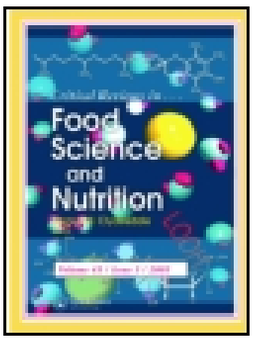

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Superchilling of muscle foods: Potential alternative for chilling and freezing

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ABSTRACT

Superchilling is an attractive technique for preservation of muscle foods which freezes part of the water and insulate the food products from temperature fluctuations thereby enhancing the shelf-life during storage, transportation and retailing. Superchilling process synergistically improves the product shelf-life when used in combination with vacuum or modified atmospheric packaging. The shelf-life of muscle foods was reported to be increased by 1.5 to 4.0 times relative to traditional chilling technique. Advantages of superchilling and its ability to maintain the freshness of muscle foods over freezing has been discussed and its potential for Industrial application is highlighted. Present review also unravel the mechanistic bases for ice-crystal formation during superchilling and measures to ameliorate the drip loss. The future challenges especially automation in superchilling process for large scale Industrial application is presented.

KEYWORDS

Superchilling; muscle foods; packaging; shelf-life; ice-crystal formation

Introduction

The muscle foods derived from livestock, poultry and fish are highly perishable therefore, require optimal handling, packaging, storage, distribution and retailing methods. Refrigeration of muscle foods is a commonly used process to ensure better quality, safety and improved shelf-life. It has been reported by International Institute of Refrigeration (IIR 2009) that globally 25–30% of perishable food products are wasted due to spoilage and the use of efficient refrigeration during post-harvest storage can salvage most of this wastage. A recent report suggests that in the year 2015, China has produced 58 million tonnes of pork equivalent to 300 billion USD, and roughly a wastage of 10% of total production results in loss of 30 billion USD which is more than the GDP of 90 smaller countries. If the refrigerated shelf-life of pork is increased from 4–5 days to approximately 30 days, the wastage will reduce from 10 to 5% which roughly saves 15 billion USD. Temperature control, an essential part of food supply chain starting from production, storage, and delivery, is used to increase the shelf life of food products by reducing the rates of enzymatic proteolysis, lipid oxidation, and microbial degradation. To reduce biochemical degradation and microbial spoilage, different preservative methods have been employed for storage and distribution of meat and fish products. Traditionally, methods of meat preservation may be grouped into three broad categories – preservation by 1) control of temperature, 2) control of moisture and, 3) inhibitory processes (ionizing radiation, packaging, etc.) (Zhou et al. 2010). The most commonly used methods employing low temperature include refrigerated storage between 0 to 4°C or frozen storage at −18 to −40°C (Gallart-Jornet et al. 2007). Chilling is critical for meat hygiene, safety, shelf life, appearance and eating quality (Ockerman and Basu 2014). Whereas, freezing plays a major role in the meat industry to ensure the safety of meat or meat products during storage and transport. Fresh/chilled meat normally freezes at about −1.5°C or below and storage at lower temperature ensures stable product with increased shelf life (Warris 2000). Storage of meat below the freezing point is useful in prolonging the shelf-life and hindering chemical and microbial changes (Lawrie and Ledward 2006). In both developed and developing countries, chilled meat commands a premium over frozen meat. Hence, meat processors around the world, continually look to increase the proportion of chilled products that they export. However, the limited storage life of chilled/refrigerated meats is the limiting factor affecting the distribution chain and limit the versatility and market penetration of meat products. Moreover, cold chains from harvest to the consumer have many weak links, especially power failure, fluctuations of voltage and temperature abuse are frequent. These results in reduced product quality, shortened shelf life, spoilage and export rejections/product recalls. Therefore, chilling has been identified by the meat industry groups as a priority area for improvement. The challenge is to develop an appropriate chilling condition for enhanced safety and shelf-life as a means to find an industrial alternative to the use of freezing/thawing for production buffers, thereby reducing labor, energy costs and product weight losses without compromising for quality of meat. Considering the emerging industrial needs for development of energy efficient and sustainable processing technologies, few researchers have reported the use of superchilling technology as a potential process for improving the shelf life of muscle foods mainly fish and their products. However, its application in meat and meat products is very much limited and in this article, an effort was made to review the superchilling process, its effects on meat quality and safety, adverse effects of ice crystal formation during superchilled storage,

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measures to minimise the ice crystals, potential for industrial application and future scope.

Superchilling

In 1920, Le Danois described the superchilling process for the first time, even though the term "superchilling" or "deep chilling" was not used (Zhou et al. 2010). Generally, superchilling implies temperatures in the borderline between conventional chilling and freezing. The definition of superchilling process has been described in different ways by several researchers – Ando et al. (2004) defined it as the temperature zone below 0°C but where ice crystals are not formed. The concept of superchilling technology was described by Beaufort et al. (2009) and they reported that food is stored just below its initial freezing temperature, or in a more precise way, the temperature of the food product is lowered to 1–2°C below its initial freezing point (Duun and Rustad 2007). The term "superchilling" or "partial freezing" or "shell freezing" is described by Magnussen et al. (2008) as a process where a minor part of the product's water content (5%–30%) is frozen. After initial surface freezing (1–3 mm layer of ice), the formed ice will absorb heat from the food interior and will eventually lead to an equilibration of temperature between interior and exterior during food storage and distribution (Magnussen et al. 2008). The superchilling technology can be divided into two parts – superchilling process and superchilled storage. The whole process of superchilling/deep chilling can be further divided into two stages: (1) In the first stage (pre-cooling stage), the product is cooled to its initial freezing point followed by (2) removing the latent heat of crystallisation (phase transition stage) in the second stage (Kaale and Eikevik 2013). The degree of superchilling, one of the most important parameters defining the quality of superchilled food (Stevik and Claussen 2011; Stevik et al. 2010) depends on the proportion of water frozen (approx. 5%–30%) and preserved within the food product. Lower the degree of superchilling, better the sensorial attributes of a fresh food but a degree more than 30% may lead to higher drip loss (Stevik and Claussen 2011).

The main reason for implementing superchilling technology is because of its ability to combine the favorable effect of low temperature along with the conversion of some amount of free water into ice (Kaale and Eikevik 2014), and thereby making it less available for deteriorative processes (Aune 2003). For a shorter period of storage or transport, this process provides a refrigeration reservoir and there is no need to have external ice around the product (Wang et al. 2008). This approach reduces the amount of ice during supply chain minimizing the transport weight as well as cost and also have a positive impact on the environment (Bahaud et al. 2008). It has been used for preservation of salmon fillets and seabass through the distribution chain by using chambers with controlled temperatures at −1 to −3°C without ice (Aune and Nordtvedt 1999; Chang et al. 1998; Huss 1998; Magnussen et al. 2001; Nordtvedt et al. 1998). However, for long term storage, refrigeration at superchilling condition (1–1.5°C below the product's freezing point) is needed. The shelf life of superchilled food is far shorter than that of frozen food, but longer than that of chilled food (Wu et al. 2014) and in comparison to traditional chilling, it can improve the shelf-life of foods by 1.5–4 times (Einarsson, 1988; Kaale et al. 2011). Gallart-Jornet et al. (2007) reported superchilling as a promising method for minimizing the biochemical degradation, protein denaturation and structural damage in Atlantic salmon compared to frozen storage.

On the contrary, the main concern of this technology was reported to be the formation and growth of ice-crystals (Einarsson 1988). At superchilling temperature, microbial activity is reduced and most bacteria cannot grow (Kaale et al. 2011) but autolytic, enzymatic or other chemical reactions may take place at a higher rate (Einarsson 1988) or even accelerate as reported by Magnussen et al. (2008). A thorough understanding of the degree of superchilling and growth of ice-crystals during superchilling process and superchilled storage are required in order to alleviate its negative effects on final food quality.

Formation of ice-crystals

Crystallization, an important thermo-physical phenomenon, occurs through the conversion of water into ice in phase-transition stage and is a key factor in determining the efficacy of the superchilling/freezing process as well as the quality of superchilled or frozen food (Kiani and Sun 2011; Kiani et al. 2011; Alizadeh et al. 2009; de Paula et al. 2011). Crystallization is the organization of molecules into a solid phase within a fluid (Cook and Hartel 2010). The process is divided into 4 stages (Cook and Hartel 2010; Hartel 2013):

(1) *Supercooling* – the driving force for nucleation and occurs when the temperature of liquid drops below its freezing point.
(2) *Nucleation* – Hartel (2001) has described nucleation process as the birth of a crystal. It initiates the driving force, which overcomes the energy barrier for crystallization and a stable nucleus is formed. Nucleation can occur in two different ways: spontaneous formation of the nucleus from a solution is termed as primary nucleation whereas secondary nucleation involves the formation of the nucleus from an already formed crystal or fragment of crystal.
(3) *Growth* – Once the nuclei are formed, crystals quickly begin to grow in size based on the driving force for crystallization (Hartel 2001, Mullin 2001). The growth of the crystals may occur through aggregation even though the mechanism of deposition of molecules onto the existing crystal lattice was hypothesized by Hartel (2013).
(4) *Recrystallization* – The final stage of crystallization describes the changes in size and shape of crystals while the total crystal mass remains constant (isomass recrystallization), or growth of large crystals at the expense of small crystals (migratory crystallization) or joining of two crystals to form a single crystal (accretion) (Donhowe and Hartel 1996a, b; Fennema et al. 1973).

Nucleation and crystal growth are the two major processes of crystallization and their interaction determines the characteristics of ice crystals (deMan 1999; Kiani and Sun 2011; Kiani et al. 2011), which in turn along with their location (intracellular or extracellular) determines the quality of superchilled or frozen food. The rate of supercooling is the most important parameter for nucleation and controls the number and

size of ice-crystals formed. Regardless of superchilling rate, crystallization is initiated in extracellular fluid (Zaritzky 2006). At a low rate of superchilling (< 1°C/min), large ice crystals are formed exclusively in extracellular areas (Kaale et al. 2013a). The exterior of the cells cool more rapidly than the interior and extracellular fluid reaches a critical temperature at which water is separated from the solute to form extracellular ice crystals (Zaritzky 2006). Formation of crystals can keep a better pace with the slow rate of heat removal – few nuclei become activated and large crystals are formed (George 1993), which in turn lead to irreversible damage of the ultrastructure of muscle cells and tissues (Chevalier et al. 2001; Zhu et al. 2003), accelerate enzymatic action and oxidation rate (Alizadeh et al. 2007; Do et al. 2004). On the contrary, rapid superchilling results in the formation of both intra- and extracellular ice-crystals. Though the cells are dehydrated due to the formation of extracellular crystals, due to the rapid rate of superchilling, intracellular water freezes before it diffuses out of the cells. Moreover, formation of crystals cannot keep pace with the rate of heat removal leading to activation of more nucleation sites, increase in the number of small ice-crystals, minimum damage to muscle structure, less drip loss and other quality parameters during thawing (Alizadeh et al. 2007; Kaale et al. 2013c; Petzold and Aguilera 2009).

One interesting phenomenon is that researchers have found differences in the size of the ice-crystals formed in white and red muscle. The average diameter of the crystals formed in the white muscle was comparatively larger (29 ±1 mm) than that of red muscle (17±2 mm) (Kaale and Eikevik 2013). Moreover, the crystals found in red muscle was found to be well arranged and more spherical in comparison to crystals from white muscles. There was no difference in the increase in the sizes of crystals during storage of both muscles (Kaale and Eikevik 2013). Due to the large temperature gradient between pre-chilling and storage process, sizes of the crystals vary greatly among the surface, mid-central and central layers of the superchilled salmon fillets. The average diameter of the ice crystals formed in the central layer of salmon is 3 times larger than those formed at the surface (Kaale et al. 2013b, c).

Measurement of ice-fraction

Measurement and quantification of ice crystals will help to understand the principles governing crystallization in foods as well as to modify processing operations to ameliorate ice crystal formation. A time-consuming and destructive calorimetric method, that cannot visually observe or control the process online, is currently employed in the measurement of ice-fraction. There is a need for online, non-invasive method for better assessment of ice crystal formation. Microscopy is an age-old method for studying food structures, including crystals (Hartel 2001). Equivalent diameter (μm) of ice crystals and its evolution at the surface, mid-central and center of salmon fillets during superchilling storage was reported by Kaale et al. (2013a, b, c). In addition to polarized light microscopy, scanning electron microscopy (SEM), and transmission electron microscopy (TEM), other applications of microscopy for studying ice-crystals in food include confocal laser scanning microscopy (CLSM) and atomic force microscopy (AFM) (Baier-Schenk et al. 2005; Shimoni 2008; Rousseau and Smith 2008). Stevik et al. (2010) reported that online near-infrared spectroscopy (NIR) can be used to determine the ice-fraction of superchilled salmon with low prediction error (2.5%). The researchers also suggested that measurement of ice-fraction at product level will allow better control over the quality parameters such as water holding capacity (WHC) and drip loss. In situ methods such as magnetic resonance imaging (MRI) is used for characterizing crystals in foods particularly of ice in frozen foods (Hindmarsh et al. 2004) and of lipids during storage (Deka et al. 2006, Maleky et al. 2012). Due to the complex component of muscle foods, superchilling conditions, as well as the development of ice-crystals, are diverse in these foods. A thorough study of growth mechanisms of ice-crystals and their characteristics will provide a scientific basis for evaluation of quality parameters of muscle foods such as texture, drip loss, protein denaturation and oxidation.

Controlling crystallization

Several strategies have been employed to get a better control over crystallization process, uniform product quality and extended shelf-life.

Novel freezing technologies such as high-pressure freezing (HPF), electrically and magnetically assisted freezing (EF & MF), ultrasound assisted freezing (UAF), microwave assisted freezing (MWF), osmo-dehydro-freezing (ODF) etc. have been employed to mitigate the negative effects associated with ice-crystal formation and its effect on food quality. High-pressure freezing not only improves the quality of frozen food by controlling the ice-crystals formation but also have positive effects on food safety due to microbial inactivation (Realini et al. 2011). Atlantic salmon was frozen under three levels of pressure viz. 100 MPa (–8.4°C), 150 MPa (–14°C), and 200 MPa (–20.7°C), respectively with the pressurization rate of 40 MPa/s. It was found that a large number of regular and fine endocellular ice crystals was formed and distributed homogeneously, which significantly improved the microstructure of salmon in comparison to conventional air blast freezing at −30°C (Zhu et al. 2003). Fresh boneless pork rib portions treated by high-pressure shift freezing (100–200 MPa) showed no evidence of distortion of cells and only tiny and regular ice crystals were formed compared with air-blast freezing and liquid immersion freezing (Zhu et al. 2004). Freezing assisted by a high-voltage static electric field was reported by Xanthakis et al. (2013) in pork frozen by high-voltage static electric fields of 3, 6, 9 and 12 kV, and stated that high voltages were effective in the formation of small ice crystals. In general these researchers have reported that higher the power of the electric field, smaller the size of the ice crystals. Apart from high pressure and electric field assisted freezing, Anese et al. (2012) studied electromagnetic assisted freezing in pork loin by combining cryogenic fluid flow and radio frequency pulses with a voltage of 2 kV leading to significant improvement of pork microstructure due to the large quantity of smaller ice-crystals and less cell disruption. Under the influence of ultrasound, the size of the ice-crystals are smaller and cell damage is reduced (Sun and Li, 2003). Significant impact on the crystallization process was observed during the microwave (intensity levels 40, 50 and 60%) assisted

freezing of pork tender loin (Xanthakis et al. 2014). These authors have reported reduction in size of ice crystals by 62% on an average.

Application of anti-freeze proteins was proved to be promising in preserving the quality of frozen foods. These proteins, adsorb strongly to the ice crystal surface and prevent further growth or recrystallization (Hartel, 2013; Mishra et al. 2010; Wang and Sun, 2012). Even, cryoprotectants offer an effective approach to reduce the deteriorative process during superchilling (Liu et al. 2014a, b). Superchilling of common carp (*Cyprinus carpio*) surimi at −1°C and −3°C resulted in a marked reduction in the microstructure deterioration of the myofibrillar protein gels, and the addition of cryoprotectants (a commercial blend of sucrose and sorbitol; 1:1) further reduced this deterioration.

Effect of superchilling on the quality characteristics of muscle foods

Consumers continue to demand foods that are minimally processed, retain freshness with adequate shelf-life. Superchilling is considered as an attractive compromise between conventional chilling and freezing for many food products (Duun and Rustad 2008). However, till date, most of the researchers have mainly reported the effects of superchilling on the quality parameters of fish, seafood and their products. In general, the protocols reported by different researchers for superchilling fish or seafood is summarized in Fig. 1. Effect of superchilling on the quality and shelf-life of meat and meat products is minimally investigated. Researchers have mainly utilized superchilling in combination with either vacuum packaging or modified atmosphere packaging (MAP) for extending the quality and shelf-life of muscle foods. The optimal superchilling and packaging conditions and the salient findings from the limited available literature are presented in Table 1. The negative effects of superchilling can be mitigated and shelf-life of muscle foods can be extended by combining this technology with modified atmosphere packaging (MAP), and vacuum packaging etc. Synergistic effects of vacuum packaging and superchilling in improvement of shelf life were observed in Atlantic salmon (Duun and Rustad 2008), boneless pork roasts (Duun et al. 2008) and hairtail (Luan et al. 2017). Wang et al. (2008) reported a shelf-life of 21 days in superchilled-MAP stored fresh cod compared to 14 days for chilled-MAP storage. Quality and shelf-life improvement were also recorded in MA packaged superchilled cod loins (Lauzon et al. 2009), fresh Atlantic salmon fillets (Sivertsvik et al. 2003) ready-to-cook spotted wolf-fish (*Anarhichas minor*) (Rosnes et al. 2006) and lamb (Bellés et al. 2017). As per the available literature, most of the researchers have suggested the use of temperature ranging between −1°C to −3°C for different muscle food products. Existing data suggests improvement in quality of muscle foods in addition to enhancement of shelf-life from 2–4 fold compared to traditional chilling conditions. However, with reference to ice crystal formation and drip loss, superchilling technique poses some challenges and further research studies are required to address them.

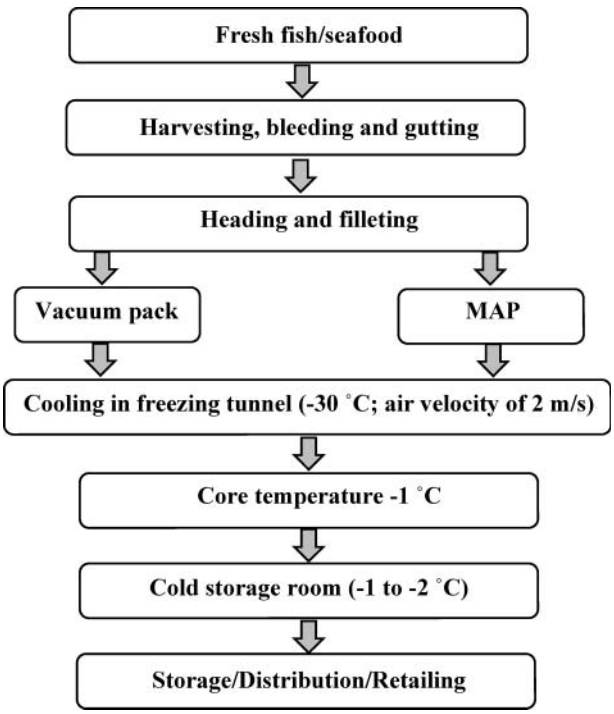

Figure 1. Processing steps for superchilling of fish/seafood.

Potential for industry application

An industrial automated chilling line demands energy efficient process along with high capacity and superior product quality. Establishment of superchilling technology in a meat production plant can provide benefits during the whole supply chain starting from processing, storage, transport and distribution by improved temperature control. For meat, fish and seafood products, this technology will be a boon in the extension of shelf-life. Besides the cost of manpower and unit operations for freezing-thawing, weight loss of the products during this processes result in huge economic loss. As a commercial practice, superchilling, can reduce the use of freezing/thawing for production buffers, minimize labour cost, energy costs and improve product yield (Zhou et al. 2010). It may reduce the process time and thereby the capacity of chilling equipment is increased. Superficial ice formation in superchilled products will protect from temperature abuse. Recent work at Campden BRI (funded by DEFRA and industrial partners), UK, showed that the effect of superchilling using a conventional blast chiller did not result in a significant loss in quality compared to the chilled product. The shelf life of cook-chill prawns could be increased up to 22 days by superchilling process (IIR News 2015). In addition to improving shelf life, the company claims that superchilling process can also reduce energy use and waste. The energy required to produce and distribute chilled and superchilled salmon was calculated. Though more energy was required for superchilling fish during manufacture, more fish can be packed into each vehicle and as no extra ice is required during transportation, the number of journeys required were reduced. The extra energy used during superchilling process was equated in fuel savings.

The food industry is under constant pressure to produce fresh, additives-free fish and meat products with extended shelf

Table 1. Effect of superchilling and packaging on the quality and shelf-life of muscle foods.

Species	Superchilling condition	Packaging	Salient findings	References
Atlantic cod (*G. morhua*)	−2.2°C up to 34 days	—	Lower drip loss and increased shelf life upto 34 days with reduced growth of sulfide producing bacteria compared to ice chilled cod.	Duun and Rustad (2007)
Atlantic salmon (*Salmo salar*)	Superchilling at −1°C for 9 days and 16 days; followed by filleting and dry salting at +4°C	—	Superchilling for 9 days showed promising results in minimising biochemical quality degradation relative to increased protein denaturation and structural damage in frozen storage; Observed negative effect on textural attributes with longer superchilling storage.	Gallart-Jornet et al. (2007)
Atlantic salmon (*Salmo salar*)	−1.4°C or −3.6°C up to 34 days	Vacuum packaging	Shelf-life doubled in superchilled sample compared to ice-chilled storage; textural hardness was significantly higher in fillets stored at −3.6°C compared to those stored at −1.4°C; higher degree of protein denaturation was observed in cod fillets stored at −1.4°C	Duun and Rustad (2008)
Boneless pork roasts	Superchilling at −2°C	Vacuum packaging (Dixievac®)	Significant increase in shelf-life compared to traditional chilling at +3.5°C; superchilled roasts maintained good sensory quality and low microbiological counts during the storage up to 16 weeks; drip loss was lower than chilled and temperature abused samples.	Duun et al. (2008)
Cold smoked salmon	−2°C for 28 days	—	Superchilling had a limited impact on some of the organoleptic properties (color and odor); the prevalence of *L. monocytogenes* was more after 28 d at −2°C/28 days than −2°C/14 days.	Beaufort et al. (2009)
Atlantic Salmon (*S. salar*) fillets	Storage at −1.5°C	CO_2:N_2 in MAP_1 (75:25); MAP_2 (25—75:25—75); MAP_3 (60—90:10—40); laminates of PA/PP or PA/PE with different gas-to-product volume (g/p) ratio (1.2—2.5)	Highest shelf life of 22 days was recorded for Salmon fillets stored in combination with superchilling and MAP (CO_2: N2 90:10) in comparison to 11 days in traditionally chilled fillets.	Fernández et al. (2009)
Nile tilapia (*Oreochromis niloticus*)	Storage at −1°C	MAP (50% CO_2/50% N_2)	Storage at −1°C for 20 days in air-packaging was found to be the best condition for fresh tilapia fillets; MA packaging negatively influenced color, drip loss, and texture of products.	Cyprian et al. (2013)
Buffalo meat steaks (*Bubalus bubalis*)	Storage at −1°C to −2°C compared with 4°C and −18°C storage	Vacuum packaging	Based on microbiological counts and sensory evaluation, fresh buffalo meat steaks were stable for 30 days, 80 days and more than 180 days at 4°C, −1°C and −18°C temperature, respectively	Naveena et al. (2013)
Common carp (*Cyprinus carpio*) surimi	−1°C or −3°C, mixed with 4% commercial cryoprotectant blend (sucrose/sorbitol, 1:1)	—	Superchilling at −3°C with cryoprotectants maintained low microbiological counts throughout the storage period, inhibited lipid oxidation, and improved the microstructure of the protein gel compared with superchilled storage at −1°C and frozen storage at −18°C.	Liu et al. (2014a)
Atlantic salmon (*Salmo salar*)	−1.7°C up to 28 days	Vacuum packaging	No significant differences were observed between 3 and 14 days of storage but a decrease in liquid loss was noted at day 21 both at the center and surface of the superchilled samples.	Kaale et al. (2014)
Rabbit meat	Storage at −2.5°C and −4°C for 36 days	—	Shelf life of rabbit meat was increased by at least 3 times and 5.5 times by superchilled storage at −2.5°C and −4°C; the latter condition can markedly inhibit the deterioration of sensory and nutritional quality.	Lan et al. (2016)
Yellow-Feather Broiler Meat	Storage at −2°C	Modified atmosphere packaging (CO_2/N_2: 80%/20%)	Superchilled storage reduced the total viable counts by at least 2.5 log CFU/g in comparison to samples stored at 4°C.	Zhang et al. (2016)
Hairtail (*Trichiurus haumela*)	Storage at −3°C with immersion in 6.0 g/L tea polyphenols	Vacuum packaging	Tea polyphenols combined with superchilling was effective in preventing quality deterioration by lowering the activity of endogenous autolytic enzymes, inhibiting the lipid oxidation and microbial growth compared to superchilling alone and frozen storage (−18°C)	Luan et al. (2017)
Swimming Crab (*Portunus trituberculatus*)	Storage at −3°C	Packaged in a PA/PE pouch with mixed gas (MAP_1: 100% CO_2; MAP_2: 10% O_2/80% CO_2/10% N_2; MAP_3:10% O_2/60% CO_2/30% N_2; MAP_4: 10% O_2/40% CO_2/50% N_2)	Combination of superchilling and MAP_3 (10% O_2/60% CO_2/30% N_2) treatment prolonged the shelf life of swimming crab to 15—20 days. MAP_1 treatment showed a negative effect on the drip loss and overall acceptability.	Sun et al. (2017)

life, and superchilling offers a cost effective and simple method of achieving this target. The research works and trials so far indicate that some products respond more favorably to superchilling than others such as fish, seafood, and meat, in which extensive use of this technology showed promising results. However, the effect on ready to eat meat or fish has not been reported. The potential benefits of this technique are likely to be felt by manufacturers and the target of a superchilled chain all the way to the chilled-foods counter will be fulfilled.

Future challenges

A sudden change from traditional chilling, freezing, thawing to the more complex superchilling technology is difficult as the latter demands more accurate information on product variation and flow. Special care has to be taken prior to, during, and after, the superchilling process. Calculating the time and temperature distribution during superchilling process is a challenging task (Magnussen et al. 2008). To maintain the superchilled state, the product should not be exposed to any external influences such as temperature fluctuation. An appropriate packaging and strict control of temperature throughout the storage will only allow to get maximum benefits from this process. Any changes in temperature or storage condition may cause melting of ice crystals and recrystallization into large-sized ice crystals (Wu et al. 2014)

Another challenge is to define the optimal degree of superchilling to get the desired quality attributes and improved shelf-life (Magnussen et al. 2008). Most of the equipments are not suitable for the superchilling process – industry needs support from researchers and they should work together to design the appropriate equipment for superchilling process and develop softwares of chilling time, temperature, humidity, airflow and refrigeration load. Understanding the diversity of microbes under superchilling conditions will pave the way for ensuring the increased safety among consumers. More focus on how to control and keep the required storage temperature after initial superchilling is vital. Further research on energy savings due to superchilling and temperature control during distribution is needed, including different cold chain scenarios.

The majority of studies in the area of superchilling have focused on increased shelf life and quality changes of muscle foods during superchilled storage, however, to strengthen this process at a commercial level, more emphasis needs to be given to the on-line monitoring and control of the process. The introduction of on-line measurement techniques to understand and control the ice fraction in specific products during superchilling and superchilled storage (Stevik et al. 2010) is an urgent need. By introducing these techniques to the process and relating them to the quality of the end-product, optimum superchilling for each product can be achieved. Integrating the superchilling process in the existing automated commercial production lines is another challenge.

Conclusions

Superchilling process offers three benefits: maintaining freshness, preserving quality and increasing shelf-life. Another beneficial aspect of superchilling process is lower energy requirements relative to frozen storage. Superchilling ensures that the product appear non-frozen despite the presence of ice in it. Automated processing needs to be developed to fully exploit the advantages of superchilling. Establishing the relationship between biochemical, and sensory quality versus ice crystal growth for each product will augment its usage. Superchilling preservation technology is still in its infancy and the consumer awareness for superchilled products is currently very low. The potential benefits of this process can be applied in muscle foods if the positive effects of superchilling are exploited commercially.

Conflict of interest

The authors declare no conflict of interest.

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