2008) reduced the thickness of mango slices from 16 mm to 8 mm which resulted in a decreased drying time of 62%.

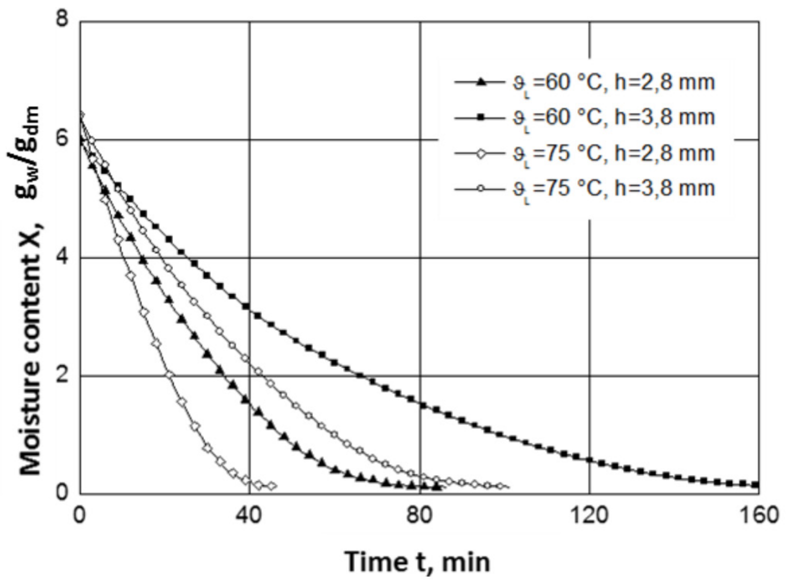

Figure 1.1.2: Drying behaviour of apple slices of different thicknesses at different drying parameters: 60 °C air temperature (air velocity 3.4m/s, dew point 17.5 °C), 70 °C air temperature (air velocity 4.3 m/s, dew point 17.5 °C)

The reduced drying time reduces the exposure time of the heat which can reduce thermal deterioration. Bashir(2008) showed that the colour of onion rings was not negatively influence up to a thickness of 6 mm, at increasing thickness the heat exposure increases which affected the colour negatively.

1.2. Influence of initial moisture content

As many fruits and vegetables are seasonal the availability throughout the year is assured by storage under controlled atmosphere (CA). To observe the influence of the storage duration, samples of apples, stored for three months and for five months were dried under the same conditions.

The apple slices were dried at 60 °C air temperature, dew point temperature of 17.5 °C and an air velocity of the drying air of 3.4 m/s. Figure 1.1.3 shows the drying curves of apple slices stored for 3 months. The initial moisture content of the three apples varies greatly with values ranging between 8.3 and 5.5 gw/gdm. However, almost all samples reached the required moisture content of 0.13 gw/gdm after almost the same drying time. The samples with the highest initial moisture content even dried a little bit faster than the others. This outcome corresponds with the results of Nguyen and Prince (2007) for bananas.

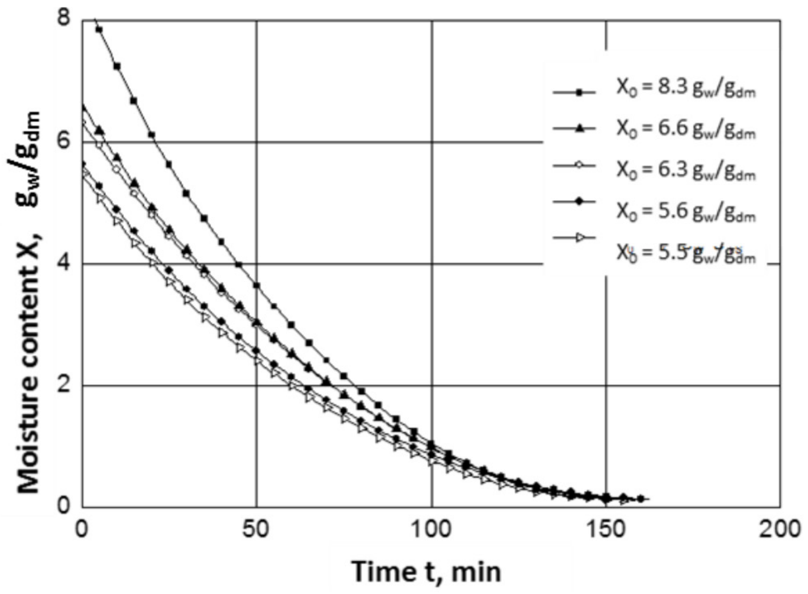

Figure 1.4 shows the drying curves for apples dried stored for 5 months. Like for the previous mentioned apples, the required moisture content was almost achieved at the same time. Further, it is shown that apples stored for a longer time have lower initial moisture contents, which means they significantly lose water during storage.

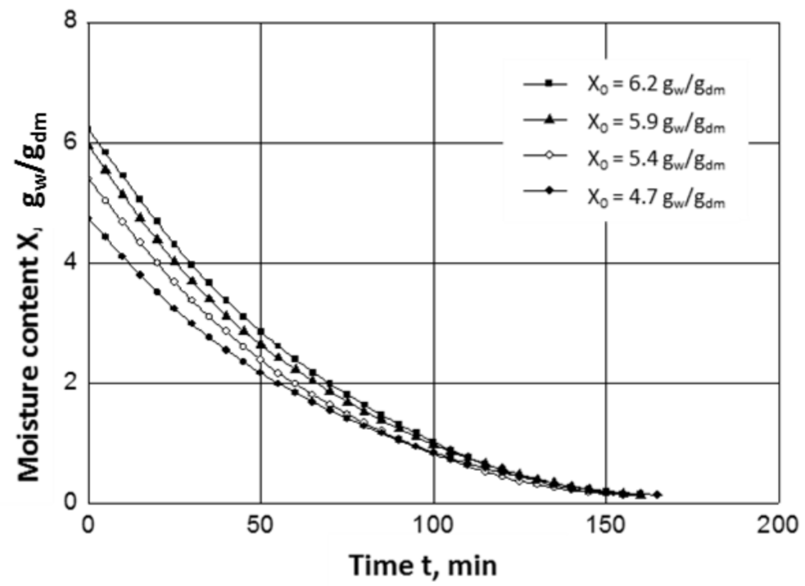

Figure 1.1.4: Drying behaviour of apple slices with different initial moisture content (after 5 months storage) dried at 60 °C (air velocity = 3.4 m/s, dew point = 17.5 °C)

Figure 1.5 expresses the drying time as a function of initial moisture content for samples stored for 3 and 5 months. The figure indicates that the storage duration at the same initial moisture content does not affect the drying time of apple slices. All samples achieved the final moisture content after almost the same time. Further, with increasing initial moisture content the drying time slightly decreases.

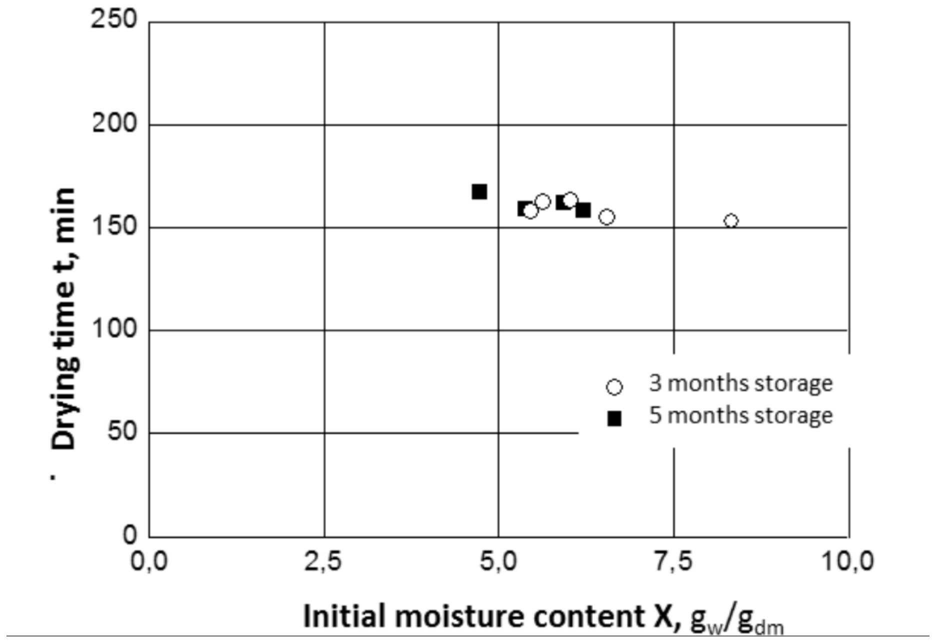

Figure 1.1.5 Drying time of apple slices down to a final moisture content of 0.13 gw/gdm related to initial moisture content. Drying conditions like in Figure 3

The drying rate of samples with increased initial moisture contents is higher until a moisture content of 0.4 gw/gdm is achieve, which is shown in Figure 1.6.

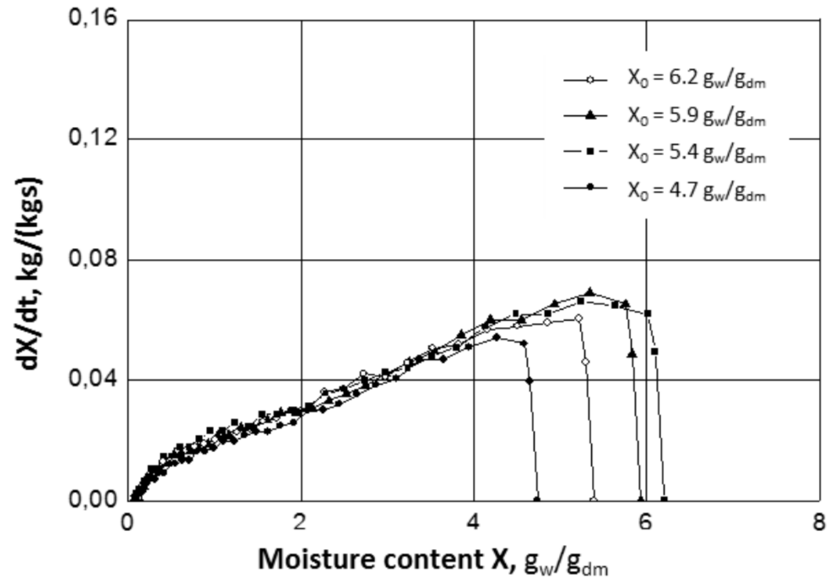

Figure 1.1.6: Drying rates for different initial moisture contents as a function of moisture content, drying conditions like in Figures 3

The initial moisture content does not significantly influence the product temperature and the change in colour (TCD= total colour difference) as it is shown in Figure 1.7.

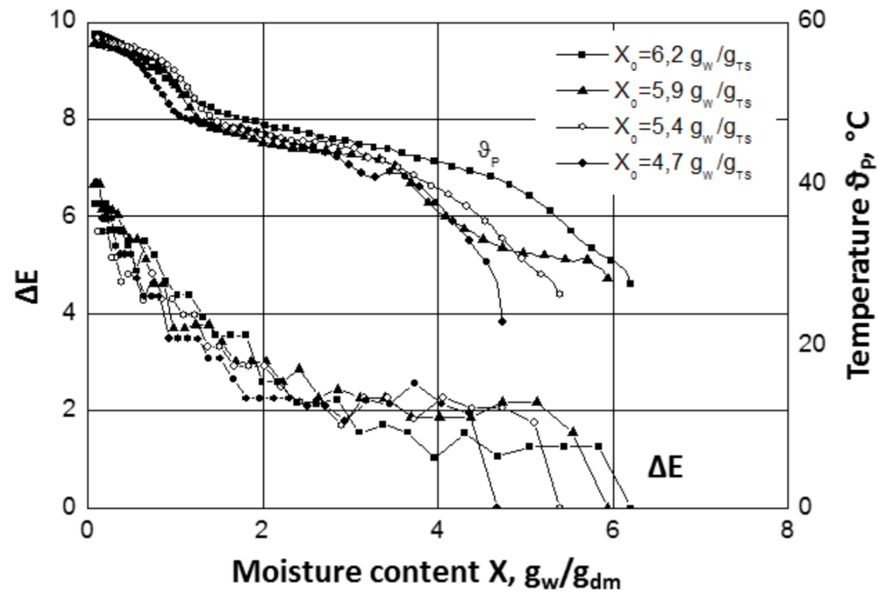

Figure 11.7: Product temperature and colour change ΔE for different initial moisture contents X as a function of moisture content, drying conditions like in Figure 3

The shrinkage as a function of initial moisture content is shown in Figure 1.8. The development for all samples is similar, however, they depend on the initial moisture content with leads to a parallel shift of the curves on the x-axis.

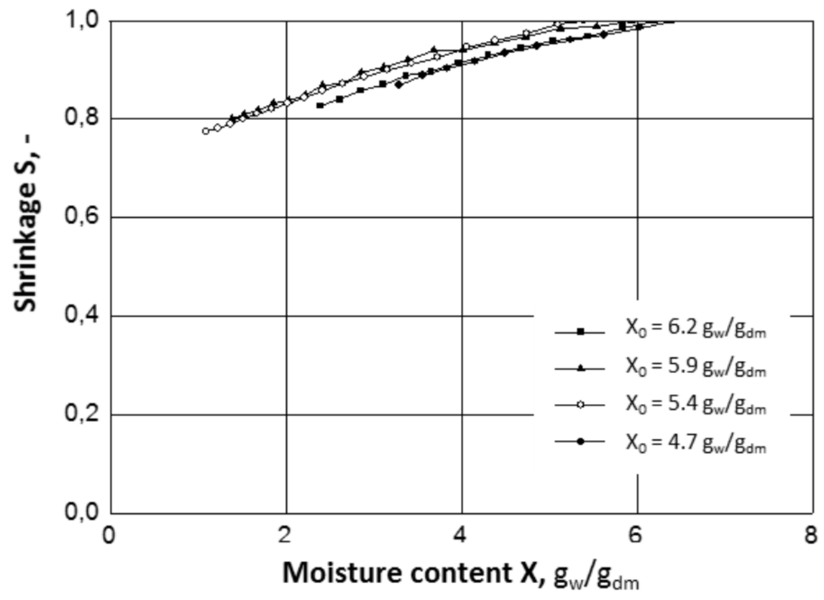

Figure 1.1.8: Shrinkage S for different initial moisture contents X0 as a function of moisture content, drying conditions like in Figure 3

To observe the microstructural causes for the different drying rates, topographic (Figure 1.9) and SEM (scanning electronic microscope) analysis (Figure 1.10) were conducted after drying. The samples used for this were the ones stored for 3 month under CA with the highest (8.3 gw/gdm)(sample 1) and lowest (5.5 gw/gdm) (sample 2) initial moisture content. For analyses of the roughness three horizontal and two vertical lines were put through the topographic map and their development was analysed. Minima and maxima allow a statement regarding the roughness and the frequency of roughnesses. Figure 1.11 and 1.12 show from top to bottom first the horizontal from top to bottom and then the vertical lines from left to right.

The roughness of dried apple slices with different initial moisture content is obviously different. Sample 1 (X0 = 8.3 gw/gdm) shows only a few peaks for roughness, and the average deepness is relatively low compared to sample 2 with the lowest initial moisture content (X0 = 5.5 gw/gdm). Sample 2 shows much more roughness. The number and extent of peaks are much bigger compared to sample 1.

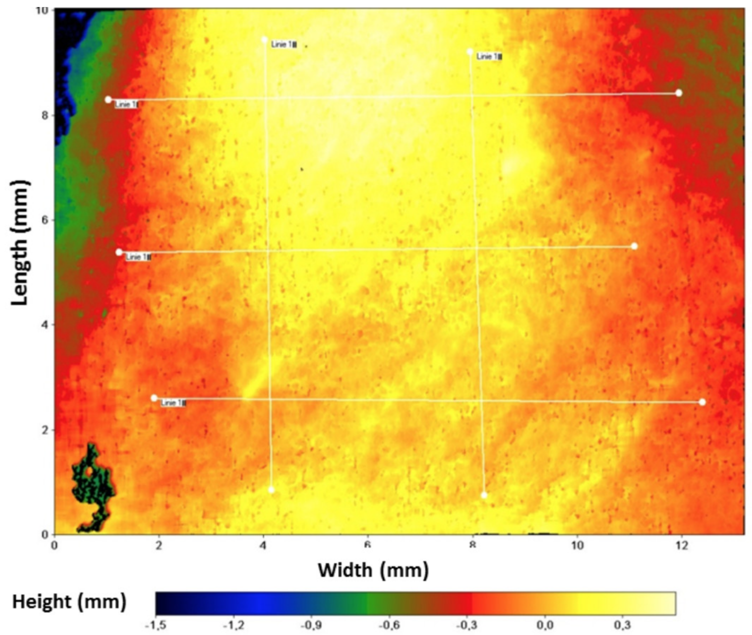

Figure 1.1.9: Topographic mapping of the surface of sample 1 after drying, X0=8.3 gw/gdm

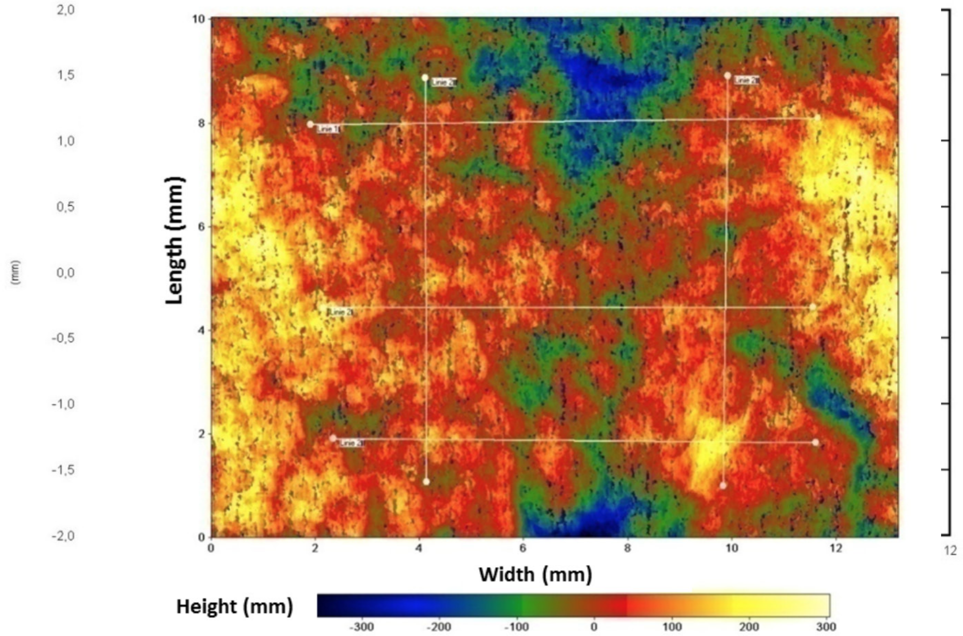

Figure 1.1.10 Topographic mapping of the interface of sample 2 after drying, X0=5.5 gw/gdm

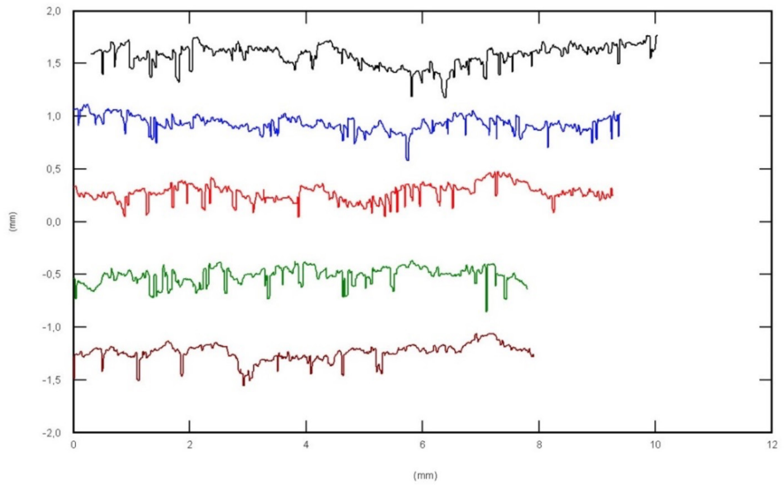

Figure 1.1.11: Values for roughness, sample 1, X0 = 8.3 gw/gd

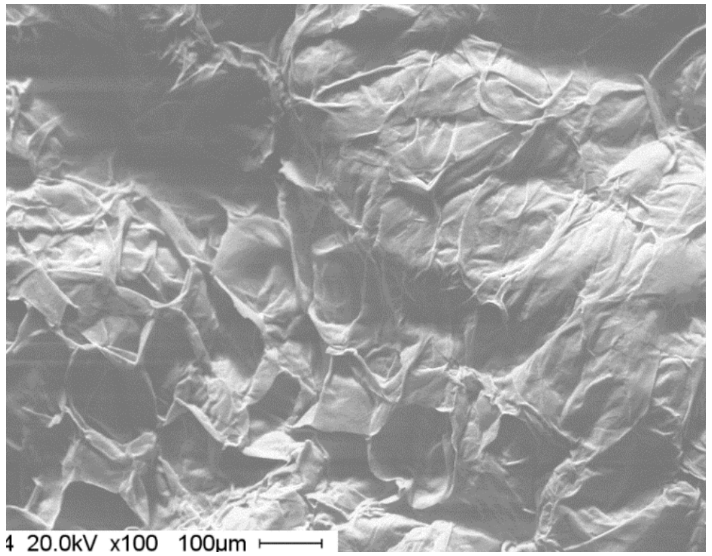

Figure 1.1.12: Values for roughness, sample 2, X0 = 5.5 gw/gdm

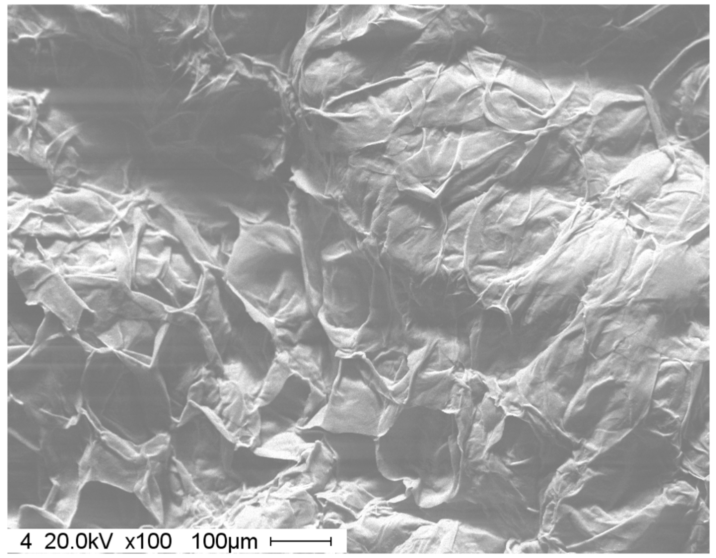

Figure 1.1.13: Visible surface of sample 1, magnified 100 times, X0 = 8.3 gw/gd

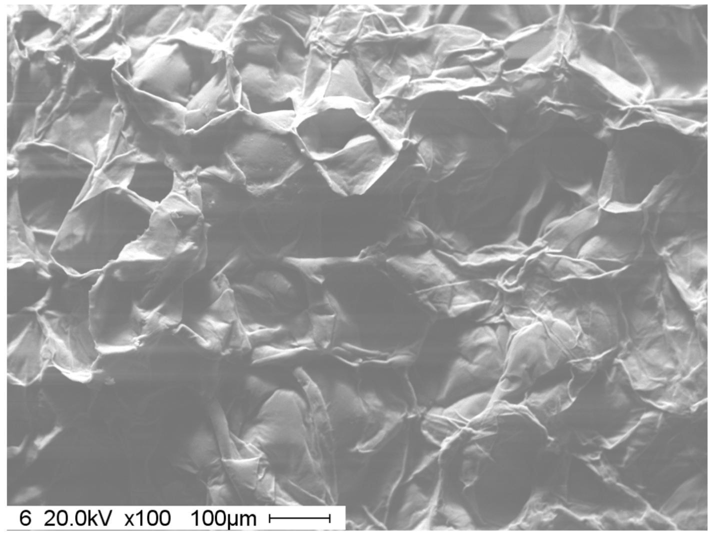

Figure 1.1.14: Visible surface of sample 2, magnified 100 times, X0 = 5.5 gw/gd

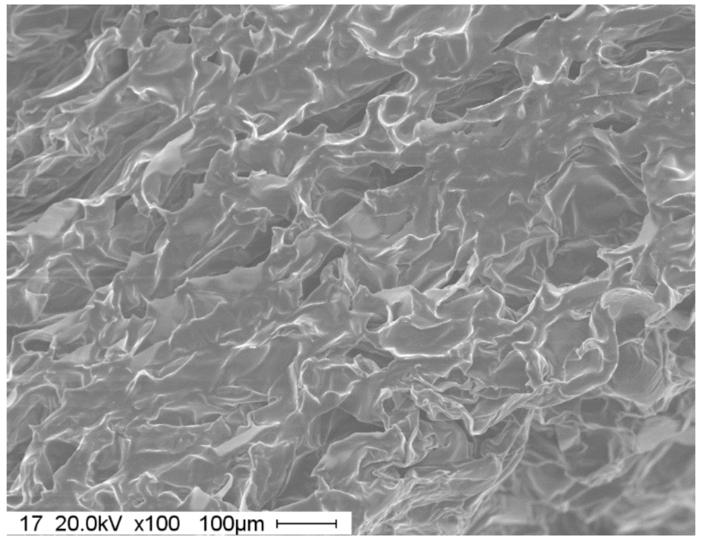

Figure 1.1.15: Vertical interface of sample 1, magnified 100 times, X0 = 8.3 gw/gdm

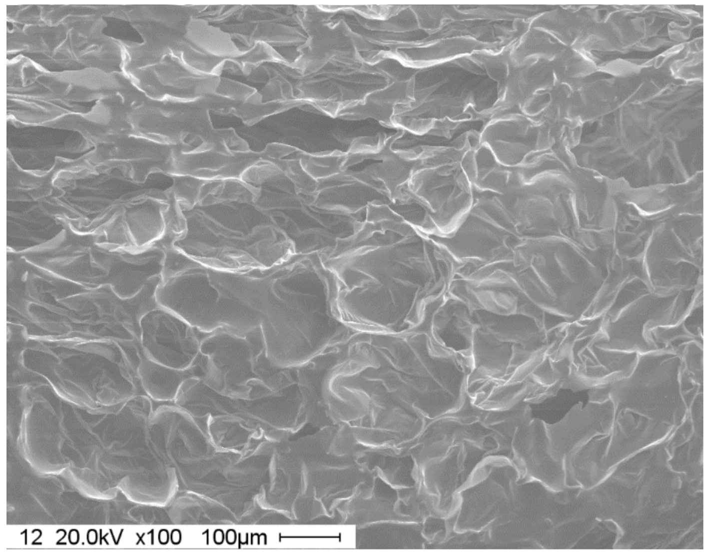

Figure 1.1.16: Vertical interface of sample 2, magnified 100 times, X0 = 5.5 gw/gdm

The SEM images show significant differences of the structure of both samples. In sample 1 the structure slumped down, there are rarely sections in which the cell residues appear open. Sample 2 shows a much better preserved structure, many cell residues are open, there are less sections which completely slumped down. The average cell size in sample 1 is bigger than in sample 2. Further, the cell walls of sample 1 are obviously thinner than of sample 2. The observations show that samples with lower initial moisture contents have stronger cell walls than samples with high initial moisture contents. This makes a diffusion of moisture more difficult and the capillary effect is bigger in smaller cells.

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2. Influence of drying conditions on product quality

University of Tuscia, Department for Innovation in Biological, Agro-food and Forest systems, Italy

Massantini, R. & Moscetti, R.

The aim of food drying is the reduction of the amount of free-water to slow down deteriorative processes, which are principally caused by microbial growth, chemical reactions and/or enzymatic activities. Fruits and vegetables are particularly susceptible to deteriorative processes, since their initial water content range is from 74%–90% w/w (weight/weight) (Koszela et al., 2014), and then, water activity allows microbial growth (aw > 0.60). However, despite these advantages, drying may cause damage and severe changes in the physicochemical, organoleptic and nutritional properties of products (An et al., 2016; Filkova and Mujundar, 2014; Ratti, 2001). In particular, during drying of fruits and vegetables, many quality changes occur, such as: changes in colour due to enzymatic and/or non-enzymatic browning reactions, changes in texture and shrinkage and loss and/or degradation of nutritional compounds (e.g., ascorbic acid, carotenoids, phenolic compounds and the like) (Nindo et al., 2003).

2.1. Nutritional quality changes

The nutritional quality of fruits and vegetables depends on their chemical composition, which shows a wide range of variability depending on the species, cultivar and maturity stage. The heating process leads to the degradation and/or isomerization of most of the chemical compounds. Due to the complexity of the food matrices, some chemical compounds are chosen as markers of nutritional quality (Vicente et al., 2009). For fruit and vegetables, the following compounds are chosen as marker, ascorbic acid, carotenoids, vitamin E and phenolic content.

2.1.1. Ascorbic acid

The ascorbic acid (AA) is an essential nutrient in the human diet. Since fruits and vegetables have a high content of AA, it is commonly used as a quality marker. AA is an antioxidant, heat labile and water soluble compound and is able to regenerate tocopherols (vitamin E) from its oxidized form (Liu and Russell, 2008). High temperature, long drying cycle and exposure to oxygen cause a strong reduction of its concentration in fruit and vegetables, i.e. tomato may loss about half of its original AA content during drying at 75 °C (Ashebir et al., 2009). Furthermore, it has been observed, in a study on fluted pumpkin leaves, that high temperature over a short-time at low pH leads to a better retention of AA than a lower temperature over a long process at high pH (Ariahu et al., 2011). During hot-air drying, vitamin C losses are greater than the ones related to freeze drying (Shofian et al., 2011). A slight loss of AA occurs during blanching in hot water due its water-solubility. However, the pre-treated product retained better AA during drying (Barbosa de Lima et al., 2015).

2.1.2. Carotenoids

Carotenoids are a large class of tetraterpenes responsible for the bright red, yellow and orange colour in many fruits and vegetables. Due to their highly hydrophobic nature, carotenoids are mainly present within the lipid membrane or in complexes with proteins (Gruszecki, 2010). There are more than 600 compounds classified as carotenoids, and most of them are human precursors of vitamin A. In plants, they help in photosynthesis and prevent the oxidation of chlorophylls; in human beings, consumption of β-carotene and lutein, the two most important dietary carotenoids, reduces the risk of lung cancer and chronic eye diseases like cataracts (Lefsrud et al., 2008). Slight decreases in total carotenoids content were observed during hot-air drying of carrots (Urrea et al., 2011); moreover, coupled blanching and drying releases carotenoids from lipid membranes and complexes, resulting in better bio-availability (Divya et al., 2012; Seybold et al., 2004). Despite this positive effect, heat induces the isomerization of carotenoids from trans form to cis form, which is more susceptible to oxidation (Strati and Oreopoulou, 2016). Finally, it was seen that the lycopene concentration decreases more in freeze drying than both air and microwave drying (Siriamornpun et al., 2012).

2.1.3. Phenols

Phenols are a large class of compounds that have at least an aromatic ring with one or more hydroxy-substituents; they may include functional derivatives (e.g., esters). Phenol compounds have antioxidant activity and in plants they act as a defence mechanism against pathogens and parasites; for this reason, the peel commonly has a higher level of phenols than the flesh (Chinnici et al., 2004). Commonly, they are also associated with sensorial characteristics (i.e., astringency, colour, etc.) (Romaric G. Bayili, 2011). Fruits and vegetables rich in phenols are commonly blue or red. The regular consumption of fruits and vegetables rich in phenols is associated with a reduction in the risk of developing chronic diseases, such as cancer and cardiovascular disease (Liu, 2004). Significant loss of phenols occurs during mechanical processing (e.g., peeling, slicing or shredding); all these steps directly expose phenols to oxygen (Wlodzimierz and Grajek, 2010). Higher loss of phenols occurs in air drying compared with freeze and microwave drying. This is because it requires a higher temperature and a long drying time (An et al., 2016; Vega-Gàlvez et al., 2012).

2.1.4. Vitamin E

Vitamin E comprises a group of fat-soluble compounds which include both tocopherols and tocotrienols. α-tocopherols are the most abundant in the human body (Lodge, 2005).Vitamin E compounds are highly susceptible to both oxygen and light exposures during processing and/or storage (Vicente et al., 2009). Fatty foods, broccoli and leafy vegetables are good sources of vitamin E. During drying of chestnut at 50°C for 10 h, vitamin E content slightly decreases (Delgado et al., 2016). Around 10% loss of vitamin E are mainly reported during cooking and microwaving of product (Lešková et al., 2006).

2.2. Discolouration

Colour preservation is crucial to make processed fruit and vegetables attractive and acceptable. The colour is the first attribute considered by the consumer to make a buying decision (Shewfelt, 1999). For this reason, several researches have, as a matter of study, considered colour preservation during post-harvest handling and processing of fruits and vegetables (Shewfelt, 1999). During drying, many phenomena are responsible of colour changes. The most common ones are pigment degradation (e.g., chlorophylls and carotenoids) (Roshanak et al., 2015) and the occurrence of browning, due both to enzymatic and non-enzymatic reactions (Maskan, 2001).

2.2.1. Chlorophylls and Carotenoids

The colour of green and yellow/red/orange vegetables is mainly due to pigments closely related to chlorophylls and carotenoids, respectively (Brennan, 2006). These pigments are easily degraded during post-harvest processing by light, heat, oxygen and enzymes (Madhava Naidu et al., 2016). However, it should be noted that the type of product and its origin, pre-treatment and type of drying affect the degradation rate of chlorophylls and carotenoids (Brennan, 2006) Furthermore, high temperature and low pH stimulate the conversion of chlorophylls into pheophytins by replacing the central magnesium in the chlorin ring with two hydrogen ions (Marangoni, 2017); when chlorophyll is converted into pheophytin, the hue changes from light-bright green to olive brown. The conversion rate of pheophytins' formation seems to be slowed down at a water activity (aw) lower than 0.32 (Roshanak et al., 2015). In addition to this reaction, chlorophyll degradation is related to fat peroxidation. In this reaction, lipoxidase and oxygen play the major role (Cui et al., 2004).

2.2.2. Enzymatic Browning

Polyphenol oxidase (PPO) and peroxidases (POD) enzymes are mainly responsible for enzymatic browning. The pathway results in phenols' degradation and starts with the conversion of the L-phenylalanine to the trans-cinnamic acid by the phenylalanine lyase (PAL) enzyme (Cecchini et al., 2011; Mencarelli et al., 1995). Consequently, PPO converts trans-cinnamic acid to ortho-quinones, which spontaneously polymerize to melanins (brown pigments responsible for brown colour and off-flavour) (Degl'Innocenti et al., 2007; Taylor et al., 1993). In the food processing industry, the results of the activity of these enzymes are often undesirable. One exception is made for Sultana grapes, because consumer seems to prefer brown dried grapes (Grncarevic and Hawker, 1971). Several solutions were adopted to inhibit the enzymatic browning, such as: [1] the use of heat as pre-treatment, to inactivate the enzyme, and [2] the use of sulfur dioxide or sulfites, which are able to complex the o-quinones making them unavailable for the formation of melanins (Yingsanga et al., 2008). Another way to reduce the enzymatic browning is to lower the pH of the products using acid (e.g., citric, malic, phosphoric and ascorbic acid) or combining different unit operations (e.g., osmotic dehydration followed by air drying) (Ioannou, I.; Mohamed, 2013).

2.2.3. Non-Enzymatic Browning

Non-enzymatic browning (NEB) consists in a series of chemical reactions that occur during a thermal process, resulting in changes in colour, texture, antioxidant compounds and aroma (Martins et al., 2000; Perera, 2005). The most important non-enzymatic process is caramelization, which involves the pyrolysis of sugars and the Maillard reaction (MR) (Manzocco et al., 2000). In 2913, the Maillard reactions was first described by Louis Maillard, a French chemist, while, in 1953, John E. Hodge was the first scientist to describe the chemical pathway of the MR. Its initial stage involves the reaction between a reducing sugar and a free amino group (e.g. amino acid, polypeptide or protein) to give N-substituted glucosamine, which then rearranges to form the Amadori and Heyn's products (Hodge, 1953). MR is a complex net of parallel and consecutive chemical reactions, which are related to product characteristics (e.g. pH, moisture content, etc.) and the processing parameters (e.g. temperature and heat exposure time) (Cernîşev, 2010; Martins et al., 2000). At a pH lower than 7.0, the reaction primarily leads to the formation of furfural and hydroxy-methylfurfural (Garza et al., 1999; Hodge, 1953; Martins et al., 2000), while at a pH higher than 7.0, 4-hydroxy-5-methyl-2,3-dihydrofuran-3-one (HMFone) and fission products (e.g., acetol, pyruvaldehyde and diacetyl) are mainly produced (Cernîşev, 2010; Martins et al., 2000). Despite the pathway, all these compounds are highly reactive and, thus, are involved in further reactions responsible for the development of brown pigments (e.g., melanoidins) (Garza et al., 1999). Commonly, NEB development is monitored through [1] the content of sugar of product (e.g., sucrose, fructoseglucose, etc.) (Garza et al., 1999; Wegener et al., 2017), [2] the content of HMF (Contreras-Calderón et al., 2016; Garza et al., 1999) and furfural (Contreras-Calderón et al., 2016), [3] the browning colour intensity by using spectral measurement at 420 nm (Contreras-Calderón et al., 2016; Garza et al., 1999; Hurtado et al., 2016; Wegener et al., 2017). In general, NEB often reduces the quality of processed foods (Sharma et al., 2014) with some exceptions, e.g., roasted coffee and bakery products, in which MR is responsible for better colour, taste and aroma (Jaeger et al., 2010).

2.3. Physical changes

During drying, physical changes occur, and often, they strongly influence drying product characteristics. The main physical changes (i.e., shrinkage and texture) are discussed below.

2.3.1. Shrinkage

During drying, fruits and vegetables lose water, and the cellular membranes collapse. These phenomena are responsible for reduction in shape and size of food tissues, also known as shrinkage (Aprajeeta et al., 2015). Moisture gradually moves from the centre of the food tissues to the external surfaces (Bonazzi and Dumoulin, 2011). Several studies confirmed that there is a linear correlation between moisture content (MC) and shrinkage (Dehghannya et al., 2015; Nadia, 2011; Yadollahinia and Jahangiri, 2009). During the initial stage of air drying, shrinkage increases rapidly; consequently, shrinkage slowly increases until it reaches an equilibrium point (Kerdpiboon et al., 2007). It was observed that a stronger shrinkage phenomena occurs in both microwave and hot-air drying than in freeze drying (Bonazzi and Dumoulin, 2011; Prothon et al., 2003). Increases in product temperature raises the rate of cellular shrinkage following the Arrhenius-type behaviour (Yadollahinia and Jahangiri, 2009). However, in a study performed on strawberries, a similar rehydration behaviour was noticed after microwave and freeze drying (de Bruijn et al., 2016).

2.3.2. Texture

Textural parameters of fruits and vegetables are perceived with the sense of touch and hearing, either when the product is picked up with the hand or placed in the mouth and chewed (Bourne, 2002). Texture is the result of complex interactions among food components at micro- and macro-structural levels (Guiné and Barroca, 2012); using tomatoes as an example, the greatest contributors to the texture are the insoluble solids, which are derived from the cell walls (Lešková et al., 2006). Other parameters are related to changes in texture (e.g. structure of tissue, turgor pressure, porosity, cellular orientation and composition). During drying of fruits and vegetables, several changes in texture are common (e.g., hardness, cohesiveness, springiness and chewiness) (Kotwaliwale et al., 2007).
Changes in texture are commonly measured using a texture profile analyser (TPA) (Cecchini et al., 2011; Tan, 2000). The high temperature and long drying time in hot-air drying often result in heat-damage and losses in texture (Vega-Gàlvez et al., 2012). During the hot-air drying of apple slices, three phases in texture were observed: softening, in which gradual changes in firmness appear, uniform hardness and hardening (Martynenko and Janaszek, 2014). The last step is due to a limited moisture diffusion rate (Martynenko and Janaszek, 2014). In a study made on carrots, it was deducted that microwave drying is faster than hot-air drying and, moreover, final product shows better textural properties (Lin et al., 1999).

2.3.3. Moisture content and water activity (aw)

Moisture content is an indicator of the amount of water contained in a solid sample (e.g., soil, fruit and vegetables). Moisture changes during drying are usually expressed as dry basis of moisture content (MCd), which corresponds to the ratio between the amount of water in the sample (mw) over the residual solid content (mRSC), both expressed in the same unit (e.g., g/g or kg/kg).
However, regarding other food industry applications, moisture content is commonly expressed as wet basis (MCw), which is equal to the ratio between the amount of water in the sample (mw) over the total weight of the sample (mtot).

The relationship between MCd and MCw is described by the following equation:
During drying, mw decreases, and mRSC remains constant. Microbial growth is more related to the amount of free-water contained in food rather than the amount of total water (Gabriel, 2008). In order to control microbial growth, then, another parameter should be introduced: the water activity (aw), which is represent as the ratio between the vapor pressure of water in a substance (Pa) over the vapor pressure of pure water (P0) under identical thermodynamic conditions.

The aw affects not only microbial growth control, but also shelf-life of food, discolouration rate, enzymatic activity and modulation of chemical reaction rate (Bonazzi and Dumoulin, 2011). The relationship between moisture content and water activity during drying is complex, non-linear and unique for each food product. This is due to colligative, capillary and surface effects (Sablani, 2007).

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3. Quality changes in fruits and vegetables during drying

University of Kassel, Department for Biosystems and Agricultural Engineering, Germany

3.1. Apples

Shestha, L.

In recent years, fruit drying is a very common practice to diversify the product, easy in handling/distribution and to extend their shelf life with reduction of decay and microbial growth. Different kinds of drying methods such as open air, hot air oven, and freeze-drying treatments can be applied to have higher nutritional dried products. Since dried fruits have higher total energy, nutrient density, fibre content, and often significantly greater antioxidant activity compared with fresh fruits as a consequence of concentration (Bennett et al., 2011).; the consumption trends of dried fruits as snacks or to incorporate into some other food formulations are tremendously increasing (Alberti et al., 2014; Garau, Simal, Rossello, & Femenia, 2007).
However, drying causes physical, structural, chemical and biological changes that affect quality attributes, such as the texture, color, flavor and nutritional value, and particularly the contents of nutrients and phytochemicals, which are relatively unstable to heat (Lee, 2012; Vega-Gálvez et al., 2012; Witrowa-Rajchert & Rząca, 2009). The chemical composition of apples varies prominently due to production region, cultivation practices, harvesting and storage conditions and cultivars (Feliciano et al., 2010; Kalinowska et al., 2014; Raudone et al., 2016).
Nevertheless, apples consist of several chemical variations, its intake have potential for modulating human metabolism for the prevention of degenerative disease such as cardiovascular diseases reduction, certain cancers, diabetes, reduce cholesterol level and weight loss (Kalinowska et al., 2014). This preventive functionality is due to presence of diverse phenolic compounds and flavonoids in apples. These compounds contain large number of double bonds and hydroxyl groups, which generates their antioxidant activity (Khanizadeh et al., 2008; Tsao, Yang, Xie, Sockovie, & Khanizadeh, 2005). Five major groups of polyphenolic compounds are found in apple: hydroxycinnamic acids (primarily chlorogenic acid), flavan-3-ols [(+)-catechin, ()-epicatechin and anthocyanidins], flavonols (mainly different quercetin glycosides), dihydrochalcones (phloridzin is the most abundant) and anthocyanins (predominately cyanidin-3-galactoside) (Oszmiański, Wojdyło, & Lachowicz, 2016; Tsao, Yang, Young, & Zhu, 2003).
The content of phenolic compounds is particularly high in the peel, compared with the flesh or the cores of apples (Lacueva et al., 2014; Wolfe, Wu, & Liu, 2003). In apple flesh, procyanidins constitute about 56% of total phenolics, followed by hydroxycinnamic acids (40%) and dihydrochalcones (4%). Nonetheless, phenolic content varies according to cultivar (Tsao et al., 2003).

3.1.1. Impact of pre-treatment and pre-processing waiting time on apple drying on browning reactions

The basic purpose of fruit processing such as drying is to extend the shelf life and to maintain the nutritional and sensory quality attributes by limiting the activity of microorganisms and the chemical changes that would otherwise adversely degrade the acceptable quality of final product. It is very common challenge that extensive changes on the quality characteristics occurred while convective drying process. There are many factors which influences the drying process such as temperature of drying chambers, air velocity, and humidity and so on.
Besides, nature of raw material and chemical reaction while pre-processing steps is also function of many factors, mainly reactant concentration, temperature, pH, oxidation-reduction potential and inhibitors and catalyst reactions. The changes take place on pre-processing step usually accompanied by significant changes to the drying process. This occurs not only during convective drying but also unconventional one, such as high hydrostatic pressure (Janowicz and Lenart, 2018). Thus, it is essential to optimize the pre-processing operation prior to drying processes. For instance: the breakdown of cell tissues while pre-processing such as cutting and slicing of apple, lead to enzyme reaction and thus browning reactions.
The browning reaction also get accelerate during drying process due to chemical reactions like Maillard browning resulting the product in a darker colour. Therefore, in order to optimize nutrient and appearance retention, several pre-treatment are applied to apple slices prior to drying process. However, it also depend upon the cultivars, processing environment and air exposure time at room temperature.

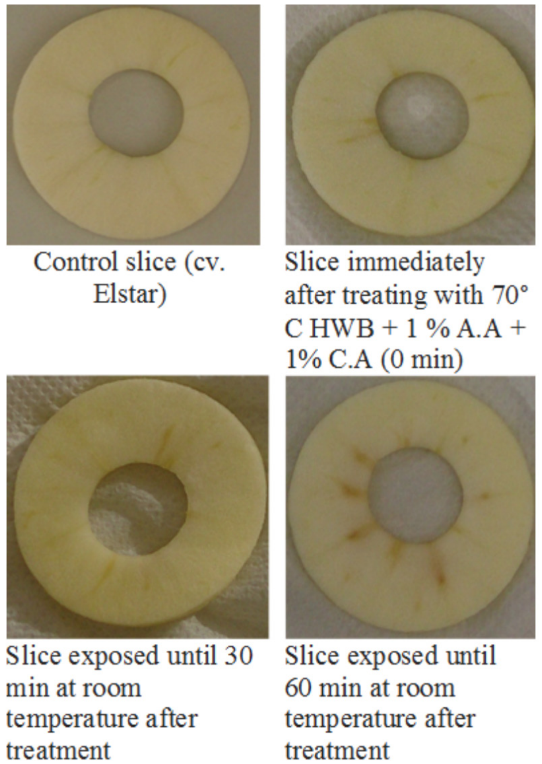

Figure 3.1: Effect of air exposure timing on the apperance of apple slice treated under 70 C HWB + 1 % A.A + 1% C.A

Figure 3.1 shows the effect of air exposure time at ambient temperature on treated apple slice (70 °C hot water blanched + 1% AA + 1% CA). Result showed slice exposed for longer time at ambient temperature might leads to discolouration even though pre-treatment such as 70 °C hot water blanching in combination of 1% ascorbic acid and citric acid was applied. Using only browning agents might not give better result but also other external factor such as longer waiting time might lead to browning reaction. The change in colour seem to be high compared to control sample when a heat treatment was applied. This can probably be ascribed to the occurrence of MR, in which the high content of sugar (mainly fructose in apple fruit) reacts in presence of heat source consequences discolouration (Hecke et al., 2006; Laroque et al., 2008). At the higher water blanching temperature, the browning reaction`increased.
Eventually, the temperature at 70°C was sufficient to inactivate the enzymes, while apple slices lost the tissue integrity with cell breakage, facilitating more contact to air and the release of endogenous enzymes. These ultimately encountered substrates in different cell compartments, leading to the detrimental consequence of surface colour changes. Moreover, the opening of the cellular pores during the heating process might have led to the induction of secondary product synthesis, including a variety of phenolic compounds.

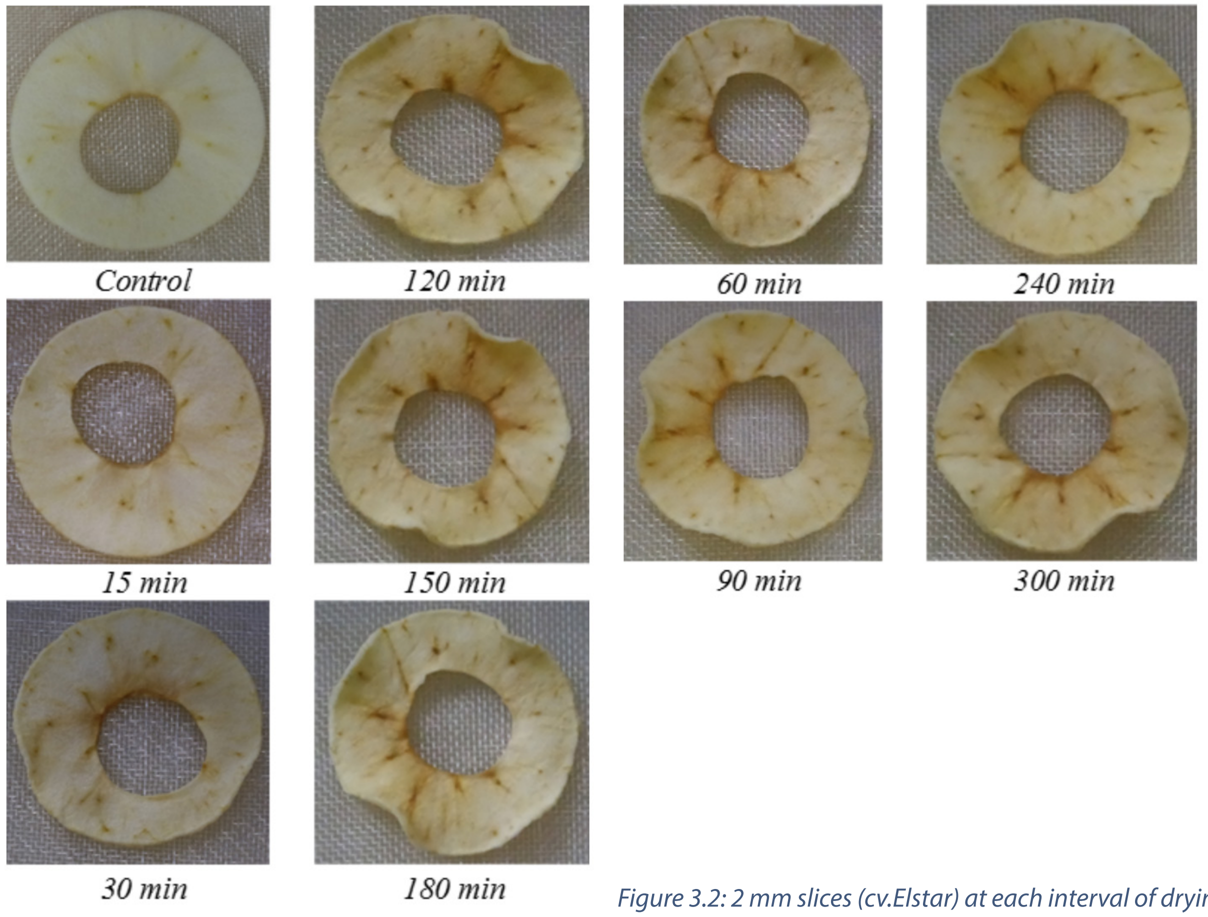

Figure 3.2: 2 mm slices (cv.Elstar) at each interval of drying period at 70 °C

Therefore, blanching treatments can have an adverse effect on cell membranes that might deteriorate in different ways such as changes in composition, structure, function or the loss of protein functionality (Gonzalez and Barrett, 2010).

Figure 3.2 shows a visual comparison of 2 mm apple slice at each interval of drying process at 70 °C. The drastic change in colour can be observed until 90 min drying time. After then, the change in colour seems to be uniform till end of drying process. The reason might be due to less time to air exposure (< 30 min) during pre-processing step. Apple cells contain phenolic compounds, located in the vacuoles, and the enzyme polyphenol oxidase (PPO) located in plastids. A contact of phenols and PPO trigger a reaction known as enzymatic browning. Polyphenols are oxidized to quinones by the PPO. These phenols and PPO are polymerized with other quinones or phenolics to form brown pigments. Colour changes are significantly influenced by both the PPO activity and the phenolic concentration, but the significance differs between different apple cultivars (Holderbaum et al., 2010). Furthermore, the colour of dried apples is affected by both enzymatic and non-enzymatic browning (Lavelli and Caronni, 2010)
Maillard reaction take place as a series of chemical reactions between reducing sugars and amino compounds occurring in presence of heat. The main variables affecting the extent of the Maillard reaction are temperature and time which depend on processing conditions as well as pH, water activity and type and availability of the reactants which are based on product properties but may be changed because of the processing of food and raw materials (Jaeger et al., 2010). Hence, this indicates the evolution of different browning mechanisms in apple slices and thus particular apple cultivar require corresponding anti-browning agent and/or less air exposure at ambient temperature to prevent the brown colour development.
During processing such as peeling, slicing, drying; the phenolic composition of apples may be modified by oxidative reactions (antioxidant activity of the phenols and oxidative browning). Phenolic compounds act as antioxidants and substrates for oxidative browning reactions, namely, polyphenoloxidases (PPO) and peroxidases (POD) that eventually might impact on organoleptic and nutritional qualities. Thus, the stability of antioxidants should be considered during the processing of fruits and vegetables. For instance: Henríquez, Córdova, Almonacid, & Saavedra, 2014 mentioned the degradation of total phenolic content in apple peels increased with high drying temperature during a conductive drying process. Furthermore, the declination concentration of polyphenols during drying phenomenon occurs due to (1) enzymatic or non-enzymatic degradation; (2) formation of insoluble oxidation compounds; (3) production of polymers; and (4) decomposition of thermolabile compounds (Henríquez et al., 2014; Nicoli, Anese, & Parpinel, 1999). Therefore, a long term drying process or drying at higher temperature affect the antioxidant properties and phenolic compounds.

There are not as such many studies on degradation of apple slices during drying processes. Nonetheless, the basic principal of phenolic component degradation can be gathered from other commodities. For example: the highest degradation of polyphenolic content and antioxidant present in red grape pomace was observed at the higher air-drying temperature (i.e. above 60 °C). The main reason was due to release of bound phenolic compounds; partial degradation of lignin which could lead to the release of phenolic acid derivatives; and/or the beginning of thermal degradation of the phenolic compounds (Larrauri, Rupérez, & Saura-Calixto, 1997). Karaaslan et al., 2014 observed high degradation of anthocyanins and phenolic compounds at 75 °C vacuum drying of pomegranate arils while at 55 °C drying temperature, the preservation of phenolic content was highest. Moreover, additional pre-treatment such as blanching resulted higher amount of phenolic compound compared to untreated samples during drying processes. Less losses of phenolic compounds were observed at temperature below 60 °C hot air drying in several studies: apple pomace (Heras-ramírez, Quintero-ramos, Torres-muñoz, & Salas-muñoz, 2012); litchi pericarp (Kessy, Hu, Zhao, & Zhou, 2016); peaches and apples (Rababah, Ereifej, & Howard, 2005); Persimmon (Akyildiz, Zorlugenc, Benli, Aksay, & Fenercioglu, 2008). Results from the several studies showed that higher drying temperatures and longer drying times destroy the phenolic compounds. On the contrary, hydroxycinnamic acids found in apricots, apples and plums have a higher hydroxycinnamic acid content at higher drying temperatures. This is due to the deactivation of oxidases and the creation of new cinnamates during the drying processes (McSweeney & Seetharaman, 2015).
Hence, understanding the drying in impacting the bioactive phenolic compounds and selecting appropriate drying conditions is significant in preserving the nutrients. Mainly, temperature elevation and oxygen presence in the environment negatively affect the phytonutrient content. Moreover, heat applications, process duration and light effect are also factors involving degradation of these compounds.

3.2. Carrots

Saleh, R.

Carrot is a very important source of vegetables for people around the world. The crop is the second most consumed vegetables in the world and it has been identified as the healthiest vegetable due to its abundant of phytochemical constituents such as carotenoids, vitamin C and minerals (Anon, 2011). These nutrients provide significant health benefits to human in terms of antioxidant capability, anti-cancer property, anti-inflammatory and many others (Zeb and Mahmood, 2004). The main carrot producer in the world is China with 26.91% production of the world's carrots in 2013 and followed by Russia and Germany (Jared & Lopez, 2016). The crop is also a second most important crop after tomato in European countries and Germany has ranked number two with 526,900 metric ton of carrot's production in 2015 (Anon,2016). Carrot always consume in fresh but it also can be used as an ingredient in the preparation of different food mixture especially in the instant food industry. Carrots are used in many dishes around the world such as, stews, soups, curries, salads and it can also be incorporated into bakery products such as cakes and bread. The crop can be processed into various products such as canned, dehydrated, juice, beverages, candy, preserves and pickles (Aggarwal and Kaur, 2014).

countries	Production (metric ton)
France	560,000
Germany	526,900
Spain	410900
Belgium	245400
Denmark	89200
Ireland	40200
Greece	32500
Chec Republic	23500
Estonia	18100
Bulgaria	7900

Source : EUROSTAT, 2016

Table 1.3.1: Major carrot production in the European countries (2015)

In recent years, the development of carrot based product for the healthcare and cosmetic industry has been increased steadily due to its health benefit properties of carotenoids which is the precursor for vitamin A. Most carrot based manufacturers preferred to dry the crop before further processing because carrot is a highly perishable commodity with short storage life under ambient condition. In view of this, drying is the most important unit operation in carrot processing. Many studies have been conducted on carrot drying with the same goal of maintaining product quality as much as possible as well as minimizing energy consumption in order to reduce overall production cost.

Several drying techniques with different drying modes and setting parameters have been investigated by many researchers in order to obtain high quality product in terms of physical appearance and nutrient content especially by maximizing the retention of carotenoids in carrot. The most common method of carrot drying is by hot air drying of various shapes of carrot (Mulet et al, 1989: Ratti 1994: Krokida and Maroulis, 1997: Khraisheh et al, 1997 : Lin et al, 1998). Those authors reported different quality attributes prior to drying. Maintaining the quality of raw material after drying is very important for quality assurance and evaluation of the finish product. Based on this, there is a need to develop specific drying strategies of carrot in order to retain its quality which attributes to its health benefits. Preserving the bioactive compounds such as carotenoids during drying is very important in order to ensure maximum health benefits to consumer.

Many research had been done on different drying technique of carrot but less studies were found on manipulating different drying strategies in relation with product quality for process control and optimisation. The inadequacy of drying information related to product quality will generates the following problems:

- Over drying that causes mechanical damage to the structure of the product, such as excessive fragility, collapse of the support structure and pulverizing, with consequent loss of quality.
- Inadequate drying which means that the final moisture content obtained after the process is above the minimum requirement. This will lead to poor shelf life due to microbial activity, browning and degradation of phytochemical.
- Inconsistency of product quality due to improper drying technique. This will lead to low quality of end product.
- Non-uniformity in drying due to geometrical configuration and different thermo mechanical properties will cause non-uniformity drying due to differences in thickness of dried layer.
- Inefficient use of energy due to inappropriate selection of parameters that cause additional energy consumption
- Excessive drying times due to inadequate selection of drying parameters, which generates low production rate and degradation of product quality

3.2.1. Quality of Dried Carrot

The commonly examined properties in dried carrot can be classified into two major categories: the engineering properties of the drying products and also physico-chemical quality. The engineering properties involve effective moisture diffusivity, effective thermal conductivity, specific heat and equilibrium moisture content which are essential in the design of food processes and processing equipment, and optimisation of a process control. Most of the measured physico-chemical quality of the dried carrot comprises of a number of parameters such colour, rehydration capacity, shrinkage carotenoids and vitamin C. Although these properties are not necessary for prediction of drying time and process modeling, they are important for characterization and prediction of the quality of dried product (Krokida and Maroulis, 2000). They are also very important for the development of new industrial products with desired properties or for quality improvement of already existing ones. So, this paper will focus on the physico-chemical quality of dried carrot.

3.2.2. Influence of pretreatments on quality of carrot

Pretreatments prior to drying such as blanching and dipping in chemical solution such as citric/ascorbic acid, calcium chloride and other solutions had been documented to minimize the loss of nutrients in carrot. Several researchers reported that carotene loss can be as high as 80% if the crops are dried without pretreatments (Sablani, 2006). The main purpose of pretreatments is to inactivate certain enzymes such as peroxidases and catalases that could cause nutrients deterioration and discoloration of product such as browning (Shivare, et al. 2009). The heat of blanching also destroys colour related enzymes such as oxidases, lipoxygenases and chlolophyllase and leads to better colour retention in dehydrated product (Cui et al., 2004). Hot water blanching at low temperature of 77°C for 20 to 30 minutes also had a positive effect on the firmness of carrot as compared with high temperature blanching of 100°C for 4 to 5 minutes (Lee et al., 1979). High temperature of hot water blanching at 95°C for 5 minutes was found to be the most effective pretreatment to inactivate peroxidases in carrot slices with good retention of carotenoids at 55% respectively (Shivare et al., 2009). Blanching also cause reduction in some nutrients like vitamin C in carrot as the content was reduced to 38% after hot water blanching at 90°C for 7 minutes (Lin et al., 1998). However, contradict findings was observed by Bognar et al. (1987) on carrot slices. The author found that microwave blanching of carrot slices could retain 100% of vitamin C as compared with hot water blanching. Blanched carrot followed by freeze drying also showed better colour quality as reported by Patras et al. (2011).

3.2.3. Influence of drying methods and process parameters on quality of carrot

Preservation of carrot by removal of water to a certain level at which it is safe for storage through drying process has been widely documented by many researchers. Longer shelf life and significant reduction in the volume of the product are the main purpose of drying. However, the quality of dried product greatly depends on drying methods and process parameters (Krokida and Maroulis, 2000). The most common method of drying is by hot air convection drying. In hot air drying, degradation of product quality by thermal damage is directly proportional to the temperature and the length of time (Vadivambal and Jayas, 2007). Higher temperature and longer drying time may cause quality degradation in terms of flavor, colour, nutrients and also the rehydration capacity of the dried product (Lin, et al., 1998; Vadivambal and Jayas, 2007 Drouzas et al., 1999). High temperature and long drying time will cause the volatile compounds to be vapourised and lost with a water vapor, resulting in off flavor of the dried product. Different levels of quality degradation in terms of physical and chemical content of carrot during drying was observed in numerous publications by different researchers.

3.2.4. Physical Quality

Physcial quality of dried carrot always measured in terms of shrinkage, rehydration capacity and colour. The most common parameter is the colour changes of carrot during drying. According to Kudra and Strumillo (1998), the changes in colour during dehydration not only due to evaporation of the surface water but also due to certain reactions, such as enzymatic browning, non-enzymatic browning and caramelization reactions. These reactions may be undesirable for many products, thus preserving the colour during drying is the subject of various procedures, such as temperature deviation of specific ranges, intermittent drying and the use of colour protective acids. Prabhanjan et al. (1995) observed that, the colour retention was better in microwaved dried carrot as compared with hot air drying. Similar observation also reported by Lin, et al. (1998). The author reported that hot air dried carrot slices were darker, with less red and yellow hues than the freeze dried and vacuumed microwaved dried. Freeze dried samples had the highest degree of lightness, with a slightly lower yellow hue than that of vacuumed microwaved dried. The darker appearance of the hot air dried compared to the freeze dried samples may be due to the exposure to heat during drying. It might also be expected that the air dried appear darker since the density of these slices was greater than freeze dried product, yielding a higher concentration of pigment per volume of tissue. This is further explained by Howard et al. (1996) which stated that the lightness of carrot as indicated by L value of chromaticity index during drying is affected by processing temperatures, with higher temperatures causing darker colour. A similar observation was also reported by Abbatemarco and Ramaswamy (1995). Krokida et al., (1998) studied on degradation kinetics of colour on carrot and stated that, the yellowness and redness of carrot is highly dependent on temperature and humidity during drying. Other quality attributes of dried carrot is the shrinkage and rehydration ratio which are significantly affected by process parameters such as temperature, air velocity and relative humidity as reported by Hong et al., 2010. The author observed that, high rehydration ratio of dried carrot was observed when dried at lower drying temperature of 40°C with 13.0 m/s air velocity and 40% RH. Studies on thin layer drying of carrot using microwave and hot air dryer by Prabhanjan et al. (1995) also showed that product shrinkage was minimal with high rehydration capacity when dried at maximum power level of microwave application.

3.2.5. Nutrients retention

Drying cause quality changes in carrot in terms of nutritional retention and the information can be found in many literatures. Nutrients retention of carrot after drying was always measured in terms of carotenoids content. The carotenoids are very important nutrient indicator in dehydrated carrot and it is sensitive to light, oxygen and enzymes (Cui et al., 2004). This author also explained that temperature and oxygen will cause more degradation of carotenoids that will significantly affect the colour retention in dried carrot while lipoxygenases are the major enzymes involved in carotenoids degradation. The extent of the changes greatly depends on pretreatments, drying methods and process parameters (Cui et al., 2004). Reduction of carotenoids up to 68% in carrot during microwave drying was observed by Park (1987). High temperature of 150°C with short time drying of 12.5 minutes had shown minimal losses of 15.7 % of carotenoids in carrot (Mudhahar et al., 1989). Mohamed and Hussein (1994) observed that carotenoids content was highest when dried at 40°C for longer time.

The author also suggests that carotenoids are more sensitive to drying temperature than drying time. Abonyi et al. (2002) observed that, drying using refractance window method could retain comparable amount of vitamin C and carotenoids in carrot as compared with freeze drying but low retention of carotenoids was observed in drum dried product due to severe heating applied during drying. The loss of ß-carotene in carrot also found to be lower at 58% and 62% when using low pressure super-heated steam dryer and vacuum dryer as compared to hot air drying (Suvarnakuta, et al., 2005). Drying at 60°C with low air velocity of 0.6 m/s using cabinet dryer was found to give a better retention of unblanched organic carrot up to 62 % (Saleh, unpublished work). High degradation of carotenoids up to 80% reduction in carrot was observed when drying at 80°C (Anthanasia and Konstantinos, 2010). Furthermore, some researchers dried carrot using fluidized bed dryer with different drying mode such as reported by Pan et al. (1999) and Brod et al. (1998). High retention of ß-carotene in carrot was observed when intermittent drying was applied as compared with continuous drying (Pan et al., 1999).

3.2.6. Concluding remarks

Quality losses can occur during pre-treatments, and along the drying process itself. The variation of different cultivars of carrot will have a considerable influence on the quality retention since different authors reported on different varieties of carrot which is obtained from different location all over the world so the degradation levels of the nutrients greatly depends on the nature of the crop and also the environmental condition where the crop had been grown. Pre-treatment methods and the factors influencing the loss of quality during drying were identified and discussed. In general, pre-treatment methods, different drying technique and selection of process parameters during drying will significantly affect the quality retention. More data on kinetics of nutrient losses during drying need to be generated in order to develop an optimization model for process control along the production chain. Further research in terms of manipulating different drying strategies is also needed in order to develop an improved process for better understanding of the drying characteristics and its effect on the product quality of carrot. It is also very important to monitor the physiological changes of the quality degradation in carrot during drying process in order to identify specific ways to reduce such losses so that high quality product will be produced in the future.

Figure 3.3: Fresh carrot slices

Figure 3.4: Blanched and unblanched carrot slices

3.3. References

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I.2 DRYING STRATEGIES, PROCESSES AND ENERGY

4. Recommendations and practical drying experience (best practice processing)

University of Kassel, Department for Agricultural and Biosystems Engineering, Germany
Meridian Fruchthandelsgesellschaft mbH, Germany
Sturm, B., Esper, A.

4.1. Background

Currently, particularly in small and mid-scale production the technological set-up tend to be outdated. The process settings are based on empirically found values which might have been found decades ago. Drying times tend to be longer than necessary, which in combination with sub-optimal insulation and air flow management leads to increased energy demands.
Producers have to react to changing customer demands, utilizing the existing hardware, which in many cases leads to a further decrease of the overall efficiency of the processes involved. In most processes, product related information is not monitored but the process is treated as a black box. However, there is a great potential for development of processes which are include product information, e.g. utilizing product temperature as direct means of measurement of changes in physiochemical characteristics of product.
The goals for optimized drying can be directly deduced from the above. There is a need for targeted control of the process in terms of particular product characteristics (e.g. colour, shrinkage, chemical composition). The solutions need to be easily implementable in practice. Ways need to be found to decrease energy demands. With a reduction of processing time the throughput of the system can be increased.
The aim of this chapter is to give tips on how to optimize the performance of existing drying devices and in consequence of product quality through the implementation of a set of practicable measures.

4.2. Recommendations

4.2.1. Processing chain for drying

Depending on the raw material in question and the intended characteristics of the final product a number of different processing steps besides the actual drying are involved (Figure 4.1). It is of utmost importance to understand the impact of each of these steps on the development of the product quality but also process effectiveness and in consequence resource demands.

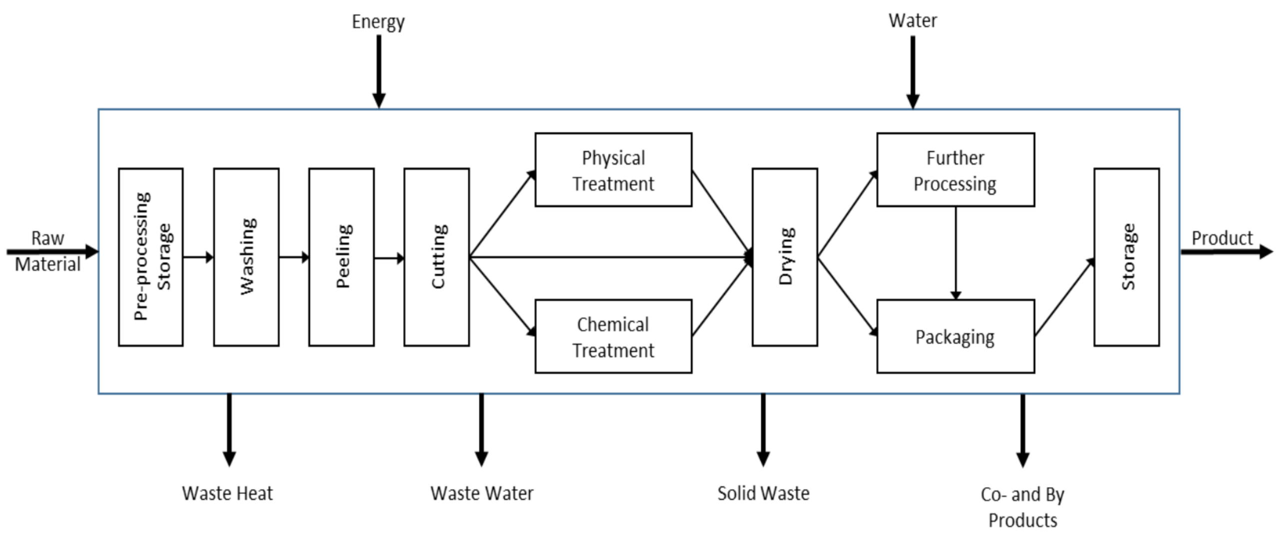

Figure 4.1: Overview of processing steps in the production of dried agricultural goods (Sturm, 2017)

As aforementioned, every step throughout the drying process has a decided influence on the final product quality but also the effectiveness of the process itself.

4.2.2. Storage before processing

Generally, there are two types of plant based agricultural produce. Ones which are highly susceptible to deterioration (e.g. herbs, medicinal plants, hops) and others which can be stored for extended periods of time (e.g. apples, carrots, potatoes). All raw materials, however, undergo significant changes throughout the storage time. Thus, it is of great importance to reduce the storage time pre-processing as much as possible and to provide the best practically implementable conditions throughout this time period:

- Highly susceptible materials (will be further elaborated in the best practice case)
  - Ensure that harvesting tools and cutting tools are sharp

    → Blunt tools lead to significant damage in the material
  - If possible, dry the materials immediately after the harvesting process
  - If immediate processing is not possible, ensure that the material is sufficiently aerated throughout the lag-time to avoid "sweating" and increased microorganisms activity

    → Foresee an appropriate ventilation system
- Storage products

- Appropriate cold and controlled atmosphere storage can reduce the speed of deterioration but not entirely stop them. Inadequate storage conditions, however, accelerate quality changes.

  → Process the raw material as soon as possible after harvest to retain the maximum possible raw material quality.

  → Ensure that the storage conditions are appropriate if longer term storage is necessary

4.2.3. Preparation

Particularly in fruits, vegetables and meat the preparation of the raw material requires several mechanical processes such as peeling and cutting. These processes lead to a mixture of chemical components from within and between the cells which in the natural state are separated. Further, the cut surface is exposed to the surrounding air, providing oxygen to accelerate reactions. These reactions usually lead to colour changes which are indicative for quality loss.
The use of appropriate tools (i.e. slicers, cutters etc.) can help to reduce these negative effects through a reduction of uncontrolled cell wall rupture. In this context several aspects are of great importance to guarantee an optimum quality:

- Avoid cutting devices which rely on high mechanical pressure (e.g. cutting knife that has to be pushed down hard): the pressure can lead to bruising on the impact side and the side that is lying on the chopping board
- Use smooth blades, avoid serrated blades (will be destructive to the structure of the raw material)
- Sharpen the cutting device regularly: a blunt knife results in a ruptured structure of the cut surface rather than a clean cut one and leads to increased browning
- If possible use ceramic knives
- Clean the cutting device regularly when the preparation of the raw material requires significant amounts of time: over time there is a build-up of substances on the cutting edge which react with the surrounding environment. Parts of these substances will then be transferred to the cut surfaces of the later particles, leading to an increase in degradation. In meat handling this can also lead to the increase of microbial contamination.

4.2.4. Pre-treatment

As described in the previous chapters, there are several means of pre-treating raw material to reduce the adverse effects of the surrounding air during preparation and processing. These are the use of natural antioxidants or blanching. The use of antioxidants, e.g. ascorbic acid or citric acid solutions, is often effective for the retention of colour and naturally present components, however, the expenditure can be significant. Conversely, in blanching, the expenditure is once for the device and otherwise the process relies on water. However, as described in the previous chapters on quality of products, with blanching there is a degree of thermally caused degradation processes. In case of the enzymes which are responsible for enzymatic browning and other degradation processes this is wanted. However, for many other components it is unwanted.

- Natural antioxidants
  - Recommendable concentrations strongly depend on the produce in question, the raw material quality and heterogeneity thereof
  - The effectiveness further depends on:
    - Lag time until drying
    - Processing conditions in drying
  - In some cases no apparent advantage of pre-treatment is visible
- Blanching
  - Degradation of chemical components is a function of temperature and time

    → Blanching at low temperatures for extended time significantly damages the heat sensitive valuable components in the raw material
    Extended blanching periods lead to leeching of components from the raw material into the surrounding water

    → High temperature – short time blanching is recommended to increase quality retention of the raw material. Tests conducted within SusOrganic have shown that the least damaging blanching approach for sliced carrots (5mm thickness) would be 90°C – 95°C for less than 1.5 and 3 min, respectively.
  - Only use blanching if absolutely necessary:
    - Usually the retention after drying is lower than with non-pre-treated samples
    - Blanch when a long storage time is intended: degradation of non-pre-treated samples is higher than that of blanched samples
    - Blanch when it is not possible to further process the raw material immediately after cutting, see the following sections
- Selection of variety
  - Chose varieties which are less susceptible to oxidation

4.2.5. Lag time between preparation and drying

In fruits and vegetables the duration of time between cutting and drying has a significant impact on the resulting enzymatic browning. If using a cabinet dryer an easily implementable measure is to start the drying process immediately and insert each tray as soon as it is filled. This will significantly reduce the time period in which enzymatic browning is effective. However, the approach of gradually filling the dryer also results in having to gradually remove the trays times rather than stopping the process at once.

- Immediately transfer the raw material into the dryer after cutting once one tray is full

Energy demand will not be significantly impacted by this approach as the drying process usually is accelerated for the individual particles. In practice, driers are often overloaded in comparison of the dryer's capacity to remove water from the system, which leads to an increase in drying time and simultaneously of deterioration processes

4.2.6. Impact of particle thickness

Heating of and water transfer from the product particles depends strongly on the geometry thereof. While it might seem to be better to have thick particles as this means less preparation time and a higher capacity of the dryer, this often has very negative effects on the product quality due to the increased processing time. As shown in scientific and practical tests, a reduction of particle thickness by 50% leads to a reduction of drying time by up to 70%. An example for apple drying is given below (Figure 4.2).

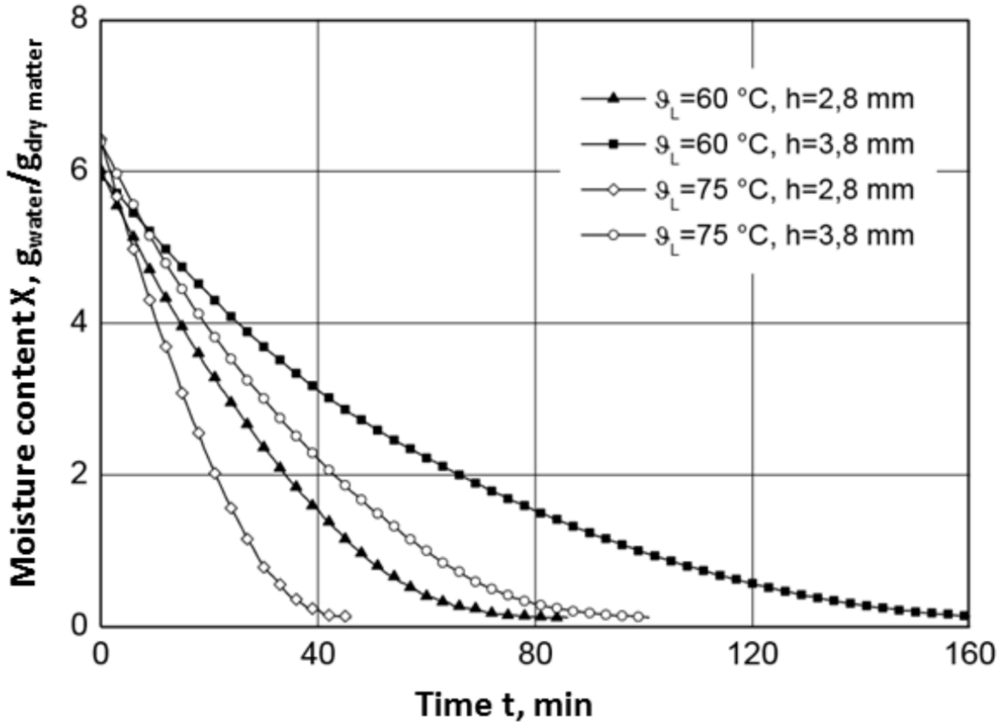

Figure 4.2: Drying behaviour depending on slice thickness and temperature (adapted from Sturm, 2010)

- Decrease particle thickness to increase drying efficiency and product quality
- Establish cost-benefit of increased work load in preparation

4.2.7. Drying

As previously discussed, changes in the product are a function of temperature and time. This means that long time processing at very low temperatures might have a higher impact on the degradation of produce than a shorter drying process for a shorter time.
Cabinet dryers often show issue of unequal air distribution both between the trays and across the individual trays. This leads to a situation where trays need to be changed over, sometimes repeatedly. Where possible, the physical system should be modified to provide even air distribution by progressively reducing the width of the air channel as displayed in Figure 4.3 or taking other appropriate measures.

Figure 4.3: Air flow distribution in a cabinet dryer (Innotech Ingenieursgesellschaft mbH)
Dryers are designed with a given maximum heat supply and fan capacity.

This results in a defined maximum drying capacity. At the start of the process, when the produce is still very wet, the amount of water that needs to be removed per minute is a multiple of the later stages. It therefore is of great importance to not overload the dryer.
In many cases the fans in relation to the heaters are under-dimensioned. This means that the air flow cannot transport the evaporated water away from the product. As a consequence water condenses on the surface of the particles and supports degradation.

- Ensure that the air distribution in the dryer is even, otherwise there will be great differences in final moisture content and product quality
- Stop drying when desired moisture content is reached
  - Use your knowledge
  - Low cost measurement devices currently not on the market
- Avoid overloading → check fan and heater capacity

- Reduce drying temperature at the start of the process if fan capacity is too low to transport the water away
- If possible invest in variable speed drive fans with sufficient capacity for the start of the drying

4.2.8. Best practice processing hops and herbs

Hops and herbs are usually dried in bulk dryers, where the air enters the system from underneath. Depending on the processed volumes, multi-stage dryers might be used. The following best practice example outlines easily measures for the increase of productivity and product quality

4.2.8.1. Preparation / raw material handling

Herbs and hops are extremely susceptible to degradation after harvest. As a general rule they need to be dried no longer than 4 hours after the actual harvesting process to ensure an acceptable final product quality. Storage conditions during this time also have a significant impact on such degradations. If the raw material is stored one needs to make sure that the bulk is adequately aerated to prevent build-up of free moisture. Figure 4.4 shows an example of hop leaves which were stored optimally before drying (left) and such which were not aerated and, thus, started "sweating" (right) which resulted in a decided change in colour. This in turn indicates significant chemical changes within the product.

Figure 4.4: Ideally stored hops (left) and sub-optimally stored hops (right) pre drying (Münsterer, 2015)

4.2.8.2. Pre processing

If herbs are shredded before drying to increase the drying rate the quality of the product might significantly suffer as the cut surfaces allow for enzymatic reactions to happen which otherwise could not.

4.2.8.3. Drying

4.2.8.3.1. Air distribution

The evenness of air distribution is crucial for a uniform drying behaviour of the produce. Therefore it is of utmost importance to take all measures that are practically feasible if the problem of uneven distribution is known. Figure 4.5 depicts the problematics of an incorrect air inlet design of a through flow dryer commonly used for herb and hop drying. With a decrease of air speed (and thus volume flow) from left to right, drying time significantly increases.

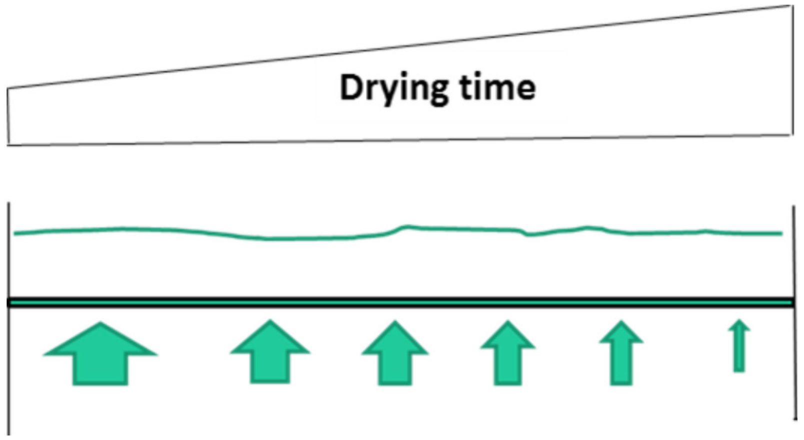

Figure 4.5: Impact of uneven air distribution on drying time across the length of a dryer (Sturm, 2017b)

In practice, producers often try to make up for these uneven conditions by regular redistribution of the drying produce. This is a very labour intensive and exhausting activity, particularly considering that surrounding temperatures can be in the region of 40-45°C and air humidity of up to 100%. These actions mitigate the problem to some extent, however, will never lead to a result in terms of drying time and product quality as an even air distribution would give. Therefore, where possible, measures should be taken to ensure that the drying air is equally distributed.

Besides single stage through flow dryers multi stage dryers are widely spread in herbs and hops processing. In these dryers usually only the top (filling fresh material) and bottom (removing final product) stages are accessible for the processor. The hops are tipped through the stages which leads to an unequal distribution of the material and, therefore, unequal drying and the development of "hot spots" of high moisture contents, see Figure 4.6.

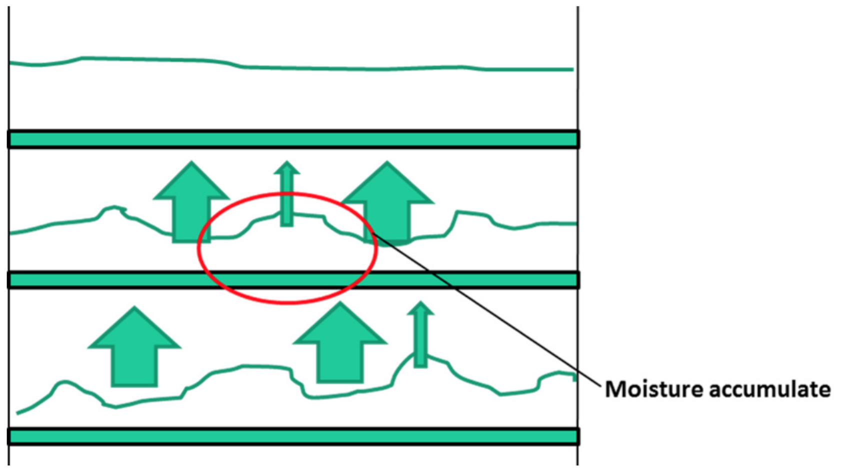

Figure 4.6: Produce distribution and air flow distribution in a multi stage dryer (Sturm, 2017b)

4.2.8.3.2 Bulk height / weight

Drying time, temperature changes through the bulk and the development of air humidity directly depend on the higher/specific weight of the raw material, see Figure 4.7. The air passing through the bulk transfers heat to the produce and removes water from its surface. This leads to a simultaneous decrease of air temperature and increase of its relative humidity. The more material is filled into the dryer, the greater are the decrease in temperature, increase in air humidity and duration of the drying process.
In this context it is crucial to ensure that water removed from the lower layers of the bulk does not re-condensate in the upper (still colder layers). At the same time all water at the surface of the produce in the upper layers needs to be reliably removed. This can be achieved by an increase of air flow rate (specific volume flow) at the start of the process, when the material is still wet and loses high amounts of water. If this is not possible because the fan already runs at 100% capacity it is advisable to reduce the drying temperature in this phase to decrease the water evaporation rate and in turn prevent moisture build up in the upper layers. Further, the relative humidity above the bulk should always remain below 70% which coincides with the equilibrium moisture content.
In many herb and drying operations producers fill their driers based on the bulk height. However, practical tests conducted in the context of hop drying have shown that using bulk weight is a more accurate measure, leading to an increase of uniformity between individual batches.

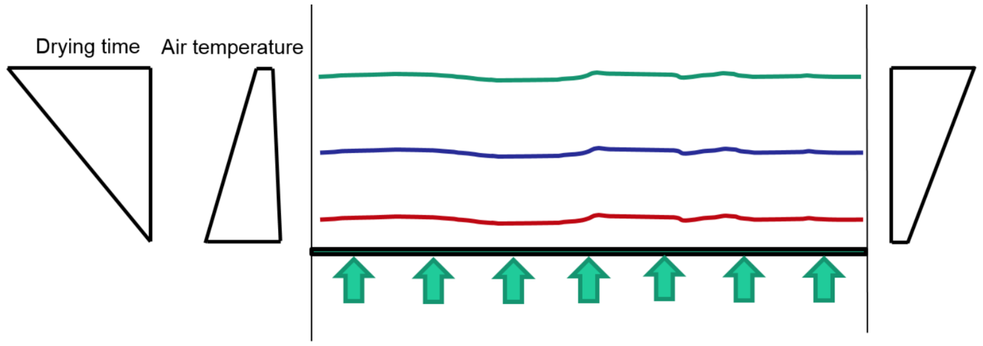

Figure 4.7: Impact of bulk height/weight on temperature decrease, air humidity increase and duration of drying process

4.2.8.3.2 Bulk density / variety

Bulk density strongly depends on the nature of the processed material and its variety. As a general rule bulk density increases with a decrease of particle. Thus, the pressure drop through the bulk increases. Therefore, it is important to adjust the bulk weight accordingly.
Depending on the type of plant and the intended purpose, plants are either dried as a whole or only specific parts are considered. Each of these parts (see Figure 4.8) has a different composition and, thus a different drying characteristic. If dried separately it is fairly easy to adjust the process settings accordingly. However, in cases where several parts are dried together gradients within the plant will develop. For example, in hops the leaves dry very quickly in comparison to the spindle. When the final moisture content of 10% is reached, the leaves have a moisture content of 4-6 % while the spindle has a moisture content of 12-13%. This leads to significant stress on the leaves and the active components such as aromas. In such cases a correct conditioning phase is of utmost importance to ensure long shelf life of the product.
Each part of a plant has specific drying characteristics.

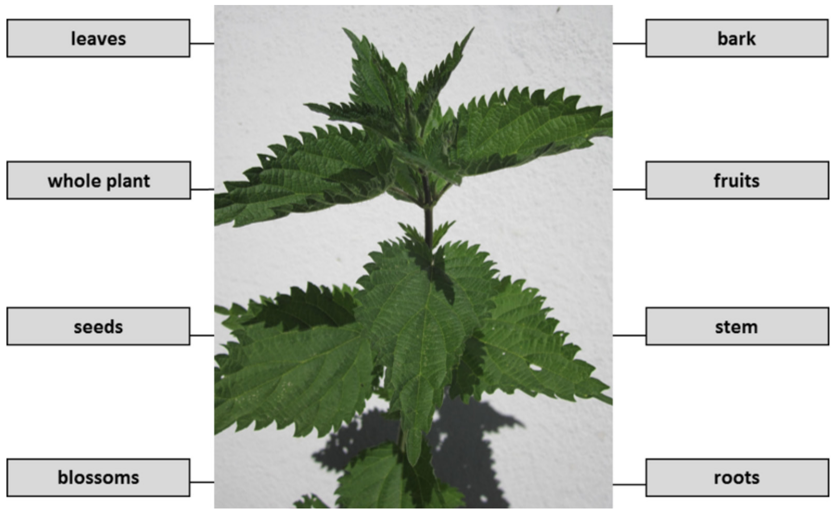

Figure 4.8: Commonly utilised plant parts

Figure 4.9 shows the components of hope cones of different species of hops.

Figure 4.9: Impact of variety on composition of hop cones (Münsterer, 2015)

4.3. Introducing product temperature into measurement and control of the drying process

It is well known that product temperature is a crucial factor related to the quality of dried products. However, in the majority of drying operations the process is controlled by setting air temperature while product temperature is completely unknown.
Particularly in the organic sector where temperatures for most processes should not exceed 45°C the use of product temperature instead of air temperature could help to increase process performance while still ensuring the protection of valuable contents within the product. Figure 4.10 depicts the typical development of air (black lines) and product (red lines) temperatures for the application of air temperature controlled drying (left) and product temperature controlled drying (right).

Sturm (2010) also found that it is possible to deduce step wise drying strategies, further increasing product quality, from the development of product temperature throughout the process

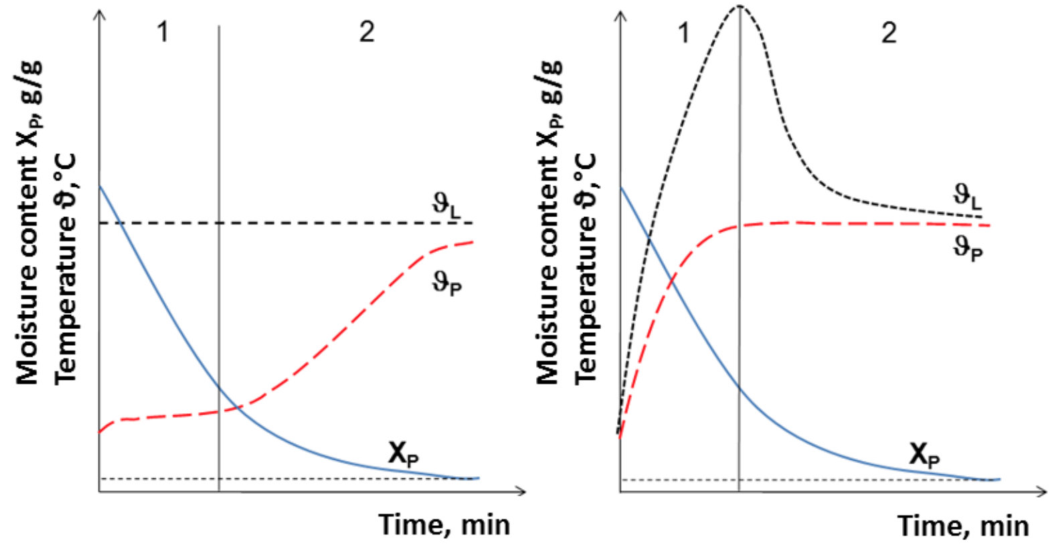

Figure 4.10: Temperature development during air temperature and product temperature controlled drying (Sturm, 2010)

4.4. Energy supply systems optimisation and renewable energy integration

Particularly in the organic sector the integration of renewable energy sources is an important aspect to further increase sustainability of production. When considering such an investment, the following points are of great importance

- Optimise the process and thermal system first
  - Assess current energy demands and compare with benchmarks and/or contact experts
  - Improve insulation where necessary
  - Optimise processing conditions
  - Recover waste heat
- Renewable energy integration considerations
  - Yearly operation times
  - Operation times throughout the day
  - Location
  - Grid energy mix
  - Renewable energy integration options in relation to sustainability
    - Biomass
      - Wood burners weasy to implement, can also be
      - Sustainability depends strongly on the forest management

- Heat pumps
  - Better suited for operations that run for long periods
  - Sustainability depends strongly on energy mix in the country
- Solar thermal and solar photovoltaics
  - Only suitable for operations that run for a significant number of hours per year
  - Only of use for regions with sufficient radiation in the processing periods

4.5. References

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5. Improved drying strategies

SINTEF Energy Resaerch, Trondheim, Norway
(Bantle et al., 2016)

5.1. Einleitung

Drying of fruit and other foods is ancient preservation technique which improved food security centuries before the process was industrialized. The industrialization of the drying process improved food security, process stability and product quality, while at the same time the production was no longer depended on the local climate. Most producers have developed their own process parameters over the years, which give their product its characteristic appearance and taste. However, the process equipment used for the production is similar, since the main controlled parameters are temperature and humidity of the drying air.
Every drying process depends on the availability of a drying agent (mostly air) which removes the evaporated water from the product and at the same time supplies the necessary latent heat for water evaporation. Therefore, drying is a combined heat and mass transfer process. The design of a drying chamber ensures a good contact between the drying air and the being dried product and is therefore important for the drying rate, production time and product quality.
A supply system for the drying agent provides the necessary amount of drying air with a certain temperature and humidity. The economy of the drying process depends on the design of the supply system, while the product quality is among other parameters defined in the drying chamber. In the following, the different characteristic drying systems which are used in the industrial productions are summed up.

5.2. Heated ambient air drying (HAAD)

Traditionally, the ambient air was used for the production of dried fruits and a large amount of facilities still use the ambient air as a drying agent, especially in regions where the local climate is suitable to the drying conditions of the production. A drying system based on the ambient air has a relatively simple configuration and therefore low investment costs. This might be one reason for the popularity of these systems. The temperature of the ambient air in the most cases is not equal to the required drying temperature; hence, the air is first heated in a heat exchanger before it is directly ventilated into the drying chamber. For hygienic reason, it is generally recommended to install a filter element before the ambient air is used in the process. By controlling the heat exchange, it is possible to maintain the correct drying temperature. The humidity of the drying air can be adjusted by mixing a part of the wet air at the outlet of the drying chamber with the fresh drying air. HAAD systems depend on the seasonal variation of the ambient air, and problematic operation points might occur when the ambient humidity is too high. The economics of the process depends consequently on the amount of required heating and the seasonal variation of the ambient air parameters. If the heating energy can be supplied by excess energy from other operations of the production plant, the process can be quite economic. However, if a primary energy source for the heating of the HAAD system is necessary, the drying efficiency (which equals to the latent heat of evaporation, divided by supplied energy to the system) can be low. This is especially true in regions where a large discrepancy between the conditions of drying air and ambient air is present.

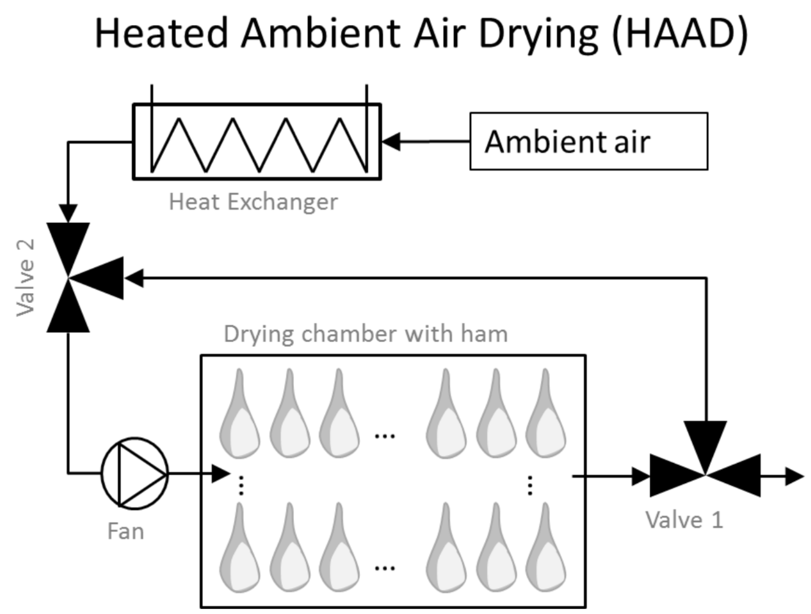

Figure 5.1: Sketch of a heated ambient air drier which is commonly used in the industry.

5.3. Closed looped drying system

When the drying air is circulated through the process in a closed loop, there will be no influence or disturbance with the ambient air and the process is more stable and needs less regulation after initial adjustments. Still, the evaporated water which was taken up from the product needs to be removed from the drying air. Commonly, this is done by cooling the air down below its dew point, so that the moisture is condensed out. The dehumidified air needs then to be heated up again in a second heat exchanger to its desired drying temperature. The heat exchangers for cooling can use a cooling medium which is tempered by a separate cooling system. The same principle can be also used for the heat exchanger for re-heating of the drying air; however, in some cases also direct heating is used here in order to avoid another heating system and to minimize heat transfer losses.
The regulation of a closed loop system is done by controlling the mass flow of the heating or cooling media by their respective pumps. It is also possible to use excess heat from other processes in the production plant for reheating of the drying air; however, for cooling normally a refrigeration cycle is necessary. The investment costs for a closed loop drying system are moderate but can be high due to the need of two different thermal operations (cooling followed by heating) or when more sub-systems are needed. The drying efficiency of such system is therefore quite often lower than 30 %. However, the operation is easy to control and the process is stable, which is why this system is very common in industrial applications.

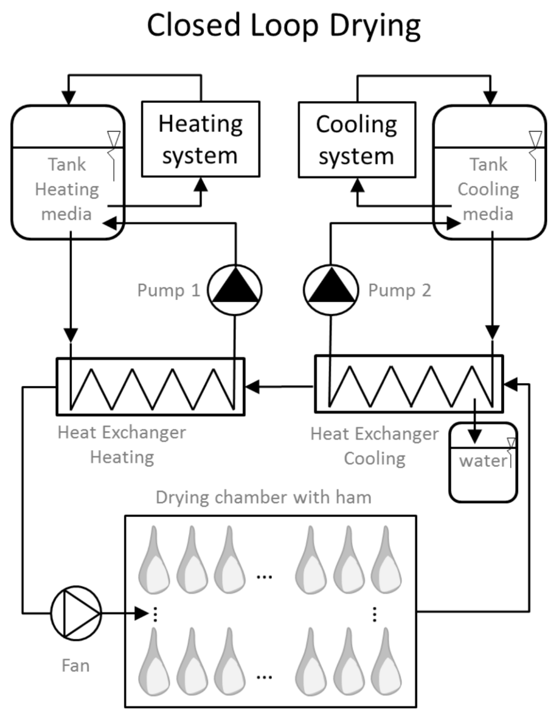

Figure 5.2: Industrial closed loop drying, which requires cooling and heating of the circulated drying air in order to remove the evaporated water.

5.4. Heat pump drying

In recent years heat pumps have been implemented in larger numbers as standard solutions in different systems, processes and application. Especially for heating of domestic houses the market share of heat pumps has increases, also because the technology is classified as renewable energy. Industrial heat pump systems are commonly classified as energy efficiency measures, where low temperature heat sources are upgraded in order to supply a higher temperature heat demand. The market share of heat pumps in certain countries is quite low (e.g. Germany) and local energy prices as well as return of investments considerations have surely an important influence on decision makers.
A German study (Wolf et al., 2014) evaluated the potential of industrial heat pumps for different industrial sectors based on statistical data for 34 European countries. Industrial heat pumps with a heat sink of up to 100°C were classified as conventional available heat pumps. It is important to notice different refrigerants are developed or are under development for these temperature areas while natural refrigerants (R717, R718 and R744) are already existing and implemented. The heat demand up to 100°C was estimated to be 650 TWh/year for Europe and especially the sectors Food and Tabacco, Wood, Paper and Chemical are identified to have corresponding heat

demands. Among these sectors the processes Drying, Evaporation, Cooking, Washing and Cleaning require commonly temperatures below 125°C and especially for Drying and Evaporation the excess heat of the process are ideal heat sources for the heat pump.
Convective drying, based on air as drying agent, is one of the most common preservation technologies and over 85% of all drier are of an air-drying type. The energy saving potential for heat pump assisted drying (HPD) is large and the Handbook of Industrial Drying states a drying efficiency of 95% for HPD compare to 35-40% for hot air drying. However, industrial HPD systems mostly operate at drying temperatures below 30°C.

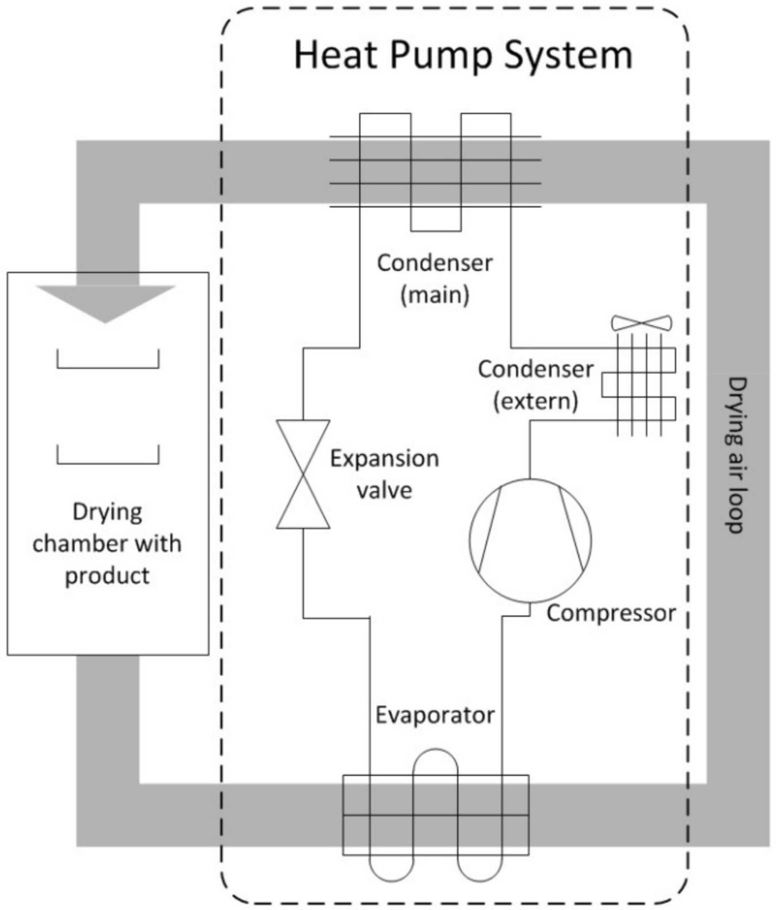

Figure 5.3: Principal layout for heat pump assisted drying for convective (air) drying in closed loop.

Heat pumps are characterized by the possibility to utilize a heat sources at low temperatures (at the evaporator) and supply a heat sink at a higher temperature (condenser). For the case of drying this combined heat and cool load is used for the recovery of drying energy (basically the latent heat of evaporation of water) and deliver this energy back into the drying process in the form of de-humidified and re-heated drying air (as illustrated in Figure 4.3). Heat pump drying consists of two loops: one loop for the drying air and one refrigeration cycle. At the evaporator

of the heat pump, the drying air is cooled down below the dew point and the moisture from the air is condensed at the surface of the heat exchanger. Energy is hereby transferred to the refrigerant, which is evaporated. The evaporated refrigerant is then compressed and can now be condensed in the condenser at higher temperature. Hereby the formally transferred energy is given back to the drying air which is then re-heated to its initial desired condition. It is necessary to install a second, external condenser in order to transfer the excess heat out of the system. The main source for the excess energy is the compressor, which also should be equipped with a rotation speed control in order to ensure optimum working conditions at varying heat and cooling loads. It is also recommended to install a bypass valve for the drying air, so that only the necessary amount of drying air is cooled and re-heated; this makes the operation more efficient.
The principle can be also used for open loop drying systems when the ambient air is heated to the initial drying temperature with help of the excess heat from the cold and humid drying air which is exhausted form the drying chamber. However HPD for open drying loops have no possibility to control the humidity of the drying air and most systems are therefore based on closed loop drying.

5.5. Performance simulation for a R744 heat pump drier.

HPD requires that the drying air is re-heated after de-humidifying to its initial drying temperature. This involves a significant temperature glide and sub-critical refrigerants will result in high heat transfer losses due to their stable condensation temperature as soon as condensing temperature should be a few Kelvins higher than the temperature of the outlet air. This could be avoided by using a working fluid in a trans-critical state, which rejects heat at gliding temperature. The thermodynamic properties R744 seem to be a suitable refrigerant for heat pump drying, especially for drying processes between 30°C and up to 70°C. Being a natural refrigerant, R744 has per definition a Global Warming Potential of 1 and Ozone Depletion Potential of 0; hence its environmental impact is negligible compare to commercial available HFOs.
For the SusOrganic project the potential of heat pump drying was analysed on the example of a heat pump drier which uses R744 as natural refrigerant for a drying process at 45°C, 60°C and 75°C (see Figure 5.4).

Figure 5.4 shows the drying air loop in a Mollier diagram for different drying temperatures. It must be noticed that the point C does not cross the saturation line of the moist air even though a significant amount of water was removed from the air. This can be explained by the temperature profile of the air through the evaporator. The air in direct or close contact with the heat exchanger area is cooled down to the saturation line at temperatures lower than point C which enables condensation. Point C in the Mollier diagram represents the average temperature and humidity of the drying air.
The simulations show that the desired drying conditions for the drier can be reached with the suggested R744 heat pump system (Figure 5.3). Table 5.1 is summarizing the energy flows, process performance and operational conditions of the system.

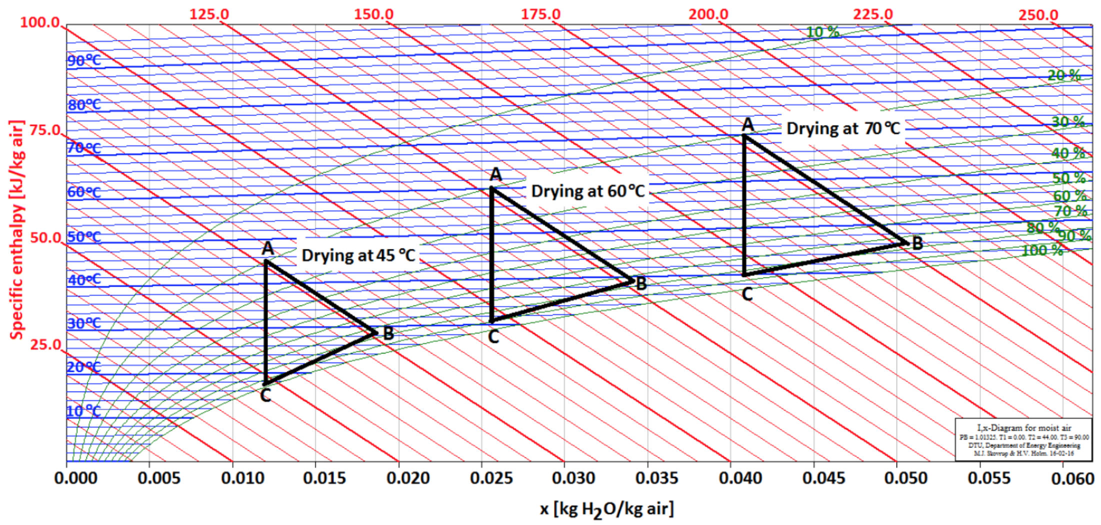

Figure 5.4: Mollier-diagram for the drying process at the different temperatures, where A denotes the inlet to the drying chamber, B the outlet and C the state after vapour condensation before reheating. For drying at 70 °C these states were at point A: 20 % relative humidity and 70 °C; point B: 75 % relative humidity and 46.4 °C and point C: nearly saturated at 39.4 °C.

Drying temperature:	45°C	60°C	70°C
Heat flow in evaporator	101 kW	109 kW	118 kW
Heat flow in gas cooler	100 kW	108 kW	116 kW
Compressor power	23 kW	28 kW	32 kW
COP for heating	**4.3**	**3.9**	**3.6**
COP for heating and cooling	8.8	7.8	7.2
SEC	968 kJ/kg	917 kJ/kg	865 kJ/kg
SEC	**0.269 kWh/kg**	**0.255 kWh/kg**	**0.240 kWh/kg**
High pressure	75 bar	100 bar	130 bar
Low pressure	37.9 bar	45 bar	57.3 bar
Mass flow of CO_2	0.56 kg/s	0.62 kg/s	0.72 kg/s
Moisture content air into dri-	0.012 kg/kg	0.025 kg/kg	0.039 kg/kg
Moisture content air from	0.018 kg/kg	0.033 kg/kg	0.049 kg/kg
Air temperature after con-	17.1 °C	30.5 °C	39.4 °C
Air temperature from drying	28.8 °C	39.2 °C	46.4 °C
Removed water	**0.024 kg/s**	**0.031 kg/s**	**0.037 kg/s**
Temperature after compres-	73 °C	87 °C	96 °C
Temperature before throttling	24.5 °C	27.0 °C	30.2 °C

Table 5.1: Energy flows, efficiencies and operational conditions for R744 heat pump assisted drier at 45 °C, 60 °C and 70 °C.

Figure 5.5, Figure 5.6 and Figure 5.7 show the R744 heat pump cycle in temperature-entropy diagram at different drying temperatures. Since the drying temperature is higher than the critical point it is necessary to cool the refrigerant further down. In the present cases this was achieved by pre-heating DHW (domestic hot water), but also other heat sinks are possible to consider. The diagram shows also the corresponding cooling and re-heating of the drying air. It must be noticed that the necessary dehumidification of the drying air is achieved in the evaporator of the heat pump, which must be designed to handle and remove water condensate.

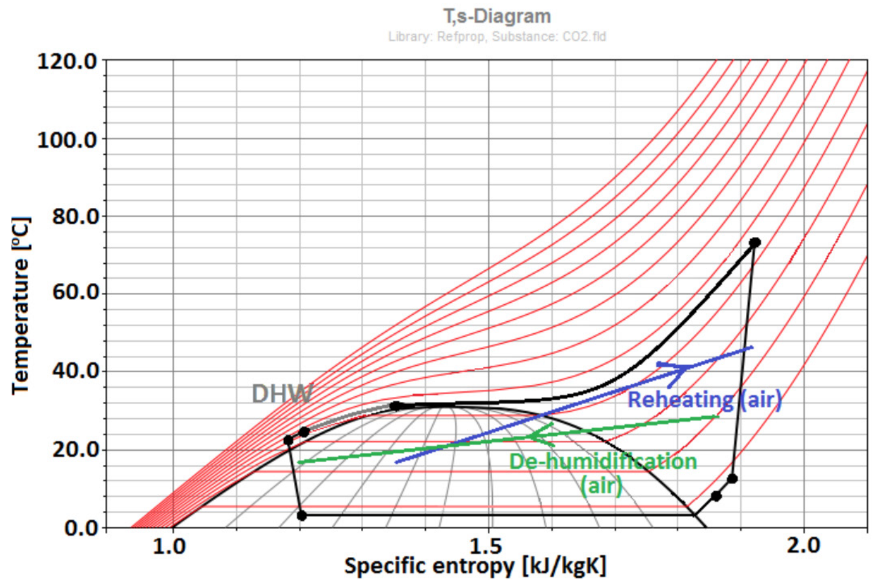

Figure 5.5: Heat pump assisted drier with R744 for drying temperature of 45°C.

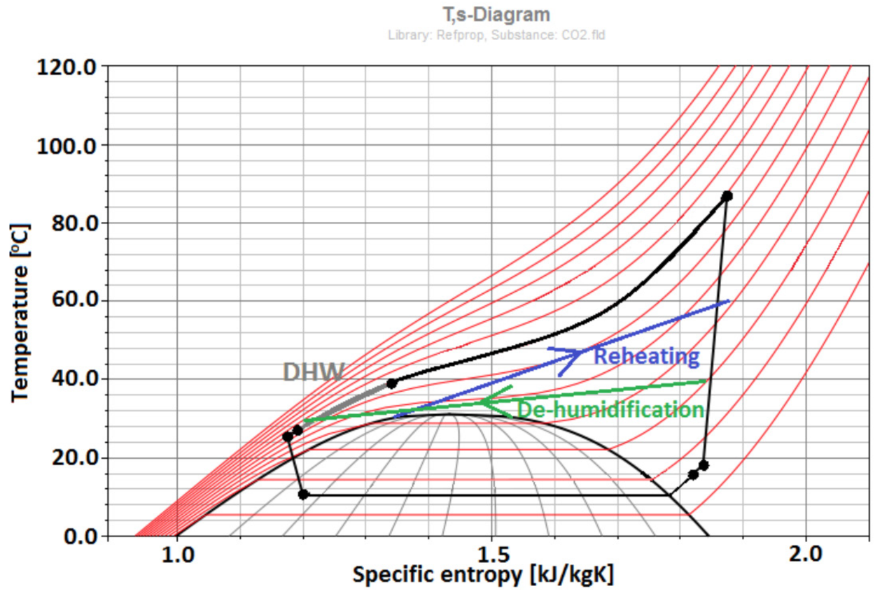

Figure 5.6: Heat pump assisted drier with R744 for drying temperature of 60°C.

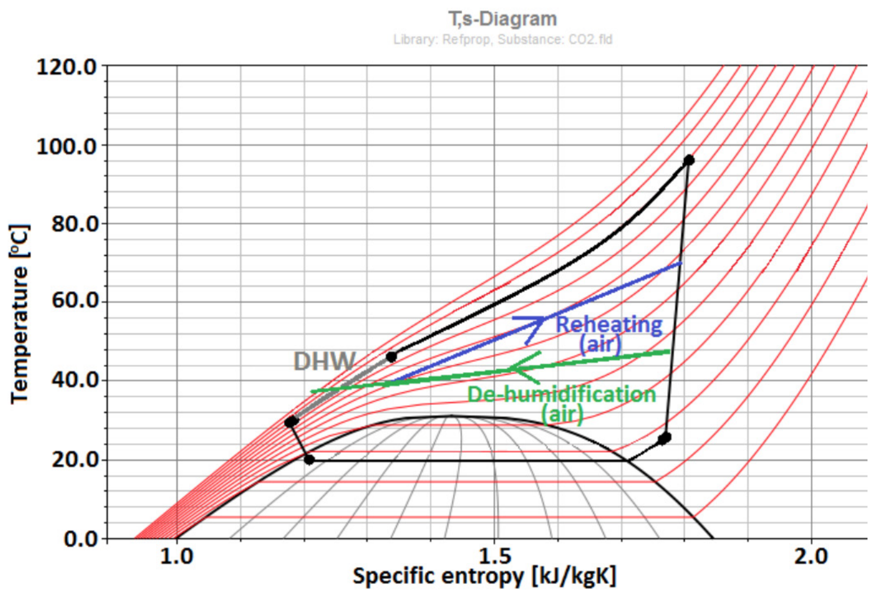

Figure 5.7: Heat pump assisted drier with R744 for drying temperature of 70°C.

5.6. Analyse of the heat pump drier performance

Drying of biological material is a combined heat and mass transfer process where water is removed from a solid matrix by evaporation. In the considered temperature range the latent heat of evaporation is about 2250 kJ or 0.63 kWh in order to evaporate one kilogram of water. The performed investigation showed that a heat pump assisted drying process would need between 0.24 and 0.27 kWh/kg, depending on the drying temperature. Thus, compared to the latent heat of water, the energy savings would be about 60 %. For an actual open type drying process, which uses and regards re-heated ambient air, the specific energy consumption is normally at least 0.8 kWh/kg, but can be even as high as 2 kWh/kg. However, it is difficult to compare these drying systems strictly on energy evaluations, since aspects like humidity control (which is possible with heat pump drying) are difficult to include in open type drying systems. Most reported energy savings for heat pump assisted drying were between 30 and 50 %, however based on different refrigerants. Introducing a heat pump seems possible at all the three temperatures considered, and would result in similar or slightly better energy savings as reported in different studies over the last years.

Closed loop drying requires controlled cooling, dehumidification and re-heating of the drying air and these processes result naturally in temperature glides. Since the R744 cycle operates in the trans-critical state the heat exchange losses for re-heating will be smaller compared to a heat pump cycle with constant condensation temperature. The choice of a trans-critical process also results in appropriate temperature differences in the heating process, and thus gives the ability to reduce exergy losses. The temperature glide for the air during cooling is smaller and it is more important to obtain a corresponding temperature glide for the heating process. The thermal properties of R744 in the trans-critical state are advantageous for the concept of heat pump assisted drying in general.

With increasing drying temperature, the COP of the heat pump decreased and the net energy use increased. The process efficiency of the heat pump assisted drying was at the same time increased since the amount of removed water was higher at higher drying temperatures. This effect compensated for the reduced COP at higher drying temperatures. Similar results were found in experimental tests of CO2 dryers. Using a CO2 heat pump in fluidized bed drying at 40 °C 20 % humidity and 50 °C and 13 % humidity, both with 60 % humidity after drying, resulted in SEC values of 0.606 and 0.268, and COPs of 2.31 and 4.18. As these two reported results differ significantly, the amount of water removed seems highly important for the performance; the better of the two reported results being similar to the case with 45°C drying temperature in this study.

Closed heat pump assisted drying loops, like the ones modelled here, always give a surplus of heat (primarily from the compression work), and thus an additional heat sink is necessary for this case, since the heat flow for cooling and re-heating of the drying air are equally large. The second gas-cooler (or condenser when using other refrigerants) gives the possibility to control the drying conditions continuously, resulting in stable drying temperatures and humidity. Systems which do not have this second gas-cooler (or condenser) are quite often operated in on/off regulation, when the drying temperature is getting to high. For CO2 cycles operating close to or above the trans-critical point, it is also crucial to achieve sufficient cooling before throttling in order to obtain an efficient process. Closed systems must have a cold heat sink like a water cooler in order to achieve high performance. For the present study water was considered as heat sink and it was assumed that this will function as pre-heated domestic hot water. Other heat sinks, like ambient air could be also considered for this purpose; however it is recommended to implement a heat sink at stable temperature levels in order to sustain process stability. The heat transferred in the second gas-cooler was not considered in the calculation of specific energy consumption of the drying process.

The investigated heat pump system was based on a drier capacity which allows removing around 100 kg water per hour, depending on drying temperature and condition. The capacity of industrial driers can range from a few kilograms up to several tons of removed water per hour; so it is difficult to conclude on a general applicable drier size. The investigated system can be up- or downscaled to different drier sizes without influencing the process efficiency under the pre-condition that the size of the components of the heat pump can be adapted. The size and efficiency of the compressor are hereby the most limiting factors. With currently available compression technology it should be possible to upscale the system to a drier capacity of 500 kg/hour. Another factor which needs to be considered is the design of the gas-cooler and evaporator, which must be efficiently designed for heat exchange with large air flow. The size and power of a fan to circulate the drying air will depend the design of the exchangers and the drying chamber. The fan of the drying system will be an additional energy demand, which will reduce process efficiency. In the present study the fan power was not considered since the drying system but also the heat exchangers geometry was simplified. However also for open type drying system a certain fan power is needed which will also reduce the process efficiency with similar magnitude.

Further design evaluations should also include the possibility for cleaning of e.g. heat exchanger for reasons of sanitation especially in the food industry. Quite often, when drying biological material the air will be polluted with particles etc. which can agglomerate in the heat exchanger. Hence, cleaning must be also a design aspect for reducing thermal resistance and sustaining high heat transfer in the heat exchangers.
The present investigation did not evaluate the drying product and quality aspects. In general the system will have an energy saving potential for all drying processes which require a drying temperature between 45°C and 70°C. Food products like grain, fruits and vegetables, but also pulp, paper or wood could be dried at these conditions; and the list can surely be extended further. However, the drying conditions need to be determined in correlation with a required quality and specific drier type, which was beyond the scope of this investigation. In a wider perspective the investigated heat pump drier (based on renewable energy sources) can help to reduce the dependency on fossil fuel.
The present study did not investigate investment cost or return of investment and solely focussed on the energy saving potential. Based on the performed analyse it will be possible to calculate these numbers for specific drying processes and products. The energy saving potential of R744 heat pump assisted drying was clearly identified and the dependency on the drying temperature (not the COP of the heat pump) was outlined.

5.7. Summary

The potential of using R744 as refrigerant in heat pump assisted drying process was investigated. The specific energy consumption of the drying process can be reduced to 0.269 kWh/kg at drying temperature of 45°C, 0.255 kWh/kg at 60°C and 0.240 kWh/kg at 70°C. The process efficiency was mainly influenced by the amount of removed water from the drying air, while the COP of the heat pump had only a secondary influence. Common open type driers have in general specific energy consumptions between 0.8 and 2 kWh/kg, so the energy saving potential is significant. Especially the temperature glide in the trans-critical R744 cycle can be advantageous for heat pump drying compared to sub-critical heat pump operation with stable condensation temperature. The drying process is characterized by simultaneous occurrence of heat demand and available waste heat, which is in favour for the implementation of a heat pump assisted drying in general. In a wider perspective heat pump drying (based on renewable energy sources) can help to reduce the dependency on fossil fuel. The potential for industrial heat pump assisted drying in the investigated temperature range is large in the in the food, tobacco, wood and paper industries.

5.8. References

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Wolf, S., et al. (2014). Analyse des Potenzials von Industriewärmepumpen in Deutschland (in German) Forschungsbericht. Universität Stuttgart, Institut für Energiewirtschaft und Rationelle Energieanwendung.

6. Comparison of process control concepts

University of Tuscia, Department for Innovation in Biological, Agro-food and Forest systems, Italy
Massantini, R. & Moscetti, R.

6.1. The present and future of drying technology

Drying is a relatively complex, dynamic, unsteady and nonlinear process that is affected by the properties of the wet material, the scale of production and compliance with regulations (e.g. European Organic Regulation), as well as operating and environmental conditions (Aghbashlo et al., 2015). Such factors can impact quality traits as well as organoleptic, nutritional and functional properties and thus result in reduced consumer acceptance (Brosnan and Sun, 2004; Vega-Gálvez et al., 2012). Drying is one of the most energy-intensive processes in the food industry (Akpinar et al., 2003) and potentially contributes to climate change as most dryers use fossil fuels (Mujumdar, 2012).
In order to alleviate the drying issues, the goal of new drying technologies should be to simultaneously maintain product quality and value, maximize drying rate and minimize environmental impact (Mujumdar, 2012; Su et al., 2015). "Smart drying", one of the newest and most promising of emerging drying techniques, involves the use of sensors, tools (e.g. emerging non-destructive technologies) and practices (e.g. monitor and control of quality and drying parameters and/or the conditions of the dryer, etc.) for enhancing drying efficiency. The idea behind smart drying technology is to obtain real-time information related to the process and the product to simultaneously modulate the drying process. The result is a standardized high-quality dried product (Su et al., 2015). Thus, smart drying can be cost-effective in both real-time monitoring of food quality and dynamic controlling of operating conditions through the entire drying process. Smart drying is a multi- and inter-disciplinary sector and its recent developments embrace the following R&D areas: artificial intelligence (Aghbashlo et al., 2015), biomimetic (Ghasemi-Varnamkhasti et al., 2010), computer vision (Brosnan and Sun, 2004), microwave/dielectric spectroscopy (Jha et al., 2011), hyper-/multispectral imaging (ElMasry and Sun, 2010), magnetic resonance imaging (Clarka et al., 1997; Su et al., 2014), ultrasound imaging (Awad et al., 2012), electrostatic sensing (Chen et al., 2013) and control systems for the drying environment. In addition, visible (Vis) and near-infrared (NIR) spectroscopy are techniques with potential applications in smart drying in terms of monitoring quality attributes (Nicolaï et al., 2007).

6.2. Computer Vision technology

Human beings use their eyes to see and visually sense the world around them. Computer vision (CV) is the science that aims to give a similar capability to a machine or computer. Its application concerns the automatic extraction, analysis and understanding of useful information from a single or a sequence of images, using an algorithmic basis to achieve automatic visual understanding (Li et al., 2015).

Since the early 1960s, with the advent of the digital computer, vision was recognized as an important tool to evaluate quality in food production, and its use was constantly increased. It is possible to evaluate the visual characteristic and defects in food products rapidly and inexpensively in a non-destructive way (Davies, 2009). Nowadays, CV is used in several different fields (e.g., food industry, robotics, medical diagnosis and industrial robotic systems). A CV system is generally composed by five elements: an illumination system, a sensor or a camera, a digitizer (only if the camera it is not digital), a computer and software capable of processing the image (Figure 6.1). Similar to human vision, CV is strongly affected by several factors (i.e., light source, background, direction of light, size of the area containing the same color and differences between individual perception) (Menesatti et al., 2012).

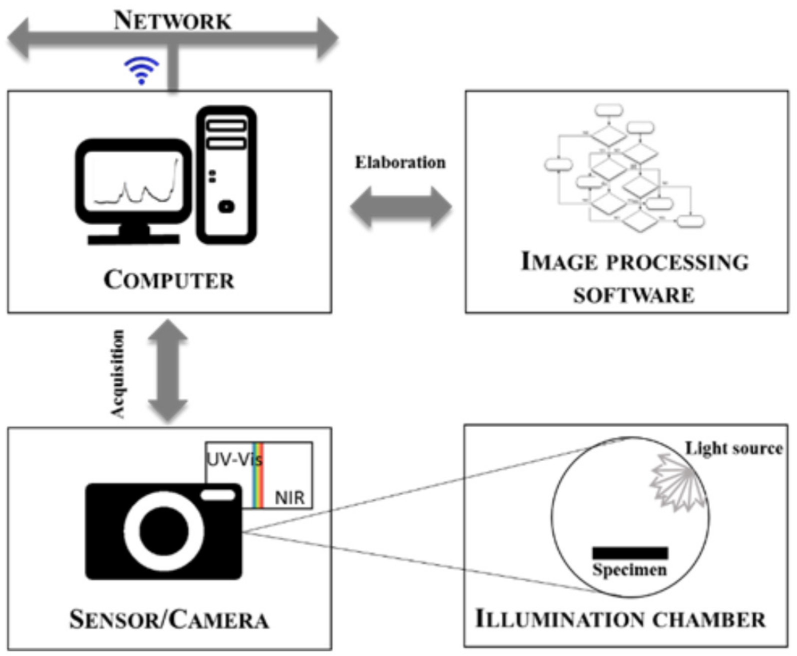

Figure 6.1: Element of a computer vision system (Raponi et al., 2017)

6.2.1. Image analysis

External changes and defects on fruits and vegetables are often characterized by differences in colour, shape and size. Commonly, a red, green and blue colour space (RGB) camera, linked to a machine vision system, makes it possible to inspect external products in a rapid, accurate and fast way. RGB cameras emulate the human eye's capacity to capture images (Batchelor and Waltz, 2001).

6.2.2. Single-Point Spectroscopy

Spectroscopy is the study of the interaction of matter and electromagnetic radiation (ER). The interaction occurs in several ways (i.e., reflectance, transmittance, absorbance or scatter of polychromatic or monochromatic radiation), as shown in Figure 6.2.

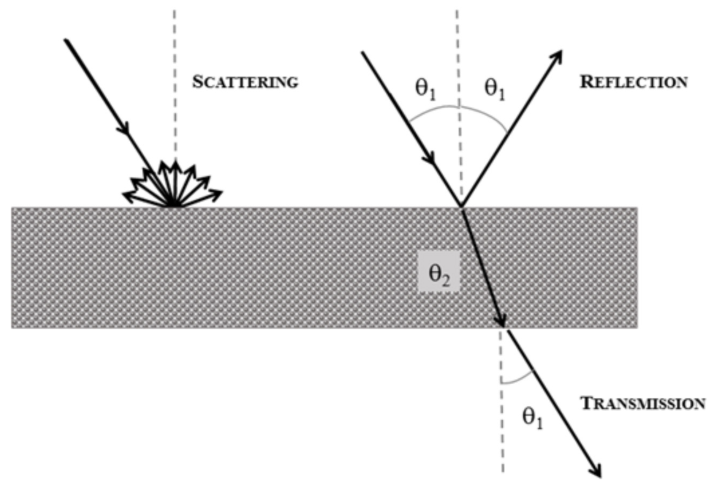

Figure 6.2: Interaction between matter and electromagnetic radiation (Raponi et al., 2017)

Different electromagnetic regions give different information related to the chemical composition of the sample. This being because each chemical bond absorbs light energy at specific wavelengths. As an example, pigments (e.g., chlorophylls, carotenoids and anthocyanins), mainly absorb in the visible spectral range, while water, carbohydrates, fats and proteins have absorption bands in the NIR region (Abbott, 1999; Munjanja and Sanganyado, 2004). For food quality evaluation (e.g., quality control and authenticity), the ultraviolet (UV), visible (Vis) and near infrared (NIR) regions are the main spectral regions used (Reid et al., 2006).

6.2.3. Hyper-/Multi-Spectral Imaging

Hyperspectral imaging systems are devices able to obtain both spectroscopic and spatial information (Mollazade et al., 2012; Moscetti et al., 2015). The data-structure of the hyperspectral image is called the hypercube, which is the 3D image containing two spatial and one spectroscopic dimensions (Figure 6.3).
HSI devices in food-analysis work in the Vis/NIR region, each using absorption and emission spectroscopy (Menesatti et al., 2008). The main advantage of HSI is the feasibility of monitoring both external and internal quality parameters. With this device, it is feasible to distinguish and analyse objects with similar colour, shape, size and overlapping spectra. The drawbacks are related to the long acquisition time needed, the high amount of redundant information and, thus, the huge amount of data acquired. These drawbacks limit HSI in on-line processing. Furthermore the computational time to develop the prediction model increases considerably (Li et al., 2015). The development of an MSI system can reduce these drawbacks, mainly due to its pos-

sibility to select the most significative wavelengths (from 3-15) in order to predict the physico-chemical attributes of interest (Zhang et al., 2014). MSI has several advantages compared to HIS such as: faster scan rate, feasibility of on-line application in the food processing industry, less computer memory required to acquire and process the images (Mahesh et al., 2015). The drawbacks are related to the device lacking flexibility. Generally, these are built by researchers according to the specific imaging task. Moreover, it is necessary to have an HSI system to use prior to the development of the MSI device.

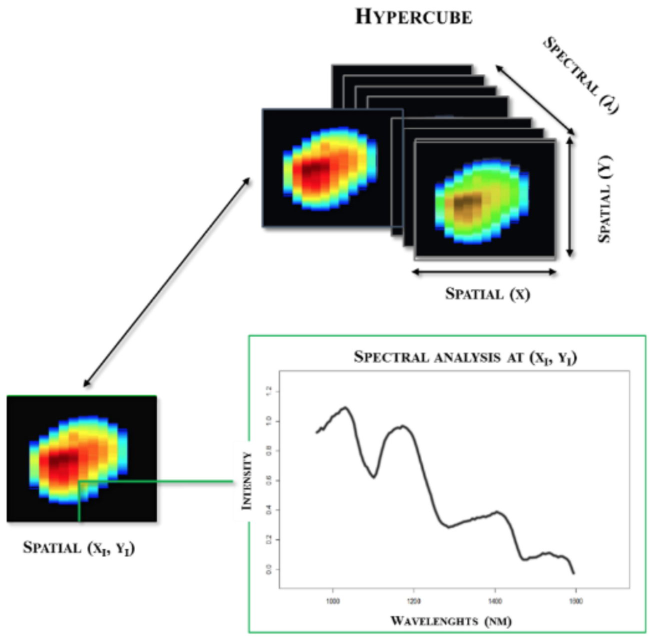

Figure 6.3: Schematic representation of a hypercube (Raponi et al., 2017)

6.3. Electronic nose and electronic mucosa

Food aroma usually contains complex mixtures of volatile organic compounds (VOCs), characterized by various sensorial and chemical attributes. Any change in the relative concentrations of these compounds can often specify the odour of the product. The change of aroma during the drying process is of a great concern. In fact, undesired aroma loss, change, distortion, or even destruction often occur and result in inappropriate quality final products. Electronic nose and electronic mucosa are electronic systems which try to emulate the structure of the mammalian olfactory system. Their outputs can be the characterizing of odorants, defects or attributes of food, concentration estimation of VOCs, etc. In other words, both instruments can detect food aroma as rapid as in seconds, which makes real-time monitoring of food aroma possible during drying. The electronic mucosa is a technological evolution of the electronic nose, which is characterized by a higher number of sensors.

6.4. Nuclear magnetic resonance imaging

The magnetic resonance imaging (MRI) is a type of nuclear magnetic resonance technology extensively used by both chemists and biochemists to obtain soft tissue images for diagnostic purposes and, thus, to identify molecular structures as well as to study the occurrence of chemical reactions. MRI uses radio waves and magnets to generate images of food sample. Scientists have explored the used of MRI to investigate changes in moisture content, water activity, salt content, etc. during drying.

6.5. Microwave dielectric spectroscopy

The microwave dielectric spectroscopy is a non-contact, reliable and very fast technique to determine changes in moisture and density of materials during a drying process. Because the microwave resonance frequency changes with the moisture content of food, this technique is particularly efficient in providing more representative moisture data continuously. The technique is totally independent from density or product load, colour and surface structure of food.

6.6. Control of a drying process through the smart drying technology

Currently, there is a need to develop smart or intelligent dryers for the next two decades. It is necessary to make drying a sustainable process implementing the latest advances in allied technologies and scientific sectors, such as: [1] computer technology, [2] microcontroller and sensor technology, [3] on-line, in-line, at-line detection technology, [4] mathematical modelling of dryers, [5] machine learning (e.g. deep learning), [6] low power wide area network and [7] big data management and cloud computing. In this context, researchers are turning to the application of smart technologies from the laboratory-scale research to the industrial production. In the meantime, Industry has become more quality conscious and thus is prone to invest on quality control in drying technology.

6.7. How to design a smart drying process, the Quality by Design approach

The concept of Quality by Design (QbD) strategy requires novel drying technologies must be designed using knowledge of the product that is to be dried as well as rigorous product quality attributes. Moreover, on the basis of the QbD approach, it is necessary to deeply understand the drying process for a careful optimization of the standard operating approaches. In other words, a QbD strategy may include several steps as shown in Figure 6.4: [1] identifying the target product profile and its critical quality attributes, which ideally are achieved to ensure a desired product quality; [2] defining the product design space (i.e. the characteristics of the product at the entrance of the drying process unit); [3] defining the process design space (i.e. the process characterization, useful to define the acceptable variability in process parameters); and [4] defining a control strategy, which may include: procedural controls, in-process controls, process monitoring, etc. Finally, a process validation must be performed to demonstrate that the final product quality is acceptable.

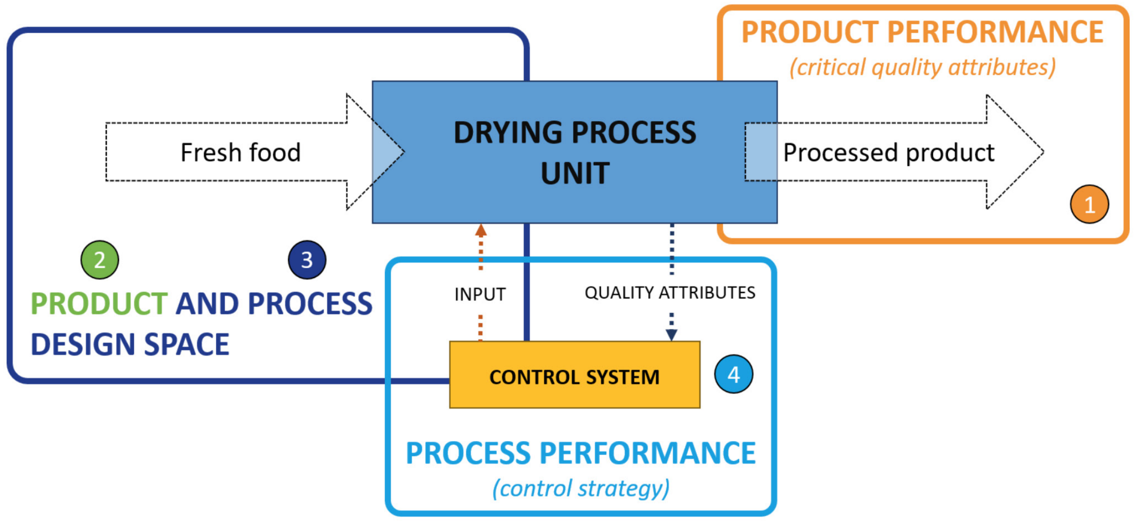

Figure 6.4: Quality by Design steps for dried food quality assurance

The QbD strategy is usually based on real-time measurement techniques, which are categorized in at-line, on-line and in-line (Figure 6.5). At-line process measurement is performed by sampling from the process and analysing the sample into the process area within the timescale of processing. In the on-line measurement, the sample is analysed and then returned to the process stream. In-line process is carried out without sampling, but by placing sensors into the process stream.

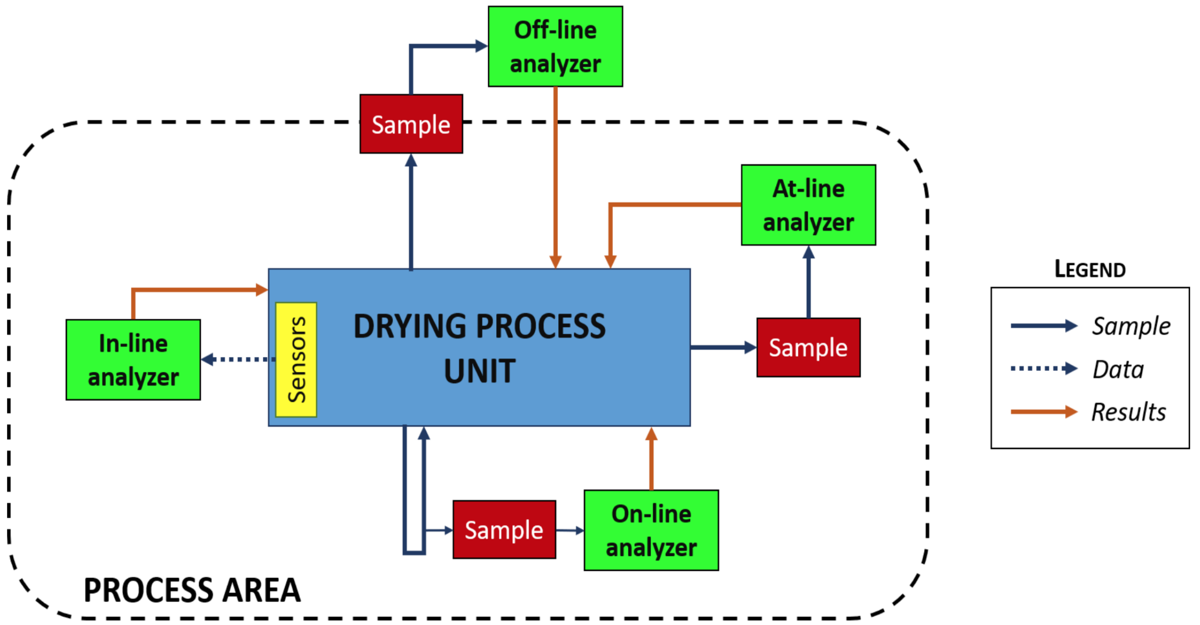

Figure 6.5: Schematic of the differences among off-line, at-line, on-line and in-line measurement techniques (Raponi et al., 2017)

6.8. Validation of a smart drying process

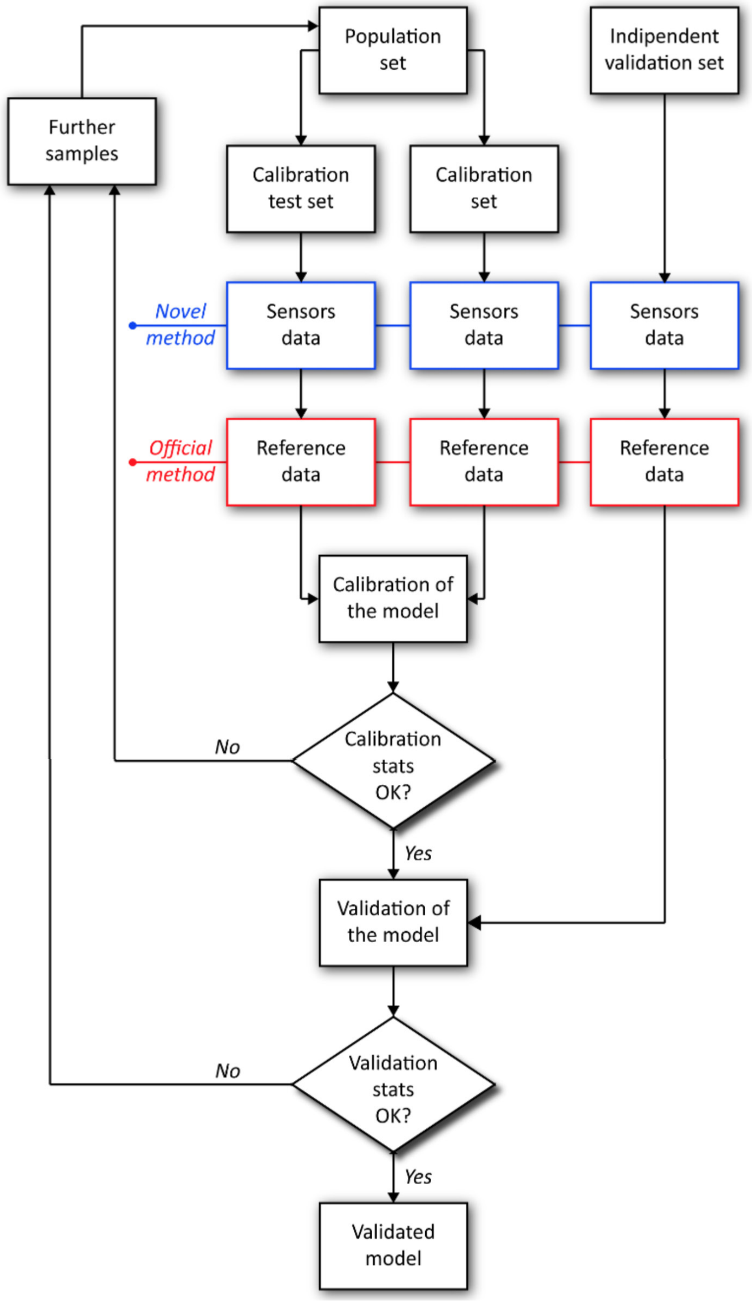

Figure 6.6: Workflow of data pre-processing, calibration and valida-tion steps

The development of in-line/on-line/at-line methods for identification, qualification and quantification of product characteristics during a drying process requires the test of various mathematical and statistical approaches. In machine learning, pattern recognition consists of the construction and study of mathematical models that can assign labels (classification) or real-valued

outputs (regression) to a given input dataset. Mathematical models may be properly developed to extract useful information from large datasets to determine sample chemical composition (e.g. moisture content, soluble solids content, colour, etc.) or perform batch classification (e.g. raw product recognition, etc.). Thus, this kind of research methodology is usually divided into three phases: #1 data pre-processing, #2 model calibration and #3 model validation (Figure 6.6).
#1 Data pre-processing. Pre-processing is a very important step, because of its capacity to enhance or reduce sources of variation prior to the development of a model. There are various pre-processing techniques and the selection of optimal method often need iteration with the calibration model.
#2 Model calibration. Calibration is the process of constructing a mathematical model to correlate the response from sensor or analytical instrument to the properties of interest of the dried samples. Calibration is followed by prediction, the process of using the developed model to predict properties of an unknown sample. Both the construction and prediction stages are vital in the generation of calibration models.
#3 Model validation. Validation demonstrates feasibility and suitability of the model for its intended purpose. The validation requirements that are commonly evaluated during the development of classification and regression models are shown in Table 6.1.

Term	Description	Classification	Regression
Sensitivity	Ability to identify positive results, given is the presence of analyte	✓	✓
Specificity	Ability to identify negative results, given that there is no analyte present	✓	✓
Accuracy	The closeness of agreement between a test result and the accepted reference value	X	✓
Linearity	Proportionality of the signal to the amount of reference material, demonstrated by the calculation of a regression line with the adequate statistical method	X	✓
Range	Range of analyte concentrations over which the method is considered to perform in a linear manner	X	✓
Trueness	The closeness of agreement between the average value obtained from large series of test results and an accepted reference value	X	✓
Robust-ness	Ability of the method to resist change without adapting its initial stable configuration	✓	✓
Detection Limiit	Minimum level from on the presence of an analyte can be detected/measured with a given certainty	✓	✓

✓ performable term X unperformable term

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I.3 LCA, LCCA AND FOOD LOGISTICS

7. Best practice based on Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA)

SLU, Department of Energy and Technology, Sweden
Gebresenbet, G. & Bosona, T.

7.1. Introduction

Increasing world population, urbanization, depletion of resources such as energy intense fossil fuels, spatial and temporal fluctuation in food availability pose serious challenges on sustainability of contemporary food value chains (FVC) in both developed and developing nations (UN, 2017; Hammond et al, 2015). Sustainability in the context of sustainable development is defined by the World Commission on Environment and Development (1987) as: 'forms of progress that meet the needs of the present without compromising the ability of future generations to meet their needs'. Sustainability is a complex concept (Borg et al., 2016). Especially, sustainability in FVC is more complex as it involves agricultural, food processing, distribution and consumption with different scale of social, economic and environmental concerns at each level of FVC as indicated in Figure 7.1.

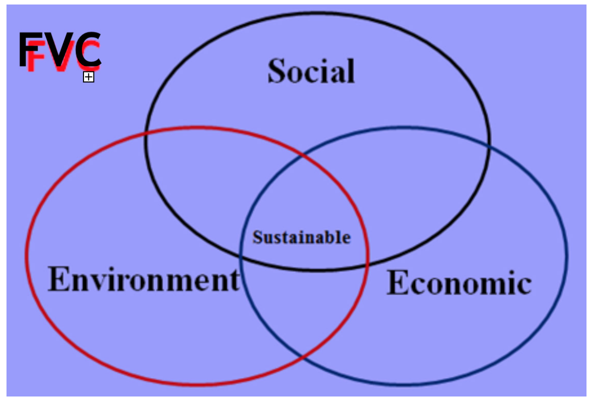

Figure 7.1: Conceptual illustration of sustainability within in FVC (food value chain)

The environmental dimension considers the increasing environmental burden such as greenhouse gas (GHG) emissions, water depletion, increased energy consumption, and damage on biodiversity etc while the economic dimension considers business development related factors such as cost of food production and supply, profitability, and contribution to local economy. The social aspect addresses issues such food safety, food quality and consumer health, consumer satisfaction, societal food security, animal welfare and working environment for society involved in food sector.

7.2. Practical LCA and LCCA studies from SusOrganic project

In order to understand the environmental and economic aspects of locally produced organic food products, some results of Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA) from SusOrganic project have been presented here. Life cycle analysis (LCA) is a method used to evaluate the environmental performance of a product (and service) considering its 'life-cycle stages'. According to ISO 14040, LCA is defined as "compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (LCA handbook, 2004).
In the SusOrganic case, the standardized LCA approach by International Standard Organization (ISO) has been used i.e. ISO 14040 describing LCA principles and frameworks and ISO 14044 (2006) describing requirements and guidelines of LCA. In general, the LCA study was conducted within system boundary from agricultural production to consumers gate (see Figure 6.2) while waste management and consumption levels have been excluded. One tonne of harvested fresh food product at farm gate or slaughtering house was used as functional unit. More description on functional unit is given in Table 6.1. Two environmental impact categories, primary energy demand as cumulative energy demand (CED) and greenhouse gas (GHG) emissions have been presented in this document. For activities that need electric energy as input, energy from Sweden national electricity grid, where renewable hydropower energy and non-renewable nuclear energy sources contribute the most shares, was assumed in all cases except organic salmon case where that of Norway has been considered.

Life cycle cost analysis (LCCA) is an economic evaluation technique that enables to determine the total cost of owning and operating a facility or a system over a given period of time and at different product (system) life cycle stages (Farr J.V., 2011). Even though it is not widely used with in food value chains, LCCA enables to provide additional information to supplement LCA based decision making. In the SusOrganic case, LCCA has been used considering the same system boundary used for LCA study described above. In order to make comparison analysis between fresh product value chain (e.g. fresh apple) and processed product value chain (e.g. dried apple), all cost values have been presented in terms of euro (€) per functional unit adopted in LCA study i.e. ton of harvested fresh product at farm or fresh meat at slaughter house. It is very important to note that this 1 ton of fresh product could be supplied to customer as fresh or processed (e.g. dried) product (as described in LCA case), but the cost value is presented per 1 tonne of fresh product prepared for processing (supper-chilling or drying), but not per tonne of processed product. In general, the system boundaries and functional units have been selected so that LCA and LCCA results from each investigated organic food products can be reasonably compared from environmental burden and food supply chain cost point of view.

The LCA and LCCA analyses were done on selected food value chains namely organic salmon produced in Norway and supplied to consumers within Norway and exported to France, Organic beef, organic apple fruit, carrot, and tomato in Sweden (see Table 7.1). Since the results of LCA and LCCA influenced by system boundary conditions and functional units considered during analysis, the values should be used with caution when comparing with results from other similar LCA and LCCA studies. Further brief descriptions have been provided here (see Figure 7.2; Tables 7.1). In both LCA and LCCA cases the major product life cycle stages considered are agricultural production, post-harvest, and transport stages. Since more than one transport segments exist in each organic food value chain, more description on transport configuration is also provided in Table 7.2. Sample result summaries are provided in Tables 7.3, 7.4 and 7.5 followed by lessons potential useful for practinioners, decision makers and other interested users.

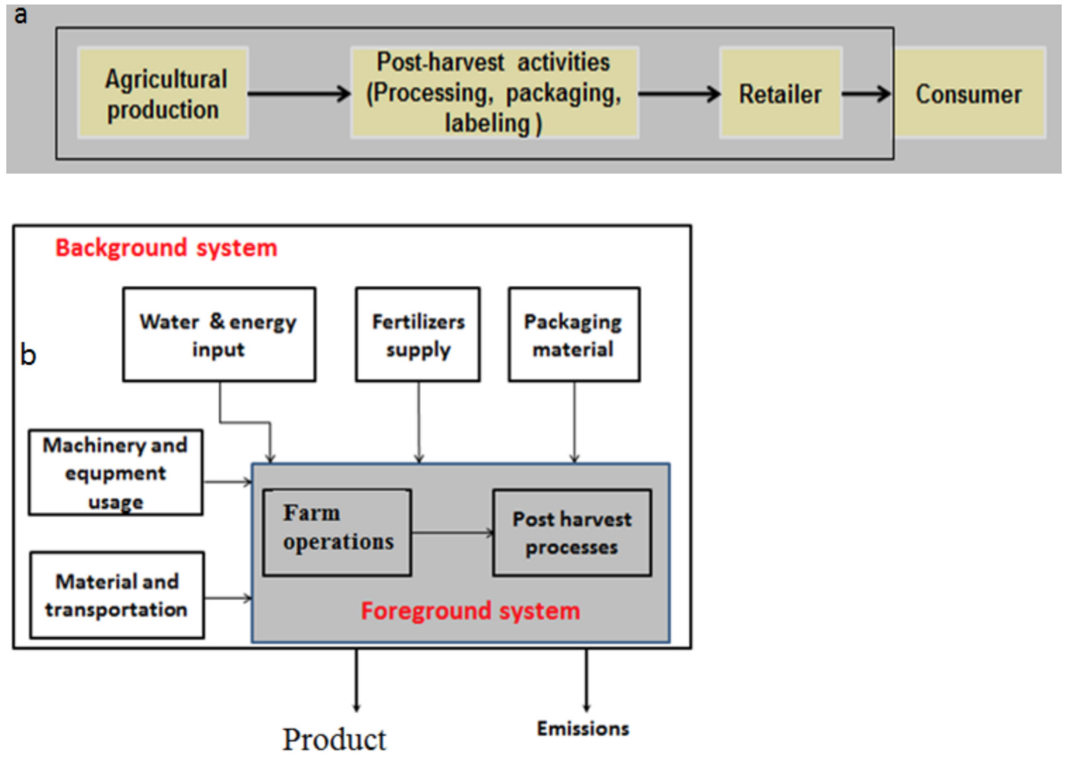

Figure 7.2: System boundary: (a) Simplified value chain describing the system boundary from farm stage to consumer gate; (b) simplified flow chart describing background and foreground system boundaries

Table 7.1: Description of systems and functional units

Organic food value chain	System description	Functional unit
Organic salmon (fresh supply)	Salmon produced and consumed as within Norway	1 ton of fresh salmon fillet at slaughtering house that is supplied to consumer
Organic salmon (supper-chilled)	Supper-chilled before distribution to consumers	1 ton of supper-chilled salmon fillet at slaughtering house that is supplied to consumer
Organic beef (fresh meat supply)	Organic beef production and local consumption within Sweden	1 ton of bone-free fresh meat at abattoir gate that is supplied to consumer as fresh meat
Organic beef (dried meat supply)	Based on assumption of meat drying in tray dryer from 74% moisture content to 5%	1 ton of bone-free fresh meat at abattoir gate that is supplied to consumer as dried meat
Organic apple (fresh supply)	Produced and supplied within Sweden. Cardboard packaging considered.	1 ton of fresh apple at farm gate that supplied to consumer as fresh apple
Organic apple (dried apple supply)	At processing facility located at 8okm from farm, apple dried in dryer from MC of about 82% to 11%.	1 ton of fresh apple at farm gate that is supplied to consumer as dried apple
Organic carrot (fresh supply)	Cultivated and supplied within Sweden.	1 ton of fresh carrot at farm gate that is supplied to consumer as fresh carrot
Organic carrot (dried carrot supply)	It is assumed that carrot drying is to be done at 80 km away from farm from MC of about 87% to 12% using tray dryer.	1 ton of fresh carrot at farm gate that is supplied to consumer as dried carrot
Organic tomato (fresh supply)	Tomato production in Sweden using greenhouse system	1 ton of fresh tomato at farm gate that is supplied to consumer as fresh tomato
Organic tomato (dried supply)	Drying is assumed to be done at 80 km away from farm. Fresh tomato at 93% MC is dried to 12% MC.	1 ton of fresh tomato at farm gate that is supplied to consumer as dried tomato

Table 7.2: Description of transport segments considered in LCCA and LCCA of SusOrganic project

Organic food value chain	Segments of food transport
Organic salmon supply within Norway	About 580km from farm/slaughter house to distribution center in Oslo, and further distribution within 50km radius
Organic salmon (Supply to France)	About 580km from farm/slaughter house to distribution center in Oslo, and further transport to France i.e. about 1700 km road transport with truck, and 95km over sea transport with car ferry.
Organic beef	10 km from farm to abattoir (animal transport), 50km from abattoir to retailer
Organic apple, Organic carrot, Organic tomato	80 km from farm to processing facility; 50 km from processing facility to retailer

Table 7.3: Life cycle stages contribution to different impact categories per functional unit

Value chain	Impact category	Unit	Agricultural Production	Post-harvest processing	Transport	Total
fresh salmon	CED	GJ	37.78	5.48	5.21	48.38
	GWP_{100}	kg CO2 eqc	1366	108	341	1815
super chilled salmon	CED	GJ	37.78	4.69	3.59	46.06
	GWP_{100}	kg CO2 eqc	1366	110	240	1715
Reduction/ Increase	**CED**	**%**	**0**	**(-)14**	**(-)30**	**(-)5**
	GWP_{100}	**%**	**0**	**(+)2**	**(-)30**	**(-)6**
Fresh beef meat	CED	GJ	6.34	1.7	0.69	8,72
	GWP_{100}	kg CO2 eqc	12889	30	45	12964
Dried beef meat	CED	GJ	6.34	9.72	0.27	16.33
	GWP_{100}	kg CO2 eqc	12889	70	18	12977
Reduction/ Increase	**CED**	**%**	**0**	**(+)472**	**(-)61**	**(+)87**
	GWP_{100}	**%**	**0**	**(+)133**	**(-)60**	**(+)0.1**
fresh apple	CED	GJ	1.32	3.33	1.46	6.11
	GWP_{100}	kg CO2 eqc	34	136	95	265
dried apple	CED	GJ	1.32	7.51	0.84	9.68
	GWP_{100}	kg CO2 eqc	34	55	55	143
Reduction/ Increase	**CED**	%	**0**	**(+)125**	**(-)43**	**(+)58**
	GWP_{100}	%	**0**	**(-)60**	**(-)43**	**(-)46**
fresh carrot	CED	GJ	0.31	1.22	1.12	2.64
	GWP_{100}	kg CO2 eqc	35	14	73	121
dried carrot	CED	GJ	0.31	5.7	0.67	6.67
	GWP_{100}	kg CO2 eqc	35	33	44	111
Reduction/ Increase	**CED**	%	0	**(+)367**	**(-)40**	**(+)153**
	GWP_{100}	%	0	**(+)141**	**(-)40**	**(-)8**
fresh tomato	CED	GJ	41	2.17	1.42	44.58
	GWP_{100}	kg CO2 eqc	366	88	93	547

dried tomato	CED	GJ	41	7.60	0.80	49.40
	GWP_{100}	kg CO2 eqc	366	49	52	467
Reduction/ Increase	**CED**	%	**0**	**(+)250**	**(-)44**	**(+)11**
	GWP_{100}	%	**0**	**(-)45**	**(-)43**	**(+)15**

a-Post-harvest stage includes drying process; b-Transport stage includes transport from farm to processing facility and from facility to retail and then to consumer gate; c-kg CO2 equivalent.

Table 7.4: Influence of energy efficiency demand for tomato drying on CED and GHG emission

Impact category	CED		GHG emissions	
	GJ	Change in %	kg CO2 eq	Change in %
Considering all life cycle stages				
30% reduction	47.18	(-)4.5	455.07	(-)2.7
Basic scenario*	49.40	0	467.44	0
30% increase	51.62	(+)4.5	479.81	(+)2.7
Excluding agricultural production stage				
30% reduction	6.18	(-)26.42	88.68	(-)12.24
Basic scenario*	8.40	0	101.05	0
30% increase	10.62	(+)26.42	113.42	(+)12.24

**-Basic scenario is the drying energy considered in dried tomato value chain indicated in Table 11.2 above.*

Table 7.5: Life cycle costing stages and their contribution to total cost per functional unit

Organic food value chain	Unit[a]	Farm stage	Post-harvest processing stage[b]	Transport stage	Total
Salmon supplied within Norway (with normal cold chain)	€	6213	475	27	6715
Salmon supplied within Norway (Supper-chilled)	€	6213	494	18	6725
Reduction/increase	%	**0**	**(+)4.0**	**(-)33.33**	**(+)0.15**
Salmon supplied to France (with normal cold chain)	€	6213	475	106	6794
Salmon supplied to France (sup-per-chilled)	€	6213	494	71	6778
Reduction/increase	%	**0**	**(+)4**	**(-)33**	**(-)0.24**
Fresh apple	€	1865	482	42	2391
Dried apple	€	1865	643	27	2537
Reduction/increase	%	**0**	**(+)33.4**	**(-)36**	**(+)6**
Fresh beef meat	€	6326	14204[c]	1550	22080
Dried beef meat	€	6326	14204[c]	885	21964
Reduction/increase	%	**0**	**(+)4**	**(-)42**	**(+)0.5**

a-The values are given per functional unit but not per tonne of final product; b-It includes packaging at this stage; c_Esi-mated based on average 4.4% operating margin at processing and retail levels which could be higher in some cases

7.3. Lessons from LCA and LCCA studies

The LCA results from SusOrganic project have been summarized in Table 7.3. The values indicate the total CED in giga joule (GJ per functional unit) and GHG emission in kg CO2 equivalent (kg CO2 eq per functional unit) as well as the contribution of three major life cycle stages namely agricultural production stage, post-harvest processing/handling stage, and transport stage per functional unit. Table 7.4 presents an example that illustrates how improving drying energy could reduce environmental burden.

Based on the LCA results under the defined system boundaries and functional units, some important lessons have been highlighted:

- Based on the investigated organic products, salmon and tomato value chains are most energy intensive. The total energy demand for organic salmon is about 48 GJ for normal cold chain supply case, and about 49 GJ for supper-chilled case. About 80% of energy input is at agricultural production stage of Salmon indicating that feed production and salmon growing stages need more attention for improvement.
- The total CED value for Fresh tomato supply case is about 45 GJ while it is about 49 GJ for dried tomato case. About 90% of the 45GJ is consumed at farm stage due to high energy for greenhouse heating and other on farm activities. Therefore, from energy point of view, agricultural production stage is hot-spot that could compromise the sustainability of greenhouse based organic tomato cultivation in Sweden.
- Regarding GHG emissions, organic beef has highest impact with about 12964 kg CO2 eq in the case of fresh beef supply, and 12977 kg CO2 eq for dried beef case. Next to beef, organic salmon has high GHG emission value with 1815 kg CO2 eq normal cold chain and 1715 kg CO2 eq for supper-chilled salmon supply case.
- The drying process increases energy demand at the processing stage while it reduces GHG emission in some cases. However, drying process reduces both the energy demand and GHG emissions at transport stages when compared with fresh product supply cases due to the weight reduction.
- In almost all cases, the drying process reduced the total GHG emission in each product value chain. The reduction varies from 8% (case of organic carrot) to 46% (case of organic apple).
- Further improvement in food processing (e.g. drying) efficiency, leads to reduction of en-

vironmental burden. For instance, if drying energy is reduced by 30%, the energy demand and GHG emission from processing and transport stages (excluding farm stage) in the case of organic tomato value chain could be reduced by 26% and 12% respectively (see Table 7.4).

- In addition to improving energy efficiency at farm stage and post-harvest stages, introducing renewable energy is important where it is applicable, to improve the sustainability of organic food value chains.

Table 7.4 presents some results from LCCA calculated at different life cycle stages. In the case of organic salmon value chain, the supper-chilling process reduces the transport cost by about 33%. However, salmon farming stage and processing (including packaging) stages constitute about 92% and 7% of total life cycle cost respectively, and more improvement effort at these stages could improve the sustainability of organic salmon.
.In the case of organic apple supply chain, the drying process increased the total cost by 6% when compared to fresh supply case. The cost at postharvest processing stage was increased by about 33% while the transport cost was reduced by 36%. That means, in the case of longer distribution distance, the cost advantage increases when compared to the case of fresh apple supply.
At farm level the beef production cost is estimated to be higher than selling price of slaughter animals indicating that organic production aid is needed to promote organic beef production in the case of Sweden. Costs at beef processing and handling stages was calculated based on average 4.4% operating margin at processing and retail levels which could be higher in some cases. Higher profit margins indicate that the operating costs at processing and retail levels could be reduced which in turn increases the overall economic sustainability of organic beef value chain. In general, the drying process increases the costs at processing stage, but it can be traded off by decreased transport demand and packaging.

8. Food drying and related food logistics

SLU, Department of Energy and Technology, Sweden
Gebresenbet, G. & Bosona, T.

8.1. Introduction

In order to sustain and improve FVCs, more systemic changes are a must in entire food supply chains. These could include introducing more efficient production and processing (e.g. drying), preserving, storing, and transporting techniques at regional or farm levels. Increasing food production in more productive areas, so that farms in the area can feed the community within the region with less environmental and economic cost, could reduce the need of food import from long distance. Such local food production should be integrated with organic food production to increase the environmental and social benefits of the local food consumers.
From environmental and sustainability point of view, further investigations are required focusing on post-harvest stages of food life cycle stages. There is huge number of researches on food sector so far, however, the focus has been mainly on agricultural production phase. Post-harvest stages such as storage, packaging, transport and food loss along FVCs got less attention (Hammond et al., 2015).
It is not only food shortage that promotes long-distance food transport with more sustainability concerns. The variation in production cost at different regions leads to transporting food from one region to other. Similarly the climate difference and seasonal variation of production are reasons for long-distance food transport (Borg et al., 2016). Table 8.1 presents the food trade volume and value of Europe in 2012 and 2016. It indicates how food trade increased both in volume and values. The import and export volumes increased by 6% and 42% respectively from 2012 to 2016. This increasing trend in food trade volume means increased long-distance food transport with increased environmental burdens and economic as well as social constraints.

Table 8.1: Example of international food trade of Europe (Eurostat, 2017)

Year	Import to Europe		Export from Europe	
	Million tonnes	Billion Euro	Million tonnes	Billion Euro
2012	87.74	85,6	64	70
2016	93	101	91	84
Increase %	6	18	42	20

8.1.1. Drying process and food transport

Best food drying experiences could play important role in this contemporary increasing trend of food transport both in transport volume and distance (see Table 8.1). This can be implemented by introducing effective and affordable processing facilities to local or regional food producers to reduce fresh food transport and reduce import to the region and also by processing food before long distance transport.
Food drying processes influence not only the food quality aspects but also the food logistics services and management. In this case, the term food logistics considers food transport, packaging, storage facilities, and information related to movement of food product along the supply chain. In wider perspective, logistics management can be defined as "the part of supply chain management that plans, implements, and controls the efficient, effective forward and reverses flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements" (CSCMP, 2011). Therefore, any improvement in the food logistics services and logistics management performance leads to sustainability of FVC. In this regard, food logistics plays important role in improving the sustainability of organic food production and supply. In this document, the role of food transport, packaging, and storage and how appropriate drying practices could influence the logistics aspect, has been described with examples from SusOrganic project. In SusOrganic Project case, the case of local product distribution was assumed in most cases (see Table 8.2).

8.1.2. Food drying and its impact on food shelf life and food loss

The increasing food transport distance and volume to feed increased and urbanized population needs to be energetically efficient. In this regard cargo ships are more efficient for long distance transport than trucks, trains, or airplanes (Harmmond et al., 2015). Some foodstuffs such as fish, meat, fresh fruit and vegetables have short shelf lives and these foodstuffs need high speed transport to avoid spoilage and satisfy the consumers which leads to high transport cost. Therefore, introducing food processing such as food drying plays great role in reducing transport cost. Because, the drying process increases food shelf lives which in turn avoid the need of high speed, costly food transport. In addition to reducing transport volume, food drying avoids the use of additional energy for storage refrigeration or freezing during food transport from farm all the way to consumer. By introducing drying techniques, small scale farms of locally produced and distributed organic food could reduce transport cost, food loss, and create more market opportunity.

Food loss is one of problems in the food sector. Throughout global food supply chains (including both organic and conventional food sectors) about 1.3 billion tons of edible food are estimated to be lost yearly (Corrado et al., 2016). Due to its environmental, economic, and social concerns food loss should get more attention. Wastage of food means wastage of resources used as input during food production, processing, packaging, storage and distribution. These include energy, natural resources (e.g. water, land) and human resources.

Table 8.2 presents the estimated food loss and associated resource loss.

Table 8.2: Estimated food loss and associated resource loss in global food supply chains

Item descritption	Unit	Quantity
Yearly food waste throughout global food supply chain	Billion tons	1.3
Water used to produce the lost food indicated above	Cubic meter	80 000
Land used to produce the lost food indicated above	Billion hectare	1.4
GHG emission associated to the above food loss	Giga tons CO2 equivalent	3.3

Source: Corrado et al. (2016).

Food loss at the downstream stages of supply chain is associated with additional resource losses in addition to loss of edible food. It is important to notice that food lost after packaging stage increases the environmental burden and economic loss. Processed food items, e.g. dried products must be able to withstand transportation and handling and to arrive in satisfactory condition at the place of destination (UNECE, 2007). In general, if processed food product is wasted at retailer or consumer stages, it is associated with more resource loss than food waste at farm level, because, at downstream stages of food supply chains, more resource inputs are used for processing, handling and transport.

This has been explained with examples from SusOrganic project. Figures 8.1 illustrates how food loss equal to 1% of functional unit (i.e. equivalent to 10 kg fresh product at farm gate) can increases the cumulative energy demand (CED) and GHG emissions. Figure 8.1 a presents typical example how energy demand is increased due to food loss along value chain. It is noticed that the loss of dried beef at consumer level increased energy loss by about 160% when compared to equivalent loss at farm gate. Similarly the loss of dried tomato at consumer gate increased energy loss by more than 130 % when compared to equivalent product loss at farm stage.

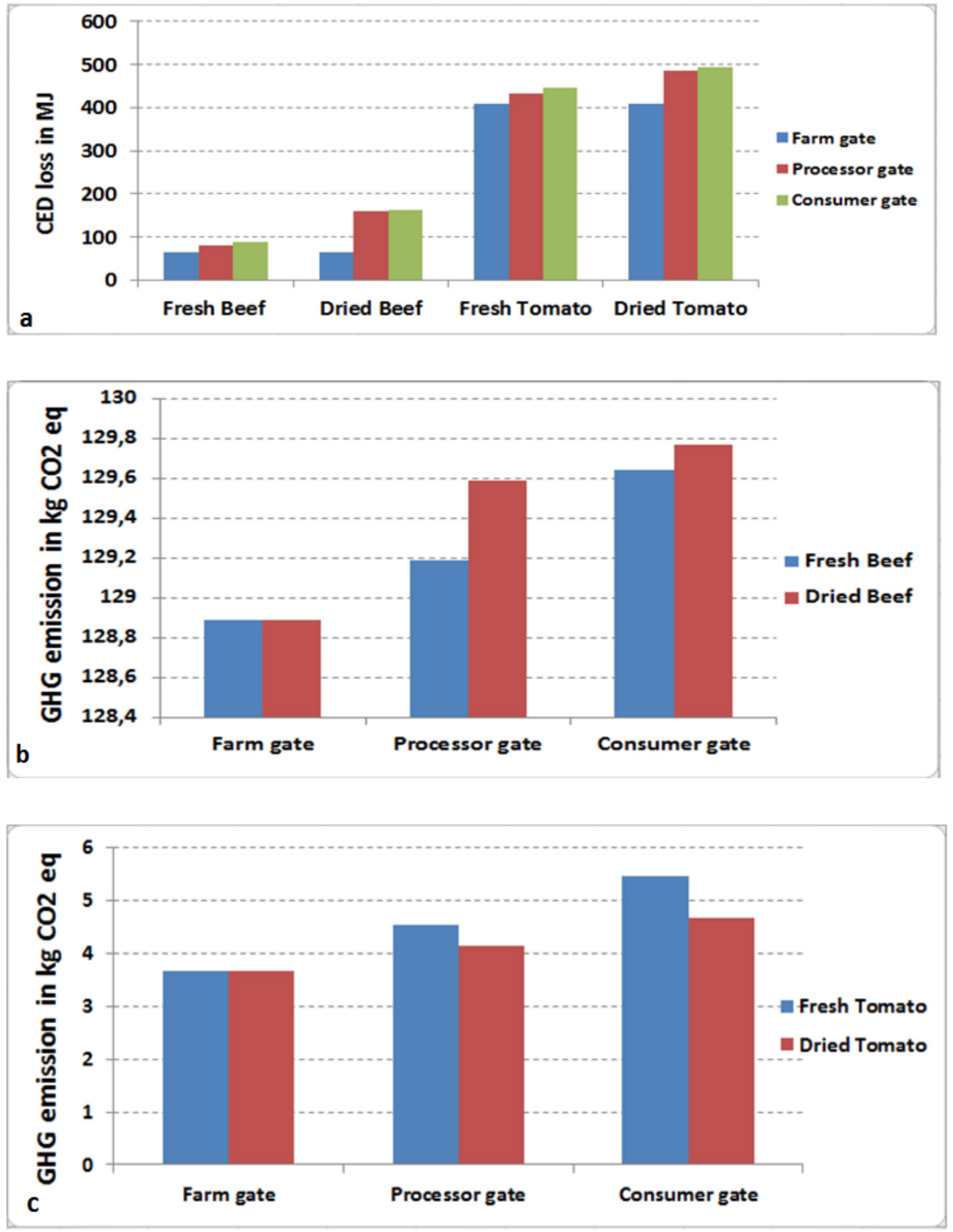

Figure 8.1: Typical illustration of additional environmental burden due to product loss equivalent to 1% of FU, i.e. 10 kg fresh product at farm level. (a) impact of food loss on cumulative energy demand of organic beef and tomato value

chain; (b) impact of product loss on GHG emission of beef value chain; (c) impact of product loss on GHG emission from organic tomato value chain

Regarding the GHG emissions, there is about 1% increase (for both fresh supply and dried meat supply cases) in emission incurred due to beef loss at consumer level when compared to loss at farm level. However, the emission incurred due to beef product loss (equivalent to 10 kg fresh meat at farm) is significant i.e. as high as 130 kg CO2 eq per functional unit (see Figures 8.2 b).

In case of tomato, the GHG emission incurred due to product loss is less when compared to beef supply case (see Figure 8.2 c). However, the emission due to loss of fresh tomato at consumer level is about 5.5 kg CO2eq which is higher by 49% than equivalent loss at farm stage. For dried tomato, these values will be 4.7 kg CO2 eq and 28% respectively. This indicates that when implemented effectively, the drying process has multiple advantages from environmental point of view:

i. It increases product shelf life which in turn reduces product loss;

ii. It reduces the overall GHG emission of tomato value chain due to reduction in packaging and transport volume (see Table 8.3); and

iii. The loss of dried tomato at consumer gate is associated with less GHG emission in comparison to equivalent loss of fresh tomato at consumer level.

However, the drying process should be integrated with use more environmentally friendly food packaging. Sustainable food packaging enables to promote locally produced organic food sector. Food packaging should be environmentally friendly, consumer friendly as well as economically affordable by food producers, especially by small scale organic food producers. Such sustainable food packaging enables to preserve freshness of food, increase its shelf life, and reduce food loss. This in turn reduces environmental burden in food value chain, increases consumer satisfaction and reduces food production cost.
For instance using plastic packaging materials causes less greenhouse gas (GHG) emissions than using paper and cardboard packaging. An Organic vegetable box scheme in UK indicated how it could reduce the GHG emission due to packaging by 70% if it uses plastic boxes instead of cardboard boxes (The Gurdian, 2010). Similarly, the LCA results of SusOrganic project indicated that using cardboard box as transport packaging could increase the GHG emission and energy consumption. For instance, the use of cardboard box for packaging (in addition to plastic packaging) could contribute about 94% and 24% of GHG emission from post-harvest stage of fresh apple value chain (123 kg CO2 eq) and dried apple value chain (55 kg CO2 eq) respectively. Regarding CED, the use of cardboard will contribute about 89% of total CED value (3.3GJ per functional unit) estimated for post-harvest processing and handling stage. For dried apple, the contribution of cardboard is 4% of 7.5 GJ energy input at post-harvest stage.
Similarly, using cardboard packaging for fresh beef meat contributes 57% of CED value (4 GJ) and about 77% of total GHG emission (134 Kg CO2 eq) from the processing (includes cattle slaughtering and packaging) stage. For the case of dried meat, the figures will be 6% of CED value (10.32 GJ) and 28% of GHG emission (97 kg CO2 eq) from processing stage that includes slaughtering, drying and packaging. For the dried meat case, the share of packaging is reduced due to increased share of drying energy consumption, which is about 80%.

8.1.3. Highlighted lessons

In relation to food drying and related logistics aspects discussed above, some major remarks have been provided:

- The location of drying process should be close to farm as much as possible. This reduces transport demand for fresh products from farm to processing facility which in turn reduces environmental burden and costs.
- It is not only processing the food produces but the appropriate packaging and handling reduce the losses and associated environmental and cost burdens.
- Whenever applicable, using renewable energy for food processing, storage, and transport reduces the environmental burden of organic food supply. But specific areas may have more cost of production if the renewable energy is more costly. Such extra cost is recommended to be within the limit that could be traded off by increased selling prices of organic food items.
- For short distance supply, the drying process impose more environmental burden. But it could be traded off by increased food shelf life, storage space and easy handling. On the other hand, for long-distance supply chains, drying process reduces transport volume and packaging which compensates the environmental burden due to drying process.
- The drying process increases the environmental burden and costs at processing stage, but it can be traded off by decreased transport demand and packaging. This indicates that as distribution distance increases, the environmental and cost advantage of dried product increases when compared to fresh product supply cases. However, its practical implementation needs integrated food value chain management that involves all actors along the chain.
- For the cases where transport and processing stages have more contribution to environmental burden (e.g. organic apple and carrot value chains) than farm stage, improving energy efficiency at processing stage and reducing transport demand leads to improved sustainability of organic food value chains. For instance, reducing the distance between processing (drying) facility (and between abattoir and farm in the case of meat value chain) enables to improve the sustainability of organic food value chains.
- Increasing production and reducing losses along food supply chains plays important role in improving sustainability of food value chains in general. In this regards, introducing appropriate drying methods and packaging plays useful role in increasing food availability and reducing environmental and economic constraints.
- In addition to increasing shelf life of organic food products, appropriate preservation methods such as supper-chilling of salmon and drying of meat, fruit and vegetables enable to sustain the supply of organic food through increased shelf-life and long transport of dried

products and satisfy demand of organic food consumers. The consumers' satisfaction is not only due to increased supply of organic food but also due to reduced environmental burden of dried food supply than long distance fresh product supply cases.

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Chapter II Chilling and freezing

II. I SUPERCHILLING

1. Concept of superchilling

SINTEF Energy Research, Trondheim, Norway
Bantle, et al.

Food security is one of many challenges mankind is facing in the future and depends closely on the growing population, available agricultural area and energy resources on the planet. Food and Agriculture Organization of the United Nations (FAO) estimates that each year, approximately one third of all food produced for human consumption in the world is lost or wasted (FAO, 2013). These losses represent a missed opportunity for the global food security, especially when considering limited agricultural resources and the fact that still around 1 billion people are suffering from hunger. FAO identifies, among others, the meat industry as a global environmental hotspot related to food wastage for consideration by decision-makers wishing to engage into waste reduction. Even if wastage volumes of meat are comparatively low, they generate a substantial impact on the environment in terms of land occupation and carbon footprint, especially in high-income regions where about 67 % of the meat is wasted and in Latin America.
The organic meat market in Norway is small and only half of the organically produced meat is sold under organic labelling. The reasons for this are not investigated in this project, however, during contact with small producers it became clear that valuable time is lost in the cold chain between slaughtering, processing and packaging before the product is ready to reach the market. In some cases, small producers do not have the infrastructure/possibility to slaughter themselves and they need to send their animals to certified slaughterhouses. After slaughtering the unprocessed raw meat is sent back to the producers for further processing and/or packaging and labelling. First then the meat can be sent out to the retailer. The organic meat is therefore a few days old before the consumer has the possibility to purchase it because of the distances, place of production and time necessary for transport and processing. Consequently, the organic meat is already exposed to quality reduction compared to traditionally produced meat in the supermarket. It can be estimated that the shelf life of organic meat is reduced by 50 % for certain cases when compared with conventional meat. Possibilities to extend the shelf life and

improve the quality of organic meat would help the producers to be more competitive in the market. It would also enable local producers to reach far distance markets, which are currently not exploited due to transportation time.
Meat and fish products are mostly preserved by traditional refrigeration processes, and needs to be sustained through the cold chain from the production facilities until it reaches the plate of the consumer. Preservation in the form of drying, dry-curing or salting is also applied for meat and fish. Compared to the global meat and fish production, this represents a non-substantial volume. Most modern storage plants today have installed refrigeration systems, chilling/freezing equipment and cold store facilities, which also fulfil certain demands on energy efficiency and environmental impact. Worldwide, the relocation of people to urban areas has required more food preservation, transportation and greater distribution of perishable food.

Consumer behaviour, especially in high-income regions, require high quality meat and fish products, which fulfil health and security requirements in the supply chain. Especially the producing and processing industry in the cold chain are facing challenges during preservation and distribution of fresh perishable products, which are accepted by the consumer. The most important factors for the quality of meat and fish products are storage temperature and time, which directly influence the shelf life and quality. For constant storage temperatures, the shelf life of a product is a simple function of the storage time (e.g. Figure 1.1). For each product, certain variations in the shelf life occur depending on product variations as well as processing and packaging.
Industrial countries normally have a sufficient cold chain where the different parts are controlled during production, processing, transportation and storage. Different studies and measurements have outlined that the segments transport and sales have challenges holding the required maximum temperature of the cold chain. This includes errors and lack of chilling in transfer operations or transport equipment (Hemmingsen et al., 2004).

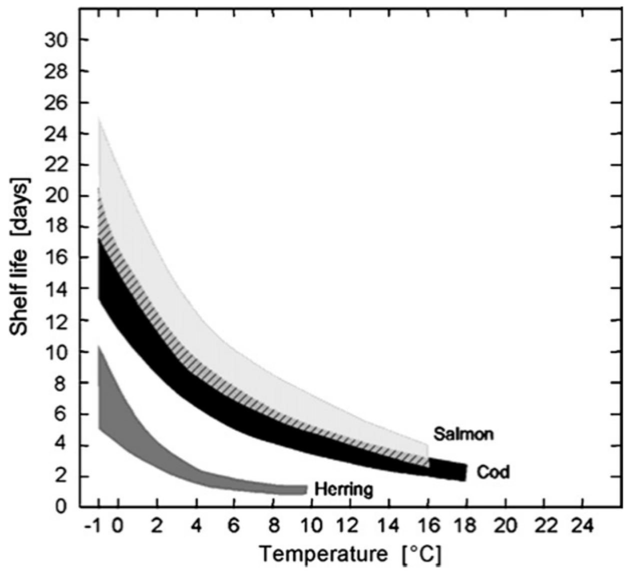


Figure 1.1.1: Generally accepted shelf life for selected Norwegian fish species. The shaded area shows estimated effects of product-processing (Magnussen, 1993)

Superchilling is in principal a partial freezing of a product with an ice content from 5 % to 20 % (Kaale et al., 2011). There is no definition of superchilling commonly agreed upon in literature and in some publications an ice content of up to 30 % was considered as superchilled. The main idea behind superchilling is that the product appear non-frozen despite the presence of ice. Hence, the acceptable amount of ice formation must be considered for each product. In literature, the term supercooling can be found for food products, which is different from superchilling. Supercooled products are also stored at temperatures below the initial freezing point, but without the presence of ice inside the food matrix. This is reached by special product handling which avoids initial ice nucleation. Superchilled products on the contrary, will have a certain fraction of ice present inside the food matrix.

The challenge for producing a superchilled product is how to control the amount of ice formation. The water present in food is embedded inside the solid material of the product, and ice formation in food products occurs over a certain temperature range. This is in contrast to ice formation of pure water which occurs exactly at 0°C and the temperature of a pure water-ice mixture can first be reduced below 0°C when all liquid water is frozen to ice. For food products the initial freezing point is normally one or two Kelvins below the freezing point of water and the temperature of the product can be reduced further (normally down to around 20°C) despite the fact that liquid, unfrozen water, is present. This is illustrated in Figure 1.1.2 and Figure 1.1.3, where the change in the specific enthalpy for food products is a smooth curve starting from the initial freezing point and stretching over a certain freezing range; instead of a sharp fall at the freezing temperature. The water in the product is partly present as ice and partly present as liquid water even at temperatures down to 20°C (also illustrated in Figure 1.1.2). Consequently, the amount of present ice for a certain product is a function of the temperature and if the storage temperature is controlled to certain stable temperature level, the amount of formed ice in the product can be controlled as well.

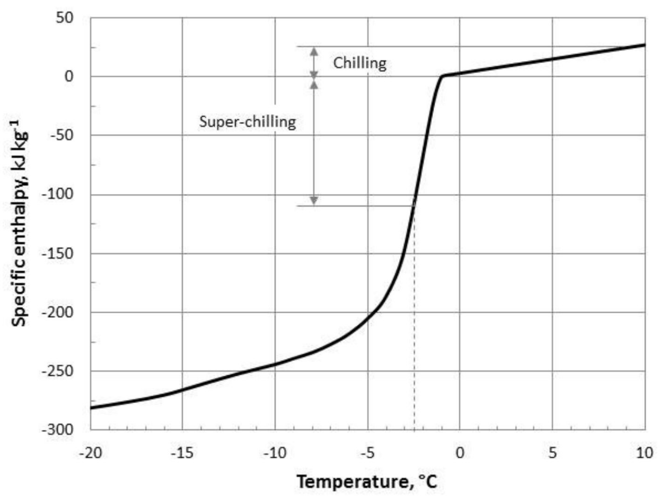


Figure 1.1.2: Energy in food products on the example of codfish filets, according to Valentas (1997)

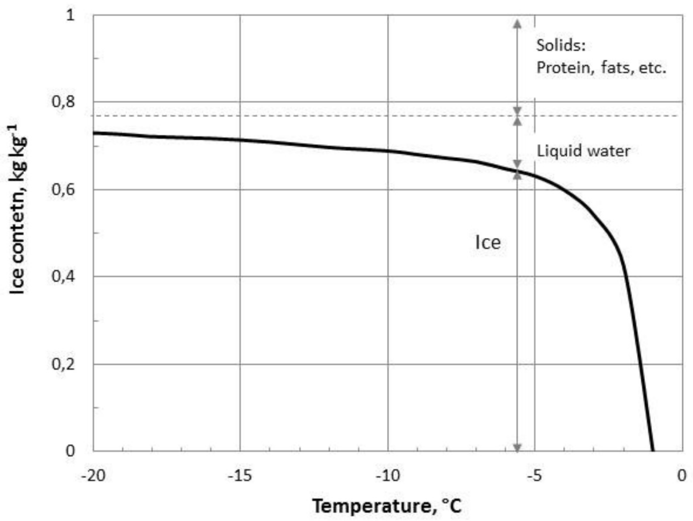


Figure 1.1.3: Ice content in food products on the example of codfish filets, according to Valentas (1997).

In literature several methods are described to obtain superchilling conditions in food products. In order to reach superchilled conditions, it is necessary to identify the temperature at which the product will form/contain the desired amount of ice. One of the easiest, but not best, method is when the product is placed at this temperature in a storage room. The product will reach superchilled conditions after a certain time, depending on the heat transfer between product and storage environment. However, experimental investigations show a rather poor control of the ice fraction, when the product is simply placed in at a certain superchilled temperature. The ice formation will be highly time consuming (>1-2 days) and will vary with the effective heat resistance of the product and storage system. Hence, placing the product at superchilled storage condition results in two practical problems: First, the storage facility will function as a partial freezer, which gives challenges for dimensioning, packaging, temperature distribution and control of ice fraction. Second, the time to build up the amount of partial ice will be very long, since the heat transfer is limited by the low temperature difference between product and ambient condition as well as the heat transfer resistance and product variations.
SINTEF has evaluated and tested a superchilling concept which is based on fast initial shell freezing using a conventional blast freezer before storing the product at superchilling temperatures. During blast freezing the outer layer of the product is frozen. The freezing time is relatively short, only 1-3 minutes, depending on product and size of product. Because of the high heat transfer coefficient and a freezing air temperature of ca -40 ºC, the freezing time is relatively short. The conditions need to be precisely evaluated with respect to freezing time, product size, heat transfer coefficient and temperature difference (between air and product) in order to result in the correct amount of ice formation. The aim of the blast freezing is to produce all ice which is required during superchilled storage before the product is put into storage. By this procedure it is ensured that the superchilled storage only needs to sustain a certain temperature and that no heat load is created for ice formation.

Figure 1.4: The different steps in superchilling of food: The present water in the product is partially frozen and after a certain time mixture of water and ice is present inside the structure of the product.

During storage of superchilled food products, the ice in the outer shell of the product will slowly distribute evenly through the food matrix, thus the shell-frozen ice will disappear, and the product will appear as fresh. As a final result, the superchilled product will have a certain amount of ice evenly distributed through the product and the product temperature is below its initial freezing point. The appearance of the product is still like an ordinary refrigerated product and it is not possible to feel or see the present ice fraction. The relation between the ice fraction and the storage temperature is given for some selected products in Table 1.1. This topic is discussed extensively in literature (Valentas 1997, ASHRAE 2006), however, with focus on the complete temperature range for freezing (down to 25°C). It is therefore recommended to determine this relation in more details for specific products in the temperature range of superchilling.

Table 1.1.1: Relation between storage temperature and ice fraction for some selected products (Tolstorebrov et al., 2014). Product variations make it necessary to evaluate the ice fraction individually.

Product	Storage temperature (superchilled)	Ice fraction	Initial freezing point
Salmon Filet	- 1.8 °C	6.3 %	-1.6 °C
	- 2.2 °C	18.2 %	
	- 2.6 °C	26.9 %	
Trout	- 2.2 °C	8.2 %	-2.0 °C
	- 2.6 °C	21.8 %	
	- 3.0 °C	27.0 %	
Makerel	- 1.8 °C	6.3 %	-1.6 °C
	- 2.2 °C	18.2 %	
	- 2.6 °C	29.3 %	

Herring	- 1.8 °C	4.0 %	-1.6 °C
	- 2.2 °C	11.6 %	
	- 2.6 °C	18.7 %	
Cod (aquaculture)	- !.2 °C	10.2 %	-1.0 °C
	- 1.6 °C	27.9 %	
	- 2.0 °C	38.6 %	
Beef, lean (Valentas 1997)	- 1.0 °C	5 %	n.a.
	- 2.0 °C	45 %	

1.1. State-of-the-Art

The main reason to apply the superchilling concept to a product is the possibility to extend the shelf life of the fresh product. The shelf life of a product depends on several factors where the storage temperature has a dominating influence. Other factors like processing hygiene, mechanical stress, packaging and product variations will also have an influence, which makes comparative evaluations of different studies difficult. However, the temperature in superchilled storage is around 5 – 10 Kelvin lower compared to traditional refrigerated storage and this temperature reduction is accomplished by the superchilling concept.

Duun and Rustad (2007) were investigating superchilling of farmed cod fillets and showed an increased shelf life of around 2 weeks compared to chilled ice storage. The drip loss for the superchilled cod was lower, however, the liquid loss by low-speed centrifugation was higher in superchilled cod fillets. This was explained by the freeze denaturation of muscle proteins. It was outlined that the superchilling process needs to be optimized with respect to freezing rate and degree of superchilling in order to minimize protein denaturation while sustaining a sufficient low temperature to ensure a shelf life increase.

The influence of superchilled storage on pork roast was investigated by the same group (Duun et al., 2008). The superchilled storage time was 16 weeks for vacuum-packed pork roast at a temperature of 2.0°C and compared with chilled storage at 3.5 °C. The sensory quality was evaluated as good and the microbiological count was low during the whole storage period. Again, the drip loss was lower for superchilled products. The group claims that the shelf life can be extended from 2 to 16 weeks when superchilling is applied. However, they also outline the importance of maintaining a stable temperature with very low fluctuation during superchilled storage.

The superchilling of farmed Atlantic salmon at storage temperatures of 1.4 °C and -3.6 °C was compared with chilled ice storage (storage temperature of around 0 °C) in another investigation (Duun & Rustad, 2008). For the ice-chilled salmon, a storage time of 17-21 days was determined, while the storage time for the superchilled salmons was doubled. No different shelf life for superchilled salmon stored at 1.4°C and -3.6°C was reported. Drip loss was identified as a major problem for superchilled salmon. The textural hardness was higher in superchilled salmon at -3.6°C and a higher protein denaturation was found for the samples from 1.4°C. Based on these findings, a superchilling temperatures somewhere between 1.4°C and -3.6°C was recommended for salmon, and salmon was considered as better suited for superchilling than cod. Similar results were achieved for rested Atlantic salmon (Erikson et al., 2011).

In a national Norwegian project (Norwegian Research Council, 2016) it was investigated how superchilling can be applied for fresh lamb (lamb-leg). A superchilling temperature of -1.6 °C extended the shelf life from 21 days to 40 days (90 % increase). The project also investigated how to implement the superchilling concept in the production and installed a blast freezing system in an existing production line hereby reducing the processing time by 1 day. This resulted in a reduction of production costs as secondary effect. The colour and pHvalue of the superchilled lamb did not vary compare to traditional chilled lamb, but drip loss was higher. The extended shelf life made it possible to reduce the demand on product freezing. This reduced the demand for freezing from 40 % down to 10 % and the energy demand by 13 %. Freezing and thawing causes leakage of proteins and other substances from the cell and for lamb the activity of the lysosomal protease cathepsin B was used to demonstrate that superchilled meat has less freeze damage compare to frozen meat (Fristad & Rustad, 2014). However, compared to fresh meat a certain higher amount of damage occurred in the superchilled meat. In general, the work showed that superchilling leads to some freeze/thaw damage compared to conventional refrigerated meat, but the damage was less compared to frozen meat.

Claussen (2011) reported for superchilled chicken meat an increase in shelf life from 15 to 30 days. However, it was not further specified at which temperature the meat was stored and other quality aspects were also not investigated in this paper.

In all performed experiments reported, the holding temperature of the storage was set in order to match the obtained ice fraction in the product from shell freezing. However, there was a general lack of information on the actual ice fraction in the investigations, because of challenges with measuring the ice fraction online (Stevik et al., 2010). In most cases, the ice fraction is determined with a disruptive method in preliminary tests for certain products.

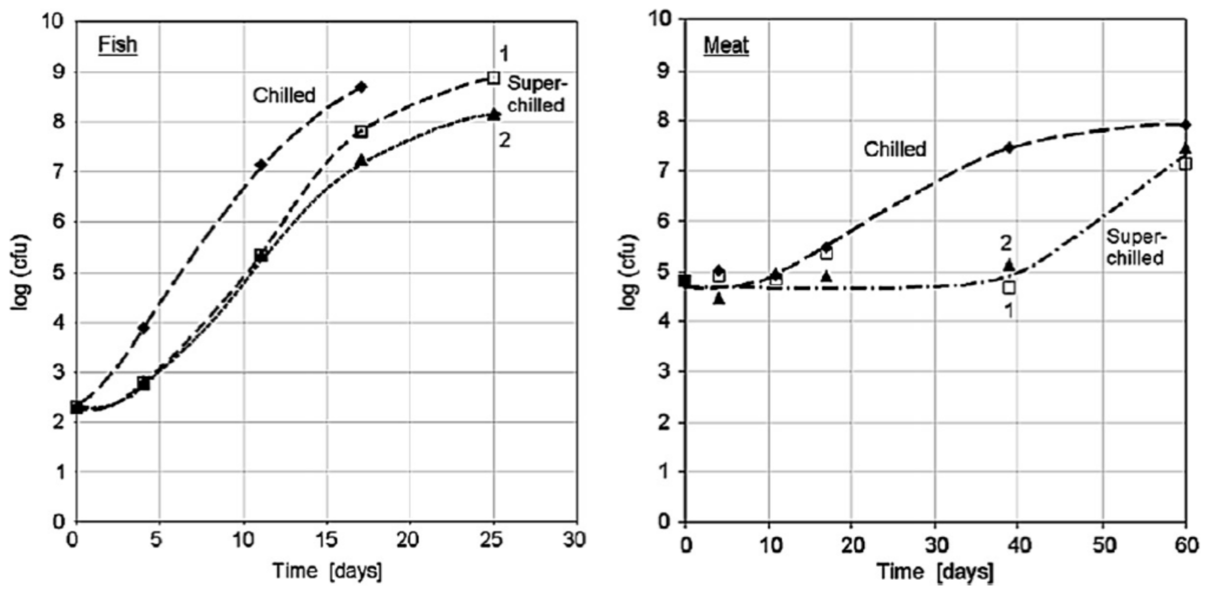
The low temperature and the partial ice content in products stored at superchilling temperatures, will result in a delayed growth of bacteria and microorganisms. The rapid chilling due to shell freezing will stop this growth and partly destroy or damage surface bacterial activity, which is beneficial for the superchilling concept in general (Magnussen et al., 2008). Figure 1.1.5 shows some examples of achieved reduced growth rates (CFU = Colony Forming Unit). The shelf life of food is based on a quality limit of 107 CFU. Above this value food is considered unfit for human consumption.

Table 1.2: Shelf life extension for selected meat and fish products in comparative studies with conventional refrigeration

Product	Superchilled storage temperature	Increase shelf life compare to conventional refrigeration
Cod fillets (farmed)	- 2.2 °C	+ 14 days
Prok roast	- 2.0 °C	+ 14 weeks
Atlantic salmon	1.4 °C and - 3.6 °C	+ 17 - 21 days

Chicken	n.a.	+ 15 days
Lamb-leg, fresh	- 1.6 °C	+ 19 days

Figure 1.1.5: Growth of aerobic bacteria on superchilled and ordinary stored fish (salmon) and meat products (pork); from Magnussen, Haugland et al. 2008. 1 and 2 refer to low and high ice content respectively. CFU is Colony Forming Unit.



Superchilling is mostly investigated for meat and fish products, where a shell freezing process was applied upfront on the superchilled storage. Significant increases in shelf life are reported, which are generally related to the lower storage temperature compared to conventional refrigeration. The superchilling process is accompanied by some quality losses or alterations like higher drip loss, which can be explained by the presence of ice in the food matrix. Storage parameters like temperature fluctuation or packaging can influence and eventuallyimprove the shelf life of superchilled products additionally. Table 1.2 gives an overview about the reported shelf life extension in literature for certain products. It is important to notice that the determined shelf life extensions are obtained in comparative studies. Product variations and different processing routines will influence on the result, however they will not account for the achieved shelf life increases.

1.2. The potential of superchilling for organic food producers

The cold chain in the industry today consists of refrigeration (+4 °C to 8 °C) and freezing (-20 °C to 25 °C) of food products. This is true for both conventional and organic cold chains. The implementation of a new process will require equipment which can supply a stable temperature around 2 °C and, in addition, a shell-freezing process. There is no technological challenge to supply refrigeration at this temperature, yet it requires modified refrigeration equipment from the supply industry and the willingness to implement a new concept in the cold chains. The additional processing equipment and modified storage conditions for superchilled products can be a barrier for the implementation for small-scale producers. However, innovative new solutions are often implemented in small or medium sized production facilities, since the production is more flexible and the market potential is more promising for these producers.

So far, two processing lines for superchilling of fish and meat products have been implemented in the Norwegian food industry, but until now the concept is not used in substantial amount in European or other markets. Superchilling can be used in different ways and under different aspects in the cold chain for organic products:

1. Extended shelf life: The most obvious advantage is the extended shelf life for superchilled products compared to conventional refrigerated products. Products with long transportation or high seasonal variations can apparently benefit from this extension. In addition, products which are only produced in limited amounts can extend their availability to the marked or reach far distance markets. The extended shelf life is maybe the most important potential for organic meat and fish producers. With this technology, it will be possible to reach far distant markets which is an important aspect in order to overcome the geographical long distances, especially in Norway. Consequently, the organic products can compete when it comes to shelf life and quality in the supermarkets, since conventional large-scale producers have a better-developed (and faster) distribution network.
2. Substitution of food freezing: Overproduction of meat and fish products are often frozen in order to preserve it for future sales. However, it is normally possible to achieve a higher price for fresh products despite the fact that freezing and freeze-storage is costly. The superchilling concept offers the possibility to store at least a certain amount of the overproduction without freezing and sell it within reasonable time as fresh. A higher market price can be achieved while at the same time the energy demand (for freezing) in the production is reduced. In the above mentioned case for Norwegian lamb, the energy demand of the production was reduced by 13 % by partially substituting freezing with superchilling.
3. Transportation: High quality fish products, like Atlantic salmon, are quite often transported on chilled ice, either on the road but also by air transport. Approximately 25-30 % of the transported weight is ice, while the remaining 70-75 % of the transported weight is the valuable product. The transportation of ice is quite cost-intensive and at the same time it produces an environmental impact (carbon footprint). By using a superchilled product the necessity for ice during transportation can be reduced or avoided. The ice present inside the product functions as thermal inertia and provides the necessary chilling under transportation. By applying this concept it would be possible to reduce the transported weight and volume by 25-30 %. Or in other words: 4 truckloads with chilled ice boxes can be reduced to 3 truckloads with superchilled product while the same amount of sellable product is transported. It must be noticed that hereby the extended shelf life of the superchilled product transported is reduced since the partial ice fraction is reduced during transportation. However, also a longer shelf life compared to traditionally transported products will be achieved.
4. Shorter processing time: Conventional chilling is a time consuming operation which needs

to be implemented in the production line. Superchilling, with initial blast freezing, can reduce process time and lower the product temperature before storage. Hereby it is possible increase the capacity of existing production lines or to compensate for varying production capacities.

5. Other effects: Superchilling is one of the first unit operations in a production line and can increase product yields e.g. due to higher firmness before skinning (Stevik & Claussen, 2011) or deboning. The rigidity of the product is in general higher for superchilled products. This can be beneficial for product handling, e.g. during fileting, slicing or automated packaging.

The superchilling concept can be implemented in existing production facilities, by the implementation of a blast freezer, which can be operated continuously. The specific chilling rate is accelerated since the heat transfer and the temperature difference in blast freezing is high. Therefore, it is relatively easy to produce superchilled products. However, superchilled storage requires a re-design of existing storage and refrigeration systems. The temperature of the refrigeration equipment must be reduced, but even more important, it must be ensured that the temperature variations and distribution in the storage rooms are small. A temperature fluctuation of ± 1 Kelvin is standard in conventional refrigerated storage. If a superchilled product is exposed to such fluctuations, it can result in continuous thawing and re-freezing of the ice inside the food matrix. This will have a poor influence on the product quality and stability. The performed investigations in the laboratory have normally a temperature stability of ±0.2 Kelvin. For industrial superchilling systems it must be carefully evaluated which temperature variation are acceptable. The authors recommend a temperature fluctuation as small as possible and to investigate the influence of temperature fluctuation further.

1.3. Challenges in Superchilling

For dimensioning and controlling of the superchilling process it is important to calculate the correct chilling time and temperature distribution (e.g. for blast freezer), because the amount of ice formed during superchilling is of great importance for the whole process. The latent heat of freezing results in a sharp decrease of enthalpy in the temperature range commonly applied for the process and consequently, even minor temperature changes can result in a significant change of the ice fraction. Food products normally consist of a complex matrix of water, protein, carbohydrates and fats, and the water is bound by different mechanisms. General equations for calculation therefore always have some uncertainties. Future work should find improved calculation methods and simulation tools fitting to superchilling. This is especially important for products that vary in shape and size.
Another challenge is the optimized determination of the degree of superchilling required for a sufficient improvement of shelf life while achieving acceptable quality attributes. Most investigations were focusing on an ice fraction between 10 % and 20 %, because the achieved quality reduction (compared to refrigerated products) was minor, while for ice fractions higher than e.g. 30 %, significant drip loss will occur. The superchilled storage temperature was set in order to demonstrate the potential of the concept compared to refrigerated storage. For a specific product, it must be determined which ice fraction or storage temperature is optimum with respect to reduced bacteria and microorganism growth and acceptable quality changes.
The industry requires in general effective and flexible processing equipment, which preserve a premium quality product. Superchilling offers certain possibilities for the industry, but the question is if they are promising enough to make the concept commercially interesting. The commercial interest will most likely be the main driving force for industrial implementation and the change from conventional freezing and refrigeration towards superchilling requires a certain readiness to take a certain risk. Superchilling will also demand more accurate information on product variation and flow, which is especially challenging for small scale producers. In addition, the equipment suppliers will meet higher requirements regarding energy and thermodynamic competence. It can be assumed that, especially in the beginning, most of the technology will be experimentally developed.
The consumer awareness for superchilled products is currently low (or not existing) and it might be a general challenge to get consumer acceptance for a third cold chain product. This aspect is currently not under evaluation.

1.4. Conclusion

Organic production in Norway is a niche market and only 1.6 % of the sold products in supermarkets are organic. For meat products, only 1 % of the meat is organic and around 50 % of the produced organic meat is sold under conventional, non-organic labels. The reasons for this development were not analysed. Long, time-consuming transportation in the cold chain from small or medium scale producers to the final consumer might be one of the reasons. Extension of shelf life due to superchilling of organic meat and fish products could help to provide the market with fresh-like, high quality organic products. The increased availability of organic meat and fish products at the market can trigger future consumer demand and help to increase the market share of organic products.
Controlled partial freezing or superchilling of food products can result in significant shelf life extensions during the cold chain. Between 10 % and 20 % of the water content of the food is frozen, and the ice functions as a thermal inertia during storage and transportation. Superchilled products in general have an extended shelf life and the technology shows good potential for implementation in the cold chain, since the product quality is comparable with that of refrigerated products. Superchilling in industry can also reduce the use of freezing/thawing for production buffers and thereby reduce labour, energy costs and product weight losses.
Superchilled products sustain quality parameters commonly associated with fresh/unfrozen products. However, some increase in product drip loss may occur during storage. Implementation of superchilling in industrial process plants and routines require a strict temperature control in the cold chain. Understanding and quantifying thermo-physical processes at and inside the food surface are important for the optimal design of superchilling equipment and packaging systems for food products.
The concept of superchilling is a new and improved cold chain process which is aiming to increase the shelf life of refrigerated products and sustain fresh-like appearance by applying

partial freezing. This requires the implementation of a new temperature level (at approximately 2°C) for the storage of products in the cold chain. In order to achieve sufficient process control it is recommended to implement a fast partial freezing in the first segments of the production line. Promising results have been achieved with blast or impingement freezing. Significant shelf life extensions are demonstrated in literature for certain superchilled meat and fish products.
The concept can be used to substitute chilled ice transportation, which will have a direct impact on the carbon footprint in the transport sector. Superchilling has the potential to reduce a substantial impact from currently wasted meat and fish volumes; especially in high-income regions with already existing cold chains, hereby contributing significantly to global food security. For industrial implementation, existing or modified equipment from today's cold chain can be used, but superchilling requires improved process control.
R&D has clearly identified the potential of this technology, especially for meat (chicken, lamb, pork) and fish (salmon, cod) products. However the industry has somewhat overlooked this technology, despite the clear benefits, the relative simple implementation also in existing production lines and the high technological readiness level. The first industrial implementations have demonstrated positive effects on shelf life, product quality, production yield, energy demand and production costs.

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1. Superchilling of organic pork and salmon

SINTEF Energy Research, Trondheim, Norway
Bantle et al.

2.1. Introduction

Organic production in Norway is a niche market and only 1.6 % of the sold products in supermarkets are organic. For meat products, only 1 % of the meat is organic and around 50 % of the produced organic meat is sold under conventional, non-organic labels. Long, time-consuming transportation in the cold chain from small or medium scale producers to the final consumer might be one of the reasons. Extension of shelf life due to superchilling of organic meat and fish products could help to provide the market with fresh-like, high organic quality products. The increased availability of organic meat and fish products at the market can trigger future consumer demand and help to increase the market share of organic products.
Controlled partial freezing or superchilling of food products can result in significant shelf life extensions during the cold chain. Between 10 % - 20 % of the water content of the food is frozen and the ice functions as a thermal inertia during storage and transportation. Superchilled product have in general an extended shelf life and the technology shows good potential for implementation in the cold chain, since the product quality is comparable with refrigerated products. Superchilling in industry can also reduce the use of freezing/thawing for production buffers and thereby reduce labour, energy costs and product weight losses.
The concept of superchilling is a new and improved cold chain process which is aiming to increase the shelf life of refrigerated products and sustain fresh-like appearance by applying partial freezing. This requires the implementation of a new temperature level (at approximately 2°C) for the storage of products in the cold chain. In order to reach sufficient process control it is recommended to implement a fast partial freezing in the first segments of the production line. Promising results have been achieved with blast or impingement freezing. Significant shelf life extensions are demonstrated in literature for certain superchilled meat and fish products. The concept can be used to substitute chilled ice transportation, which will have a direct impact on the carbon footprint in the transport sector. Superchilling has the potential to reduce a substantial impact from currently wasted meat and fish volumes; especially in high income regions with already existing cold chains, hereby contributing significantly to global food security. For industrial implementation existing or modified equipment from today's cold chain can be used but superchilling requires improved process control.
R&D has clearly identified the potential of this technology, especially for meat (chicken, lamb, pork) and fish (salmon, cod) products. However the industry has somewhat overlook this technology, despite the clear benefits, the relative simple implementation also in existing production lines and the high technological readiness level. The first industrial implementations have demonstration positive effects on shelf life, product quality, production yield, energy demand and production costs.
The aim of the SusOrganic project is to investigate the concept of superchilling for organic meat and fish products and to outline the potential of the concept for organic producers. The present study is summing up the performed experimental investigations with focus on the achievable shelf life extensions. Two different products were investigated: organic pork chop and salmon fillets. The products were supplied from local organic producers from Norway.

2.2. Materials and Method

2.2.1. Superchilling of organic salmon fillets

The experiments were performed on 1-2 Kg salmon fillets delivered by SALMAR, Frøya, Norway. The fish used in the current experiments was slaughtered and filleted pre rigor. Fillets of organic salmon with skin were used in the storage test. Direct after slaughtering and filleting the chilled fish was send on ice to the laboratory at SINTEF Energy Research/NTNU, where it arrived in the pre-rigor state after 24 hours. The salmon fillets were processed immediately after arrival and the superchilling was applied within 24 hours after the slaughtering in pre-rigor state.
The fillets were cut into pieces of 300 g and then given a test number. The sample was then divided into a piece of 100 g (nr1m) for microanalysis and the rest 200 g (nr1p) for measuring the physicals properties. All the pieces were vacuum packed before the storage. Samples for microbiological analyses were cut into pieces of 100 g vacuum packed and numbered with storage temperature and sample number. The cutting procedures were done using sterile gloves and disinfected knives. The samples for microanalysis were send vacuum-packed to independent institute for analyses and the analyse was performed within 3 hours from delivering. A number of 3 parallels was taken out for micro analysis and for physicals properties from day 0. Day 0 refers to the day when the fresh salmon fillets were placed into the cabinets.

Two different processing methods of superchilling were performed:

1. Method 1: the samples were cut into 200 g pieces, superchilled without the vacuum plastic bag, then vacuum packed with a moisture absorbing cotton piece on the skin side and stored the respective storage condition.
2. Method 2: the samples were cut into 200 g pieces, vacuum packed with a moisture absorbing cotton piece on the skin side, then superchilled and stored at the respective storage conditions.

Both methods were compared in initial trials and for the present investigation the second method was used due to sanitation reasons.
For superchilling an impingement freezer (Frigoscandia, model Laboratory) at - 37ºC was used with an retention time of 2 minutes, obtaining approx. 15 % ice content in accordance to previous research on superchilling of salmon. The ice fraction in the superchilled salmon and was measured using a calorimetric method (Haugland, Aune & Hemmingsen, 2005). The calorimetric measurements were performed in steel thermoses (Finemech Inc., Cylindrical Dewar Container, Portola Valley, USA) filled with 1.5-2.5 liters of tempered water (~ 35ºC). Approximately 0.25-0.30 kg product (salmon or pork) was weighed directly after superchilling. Then one thermocouple (Agilent Technologies Inc., Agilent 34970A, Santa Clara, USA) was placed in the fillet piece/ fillet core and one was placed near the fillet surface, before lowering the fillet into the thermos. The thermoses were tightly sealed, and the systems were left for temperature equalization under

continuous logging for approximately 24 hours. Analysis was performed on three parallels for each ice-level. Based on temperature data from the equalization process, the initial ice fraction after superchilling was calculated by means of enthalpy balances.

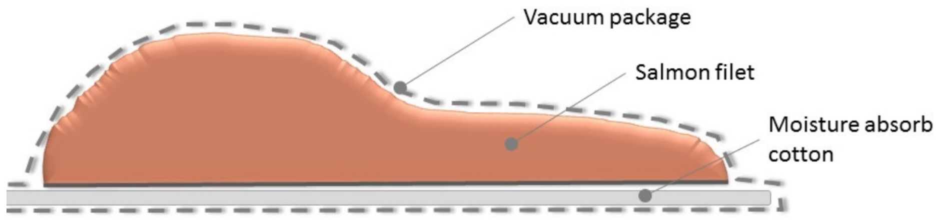

Figure 2.2.1: Packaging for salmon filets in the performed experiments.

All samples were stored in two different cabinets (Termaks KB 8182) at respectively 1.5ºC for the superchilled samples and at +3 ºC for the standard chilled salmon filets. During storage, samples stored at both temperatures were taken out at Mondays and Thursdays for microbiological analysis (total count) and physical properties (Colour, water holding capacity, drip loss and water content). 3 parallel analyses from each temperature (n=3) were perfromed. Microbiological analyses were performed by a certified extern laboratory (Analysesenteret, Trondheim/Norway).

Table 2.2.1: Experimental setup for superchilling of organic Salmon.

Setup experiments		**Samples á 200g**				**Micro**
Day	Temp.	ColourWHV	WHC	Drip loss	WC	Bacteria
0	0	X	X	X	X	X
4	- 1,5 °C	X	X	X	X	X
	+ 3 °C	X	X	X	X	X
8	- 1,5 °C	X	X	X	X	X
	+ 3 °C	X	X	X	X	X
12	- 1,5 °C	X	X	X	X	X
	+ 3 °C	X	X	X	X	X
15	- 1,5 °C	X	X	X	X	X
	+ 3 °C	X	X	X	X	X
18	- 1,5 °C	X	X	X	X	X
	+ 3 °C					
21	- 1,5 °C	X	X	X	X	X
	+ 3 °C					

2.3. Superchilling of organic pork chop

The experiments were performed on 300 – 400 g pork chops delivered by GRØSTADGRIS AS, Undrumsdal, Norway. The meat from the organic porks used in the current experiments was slaughtered and prepared at a butcher near by the farm. The meat were received at the laboratory at SINTEF Energy Research/NTNU 7 days after slaughtering with a recommended storage life for 10 days stored at +4C.

At SINTEF the pork shops were packed single in vacuum bags with an absorber sheet, then vacuumed, superchilled in the impingement freezer and then given a test number (Method 2). A number of 3 parallels were taken out for micro analysis and for physicals properties from day 0. Day 0 refers to the day when the pork shops were placed into the cabinets.

Table 2.2.2: Experimental setup for superchilling of organic Pork chop.

Setup experiments		**Samples á 200g**				**Micro**
Day	Temp.	ColourWHV	WHC	Drip loss	WC	Bacteria
0	0	X	X	X	X	X
3	- 1,5 °C	X	X	X	X	X
	+ 3 °C	X	X	X	X	X
6	- 1,5 °C	X	X	X	X	X
	+ 3 °C	X	X	X	X	X
10	- 1,5 °C	X	X	X	X	X
	+ 3 °C	X	X	X	X	X
17	- 1,5 °C	X	X	X	X	X
	+ 3 °C	X	X	X	X	X
20	- 1,5 °C	X	X	X	X	X
	+ 3 °C					
24	- 1,5 °C	X	X	X	X	X
	+ 3 °C					

Before storage, half of the samples were superchilled in an impingement freezer (Laboratory model) at 37ºC for 2,5 minutes, obtaining approx. 15 % ice content in accordance to previous research on superchilling of pork shops, as described above.

After superchilling the samples were stored in two different cabinets (Termaks KB 8182) at respectively -1.5ºC for the super chilled samples and at +3 ºC for the rest. During storage, samples stored at both temperatures were taken out Mondays and Thursdays for microbiological analysis (total count) and physical properties (Colour, WHC, drip loss), 3 parallel analyses from each temperature (n=3). Microbiological analyses were performed by a certified extern laboratory (Analysesenteret, Trondheim).

2.4. Microbiological analyses

The microbiological growth during storage was measured by method NMKL96 for CFU (colony forming unit). Dilutions of the raw material sample was moulded in iron-agar plates and incubated at 20ºC for 72 hours. The number of colony forming units is counted on plates holding between 25 and 250 colonies. (n=3 for each sample)

2.5. Physicals properties

2.5.1. Initial water content

The initial water content was determined by drying approximately 10 g of minced product in a convection oven to constant weight at 105ºC for 24 hours. The difference in weight, before and after drying was taken as the total water content of the sample. Mean values were calculated from six replicates.

2.5.2. Water-holding capacity

To measure the water holding capacitive, the amount of fish from 3 parallels were mashed together in a food processor and then split into 3 samples with 1 g of product on the filter paper. Then 1 kg container was pressed at the product for 10 minutes.
Then the wet filter papers were weight before and after the pressing procedure, and then the amount of water was calculated.

2.5.3. Colour

The surface of the product was removed before a sample was taken out for colour analyses. The colour (L, a*, b*) was measured using a Hunter Lab. The colour of the samples were defined by measuring rate of lightness (L), redness (a*) and yellowness (b*). Samples were scanned and determined by average of 3 replicates. The instrument was calibrated before each test-run. The overall colour changes was expressed by the delta-E relation according to the following equation:

2.5.4. Drip loss analyses

During packing of the samples, the weight of the fish, vacuum bag and absorber was weighed. When the samples were opened for testing, the new weight of the fish, bag and absorber were noted again. Then the drip loss was calculated based on the weight difference.

2.6. Results for superchilling of salmon filets

The storage temperature has a major influence on the shelf life of the fresh salmon filets, and to study this, microbiological growth, drip loss, colour change and water holding capacity (WHC) were evaluated during storage at different temperatures. The trials with normal chilled organic salmon ended always earlier because of common spoilage during the storage period.

2.6.1. Microbiological analysis

Results from the microbiological analysis (CFU) during storage are presented in Figure 2.2.2. The quality limit of 107 CFU/g represents a usual microbiological quality measure, above which food is regarded as unfit for human consumption.

The results in Figure 2.2 show an expected increase in microbiological counts development for both storage conditions. As expected, the CFU levels for salmon samples stored superchilled are considerably lower compared with high chilling temperatures. The CFU level for the samples stored at +3°C exceeded the quality level already day 14. This is the commonly accepted shelf life for Salmon filets chilled in normal refrigeration conditions.

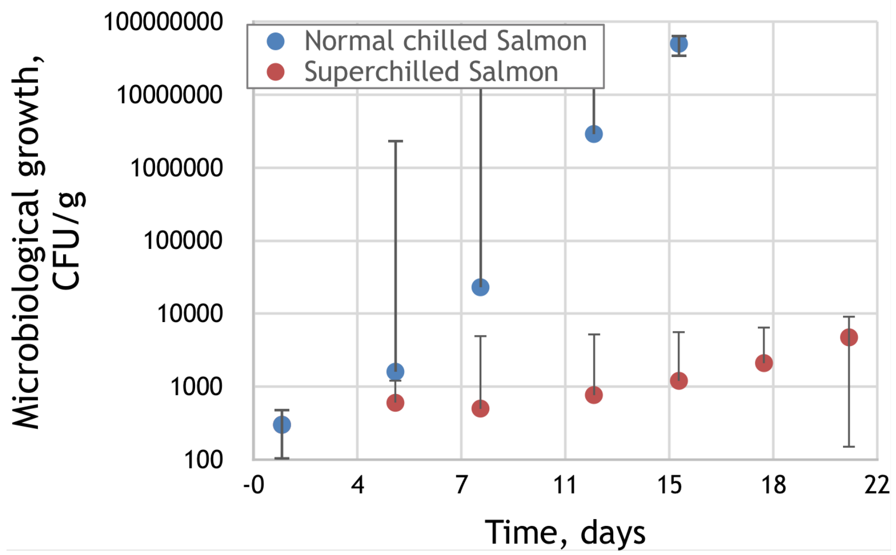

Figure 2.2.2: Number of colony forming units (CFU) in salmon fillets during storage of fresh, chilled and superchilled salmon filets processed after Method 1, with ice level of 15% (red) stored at -1.5ºC, and chilled reference samples stored at +3ºC (blue)

2.7. Physical properties

2.7.1. Inital water content

Inital water content for organic salmon was calculated to 69.5 % on wet basis (n=6). The average of initial water content for organic salmon was calculated to 69.5 %.

2.7.2. Drip loss

Results from the drip loss during storage are presented in Figure 2.3. The curves shows the weight reduces in % from day zero (100 %). The values are the average from 3 parallels, from each temperature. The drip loss trends are almost equal from both storage temperatures. Superchilled salmon showed a slightly increase drip loss in the beginning of the storage period, however towards the end the differences in drip loss are equalized.

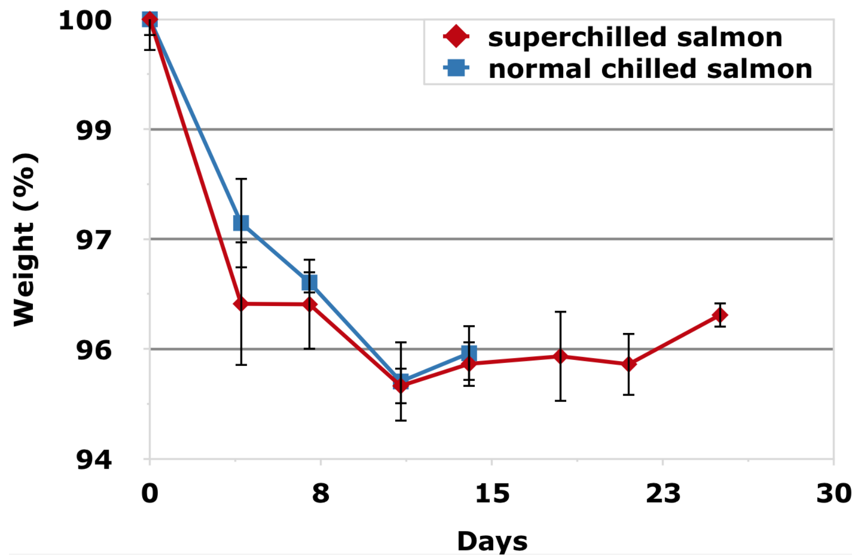

Figure 2.2.3: Percentile drip loss in super-chilled organic salmon fillets with ice level of 15% (red) stored at -1.5ºC, and chilled reference samples stored at +3ºC (blue).

2.7.3. Water holding capacity

Results from the WHC (water holding capacity) during storage are presented in Figure 2.4. Then the wet filter papers were weight and the amount of water calculated. The curves shows the weight reduces in % from the start weight. It can be seen that the water holding capacity of normal chilled salmon is lower compared to superchilled salmon.

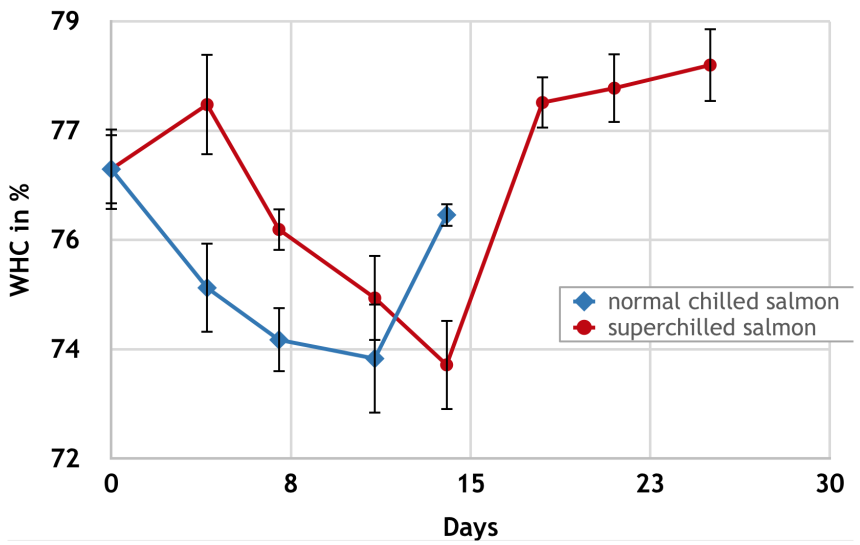

Figure 2.4: Percentile water holding capacity of superchilled organic salmon fillets with ice level of 15% (red) stored at -1.5ºC and chilled reference samples stored at +3ºC (blue).

2.7.4. Colour of organic salmon

Results from the colour measurements during storage are presented in Figure 2.5 and 2.6. The curves are the average of 3 parallel samples. The surface of the fish fillet was taken away and then a new slice from sample was used into the colour instrument (Hunter Lab). The values are from the L-scale (light vs. dark) , the a-scale (red vs. green) and the b-scale (yellow vs. blue). From these values the delta E was calculated using Equation 1. The differences are highest in the beginning of the storage period but are getting closer each other during the storage time.
The colour difference between normal chilled and superchilled organic salmon was only minor and showed overall no clear trend.

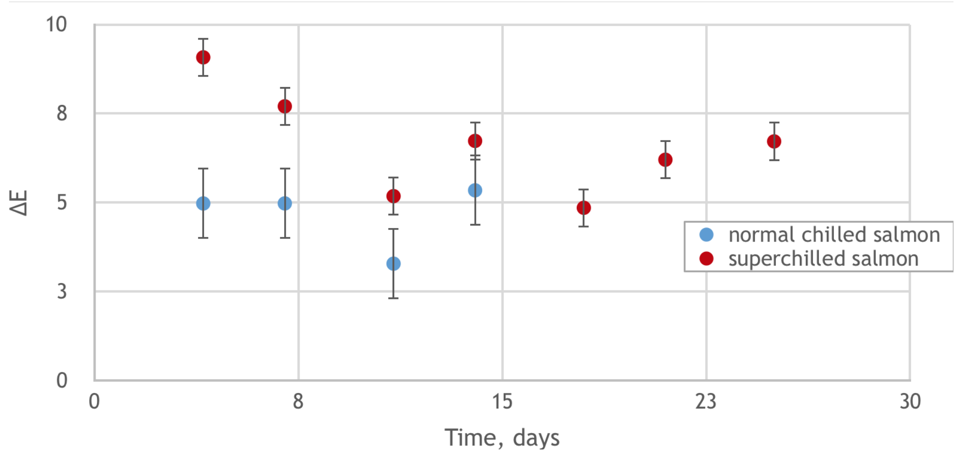

*Figure 2.2.5: Colour changes L*a*b (expressed as delta E) for normal chilled and super-chilled salmon fillets with ice level of 15% (red) stored at -1.5ºC, and chilled reference samples stored at +3ºC (blue).*

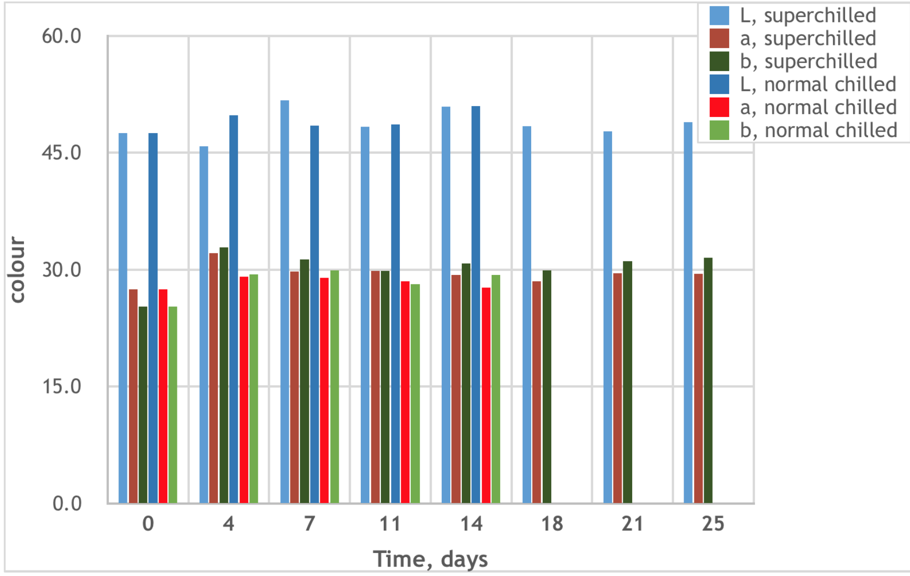

*Figure 2.2.6: Colour changes in Hunter coordinates L*a*b for normal chilled and superchilled organic salmon fillets with ice level of 15% (red) stored at -1.5ºC, and chilled reference samples stored at +3ºC (blue)*

2.8. Results for normal chilled and superchilled pork chop

2.8.1. Microbiological analysis

Results from the microbiological analysis (CFU) during storage are presented in Figure 2.2.7. The quality limit of 107 CFU/g represents a usual microbiological quality measure, above which food is regarded as unfit for human consumption. The normal refrigerated pork chop exceeded the bacterial count after approximately 8-9 days. This was shorter than expected, since the commonly accepted shelf life of pork is 14 days. The supplier however specified that he needs to send the pigs to a slaughterhouse and that the deboned animals then is delivered back to the him after around 3 days in chilled conditions. This is because the SME owns no infrastructure (and licence) for slaughtering. First after 3 days the meat is then processed/chopped further and send to the customer. This means that the product is already 7 days old when reaching the market and the time for selling the product is reduced accordingly. This time period should be added to the graphs (Figure 10.7-10.11). This explains the documented shorter shelf life. However, Figure 2.7 shows that the shelf life of superchilled pork was extended by around 14 days, despite the fact the product is already 7 days old.

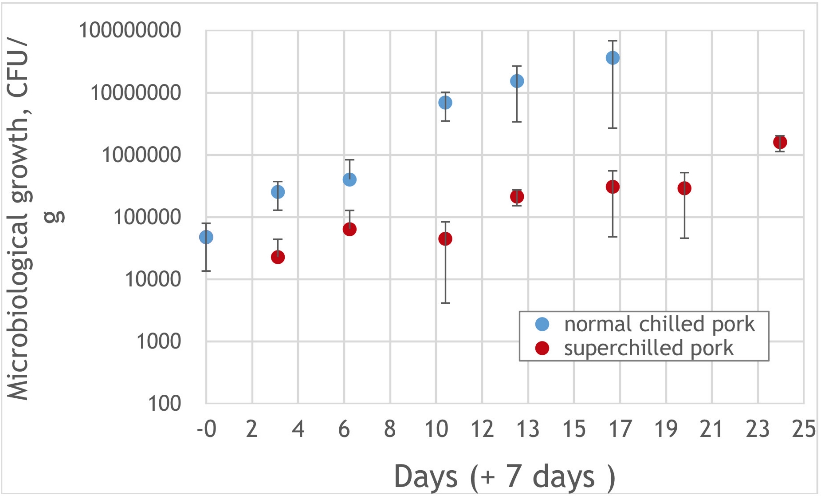

Figure 2.2.7: Number of colony forming units in pork with ice level of x (red) and chilled reference sample at +3ºC during storage

2.9. Physical properties

2.9.1. Water content

Initial water content for organic pork was calculated on wet basis (n=3). The average of initial water content for organic salmon was calculated to 63.4 %

2.9.2. Drip loss

Results from the drip loss during storage are presented in Figure 2.8. The curves shows the weight reduces in percent from day zero (100 %). The values are the average from 3 parallels, from each temperature. The drip loss trends are almost equal from both storage temperatures. Superchilled pork chop showed however a higher drip loss than normal chilled pork. This can be explained by the freeze damages to the product during the partial freezing.

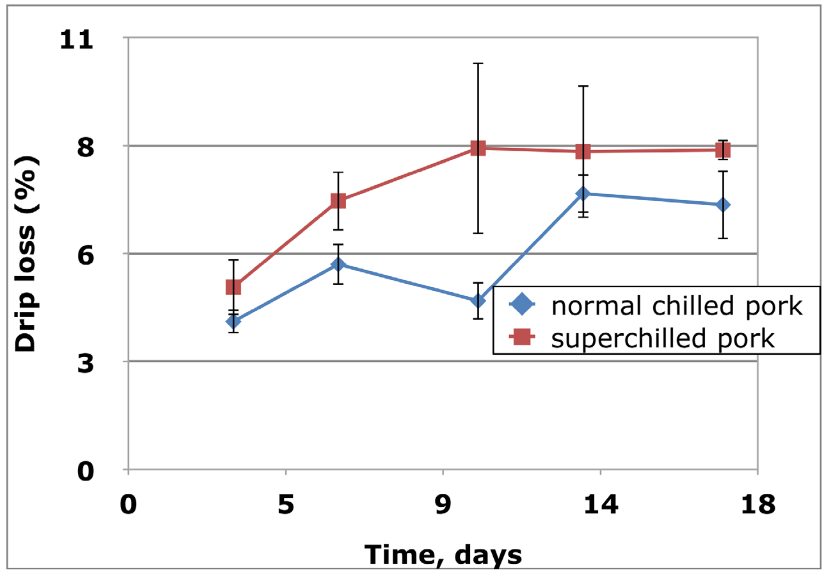

Figure 2.2.8: Drip loss for organic and normal pork chop during 17 days of storage at +3ºC for normal, chilled sample and at -1,7ºC for organic super-chilled samples

2.9.3. Water holding capacity

Results from the WHC (water holding capacity) during storage are presented in Figure 2.9. The curves shows the weight reduces in % from the start weight. It can see from the curves that the result from product storage at + 3°C is a slightly reduced WHC than the product from storage at -1.5°C. This trend corresponds to the documented lower drip loss of normal chilled pork.

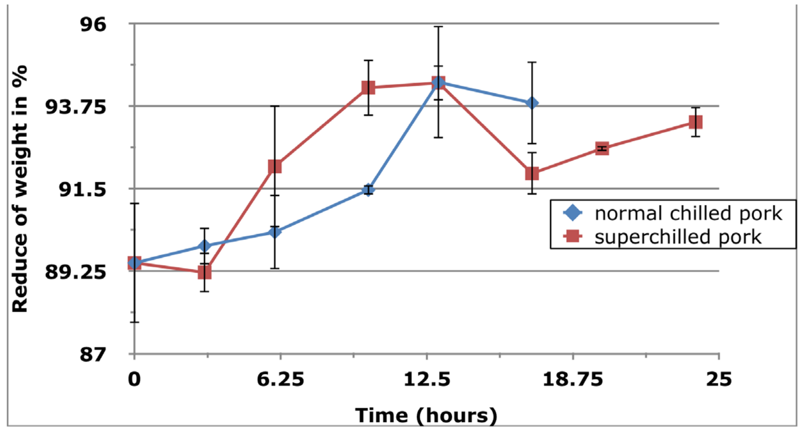

Figure 2.2.9: Percentile water holding capacity of superchilled organic pork chops with ice level of x% (red) stored at -1.5ºC and chilled reference samples stored at +3ºC(blue)

2.9.4. Colour

Results from the colour measurements during storage are presented in Figure 2.10 and 2.11. The curves are the average of 3 parallel samples. The values are from the L-scale (light vs. dark), the a-scale (red vs. green) and the b-scale (yellow vs. blue). From these values the delta E was calculated using Equation 1.
The differences are highest in the beginning of the storage period but are getting closer each other during the storage time.
The documented colour changes for organic pork chop were only minor and it was not possible to document a clear trend. The colour differences can probably be better explained by external factors e.g. like stress level at slaughtering and not by the superchilling application

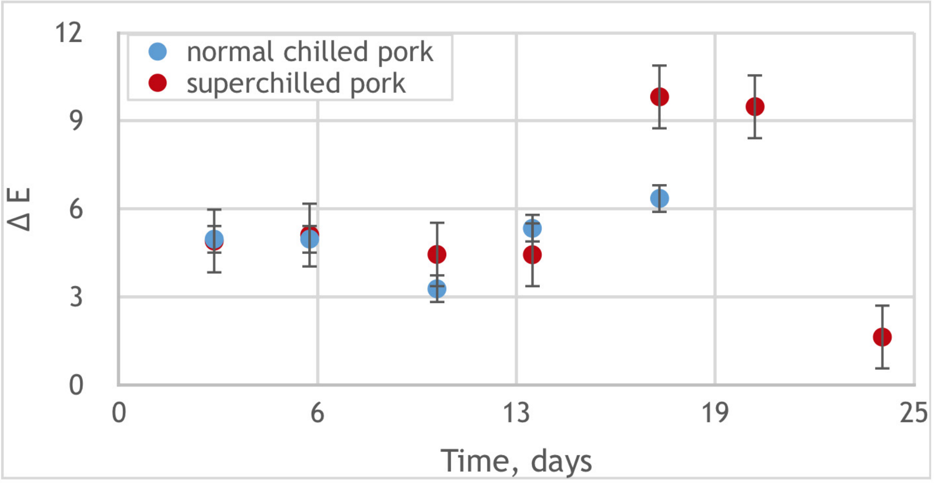

*Figure 2.2.10: Colour changes L*a*b (expressed as delta E) for normal chilled and super-chilled pork.*

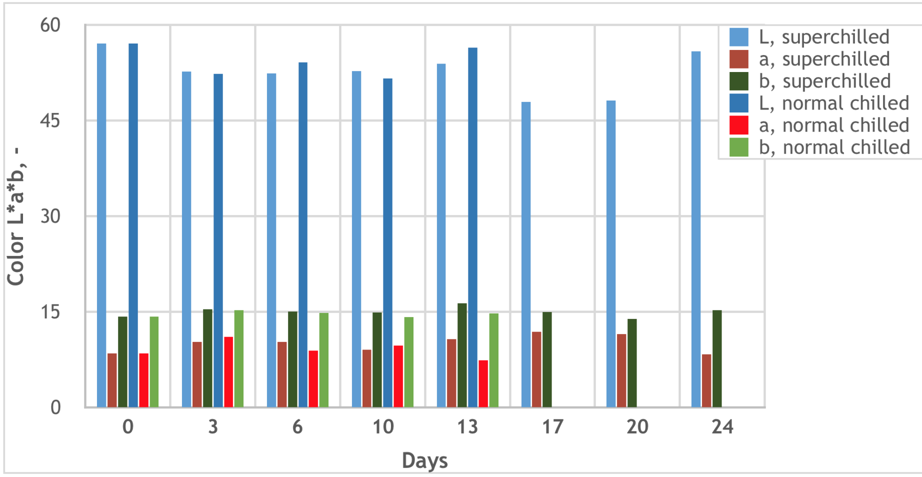

*Figure 2.2.11: Colour changes in Hunter coordinates L*a*b for normal chilled and superchilled pork chop*

2.10. Conclusions

Organic products have in general the same shelf life than non-organic products and are also stored in the same conditions of the cold chain. The superchilling concept was applied for a organic salmon product and a organic pork product which are commonly available at the Norwegian and European market. For both products it was possible to extend the shelf life by 14 days, relative to the shelf life of the product in normal cold chain. Similar shelf life extensions are documented of common fish and meat products and it seems safe to conclude that the results are transferable to organic products. In other words the shelf life of the product will depend mainly on sanitation, processing and cold chain conditions then on the organic origin of the product.
It must be outlined that the documented shelf life extension will depend on the processing conditions and sanitation of individual production sites. Individual tests must be performed on-site in order to document the absolute shelf life of a certain superchilled production line. However, the potential of the superchilled is clearly that the shelf life of the product can be increased by 14 days and is therefore double. The technology can therefore be of special interest for SME in order to increase market availability of their organic products.
It was also possible to extend the shelf life of a product which was already 7 days old. This aspect of superchilling was so far not investigated by other reserachers. This approach could be of interest extending the market exposure for organic products when it is not possible to sell it within the first days after slaughtering.

Table 2.2.3: Documented shelf life for organic salmon and organic pork products.

Product	Shelf life normal chilled (+3°C)	Shelf life superchilled (-1.5°C, 15% ice)
Salmon	14 days	28 days (+14 days)
Pok	14 days	28 days (+14 days)

The quality of food products is difficult to define and different producers will define individual quality parameters. In the present investigation the colour of the product was evaluated as a quality parameter. There was no large or significant difference between the colour of normal chilled and superchilled salmon and pork.
Another investigated quality aspect was the drip loss and water holding capacity, which give an indication of the textural changes. Drip loss and water holding capacity are related aspects and should be evaluated together. Superchilled organic products show an increased drip loss and a reduced water holding capacity. The reason for this is the freeze damage to the product during the partial freezing into superchilling conditions. The effect is documented in literature for frozen products in general is not related to the organic origin.
The performed investigations demonstrated the potential of the superchilling concept for organic products. The needed technology is available at the market and can be implemented in organic production.

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II. II FREEZING

3. Effect of freezing and freezing rate on quality of organic apples

University of Teramo, Faculty of Bioscience and Agro-Food and Environmental Technology
Pittia, P.

3.1. Introduction

Increasing is the attention given by consumers to the nutritional and health value of foods. Main interest is given to fruits as rich source of essential micronutrients (e.g. vitamin C and folic acid) and other bioactive compounds, including phenolic compounds for which some studies have evidenced chemoprotective roles in human health, as demonstrated in epidemiological studies (Van Duyn and Pivonka, 2000).
Senescence, ripening as well as microbial contamination and growth quickly impair the nutritional value of fresh fruit and various preservation actions are now available to maintain quality and safety of the fresh products. Among various techniques, freezing is recognized as one of the main processes employed for the long-term preservation and storage of fruit products (Silva et al. 2009). Freezing temperatures cause the phase transition of the free and freezable water in to ice crystals, thereby it become immobilised, and chemical, biochemical changes are significantly slowed down, and microbial growth is limited, thereby the nutritional and health value could be preserved.
Raw fruits and vegetables present large quantities of water in proportion to their weight (85-90 %) and, thus, the water phase change due to freezing makes these products more susceptible to ice crystal formation and thawing than other types of food. The quality of cellular foods after frozen-thawed is highly correlated with the integrity and viability of tissue cells. The formation of ice crystals, water migration and the inherent characteristics of cell structure are regarded as the main factors affecting the cell structure during freezing (Li et al., 2018). Actually due to their cellular structural characteristics, fruits are less resistant to the freezing process than vegetables.
Freezing due to ice formation, volume expansion during freezing and recrystallization, could thus impair cell walls integrity, damage the vegetable structure and determine the lack of product integrity and upon thawing, excessive drainage or loss of shape could occur. Overall this may affect on one side the texture and sensory properties, and, on the other side, the nutritional and health properties of frozen-thawed fruits and vegetables as in part of their micro-nutrients may be lost in the released water and enzymatic reactions may be favoured due to the damage of the vegetable structure that make easier the activity.
To improve quality of frozen products by inactivating or inhibiting enzymes that may affect quality of the product during freezing, frozen storage and after thawing, pre-treatments of fresh fruits and vegetables are recommended and the most used are blanching (for vegetables) and dipping in solutions containing acids and/or sugars as protecting agents to decrease the pH and/or to reduce the freezable water.
Organic products, compared to integrated or conventional ones are recognized for the absence and/or low presence of phytochemicals and environmental contaminants. Freezing could be an interesting preservative technology applicable more extensively also in the organic food production and currently only scarce are the products available in the market. Several may be the reasons that have limited the application of this technology to organic raw products including the limited information about their suitability to be processed.
However, the effect of organic procedures on other quality attributes of the organic products including the nutritional quality in terms of macronutrients, vitamins, and minerals, as well as the physical, functional and sensory properties are still under debate (Roussos and Gasparatos, 2009; Stracke et al., 2010; Brandt et al., 2011; Lima and Vianello, 2011).
In the Susorganic project a study has been thus developed aimed to evaluate:

- Effect of pre-treatments and in particular dipping and vacuum-impregnation by using solutions made of lemon juice. Vacuum impregnation is a new technology that due to a quick pressure reduction could accelerate the penetration of solutes and compounds of interest.
- Effect of different freezing rates

3.2. Experimental design

3.2.1. Experiment 1: Effect of pre-treatments dipping and vacuum impregnation used as to improve stability over storage time

The technological functionality of organic apples to freezing and frozen storage and the effect of dipping and vacuum impregnation pre-treatments on the apples (cv. Golden delicious) was investigated by evaluating the changes of the main compositional quality properties and physical (colour, texture) were evaluated. Organic (ORG) and conventional (CONV) apples cv. Golden Delicious of "extra" category with same origin (Trentino-Alto-Adige, Italy) were purchased in a local market.
Both the ORG and CONV apples were subjected to the two different pre-treatments, i.e. dipping and vacuum impregnation (738 mbar, 10 s) in water (control) or organic lemon juice solution 0.5% v/v (20 °C).
After pre-treatments, apple cubes were drained and packed in single layer in BOPP bags (film thickness: 30 mm) and frozen in a blast freezer (Forma, Thermo Scientific, Milan, Italy) set at - 40 °C to reproduce high freezing rate conditions. Analyses were performed after 15 and 30 and 300 days of frozen storage. Before analysis, frozen samples where thawed in monolayer at 4 °C for 15 hours.
The following analytical and instrumental analysis were carried out: moisture, pH, °Bx, texture,

starch index, colour, organic acids, enzymatic activity (polyphenoloxidase, PPO), total phenolic content (Neri et al., 2018, submitted).

3.2.2. Experiment 2: Effect of freezing rate

In the SusOrganic project the effect of freezing and variety of organic apples on the main quality attributes was investigated. In particular, ORG apples of two different varieties (Golden Delicious and Royal Gala) were subjected the freezing at two different temperatures (-18°C and -40°C) and their main quality attributes (water loss, moisture, texture, colour) as well as the retention of phenolic compounds was evaluated. The effect of dipping with a solution of lemon juice (Neri et al., submitted) was tested. Two different apple varieties were taken into account (Golden delicious and Royal Gala cv.) For comparison purposes, the study was carried out also on apples of the same variety but produced by conventional agricultural practices.

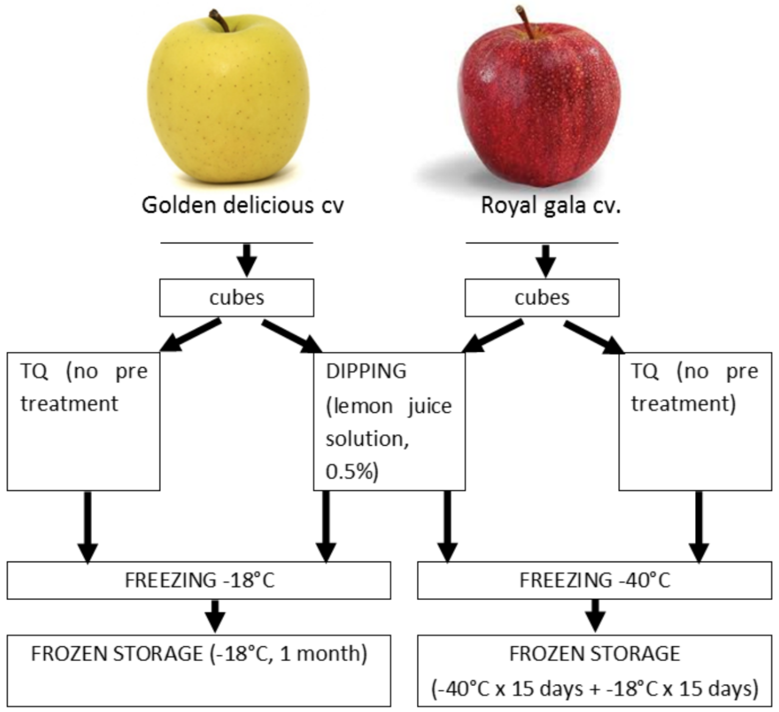

Table 3.3.1: Chemical and physical characteristics of organic and conventional Golden Delicious apple fruits.

Conventional (CONV) and organic (ORG) apples of two cultivar (cv. Golden delicious and Royal gala) were bought in a local supermarket at the same time (December 2017). For these samples it was not possible to have additional information about the area of cultivation and time of picking up that could, thus, be different also for the same cultivar between CONV and ORG.
Both the ORG and CONV apples were peeled and cut in cubes (1 cm-side) and a half of the sample was subjected to dipping in organic lemon juice solution 0.5% v/v (20 °C) and the remaining part was left without pre-treatments.
Apples ORG and CONV, dipped or not were packed in plastic bags and then frozen in blast freezers (Forma, Thermo Scientific, Milan, Italy) set at – 18° and - 40 °C to reproduce low and high freezing rate conditions. Apples frozen at -18°C were stored at the same temperature for30 days while those frozen at -40°C were stored initially for 15 days at the same temperature and then at -18°C for the remaining 15 days (in total: 30 days of storage).
The following analytical and instrumental analysis were carried out on the fresh apple cubes and after dipping and freezing (30 days): moisture, pH, °Bx, texture, colour, total phenolic content with methods as reported in Neri et al., 2018 (submitted).

3.3. Results (Experiment 1):

3.3.1. Fresh fruits characterization: ORG vs. CONV

In Table 11.1, the results of the chemical and physical analyses carried out on the Golden Delicious apples obtained by organic and conventional agriculture were reported. Organic and conventional fresh apples showed similar values of pH, soluble solids, ripeness index and starch index, that overall indicate an equal maturity grade. Moreover, these results are in agreement with those reported in literature, at equal apple cultivar, by Salvatori et al. (1998) e Mùjica Paz et al. (2003) for conventional apples.
By comparing the sugars content of the organic and conventional apples, highest amounts ($p<0.01$) were detected in the conventionally grown apples. On the other side, organic apples showed higher and lower content of tartaric acid and ascorbic acid than conventional apples, respectively. No differences between the ORG and CONV apples in the polyphenoloxidase activity while a higher total polyphenol content was found in ORG than in CONV ones in agreement with data on Golden Delicious apples of other authors (Weibel et al., 2000; and Stracke et al., 2010).
As concerns colour and mechanical properties, no differences between the ORG and CONV apples have been evidenced. A greater firmness in organic apples compared to conventional ones was reported for 'Golden Delicious' apples by Reganold et al. (2001), and Reig et al. (2007).

3.3.2. Effect of pre-treatment on fresh fruits

The dipping and vacuum impregnation (VI) pre-treatment affected the composition of apple cubes determining a significant ($p<0.05$) water gain and soluble solids loss. During dipping, mass transfers are due to osmotic and diffusion phenomena induced by the differences in soluble solids between the apples and the impregnating solution (13.25 vs. 6.25 ° Brix). On the contrary, during the VI treatment, these phenomena are combined with hydrodynamic mechanisms (HDM) and deformation-relaxation phenomena (DRP) induced by the negative pressure applied, and this explain the highest water uptake evidenced in both the vacuum impregnated samples in comparison to the dipped ones.
As regards the soluble solids variation, no significant differences ($p<0.05$) have been evidenced between the samples impregnated with diluted lemon juice. In the VI- pre-treated sample,

the addition of solutes to the fruit tissue could have counteracted the soluble solid loss which in this case is ascribable to the loss of the native, inner aqueous phase that flows out from the pores of the apple tissue as a function of the internal gas expansion and flow out.
By comparing, at equal pre-treatment conditions, the mass transfer data of the ORG and CONV samples, a lowest variation in both the soluble solid and water content was observed in all the latter ones and these results are explained by the lowest porosity of the conventional fresh apple that limited the exchanges.
By comparing results related to the enrichment in citric acid of the apple cubes due to impregnation with diluted lemon juice, it can be observed that the both ORG and CONV processed samples showed a content of this acid significantly ($p<0.001$) higher than the control, no-pre-treated fruits and, in particular, the highest values were found in the organic fruits due to their highest porosity.

Property/parameter	Organic (ORG)	Conventional (CONV)	Significance
Soluble solids (°Brix)	13.2 ± 0.3	13.5 ± 0.3	ns
Titrable acidity (Kg malic acid/ 100 Kg of sample)	0.33 ± 0.01	0.31 ± 0.01	ns
Ripeness index (soluble solids/fruit acidity)	40.8	43.3	ns
moisture content (%)	85.6 ± 0.3	86.2 ± 0.4	ns
starch index	9	9	ns
Solid/liquid density (Kg /m^3)	10.2	10.3	*
Fruit density (Kg /m^3)	0.804	0.810	*
Fruit porosity (ε %)	25.3	24.5	*
Water activity (a_w)	0.994 ± 0.002	0.991 ± 0.001	ns
pH	3.73 ± 0.02	3.77 ± 0.02	ns
Lightness (L*)	76.6 ± 1.9	76.3 ± 1.9	ns
Hue angle (h°)	91.5 ± 2.0	91.4 ± 2.1	ns
Maximum force (N)	243 ± 13	249 ± 20	ns
Total Polyphenols (mg GAE g^{-1} dm)	5.61 ± 0.52	4.31 ± 0.22	*
Polyphenoloxidase (U g^{-1} dm)	10.6 ± 1.1	10.7 ± 0.3	ns

*nsNon-significant. *, at the 0.05 probability level.*

3.3.3. Effect of pre-treatment on colour of fruit

After dipping, the samples evidenced a positive variation ($p< 0.5$) of both the L* (lightness) and h° (hue angle, index of the chromaticity) parameters in respect to the unprocessed apples.

According to what observed in other studies (Neri et al., 2016; Fito and Chiralt, 2000), the VI treatments induced a reduction of the L* parameter ascribable to the decrease of the vegetable matrix reflectivity as effect of the air-water replacement that takes place during the VI treatment. The VI treatment did not determine any change of the h° values when water was used as impregnation agent and this in agreement with other studies (Neri et al., 2016; Perez-Cabrera et al., 2011). However, when the lemon juice solution was used, an increase of the h° parameter was observed likely due to the contribution of some chromatic compounds of the lemon juice to the apple and or chromatic changes due to the pH change due to the acids enrichment of the apple matrix.

3.3.4. Effect of pre-treatment on firmness of apple fruit

In Figure 3.2, the effect of dipping and vacuum impregnation on the firmness of the apples cubes is reported. After VI treatment with dilute lemon juice, the ORG samples showed firmness values comparable than fresh fruit whilst highest values were measured on the water impregnated sample (VI_C). This result could be ascribed to the air water replacement that the VI_C treatment triggered to a larger extent as compared to those simply dipped. On the contrary, the firmness of the CONV apples, irrespective of the pre-treatment applied, was negatively influenced by pre-treatments. Since, ORG and CONV fresh fruits had same initial firmness values, the different effects impaired by processing could be explained by the different fruits porosity and/or due to differences in the cell wall composition. These phenomena could be responsible for the highest firmness evidenced on the ORG samples after treatment; these samples are in fact notably more subjected to environmental stresses in comparison to those grown by conventional methods (Asami et al 2003).

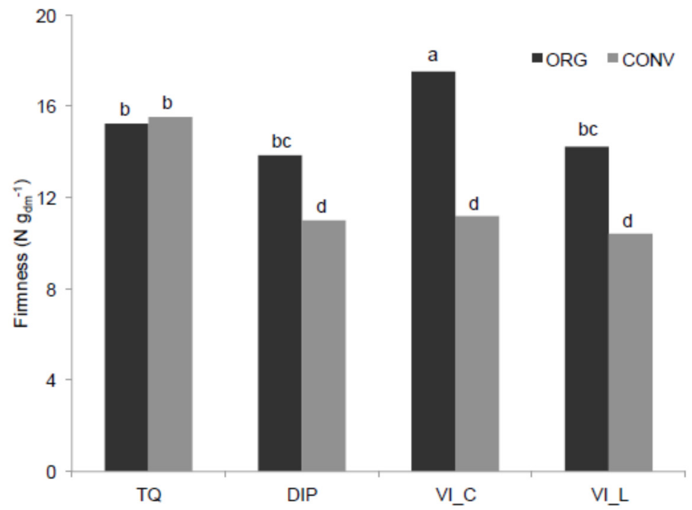

Figure 3.3.2: Firmness of organic (ORG) and conventional (CONV) apples. TQ: unprocessed; DIP; dipped in diluted lemon juice; VI_C: vacuum impregnated in water; VI_L: vacuum impregnated in diluted lemon juice. Different letters stand for statistically significant differences at $p < 0.05$

3.3.5. Effect of pre-treatment on bioactive compounds

The ORG apples showed a tendency of higher phytochemical concentrations compared to the conventionally produced apples. Moreover, before freezing, a higher content of total phenolic compounds was found in both ORG and CONV VI-pre-treated was found but only for ORG apples this differences was statistically significant ($p < 0.05$). These results can be due to the greater presence in this sample of polyphenols and other bioactive compounds deriving from lemon juice, penetrated in the vegetable matrix during the impregnation pre-treatment. This product formed as a result of enzymatic and oxidative reactions that lead to the formation of brown compounds with high chain breaking activity.
This hypothesis was confirmed by higher values of the in-vitro-antioxidant activity of vacuum impregnated with lemon juice samples of both type of apples.

3.3.6. Effect of freezing and frozen storage on colour

Overall, colour of frozen apples after thawing was negatively affected by freezing and frozen storage time due to the occurrence of browning reaction. Moreover, L* and h° data of frozen apples, was significantly affected ($p < 0.001$ level) by the cultivation method, pre-treatment and time of storage. The pre-treatments made with lemon juice addition positively affected the colour of the frozen-thawed apples obtained by the effect on both pH decrease and the antioxidant activity of ascorbic and citric acids upon enzymatic activity.

3.3.7. Effect of freezing and frozen storage on firmness

Both the ORG and CONV samples upon thawing evidenced a drastic loss of firmness within the first month of frozen storage whilst only limited additional softening were observed up to 10 months of frozen storage. This result is in agreement with other studies on other vegetables (Neri et al., 2014) and it is an index of the achievement of an equilibrium state in the frozen matrix that does not affect any further the cell domanis and structures. The negative effect impaired by freezing and frozen storage on the mechanical properties of the apples tissue is mainly caused by the mechanical damage induced by ice formation, crystal growth and the related potential stresses that impair the cell wall membranes as well as the pectin mediated cellular connexions (Neri et al., 2014). By comparing the results obtained on the ORG and CONV apples, it could be noticed that the former showed a firmness retention higher than ($p<0.05$) the latter ones. Statistical analysis evidenced a positive effect of vacuum impregnation pre-treatments on the mechanical properties of the ORG frozen apples whilst no effect was noted on the CONV samples.

3.3.8. Effect of freezing and frozen storage on bioactive compounds

After 300 days of frozen storage (10 months) the results showed a decrease of total polyphenols content and antioxidant activity of both types of apples and for all pre-treatments.
At equal pre-treatment, and frozen time, the ORG apples, that started from a higher polyphenol content, showed a similar loss of these bioactives than CONV and, after 10 months, thus, an overall higher $p < 0.05$) content was found in the corresponding samples.

3.4. Results (Experiment 2):

3.4.1. Fresh fruits characterization: ORG vs. CONV

In Table 3.2, the results of the chemical and physical analyses carried out on the two different type of apples (GD and GR), both CONV and ORG are reported.
Within each cultivar it is possible to observe a significant difference between the CONV and ORG apple properties and in particular in the case of firmness. In RG apples a significant difference could be also observed in the case of the soluble solids content (°Bx). For GD apples, the batches used for this study results significantly different in respect to that used in the previous set of experiments as evidenced by a significant lower content of polyphenols, and, in the case of the ORG ones, also in firmness.
While differences between GD and RG, naturally characterised by different compositional, physical and sensory properties, was expected, the differences noticed between CONV and ORG in the same cultivar indicates that the apples were likely produced and collected from the fields in different time and thus they don't have the same storage time and/or they were stored under different environmental conditions. During storage different metabolic paths connected with ripening modify the structural and quality properties of the apples and their rates are effected by various factors like temperature, relative humidity and atmosphere composition. Moreover, it is known that RG is an apple that during ripening tends to mealiness, losing its characteristic crispness (Piazza and Giovenzana 2015; Saei et al., 2011).

	Golden delicious cv.		Royal Gala cv.	
Property/parameter	Organic (ORG)	Conventional (CONV)	Organic (ORG)	Conventional (CONV)
Soluble solids (°Brix)	13.0 ± 0.2	13.1 ± 0.1	11.3 ± 0.1	13.0 ± 0.2
Moisture content (%)	87.4 ± 0.1	86.4 ± 0.1	89.5 ± 0.1	87.9 ± 0.1
pH	3.79 ± 0.03	3.41 ± 0.01	3.67 ± 0.03	3.89 ± 0.04
Lightness (L*)	54.02 ± 1.1	55.1 ± 1.9	53.9 ± 1.3	52.9 ± 3.1
Hue angle (h°)	85.9 ± 1.6	87.9 ± 1.8	88.6 ± 2.3	85.2 ± 1.2
Maximum force (N)	159.7 ± 13.6	284.2 ± 9.6	368.4 ± 18.6	151.1 ± 9.9

Total Polyphenols (mg GAE g^{-1} dm)	3.34 ± 0.01	1.57 ± 0.29	2.03 ± 0.06	9. ± 0.05

3.4.2. Effect of freezing rate on quality of apples CONV and ORG

Results were significantly affected by the initial characteristics of the fresh fruits and the effect of the different freezing rate obtained by freezing at -18°C and -40°C was difficult to be highlighted.
Overall apples frozen at -40°C showed a slightly lower water release upon thawing with no trends due to farming type and cultivar. As regards firmness a different result was obtained depending on the apple cultivar (Figure 3.3). In the case of the Golden delicious, samples stored at -40°C evidenced a slightly higher softening effect than those processed at -18°C, while an opposite result was observed in the case of the Royal gala with limited differences between the ORG and CONV products. Quick freezing, while applied to favour nucleation with small crystals and reduce the rate of ice crystals growth may, in some cases, has been shown to impair the structural properties by causing cracking and the corresponding textural properties.
As regards the polyphenol content after 30 days of storage of the differently processed apples, the retention (%, computed in respect to the value of the corresponding fresh product) is reported in Figure 3.4. In this case, a positive effect of the quick freezing was observed but the entity was different entity depending on apple variety and type of cultivation (CONV vs. ORG). In the case of the GD, the effect was of the same entity between CONV and ORG while for Rg the positive and, in this case, significant ($p<0.05$) effect was evidenced only in the case of the CONV product.
Differences in the ripening degree and structural properties of the two apple varieties, independently on their type of cultivation, may affect to a different extent the effect of the freezing rate and retention and protection during storage of these secondary metabolites.

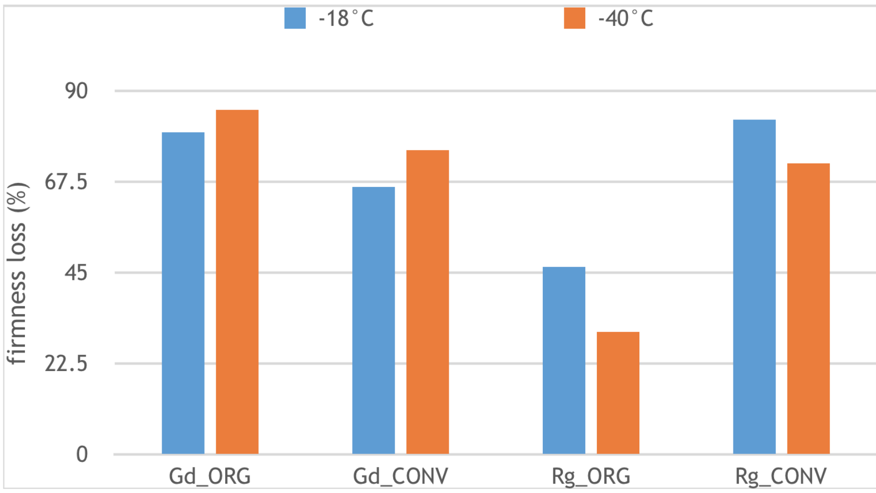

Figure 3.3.3: Loss of firmness (% in respect to the value of the corresponding fresh product) of Golden delicious (Gd) and Royal gala (Rg) apple cubes, organic (ORG) and conventional (CONV) apples not dipped after freezing at -18°C and -40°C and stored for 30 days at -18°C or -40°C

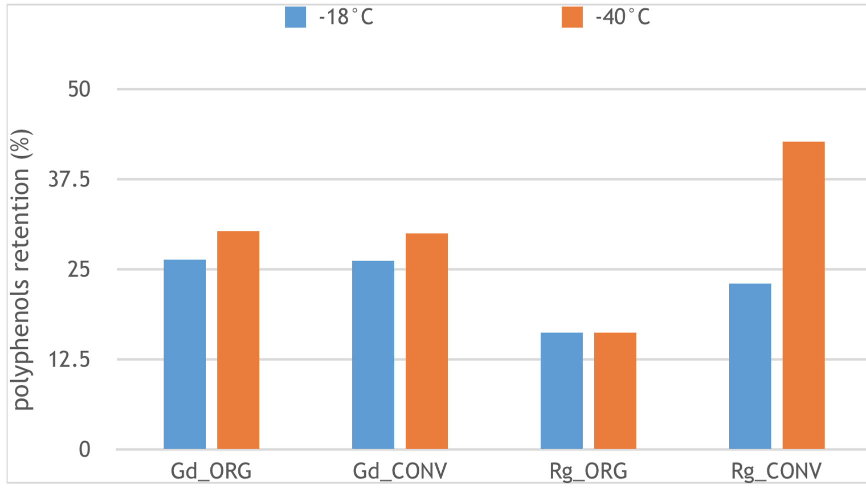

Figure 3.3.4: Retention of polyphenols (% in respect to the value of the corresponding fresh product) of Golden delicious (Gd) and Royal gala (Rg) apple cubes, organic (ORG) and conventional (CONV) apples not dipped after freezing at -18°C and -40°C and stored for 30 days at -18°C or -40°C.

The effect of dipping in the lemon juice solution combined with the different freezing rate was evidenced mostly on the colour of the differently frozen and stored apple cubes by slightly limiting the browning (L* and hue angle). No other significant effects were observed in other quality parameters (polyphenols content, firmness).

3.5. Conclusions

3.5.1. Experiment 1

This study was carried out on apples obtained by organic and conventional farming procedures of the same cultivar and with equal ripeness index. Overall initially they showed only limited differences in the organic acids and sugar content which could be correlated with a different rate of the metabolic paths during ripening. The total polyphenols content of ORG was higher in organic apples due to plant response to biotic and abiotic stresses while no differences in physical properties of fruits were observed apart from porosity which was higher in ORG apples.
Processing similarly affected both organic and conventional apples but, after processing, organic apples showed a higher polyphenols content and mechanical strength than conventional apples.
On the other side, conventional apples showed lower variations of the colour due to processing but the differences of the hue values of CONV and ORG were limited and no differences in lightness were observed.
Overall this part of the study allows to confirm the technological suitability of the ORG apples

to be subjected to freezing and freezing can preserve the content and quality properties of the initial fresh fruit.

3.5.2. Experiment 2

The effect on the freezing rate on quality properties of apples was investigated on two different apple cultivar (Golden delicious and Royal gala) both ORG and CONV.
The results highlighted that this process parameter, under the experimental conditions applied in this study, could affect some quality attributes of interest (e.g. colour, firmness, polyphenol content) of an extent that greatly depends on the initial quality attributes of the fresh product. Ripeness degree, storage time and storage conditions, independently on the farming procedures (CONV vs. ORG) affect the technological performances and suitability of the raw materials to freezing.

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II IV RECOMMENDATIONS ON COOLING AND FREEZING

University of Kassel, Department for Agricultural and Biosystems Engineering, Germany
Sturm, B.

4. Major reasons for applying low temperatures to foods

Cold storage simultaneously decreases micro-organism activity and the rate of chemical reactions within a product. Thus, shelf life and the associated food safety can be significantly increased. However, it is important to understand, that chemical reactions are not completely inhibited, i.e. further changes in the product composition occur even in the frozen state.
The effect of cooling and freezing on the extension of shelf life and the resulting product quality strongly depend on the storage temperature (in case of cooling) and the freezing speed storage temperature and thawing conditions in the case of freezing.
Furthermore, cold temperatures are necessary part for the production of certain products such as ice cream.

- Increased stability during storage (temperature dependent)
    - Refrigeration
        - Short term storage for e.g. fruits, vegetables, milk, meat, beverages
        - Combination with controlled atmosphere possible

E.g. apple or potato storage over several months
- Freezing
    - Long term storage
    - Most important low temperature treatment, as very little loss of quality occurs during storage

- Beneficial temperatures for manufacturing foods
    - Chilling/cooling
        - Milk, beverage, fat and meat industry, bakery industry
    - Freezing
        - Preservation by deep freezing and freeze drying
        - Manufacture of ice cream

4.1. Freezing

Water is the major component of foods. It acts a a dissolution medium and contains salt, poly saccharides and other soluble substances (e.g. proteins, carbo hydrates). Thus, it needs to be noted that:
- Freezing behaviour varies from pure water
- Freezing behaviour depends on product
    - Compositon
    - Particle size
    - Method and speed of freezing (technology and settings

Figure 4.1 gives an overview of initial water contents for several animal and plant based products.

Product	Water content (%)
Lettuce	95
Tomatoes	94
Water melon	92
Mushroom	91
Strawberries	89
Broccoli	89
Peaches	89
Apples	86
Bananas	75
Eggs	75
Beef	75
Pork	75
Chicken	75

Figure 4.1: Water content of plant and animal based products (adapted from BerkelyWellness, 2001 and FAO, 2018

4.1.1. Speed of freezing

Generally, two types of freezing mechanisms can be distinguished between, slow and fast freezing. In the following a direct comparison of the impacts of these two methods on product quality is given. Figure 4.2 shows a comparison of the crystal growth during slow and fast freezing, displaying the very detrimental effect of slow freezing in comparison to fast freezing.

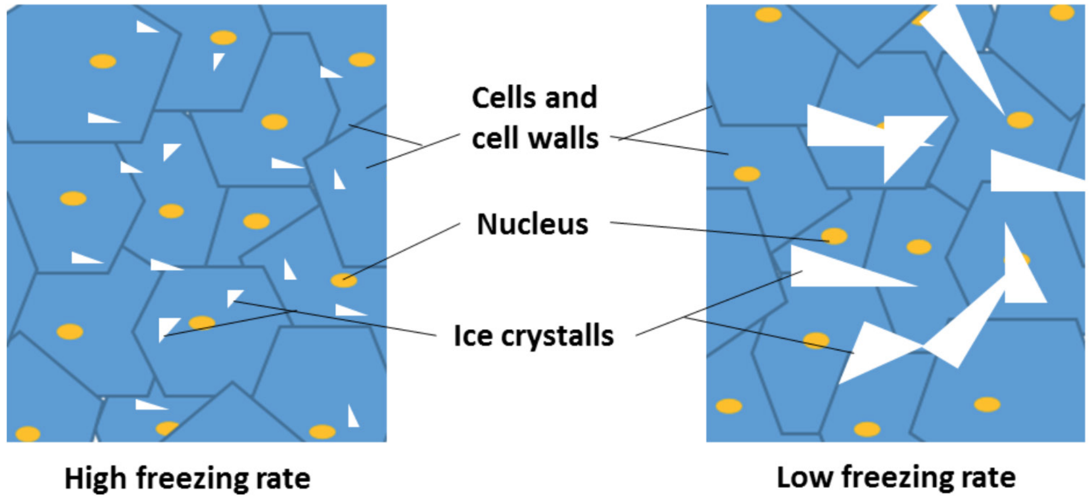

Figure 4.2: Chrystal growth depending on freezing speed

4.1.1.1. Slow freezing

- Small temperature gradient between food and freezer
    - Small number of ice crystals
    - Slow growth to large crystals possible
- During Freezing
    - Large weight loss (up to 7%) in particular in the critical range (-0.5° C to -5/-7° C)
    - High concentration of substances in residual liquid result in high enzyme activity
    - Rapid degradation reaction rate!
- After thawing
    - Significant loss of liquid and change of texture due to cell collaps

4.1.1.2. Rapid freezing

- Large temperature gradient between food and freezer
    - Formation of large number of ice crystals
    - Rapid growth to many small crystals
    - Critical crystallisation temperature range is crossed quickly
    - Little or no destruction of tissue or cell structures
- During Freezing
    - Small weight loss (1%)
- After thawing
- Minor loss of liquid or change of texture due to cell collapse

4.2. Quality affecting aspects during freezing

As mentioned earlier, freezing reduces the speed of chemical changes and reduces and/or inhibits the activity of micro-organisms. However, most microorganisms are only falling dormant in the frozen state and will be active again after thawing.

4.2.1. Micro-organisms

- Water is essential for activity and growth of micro organisms
    - But: cryophilic microorganisms can live on frozen foods!
- Stop of growth of micro organisms
    - -7° C for bacteria (90% of water is frozen)
    - -10 to –15° C for yeasts and moulds
- Total number of microorganisms is reduced by freezing
    - Decreasing temperature
    - Formation of ice crystals
    - Decreasing of moisture equilibrium: aw = f (T)
- Damage of micro-organisms depends on
    - Kind of micro organism
    - Type of food
    - Freezing process
    - Survival rate 50 – 90%
    - After thawing, reproduction and metabolization are normally continued

4.2.2. Enzymatic activity

Enzymes are relatively insensitive to freezing, but very sensitive to heat. Therefore, in frozen products, enzyme activity is only reduced, not entirely stopped. This can lead to the following:

- Enzymatic reactions possible
    - Contact with oxygen
    - Concentrated residual liquid during freezing
- These reactions may result in
    - Browning (peaches)
    - Degradation of ascorbic acid
    - Flavour changes
    - Degradation of fats
- Countermeasures
    - Blanching
    - Very deep freezing to minimize enzyme activity
    - Tight packaging (impermeable for oxygen, air)

Practical storage life (PSL) depends on the nature of the food stuffs in question. An overview for selected foods (in months for various storage temperatures) is given in Table 4.2:
Table 4.2: PSL for various products and temperatures in months (modified from WFLO, 2008)

Table 4.2: PSL for various products and temperatures in months (modified from WFLO, 2008)

Product	Temp.		
	-10°C	-15°C	-20°C
Lean meat	5-21	10-37	13-49
Fat meat	6-17	10-27	13-40
Lean fish	2-6	4-12	6-20
Fruits & berries	3-17	17-70	over 70
Vegetables	3-10	8-20	21-70

4.3. Freeze burn

Freezer burn is a food-quality issue, not a food safety issue. It appears as grayish-brown leathery spots on frozen food. It occurs when air reaches the food's surface and dries out the product. This can happen when food is not securely wrapped in air-tight packaging. This can also happen, if air is not removed from package and/or the actual temperature in the freezer is fluctuating much. Potential consequences

- Agglomeration of structural elements and interaction of macro molecules
- Denaturation of muscle proteins
- Crystallization of poly saccharides
- Irreversible drying out of the product, no complete reconstitution possible

Therefore, to ensure the retention of quality the following measures need to be taken:

- Use packing material which is air tight
- Remove all residual air from the package before freezing
- Ensure that the temperature in the freezer are not diverting from the set temperature more than ± 2°C to avoid evaporation and condensation of water from the product

4.4. Thawing

As displayed in the previous chapter, it is of great importance to ensure rapid freezing to achieve maximum retention of product quality. In thawing the approach directly depends on the further use of the produce. Generally it can be stated that the time between thawing and consumption should be minimal. The following aspects need to be considered

- Effect of slow freezing on degradation during and after thawing
    - Due to cell ruptures, enzyme activity throughout the whole product → Increased rate of degradation
    - Blanching before freezing inactivates enzymes → Degradation is reduced

The influence of freezing and thawing are difficult to be separated.

4.4.1. Rapid thawing

Rapid thawing is appropriate for produce which is intended for immediate use and where the particle sizes are small enough that the centre of the product reaches target temperature quickly enough:

- Vegetables
    - Start cooking from frozen state
- Small portions of meat, fish, poultry fried directly in frying pan
    - → Thick pieces: core is still frozen while surface is already overcooked

4.5. Animal based products

For meats and fish, several aspects need to be considered to ensure best quality retention after thawing as is described in the following.

4.5.1. Meat

- Rapid thawing after freezing of beef before rigor mortis results in a „thawing rigor"
    - Tough meat because of extreme contractions
    - Insufficient water binding properties
    - High drip loss (30 – 40%)
- Slow thawing at 0 - -5° C reduces drip loss significantly
    - Rapid rate of glycolysis
- Sensitivity in respect of drip loss
    - Beef is very sensitive
    - Veal and lamb significantly less sensitive
    - Pork is very robust

4.5.2. Fish

- Rapid freezing of entire fishes before rigor mortis
    - Reduced „gaping"
- Slow thawing required
    - Sufficient time for development of rigor mortis
- Otherwise
    - Strong shrinking
    - Drip loss
    - „gaping"
- Effect strongly dependent on type of fish

4.6. Freezing technologies

Freezing technologies can generally be classified based on the operation mode and the type of heat transfer. The choice of the appropriate technology is of great importance to ensure both high quality retention and economic viability of the process:

- Operation mode
    - Batch processes
    - Continuous processes •
- Heat transfer
    - Convection (e.g. cold air)
    - Conduction (Contact)
    - Vaporization (e.g. liquid nitrogen, L-N2, LIN)
- Suitability dependent on
    - Type of product: solid, liquid, semi-solid, paste
    - Dimensions (geometrical)
    - Required freezing rate

4.6.1. Conduction

- Small temperature difference between air stream and product
- Technologies and operation
    - Discontinuous (batch process)
      - Plate freezer (oldest construction); hydraulic pressure
      - Good contact between plate and product needed
      - Only suitable for products with flat surface
    - Continuous
      - Roller freezer
      - Conveyer beld, cooled from below

4.6.2. Convection

- High temperature difference between cold air stream and product (low heat transfer coefficient)
- Technologies and operation
    - Discontinuous (batch process)
      - Freeze dryer, freezers with top-opening, front door, rooms
    - Continuous
      - Freezer tunnel, product moved on trays or belts
    - Fluidised bed freezers
      - Free flowing products in cold air stream
      - E.g. Peas, corn, beans, small solid products

4.6.3. Freezing in evaporizing fluids

- Very large heat transfer coefficient
    - Large volumes, fast process
    - Mostly liquid nitrogen
      - TB at 1 bar: -196° C
    - Dry ice (solid CO2)
      - Tsubl. : -78 °C
- Equipment
    - Low capital investment, significant operation expenses
      - N2 or CO2 = incidentals

4.7. Summary

Quality retention for frozen goods depends on a multitude of influencing factors within the different process steps. For some products such as peas or beans it is necessary to inhibit enzymatic activity after thawing by the use of blanching prior to thawing.
The freezing step, irrespective of the product needs to be conducted as quickly as possible to prevent the growth of large ice particles which destroy the cellular structure. Failure to do so results in cell rupture, increased degradation reactions and increased drip losses after thawing.
Avoid overloading the freezing unit:

- Overloading leads to decreased freezing rate (slow freezing)
- If produce is already present in the freezer
    → Freezer temperature increases temporarily (until the fresh produce reaches target temperature), this has a negative effect on the already stored produce

The packaging needs to be air tight and all air needs to be removed from the packaging prior freezing to avoid freeze burn. The temperature fluctuation of the freezing unit needs to be kept as low as possible to avoid evaporation and consequent condensation of water on the particle surface.
The applied thawing strategy directly depends on the nature of the product, the intended use after thawing and the particle size.

Useful links:
https://www.gcca.org/
http://www.fao.org/docrep/008/y5979e/y5979e00.htm#Contents

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