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Review

Superchilling of food: A review

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ABSTRACT

Food preservation is very important for the safety and the reliability of the product. Superchilling as used for preserving foods, has been defined as a process by which the temperature of a food product is lowered to 1–2 °C below the initial freezing point. Fresh and high quality food products are in great demand worldwide. Temperature is a major factor determining the shelf life and quality of food products. Fish and meat are perishable food commodities, where better and more advanced preservation technology is needed. Deterioration of these foods mainly occurs as a result of chemical, enzymatic and bacteriological activities leading to loss of quality and subsequent spoilage. Storing food at superchilling temperature has three distinct advantages: maintaining food freshness, retaining high food quality and suppressing growth of harmful microbes. It can reduce the use of freezing/thawing for production and thereby increase yield, reduce energy, labour and transport costs. The study on the growth mechanism of ice crystals, modelling and computer simulation of foods during superchilling and superchilling storage is needed.

1. Introduction

With increasing world population and the need to supply people with fresh and healthy food, food preservation becomes increasingly necessary in order to increase the shelf life and maintain the nutritional value, texture and flavour of food. A main challenge in this respect is to maintain a stable and sufficiently low temperature which is often more difficult in fresh foods than in frozen foods. Studies on the chill chain have shown that it is a challenge to maintain an acceptable temperature during distribution and storage of food products (Aune, 2003). Superchilling is one method that can be used to maintain food products at a low temperature. Superchilling implies temperatures in the borderline between chilling and freezing. Superchilling is a process by which the temperature of a food product is lowered to 1–2 °C below the initial freezing point of the product (Duun and Rustad, 2007). At superchilling temperatures, microbial activity is reduced and most bacteria are unable to grow. Microbial growth is the most important factor limiting the shelf life and quality of fresh food products. Ghaly et al. (2010) stated that about 30% of the landed fish are lost through microbial activity alone, while chemical deterioration and microbial spoilage are responsible for loss of 25% of gross primary agricultural and fishery products every year. In addition, food systems and quality deterioration mechanisms are complex and consumers are a heterogeneous group. Fresh food, especially meat and fish, are highly perishable products due to their biological composition. The shelf life of refrigerated meat and fish is limited, primarily due to microbial activities (Duun, 2008; Fernández et al., 2010; Lambert et al., 1991). Controlling microbial activities is the key to extension of shelf-life during processing, distribution and storage of food. Temperature is one of the most important parameters affecting the growth of microorganisms (Borch et al., 1996; Bréand et al., 1997, 1999; Constantin, 1985; Doyle, 1989). The rate of food spoilage processes depends on temperature. To reduce spoilage and biochemical degradation, different preservative methods, mainly based on low temperature, have been employed for storage and distribution of food products. The most used methods include refrigerated ice storage between 0 °C and 4 °C, superchilled storage in the range of −1 to −4 °C, by means of slurry ice or in superchilled chambers without ice, and frozen storage at −18 to −40 °C (Gallart-Jornet et al., 2007).

In addition to microbial growth, enzymatic activities are important for the determination of shelf life and quality of food. The initial quality loss in most of food products such as fish is primarily caused by autolytic changes and is unrelated to microbiological activity (Gram and Huss, 1996). Of particular importance in this respect is the degradation of nucleotides (ATP-related compounds) which is caused by autolytic enzymes. Lipid oxidation (both chemical and enzymatic) leading to rancidity can also take place at low storage temperature (Duun, 2008). Due to the presence of highly

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unsaturated fatty acids, fish is more susceptible to lipid oxidation than other muscle foods such as poultry, pork, beef, and lamb (Lee et al., 2006). Lipid oxidation products are known to react with nitrogenous materials in biological systems including amino acids, proteins, phospholipids, and DNA to form brown pigments and fluorescent compounds which may have negative health effects (Kubow, 1992).

The volume and value of fresh, refrigerated foods, and also the flow of these products between countries is increasing. The level of education among consumers has increased in recent years as well as has the knowledge about nutrition and the amount of money available to spend for food products. In addition to purity and safety, product freshness is a major part of product quality and will help to prevent health problems (Matthias, 2005). Frozen foods have a shelf life of months or years while fresh products have a shelf life of days or weeks. The shelf life of superchilled food is far shorter than that of frozen food but longer than that of chilled food (Duun, 2008) and with an increased focus on fresh products, the profitability of the superchilling process from harvest (catch) transport-consumer is of great importance. The aim of this paper is to review the superchilling technology for the preservation of fresh food products.

2. Superchilling

The process of superchilling was described as early as 1920 by Le Danois, even though the terms 'superchilling', 'deep-chilling' or 'partial ice formation' were not used. The superchilling technology combines the favourable effect of low temperatures with the conversion of some water into ice, which makes it less available for deteriorative processes (Aune, 2003). The ice formed on the surface will absorb heat from the interior and will eventually reach equilibrium. Superchilling gives the food product an internal ice reservoir so that there is no need for external ice around the product during transportation or storage for shorter periods, however, for long term superchilled storage, refrigerated storage at superchilled temperatures will be needed. Generally, superchilling is positioned between freezing and refrigeration (conventional chilling), where the surrounding temperature is set below the initial freezing point. The initial freezing points of most foods are between −0.5 °C and −2.8 °C (Duun and Rustad, 2007). Ando et al. (2004) defined superchilling as the temperature zone below 0 °C but where ice crystals are not generated. Beaufort et al. (2009) defined superchilling as a technology where food is stored just below the initial freezing temperature.

2.1. Shelf-life aspects in relation to superchilling technology

There is no generally accepted definition for the term shelf life in the literature. A universal definition of shelf-life is virtually impossible to establish since it is impossible to satisfy all consumers at all times (Bin and Theodore, 1993). Shelf life can be defined as the time period for the product to become unacceptable from sensory, nutritional or safety perspectives. Shelf life is the time during which the product will remain safe, to retain the sensory, chemical, physical and microbiological characteristics, and comply with any label declaration of nutritional data (Kilcast and Subramaniam, 2000). The shelf life of foods is a function of composition, processing, packaging and environmental factors, including humidity, and temperature (Bili and Taoukis, 2007).

Studies on superchilling have shown extended shelf life of food products compared to conventional chilling. According to Einarsson (1988), superchilling results in better quality, and extends shelf life of stored food 1.5–4 times compared to conventional chilling. Carlson (1969) reviewed superchilling of fish and found that as temperature was reduced from −1 °C to −3 °C, the shelf-lives increased from 21 to 35 days. Sivertsvik et al. (2003) reported a sensory shelf life of 21 days for superchilled salmon in air, whereas modified atmosphere and air stored fillets at chilled conditions were spoiled after 10 and 7 days, respectively. The superchilled MA packaged salmon had a negligible microbial growth (<1000 colony-forming units (CFU]/g) for more than 24 days (aerobic plate count, H_2S-producing, and psychotropic bacteria) (Sivertsvik et al., 2003). This is in accordance with the results of Duun and Rustad (2008) who found a doubling of shelf life of superchilled salmon stored at −1.4 and −3.6 °C compared to ice chilled storage with respect to microbial and chemical analyses, and also with the results of Stevik et al. (2010). Fernández et al. (2009) who reported the shelf life of 22 days in superchilling in combination with modified atmosphere packaging (MAP) based on sensory, chemical, and microbiological analyses compared to 11 days control sample. In a study of MAP and superchilled storage to extend the shelf-life of fresh cod (*Gadus morhua*) loins, Wang et al. (2008) found that superchilled-MAP storage had a shelf life of 21 days compared to 14 days for chilled-MAP storage. Olafsdottir et al. (2006) found shelf-life of superchilled cod fillets based on microbial, Chemical Quality Indicators (Torry – score) and total volatile basic nitrogen (TVB-N) to be 15 days at −1.5 °C compared to 12.5–14 days at 0 °C for iced chilled cod fillets, while Duun and Rustad (2007) found that the microbial shelf life (with respect to reduced growth of sulphide producing bacteria) in superchilled vacuum-packed cod fillets stored at −2.2 °C was extended by several weeks compared to chilled cod. When comparing effect of brining and MAP on the shelf life and quality of cod loins, a shelf life of 21 days for the superchilled samples was found while for chilling the shelf life was about 14–15 days (Lauzon et al., 2009), the experiments were evaluated based on sensory, microbial, and chemical analyses. Zeng et al. (2005) showed that the total viable counts (TVC) of bacteria increased most rapidly in shrimp stored in flake ice and in brine mixed with flake ice, followed by those in liquid ice at +1.5 °C, while the lowest counts were observed in shrimp stored in liquid ice at −1.5 °C. For meat a longer extension of shelf life with respect to quality parameters (sensory, physical, biochemical and microbiological) has been found, superchilled pork roasts had a shelf life of at least 16 weeks compared to 2 weeks for the chilled references (Duun et al., 2008).

2.2. Quality aspects in relation to superchilling method

Quality is an arbitrary term and one which causes confusion among consumers, processors and researchers. Product quality is a very complex concept (Gao, 2007) which includes nutritional, microbiological, biochemical and physiochemical attributes. Microbial growth, colour, texture, off-flavour and oxidation are important factors for the safety and quality of food products. Due to the fact that colour, texture, and flavour characteristics are the main quality parameters in food products, conventional technologies such as freezing are often not preferred. Freezing may induce undesirable changes such as protein denaturation, reduced water holding capacity and increased drip loss on thawing. Methods reducing these problems are therefore wanted.

Superchilling processing technology has shown several advantages on the quality of food products, for example had superchilled salmon fillets lower bacterial counts compared to the corresponding chilled fillets (Hansen et al., 2009). Superchilling was found to be a promising method for storing raw material before salting, slowing down biochemical quality degradation while at the same time the degree of protein denaturation was low and the degree of structural damage was less than in frozen storage (Gallart-Jornet et al., 2007). On the evolution of *Listeria monocytogenes* and organoleptic characteristics of cold-smoked salmon samples, Beaufort et al. (2009) reported that storage at −2 °C (superchilling process) for 14 days did not have any serious consequences on the quality of cold-smoked salmon compared to controls (absence of superchilling). However, the prevalence of *L. monocytogenes* and organoleptic properties were higher after 28 days at superchilling, followed by 28 days in chilling, compared to samples stored at superchilling/chilling for 14 days before chilling for 28 days. During superchilled storage of kuruma prawn, the brightness of the tail colour could be retained compared to traditional refrigeration where unfavorable changes in quality such as discoloration, deterioration of texture and a rapid rise in the amount of inosine and hypoxanthine in relation to the total amount of ATP and substances derived from ATP (*K*-value) were found (Ando et al., 2004). On evaluating the impact of superchilling on the quality of pre-rigour Atlantic salmon (*Salmo salar*) fillets, Bahuaud et al. (2008) found that superchilling prevented the fillets from rigour contraction. The study of Sivertsvik et al. (2003) found no negative texture changes in the superchilled salmon and insignificant increase in drip loss, this is in accordance with the result of Duy et al. (2007) who found no negative effects on the quality in superchilled Arctic Charr fillets. These differ from the results of Duun (2008) and Duun and Rustad (2007) who found drip loss to be lower in superchilled samples than in chilled samples both in cod and salmon fillets as well as in pork roasts. Temperature fluctuations during superchilled processing and storage should be avoided (Duun, 2008; Duun and Rustad, 2007). The amount of ice in the products is highly dependent on the temperature and this has a large influence on the quality changes during storage.

There is a lot of interest in the use of superchilling technology in food processing. In the specific case of chilling of food products, superchilling may become an alternative method over conventional chilling. Duun and others (2008) reported extended shelf life and improved quality for superchilled food products. This may be a direct result of the reduction of tissue or external damage and an indirect result of the reduction of lipid deterioration and protein oxidation in the final food product.

However, some negative effects on quality have also been found in superchilled foods. Bahuaud et al. (2008) reported on freeze damage during superchilling, the upper layer of the super-chilled fillets showed freeze damage characterized by the formation of large intra- and extracellular ice crystals during superchilling. Freeze damage due to superchilling accelerated the amount of detachments between myofibres and increased the amount of myofibre breakages during storage time. Super-chilling accelerated the release of the proteolytic enzymes cathepsin B and L from the lysosomes, causing an acceleration of fish muscle degradation (Bahuaud et al., 2008). However, Duun and Rustad (2008) concluded that super-chilling did not influence the total cathepsin B and L activity in salmon muscle stored at −1.4 °C and −3.6 °C. Duun (2008) found that myobrillar proteins denatured more easily during superchilled than during chilled storage both in salmon and cod fillets and the amount of free amino acids increased more rapidly due to exoproteolytic activity. Duun and Rustad (2007) also found a higher liquid loss (LL) in superchilled samples compared to ice chilled cod fillets. The high LL was correlated to a reduction in amount of salt soluble proteins which was significantly lower in the superchilled samples than in the ice chilled samples.

Texture is an important quality parameter, and may vary depending on species, part of muscle, storage, and processing (Hansen et al., 2009). Superchilling in combination with MAP had a negative effect on the texture of salmon fillets. This is in accordance with the results of (Gallart-Jornet et al., 2007; Wang et al., 2008), but in disagreement with the results of Bahuaud et al. (2008) who found that MAP did not influence the effects of super-chilling. Measurements of texture, liquid loss and protein denaturation during superchilling in the reviewed studies indicate that the superchilling process still needs to be optimized before further commercial implementation.

3. Superchilling technologies

The superchilling process can be carried out in special cold-producing machines called freezers; mechanical freezers, cryogenic freezers, or impingement freezers. The three technologies, and all freezers, have different advantages, drawbacks and limitations. In this paper, we will compare mechanical, cryogenic and impingement freezing technologies rather than specific systems. The selection of suitable freezing equipment helps to maximize product quality, operating flexibility and return on investment (ROI) while minimizing waste, costs and downtime.

3.1. Mechanical freezers

Use a circulating refrigerant to achieve temperature reduction by heat exchange against air to the food product. Mechanical freezers are commonly used to freeze foods. Mechanical freezers, especially in continuous belt freezers, have lower operating costs than cryogenic freezers. However, mechanical freezers require higher processing times due to low heat transfer coefficients ($h \ll 50$ W/m^2 K) which, in turn, lead to a lower quality product (Salvadori and Mascheroni, 2002).

3.2. Cryogenic freezers

Generally, the term cryogenics is applied to temperature below −150 °C, but in food processing, the term cryogenic freezing is widely used to identify freezers using either nitrogen liquid (−196 °C) or carbon dioxide (−78 °C as a solid) which are applied directly to the food product to achieve temperature reduction. Cryogenic freezing offers shorter freezing times compared to conventional air freezing because of the large temperature differences between the cryogen and the product surface and the high rate of surface heat transfer resulting from the boiling of the cryogen (Zhou et al., 2010). Cryogenic freezing requires no mechanical refrigeration equipment; simply a cryogen tank and suitable spray equipment. However, there may be some distortion of the shape of the product caused by the cryogenic process that might impact on the commercial application (Zhou et al., 2010). Furthermore cryogenic freezing has a high refrigerant consumption (>1 kg of N_2 per kg of processed product) and has very high operating costs (Salvadori and Mascheroni, 2002; Soto and Bórquez, 2001). This makes cryogenic freezing a valid alternative only for expensive products such as seafood or fine fruits.

3.3. Impingement freezers

Is equipment which has a freezing chamber divided into zones where the temperature of each zone is independently controllable so that the temperature profile within the impingement freezer is coldest at a zone adjacent the outlet and warmest at a zone adjacent to the inlet for maximum thermodynamic usage of the refrigerant (Lee and Sahm, 1998). Additionally, the velocity of each of the impingement jets is independently adjustable from zone to zone so that in the zone adjacent to the entrance of the freezing chamber, the impingement jets can be adjusted to have maximum velocity air to produce maximum heat transfer coefficients and thereby an acceptable rate of cooling within the impingement freezer (Lee and Sahm, 1998). Products are placed on conveyor belts, and the high velocity air passes through the conveyor upwards and downwards. Impingement freezer increases heat transfer rates than that seen with traditional mechanical freezers because it breaks up the boundary layer at the surface and hence reduces processing time (Anderson and Singh, 2006; Erdogdu et al., 2005, 2007; Salvadori and Mascheroni, 2002; Sarkar et al., 2004). Impingement jet systems have been identified as an alternative to conventional freezing methods, given their high turbulence characteristics, which enhance heat transfer and therefore quality product (Dirita et al., 2007; Garimella and Schroeder, 2002; Soto and Bórquez, 2001).

The study of Salvadori and Mascheroni (2002) concluded that the processing times in an impingement freezer are markedly lower than the times required in conventional belt tunnel freezers, thus the use of this equipment increases the production capacity without increasing the size of the facilities. In addition the freezing times and weight losses for impingement freezing are similar to those of cryogenic freezing at a noticeably lower operating cost. The impingement freezer has a good impact on the product, as it reduces processing time by enhancing heat transfer, and therefore good quality of the product. Impingement technology advantages could give the food technologists the best way of preserving food products, for extending shelf life and improve product quality.

4. Ice crystal formation

Ice content, the percentage of the water in a product that is in solid form, is one of the most important parameters of food when freezing is involved. It is also one of the parameters that are elusive and difficult to measure (Aparicio et al., 2008). However, this depends on controlling the temperature (temperature stability) pre and during storage treatment. The process temperature should be stable enough to avoid significant levels of ice crystal growth that can cause structural damage. Temperature measurement during transient chilling and the freezing process is extremely challenging due to temperature variations both in time and space (Magnussen et al., 2008). In practice, controlling and measuring temperature must therefore be performed after chilling and temperature equalization are complete. Accurate temperature measurements can be carried out under laboratory conditions, but under industrial conditions one cannot expect to improve on an accuracy of ±0.5 °C. However, even with this accuracy, calculating the amount of ice in the product is highly uncertain due to the strong dependency of ice content on temperature in the region of interest (Magnussen et al., 2008). Fig. 1: ice content and specific enthalpy in salmon filets with varying temperature. The red columns represent variations in temperature due to error of measurement in the industry. Dotted arrows show how these errors affect the ice content and specific enthalpy (Magnussen et al., 2008).

Bahuaud et al. (2008) reported that the ice crystals formed during superchilling were large enough to damage the integrity of the fish muscle during superchilling. The large intra- and extracellular ice crystals formed during superchilling/freezing has a large effect on morphological changes, cell destruction as well as the denaturation of cell components (Bahuaud et al., 2008; Gab-Soo et al., 2004). These may result in textural changes and increased drip loss during thawing (Bahuaud et al., 2008). Fluctuating temperatures, even if the freezing temperature is quite low, accelerates the growth in size of the ice crystals formed. With a slight rise in storage temperature, the small ice crystals will presumably melt faster than the larger ones, and when the temperature drops down again, forming larger and larger crystals (Shenouda, 1980).

Studies of the characteristics of the ice crystals formed during superchilling and superchilled storage should contribute to a better scientific basis for evaluation of methods for chilling and comparison between technologies (Magnussen et al., 2008). There is, however, few published studies explaining the growth mechanism of ice crystals during superchilling and superchilled storage. For example the growth mechanism of ice crystals during superchilling storage may be related to shelf life of foods and some of the quality parameters (water holding capacity, lipid oxidation, protein denaturation and other quality parameters). Therefore, the information about the growth of ice crystals should be investigated because it could offer another way of improving the quality of superchilled foods and chilling-related technology.

5. Modelling and simulation

Studies show that, the main problem in superchilling technology is to define the degree of superchilling and control the temperature in the process that will improve the shelf life sufficiently and fulfill the demands regarding processability and quality attributes. Modelling and computer simulation of the superchilling process is a tool which could implement this task. Computer simulation and laboratory experiments of superchilled salmon fillets were reported by Aune (2003). Simulation was carried out to find the amount of the frozen water at different mean temperature in the fillets and different chilling times. The computer simulation gave satisfactory results compared to experimental results. As far as we know, there is no published papers concerning computer simulation and modelling in superchilling since 2003.

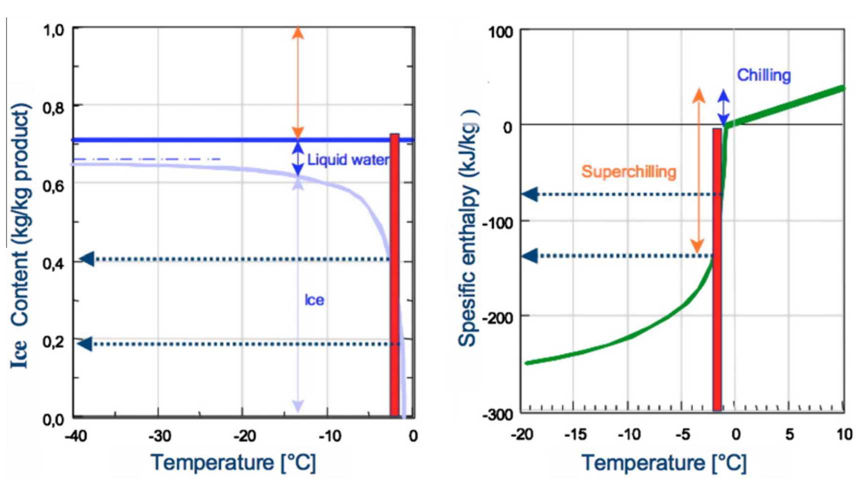

Fig. 1. Ice content and specific enthalpy in salmon filets (Magnussen et al., 2008).

However, different models have been applied in food industries and presented in the literature for simulation in one, two and three dimensions. Moureh and Derens (2000) developed a three-dimensional heat transfer model to predict the food temperature as a function of time and location within the pallet. They concluded that to ensure a better control of the cold chain, the model can help evaluate the benefits of investments such as cold-storage facilities, choice of packaging or the control of ambient temperature. Mannapperuma and Singh (1989) developed a numerical method based on enthalpy formulation of heat conduction with gradual phase change which was then used to develop a mathematical model to simulate freezing and thawing processes in foods, the results agreed reasonably well with published experimental results and with predictions by other published methods. Dolan et al. (1987) developed a one-dimensional heat transfer model in order to calculate temperature profiles and histories within a pallet of frozen food exposed to different environmental conditions. Various simulations were carried out by varying thermal properties, external heat transfer coefficient, and ambient temperature and radiation surface properties of the carton box. Among these parameters, the thermal properties exert the greatest effect on temperature distribution within the pallet.

Mallikarjunan and Mittal (1995) used a validated heat and mass transfer model and a pattern search algorithm to evaluate the effect of the optimum freezing conditions on beef quality after ageing. A computer programme was written using FORTAN 77 and they found that optimum chilling conditions provided a better quality compared to other chilling systems. Lijun and Da-Wen (2002) used a finite element analysis to model the three-dimensional transient heat transfer of roasted meat during air blast cooling process. A user-friendly computer programme developed in visual C++ by the authors was used to solve the model. The temperature predictions were in agreement with experimental values.

The typical shape factor of the food product usually makes a one-dimensional model sufficient to study the thermal behaviour of the product. Such a model has the advantage that it is simple, very fast, and yet detailed enough to estimate the real behaviour of the food product. The physical properties of food have a strongly nonlinear behaviour in the temperature region of freezing. This is especially true for the specific heat capacity, since it represents the latent heat in addition to the sensible heat.

5.1. Computer programming

A finite difference method adapted to handle the nonlinear physical properties of food is adopted to model the freezing/partial freezing processes. Solving these kind of equations need a fine resolution in space and time, and can be implemented using different computer languages such as FORTAN 77, C++, MATLAB, etc. MATLAB is well suited because this tool provides a rich set of built-in facilities for equation solving and visualization. The main task of the programme is to keep track of the average ice fraction during all stages of the product handling. Good knowledge and accurate prediction of the ice fraction-temperature dependence has significant importance for reliable determination of the thermophysical characteristics and enthalpy variation during freezing of foodstuffs as well as for proper selection of the temperature regimes during refrigerated processing and storage (Fikiin, 1998).

Based on this information, optimal time in the freezing facilities such as impingement can be found by repeated simulations. The practical methodology will include simulation and verification of the developed models using experimental data. A major advantage of such a simulation model is a better control of food quality because the process of evaluation can be followed up frequently at a cheap cost. These models, when validated, can be used to design and operate controls of temperature in superchilling.

6. Challenges in superchilling

The main challenges are: selecting optimal process conditions, such as temperature, velocity and control holding time in the superchilling unit. More knowledge is needed on the right degree of superchilling which will increase shelf life and maintain quality of food products. To control temperature during superchilling and superchilled storage is a challenging task. It is also difficult to define the degree of superchilling required to sufficiently improve shelf life and fulfill the demands of the process to achieve the desired quality attributes (Magnussen et al., 2008). The changes in the microstructure of foods during superchilling and superchilled storage, introduction of on-line measurement techniques to understand and control the ice fraction are also main challenges with this technique. Growth of microorganisms, protein denaturation and lipid oxidation at temperature below 0 °C also requires more attention. Duun and Rustad (2007) found development of white spots on the surface of fillets during the superchilled storage. This is a challenge in superchilling process since the product looks undesirable to the customers. Lastly, the superchilling technology is more expensive than conventional chilling and needs maximum accuracy with regard to processing parameters in relation to equipment used. On the other hand superchilling offers advantages with regard to shelf life compared to chilling technology.

7. Conclusions

Storing food at superchilling temperature has three distinct advantages: maintaining food freshness, retaining high food quality and suppressing growth of harmful microbes. Superchilling, as a commercial practice, can reduce the use of freezing/thawing for production and thereby increase yield, reduce energy and labour costs. Superchilling may also lead to reduced transport costs, easier handling during processing and reduction of environmental impact.

Study on the mechanism of the ice-crystals growth during superchilling storage is highly required. Modelling and computer simulation of the superchilling process is an area that needs more attention. Calculating the required superchilling times which will define the degree of superchilling required to sufficiently improve shelf life while maintain the desired quality attributes is highly important as well as maintaining a stable temperature during superchilled storage.

There is a need for improved methods to control the superchilling process. Temperature is not a sufficient parameter and ice-fraction has been introduced as a parameter to describe the degree of superchilling. However, if the positive effects of superchilling shown in the reviewed articles could be implemented at the industrial level, superchilled storage might be used to provide additional value to commercial foods.

Future aspects/trends

In the field of superchilling, progress is expected in the area of:

(i) Modeling: Computer simulation of the superchilling process, including interaction between superchilling method and raw material properties. This is important since computer simulations are cheaper and easier to use to study effect of process parameters and product properties.

(ii) The study on growth of ice crystals during superchilling storage which has effect on changes in proteins, lipids, and changes in microstructure which resulting in changes in appearance and texture of food products is an important parameter for future studies.

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