Food Science of Animal Products

Review Article

Incomplete freezing strategies for achieving long-lasting preservation of muscle foods: categories, regulations, efficiencies and challenges

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Abstract: The modern development of commercial circulation has forced the preservation of muscle foods to achieve technology innovation and transformation. Incomplete freezing is a promising technology for muscle food preservation, which can be used as a compromise strategy between traditional chilling and freezing. It can not only inhibit microorganism and enzymatic activity with a cooler environment, but also avoid the severe drip loss triggered by the generous ice crystals, thus maintaining a stable quality in the storage, transportation and consumption. However, confusing nomenclature and blurred boundary appeared in the related researches is fatal to the standardization system formation and future development. To provide a clear reference, the review describes the moisture/ice-crystal behavior succession during cooling stage of muscle foods, and takes it as guideline to classify incomplete freezing techniques into 4 categories: superchilling (from 0 °C to freezing point), micro-freezing (from freezing point to 2 °C below freezing point), partial freezing (from 2 °C below freezing point to phase-transition endpoint) and sub-freezing (from phase-transition endpoint to –18 °C). As reported, the shelf life of muscle foods could be extended by 1.4–8 times under vaious incomplete freezing compared to traditional chilling. Meaningful regulatory approaches (cryoprotectant, packaging, physical field, etc.) were also highlighted, which could further enhance the practical effects of incomplete freezing by inhibiting vital deterioration factors such as microbial growth, oxidative reactions and ice crystal formation. Finally, refinement, real-time, industrialization and digitization as main challenges were presented to provide valuable references for the future development of muscle food cold chain circulation based on incomplete freezing.

Keywords: incomplete freezing; muscle foods; shelf life; ice crystal formation; superchilling

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1 Introduction

For thousands of years, regardless of scientific and technological developments related to nature, life, engineering, and materials, cryogenic environment have remained the most common, convenient and effective approach to extend the shelf life of muscle foods, probably due to the direct inhibition for the spoilage and deterioration factors of muscle food, such as microorganisms, endogenous enzymes, and oxidative reactions, etc. Therefore, cryogenic environment has been utilized as the medium for almost all subsequent preservation methods. Generally speaking, cryogenic environment-based preservation approaches mainly refer to chilling preservation (0–4 °C) and freezing preservation (below –18 °C), which can satisfy the short-term and long-term freshness pursuit for muscle foods respectively. While a proper chilling is beneficial for post-slaughter aging and tenderness of muscle foods, however, the cryogenic environment has no capacity to long-lastingly inhibit microbial activity and oxidative degradation of myofibrillar protein (MP)[1]. Even with the application of various novel packaging and assisted technologies, the freshness limit of muscle foods under chilling condition does not exceed 21 d[2–4]. For freezing, the inevitable ice crystallization will also cause irreversible mechanical damage to muscle fibers, leading to severe damage to fiber structure and freezing denaturation of MP, which cannot be counteracted even by ultra-rapid freezing at –80 °C[5]. While freezing can deeply reduce biochemical changes, thus, it can also cause degradation of water holding capacity (WHC), color, tenderness and flavor[6]. At the same time, the circulation scope and scale of fresh muscle foods continues to expand with the development of world trade, and the effectiveness of traditional chilling and freezing preservation is gradually failing to satisfy the dual pursuit of superior edible and nutritional values. All these situations force the preservation technologies of muscle foods to accomplish innovation and transformation.

Although some assisted technologies such as electric fields, magnetic fields, plasma, and active packaging can effectively mitigate these disadvantages in the chilling and freezing process to varying degrees, temperature management is still pursued due to its cheapness and convenience. In this regard, the temperature range between chilling and freezing (–18–0 °C) has been gradually applied to achieve different degrees of preservation requirements, and this type of preservation technology has been named variously such as superichilling, deep-chilling, micro-freezing, sub-freezing, and partial freezing, which are collectively referred to as the incomplete freezing technology in present paper. Temperature located in the incomplete freezing range can further inhibit

microbial activity and prevent the growth of most spoilage bacteria[7]. Negative impacts on muscle structure caused by large amounts of ice crystals as well as considerable energy consumption for freezing and thawing process are also minimized at the same time. The combined effect of complementary strength and weakness dramatically improves the stability of muscle food during storage. In fact, a similar concept has been proposed as early as 1920 and is nowadays applied in the long-lasting preservation of various muscle foods such as beef, mutton, pork, and fish. During this period, it has been gradually realized that the incomplete freezing temperature has an siginificant influence on the preservation of muscle foods, and that the optimum incomplete freezing degree requires to be determined[8]. However, the nomenclature and boundaries of the incomplete freezing degree have evolved to be vague and difficult to define in the exploration process, which has led to an imprecision in grasping and developing the corresponding technologies. In order to provide a better understanding and reference of incomplete freezing strategies for muscle foods, this review summarizes the relevant theoretical knowledge, classifies the boundary for various incomplete freezing categories, and compiles the current research findings on this basis.

2 Moisture/ice-crystal behavior succession during cooling stage and incomplete freezing classification

2.1 Ice crystallization and quality deterioration of muscle foods

Crystallization is an essential thermophysical phenomenon that occurs in the phase change stage where water molecules undergo a directional arrangement and transform into ice[9]. When the center temperature of muscle foods drops to the freezing point, free water distributed in the fiber interstitial spaces will firstly be frozen on the surface layer. As the cooling deepens, the formed ice absorbs the interior heat and the frozen interface gradually pushes inward[10]. Ice crystals begin to extrude the spatial structure of intact MP, and the accompanying microbial, enzymatic, and oxidative reactions also de-helicalize the MP molecules[11]. Generally speaking, mild oxidation could improve the WHC of MP. Once oxidation has intensified, the combination of mechanical and biochemical damage results in the exposure of a large amount of hydrophobic groups that originally hidden inside the MP molecules structure, which decreases the WHC as shown in Figure 1. With the gradual freezing of moisture in the cell interstitial space, in addition, the increase concentration of some solutes causes the extracellular environment to become viscous and tend toward the glassy state. In this case, intracellular moisture will cross the cell membrane to extracellular due to osmotic pressure. Immobile water (the main moisture state in muscle foods, existed between muscle bundle, myofibrils and cell membranes) that was tightly bound to the muscle fibers begins to escape from the fetter and migrates to the muscle fiber gap. This part of free water eventually completes crystallization during cooling. Such processes lead to an increasing volume of extracellular ice crystals, which continuously exert mechanical pressure on the muscle fibers until a basic heat equilibrium is reached between the muscle food and ice crystals[10]. In this period, ice crystals puncture muscle cells resulting in leakage of oxidizing substances (such as peroxide), which in combination with the prolonged exposure to oxygen exacerbates the oxidation of MP and lipids in muscle foods. During subsequent thawing, although, the moisture from melting ice crystals may be partially

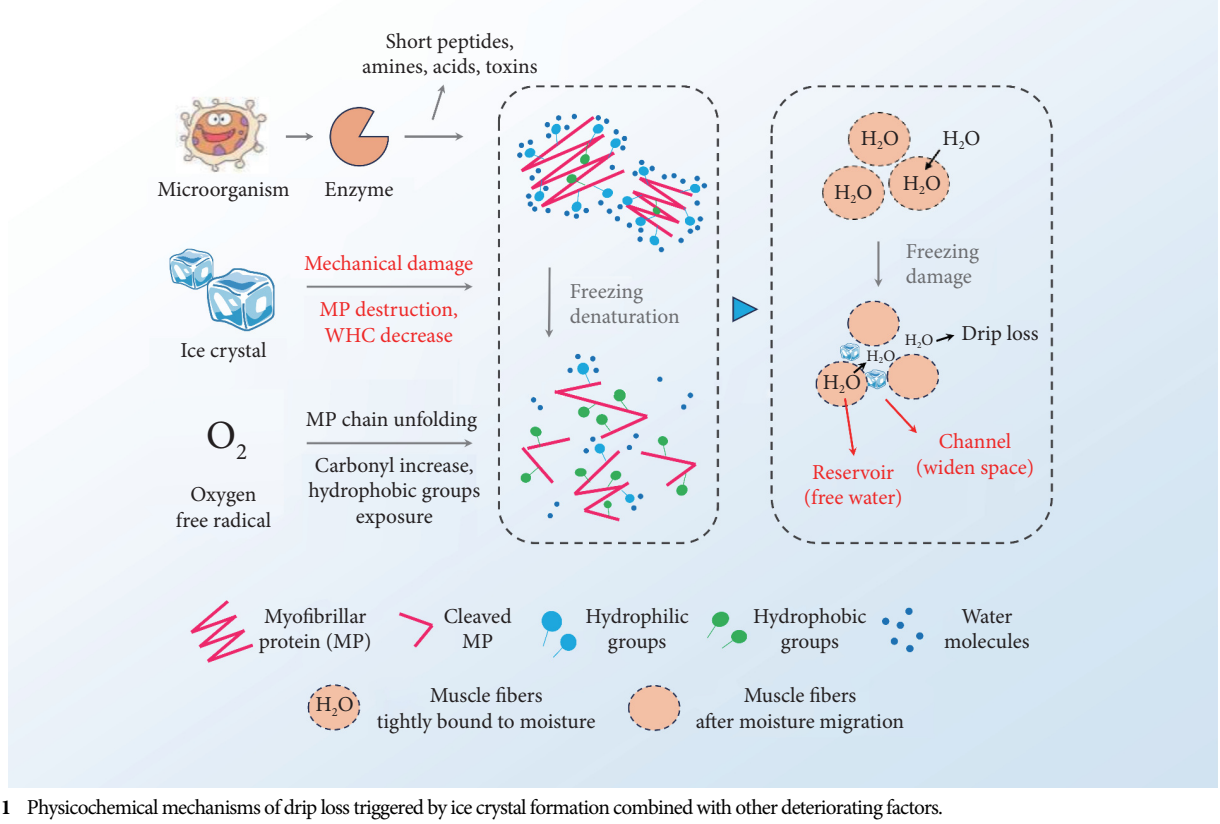

Figure 1 Physicochemical mechanisms of drip loss triggered by ice crystal formation combined with other deteriorating factors.

reabsorbed by some intact fibers. But, it is frustrating that mechanical damage to muscle fibers persists during the thawing process and even secondary damage occurs due to ice crystal recrystallization. In addition, persistent MP oxidative denaturation is increasingly detrimental to WHC, leading to an active migration of immobile water to free water[12]. Therefore, the common view that "thawing and freezing are inverse processes" is only limited to the temperature course. In the repeated cycle of center temperature, we can find that the quality of muscle foods cannot be fully restored, which is attributed to the logic inherent in cryopreservation. The inevitable formation of ice crystals and the subsequent moisture migration are the source of the disparity. Therefore, investigating and controlling ice crystal behavior is essential for cold chain preservation of muscle foods.

2.2 Moisture/ice-crystal behavior succession in muscle foods during various cooling stage

During the freezing process, the center temperature of muscle foods does not decrease uniformly, but shows a 3-stage trend of rapid-gentle-rapid decrease (Figure 2A).

The internal moisture/ice-crystal behavior of muscle foods also appears different manifestations in different cooling stages, which can be summarized as follows. 1) Pre-cooling stage: a stage where the center temperature of muscle foods drops from the cooling onset to the ice formation temperature (initial freezing point (T_{if}), slightly below −1 °C). It is a simple temperature change stage that does not involve the formation of ice crystals. The temperature difference between the muscle foods and the environment pushes the center temperature to drop rapidly to the vicinity of T_{if} with an almost linear pattern, preparing for the moisture phase change. 2) Phase-transition stage: a stage where the center temperature of muscle foods drops from the T_{if} to the phase-transition endpoint (T_{pe}, about −5 °C) and achieves crystallization, which always been described by an extremely vital term "the maximum ice-crystal formation zone". Crystallization is a process whereby a crystalline phase is created as a consequence of molecular aggregation in a solution, leading to the formation of nuclei and the later crystal growth[13]. Nucleation driving force is actived as the center temperature of muscle foods drops below T_{if}, crystallization energy level is gradually overcome and stable nuclei are formed. Accordingly, moisture in various distribution states begins to move in the manner previously described, attaching to the existing nuclei or crystallizing independently during the continue cooling. Consequently, 2 types of moisture/ice-crystal behaviors existed in the phase-transition stage: nucleation and growth[9]. However, there is no clear time or temperature boundary between those. The only reliance is on physicochemical markers such as mechanical damage, protein hydrophobicity and degradation, which is one of the reasons why the incomplete freezing degree is not well managed. The phase-transition from liquid water to solid water releases latent heat, which offsets the cryogenic environment to a certain extent, thus reducing the cooling rate of muscle foods. As the center temperature drops to about −5 °C, 80% of water has accomplished crystallization and a frozen meat is almost formed[11]. Most of the moisture/ice-crystal behavior occurs during the phase-transition stage, which is the most essential stage of the cooling process and

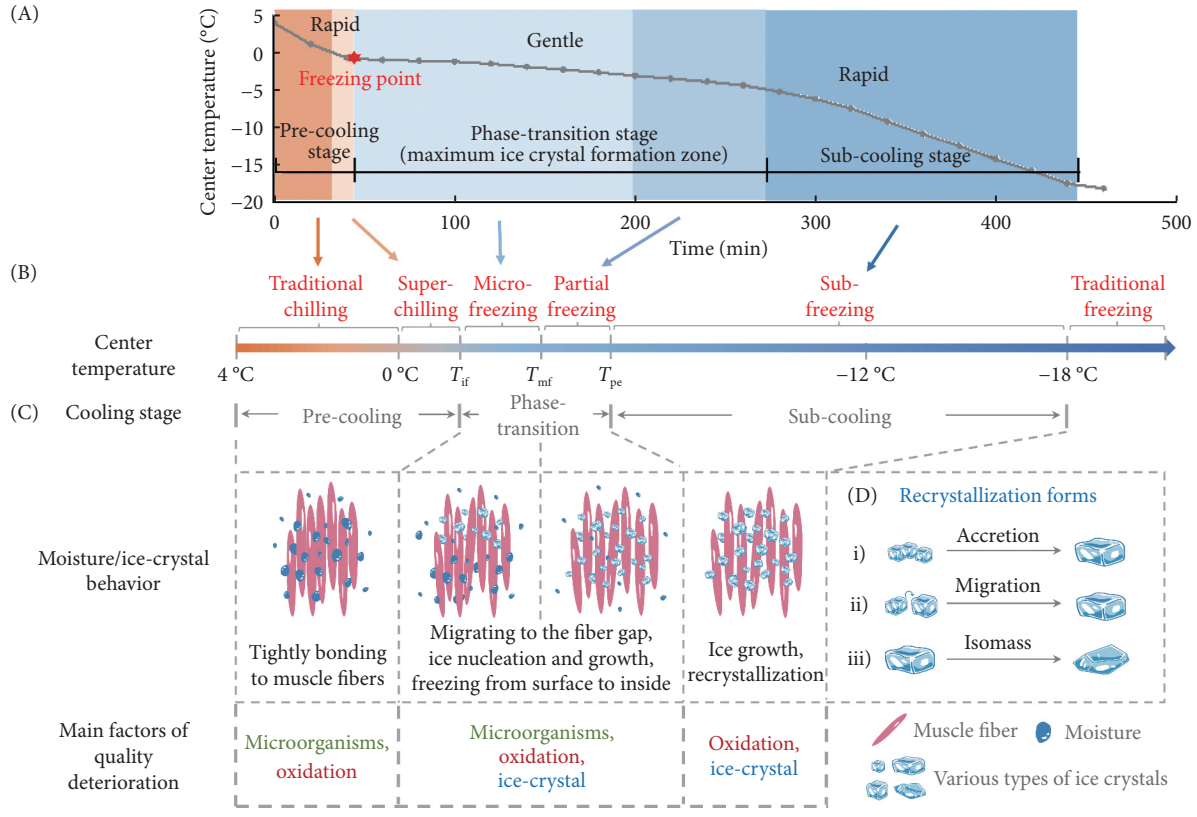

Figure 2 Classification and theoretical foundations for incomplete freezing categories of muscle foods. (A) Representive freezing curve of muscle foods. Source: center temperature variation of pork loins (approximately 100 g) at an initial temperature of 4 °C in a −18 °C environment recorded at 1 min intervals. (B) Classification of incomplete freezing categories based on various cooling stage. (C) Moisture/ice crystal behavior succession and the main quality deterioration factors for various cooling stage. (D) Three mechanisms of ice crystal recrystallization.

directly determines the quality of muscle foods after storage. In general, accelerating the phase-transition of muscle foods and applying the cooling effect uniformly to both extracellular and intracellular moisture is a classical strategy to minimize freezing damage. In this case, the moisture in muscle foods possesses an almost synergistic crystallization time, which in turn suppresses the active migration. Rapid and ultra-rapid freezing, therefore, prevent moisture dislocation, while the uniformly distributed ice crystals and the stable quality can also be observed[5]. 3) Sub-cooling stage: a stage refers to the remaining freezing process of muscle foods after passing through the phase-transition stage, which usually covers the temperature range of −18– −5 °C. After most of the moisture completes phase transition, the latent heat released is dramatically decreased, and the temperature difference between the muscle food and the cryogenic environment becomes the main driving force for cooling, again[12]. Whilst, the solid water shows a higher heat transfer rate than liquid water, which results in a faster cooling rate than previous stage. The ice nucleus has largely formed, but the growth of ice crystals continues in different forms: growth and recrystallization. Crystal growth proceeds in the manner described above, but recrystallization encompasses different scenarios. i) Accretion. Two or more close crystals with uniform combine to form a larger and independent ice crystal. ii) Migration. Two or more close crystals with varying sizes exist, and the larger ice crystal sacrifices the smaller one in exchange for its own secondary growth. iii) Isomass. The ice crystal changes in size and shape while the total crystal mass remains constant, and a larger, duller, and sharper ice crystal may be produced[9] (Figure 2D). In either case, we can speculate that recrystallization increases the mechanical damage to the microstructure of muscle foods due to its increased size. In fact, recrystallization usually causes severe secondary, tertiary, or even quaternary damage during sub-cooling and subsequent thawing process, further deteriorating the quality of muscle foods, which was confirmed by Qian et al.[5] who found that equivalent diameter of ice crystals in beef loin after 48 h storage at −20 and −80 °C had increased by 29.2% and 8.4% respectively compared to 24 h.

2.3 Incomplete freezing classification in muscle foods based on the moisture/ice-crystal behavior

In general, incomplete freezing could be described as a condition in which ice crystals originated and developed within muscle foods but did not ultimately form, and it involved a temperature interval situated between conventional chilling (0–4 °C) and conventional freezing (below −18 °C). In recent decades, however, definitions of the incomplete freezing degree at different cooling stages have been vague and abstract with the massive studies. For the same term "superchilling", for instance, Ando et al.[14] defined it as the range below 0 °C but where ice crystals have not yet formed, while Lu et al.[15], Pei et al.[16], Bao et al.[17], and Bellés et al.[6] defined it as −4, −3, −2 and −1 °C, respectively. This setting spans 2 cooling stages of muscle foods with entirely distinct moisture/ice-crystal behaviors, and creates a wide variation in the impact on the storage quality of muscle foods. Therefore, a systematic classification and definition of incomplete freezing in muscle foods is necessary to improve the prospects for its standardized application. As mentioned before, moisture/ice-crystal behavior is a key factor affecting the frozen quality of muscle foods, and should be taken as theoretical basis for the definition and classification of incomplete freezing technologies. The relevant ideas in this review have been visualized in Figure 2B.

2.3.1 *Supercooling*

Supercooling (0 °C–T_{if}) is a terrible confusion that more and more researchers extend the concept of "superchilling" of muscle foods from the uncrystallized state to below the T_{if}. In chemistry field, superchilling refers to a status in which the temperature of a material is below the theoretical freezing point but no solidification occurs[18]. This is a type of sub-stable state, and is easy to be disturbed by some tiny perturbations to induce crystallization, such as the input of few identical crystals, or a further decrease in temperature. But the "superchilling" itself is still an unfrozen state. In addition, the so-called "superchilling" is still "chilling" rather than some words as "freezing" and "crystallization", it should not be involved in the subsequent formation of ice crystals, which agrees with the study of Ando et al.[14]. Therefore, "superchilling" storage of muscle foods should be a cryogenic extension of traditional chilling storage, and the T_{if} of muscle foods is the maximum limit of such an extension. In this temperature range, the microbial and enzyme activity in muscle foods are further inhibited. Bellés et al.[6] found that the total number of colonies of lamb shanks almost did not grow with storing at −1 °C for 7 d, and was significantly lower ($P < 0.05$) than that of the same conditions at 4 °C after 28 d. Enterobacteriaceae, *Lactobacillus*, and *Pseudomonas* were all detected in the middle and later storage, indicating the more potent inhibitory effect of superchilling on microorganisms in muscle foods compared to normal chilling. Determining the T_{if} of muscle foods is a necessary prerequisite for finding the superchilling threshold to maximize its benefits for storage. We can conclude from the freezing curve (Figure 2A) that a center temperature can be identified as the T_{if} if it is followed by a sudden and prolonged slowdown in the curve slope and a clear inflection point in the function image. It is determined by the nature of the muscle food itself rather than some external conditions. The investigated T_{if} of some muscle foods have been summarized in Table 1 as a reference for superchilling storage strategy.

Table 1 Initial freezing point (T_{if}) of some muscle foods.

Category of muscle foods	T_{if} (°C)	Reference
Yellowfin tuna	−1.7	[19]
Beef loin	−1.7	[20]
Haitail	−1.9	[21]
Salmon	−1.1	[22]
Beef rump	−1.4	[23]
Pork loin	−1.0	[24]

2.3.2 *Micro-freezing*

Micro-freezing (T_{if}–T_{mf}) storage is defined in this review as the process by which the center temperature of muscle foods is reduced from T_{if} to micro-freezing temperature (T_{mf}), which is the most controversial aspect of the incomplete freezing category. Magnussen et al.[10] argued that the preservation mean in this interval should be referred to as superchilling together with the previous one. However, based on continuous researches and the introduction of refined concepts such as chilling and ice-chilling meat, micro-freezing should be proposed as a separate concept from the superchilling. T_{mf} is generally approximately 2 °C cooler than T_{if}, which is considered by the ice fraction. In the state of micro-freezing, a small percentage of moisture (5%–30%) concentrated on the surface of muscle foods can be frozen, and an

ice layer about 1–3 mm thick is formed and absorbs heat from the inside of the muscle food, ultimately leading to an equilibrium between the internal and external temperatures during storage[7,9]. Stevik et al.[25] suggested that the maximum percentage of frozen moisture is 30% under micro-freezing, and the drip loss will be unacceptable if exceeded. A previous study illustrated that the ice fraction of pork increased from 0.00% to 37.21% when the storage temperature was lowered from −3 to −1 °C, a temperature interval of about 2 °C was selected to define the micro-frozing. Micro-freezing provides a natural ice layer for storage and preservation of muscle foods, which further stabilizes the storage quality while avoiding the necessity of external ice and ultra-cold environment during storage and transportation. Thus, the transportation costs, energy loss and subsequent environmental contamination can be also mitigated to a great extent. In addition, the appropriate amount and volume of extracellular ice crystals altered the physical structure of muscle fibers, contributing to the tenderness of muscle foods as demonstrated by Lu et al.[15,26]. As opposed to supercooling, there is not a positive linear correlation between the micro-freezing efficacy and environment temperature, which is determined by the ice proportion and the mechanical damage it exerts to muscle tissue. In general, the lower the environment temperature, the higher the micro-freezing degree, the more frozen moisture and the more severe the mechanical damage are triggered. On the other hand, a lower environment temperature also accelerates the cooling rate in the surface layer of muscle foods, and the corresponding slight ice crystals can reduce the concern about structural damage. Therefore, the micro-freezing degree induced by environment temperature is essential for the quality of muscle foods. Ding et al.[8] found that the −3 °C environment effectively inhibited microbial contamination and lipid oxidation in pork, but was detrimental to the WHC and tenderness compared to −2 °C. Cui et al.[27] also concluded that −3.5 °C accelerated the disruption of muscle structural integrity in pork and fish, gradually widening the pathway for moisture loss. Such consequences are highly correlated with the unsuitable micro-freezing degree.

2.3.3 *Partial freezing*

Starting at the bottom threshold of micro-freezing storage, ice crystal generation within muscle foods exceeds 30% and gradually increases. Until the T_{pe} (about −5 °C), the ice crystals form is basically determined with the finish of phase-transition, and the storage category in this temperature range is called partial freezing (T_{mf}–T_{pe}). In contrast to micro-freezing, partial freezing pushes the moisture/ice interface inside muscle foods to varying degrees inward. The condensed moisture and its reduced activity modify the physiological and biochemical reactions of the microorganisms, thus inhibiting bacterial reproduction and achieving a longer storage period[28]. Fewer ice crystals with partially freezing also reduce thawing loss compared to deeper freezing, and even segmentation and processing can be carried out directly to a slightly firmer state without the thawing process[29]. This creates the advantages of improving processing efficiency, shortening production cycles and avoiding energy waste caused by prolonged freezing at lower temperatures. However, the division of micro-freezing limits the scope of partial freezing to generally no more than 2 °C (about −5– −3.7 to −3.3 °C), leading to a few studies and applications in the partial freezing interval. −4 °C is the most common environment temperature in the context of partial freezing studies such as Lu et al.[15,26] and Shi et al.[28].

2.3.4 *Sub-freezing*

Qian et al.[30] characterized the sub-freezing storage of muscle foods in the range of −12– −6 °C by low-field nuclear magnetic resonance technique. They found that the content of free water in muscle foods was remarkably lower ($P < 0.05$) than normal chilling (4 °C) and superchilling storage (−1 °C) after its center temperature was dropped to −6 °C, and no significant difference was found between −12 and −18 °C for free water content and shelf life indicators. Therefore, −12 °C can be regarded as a potential limit of freezing temperature as an alternative to −18 °C due to energy consumption considerations, it can also be recognized as the minimum temperature at which incomplete freezing technology can be applied in practice to differentiate it from conventional freezing. Additionally, sub-freezing (T_{pe}– −18 °C) raises the starting temperature for the thawing procedure of muscle foods, which can also prevent severe recrystallization, drip loss, and MP oxidation resulting from excessively prolonged freezing time[31]. According to our previous discussion, the sub-freezing interval is located at the ice crystal growth and recrystallization stage on the basis of nucleus formation, which is already infinitely close or even equivalent to complete freezing at some level except for the difference in the growing volume of ice crystals. Therefore, the sub-freezing quality of muscle foods is more dependent on the ice crystal behavior induced by the cooling rate. Zhu et al.[32] found that MP structure in pork was more stable at −12 °C relative to −6 °C. Li et al.[33] also discovered that rapid sub-freezing (cooling to a center temperature of −7 °C under −38 °C environment) was more beneficial in alleviating structural damage to muscle fibers and oxidative denaturation of MP. Normally, sub-freezing is capable to reach a storage period that could not be achieved by all previous methods of incomplete freezing. Quality stabilization periods exceeding 70, 160 and 365 d were observed in the studies of Liang et al.[34], Qian et al.[30] and Coombs et al.[35], respectively.

3 Regulatory approaches for incomplete freezing in muscle foods

3.1 Extending the supercooling degree

In the pre-cooling stage of muscle foods, the rapid drop of the center temperature triggered by the temperature difference can not provide enough time for crystallization, resulting in the water remaining in the liquid state when the temperature has reached near or below T_{if}. Such is the phenomenon of "supercooling", as we briefly mentioned previously. And the difference between the theoretical T_{if} and the actual nucleation temperature (T_{an}) is known as the "sub-cooling degree". A minor internal temperature rise is possible in this temperature range, due to the release of latent heat (334 kJ/kg for pure water) in preparation for crystallization. In general, the higher the supercooling degree, the more ice crystals are formed instantaneously during nucleation, and the smaller the size of ice crystals. As the initial nucleation temperature drops, moreover, the nucleation rate increases by a multiple of 10 °C, which in turn shortens the phase-transition time. This is one of the main mechanisms by which rapid cooling and small volume and large quantity of ice crystals are commonly associated[36]. Thus, we can notice that the supercooling phenomenon allows the minimum threshold for superchilling storage technology to be extended from the theoretical T_{if} to the actual nucleation temperature, since the "supercooling zone" remains free of ice crystal formation and a

better preservation effecacy can be achieved due to lower environment temperature and the absence of mechanical damage. However, the superchilling zone is a sub-stable state as we introduced earlier. As the environment temperature continues to drop, once a tiny nucleus is formed, the water molecules rapidly complete an orderly directed arrangement. It renders crystallization an event that may occur at any time. Lin et al.[20] illustrated that the unstable superchilling state caused larger ice crystal size and more severe drip loss. Therefore, a class of techniques that can lower the actual nucleation temperature, increase the supercooling degree, and widen the supercooling zone is of research interest.

The application of physical field-assisted techniques in cooling environments is effective in improving the supercooling degree of muscle foods, and magnetic field is a representative strategy in this domain. Typically, water molecules exist in a form of hydrogen bond-stabilized clusters, each containing about 30–40 water molecules[37]. Molecular dynamics simulations carried out by Woo et al.[38] showed that the exertion of magnetic field causes rotational deorientation of water molecule clusters by the Lorentz force, thus destabilizing the hydrogen bonding and spliting the large clusters into multiple smaller ones as discribed in Figure 3A. Electric field-induced molecular oscillations and ultrasound-induced cavitation effects can also result in the depolymerization of water molecule clusters, thus setting up barriers to their directional alignment and aggregation. In addition, magnetic fields can also modify the distribution of water molecules and electrons, which in turn affects the macroscopic properties of water. A relative study had shown that the increased surface tension, apparent viscosity, and friction coefficient were observed with the assistance of magnetic-field, as well as the decrease of its mobility and activity[39–40]. Active water molecules increase the difficulty of reaching the critical radius of the already reduced nucleus size, thus prolonging the supercooling degree and delaying the phase-transition stage (Figure 3B). Moreover, the depolymerization of water molecule clusters also reduces the size of subsequent ice crystals, allowing a better maintenance of storage quality.

3.2 Raising the glass transition temperature

The theory of glass transition of muscle food is an essential physicochemical concept. With the moisture in muscle foods gradually condenses into ice crystals after a certain degree of freezing, the increased concentration of the remaining cellular fluid leads to an extremely viscous state, which is called the glassy state. Under the glassy state, the internal molecular chains of muscle foods are fixed, some substances like water, proteins, and carbohydrates will lose their mobility, as well as the almost stagnant reactions such as recrystallization, moisture migration, and MP oxidation[41]. The entire muscle food system is kept in a perfectly stable state. Muscle food stored in the glassy state can commonly achieve a long shelf life of freshness. Yet, the glass transition temperature (T_g) of muscle foods are usually from –30 to –20 °C or even lower, which can not be achieved under traditional freezing conditions, let alone in the incomplete freezing range we have described. Therefore, the effectiveness of incomplete freezing of muscle foods can potentially be further enhanced by increasing T_g, so that it approaches or falls within the temperature range of incomplete freezing. Sugar-based cryoprotectants can fulfill the function. In principle, the main components of muscle foods and their molecular weights are the major factors in determining its T_g. The combinaton of saccharides and muscle foods can increase the relative molecular mass of the entire system and accelerates the viscosity, thus improving the T_g. Buera et al.[41] added sucrose,

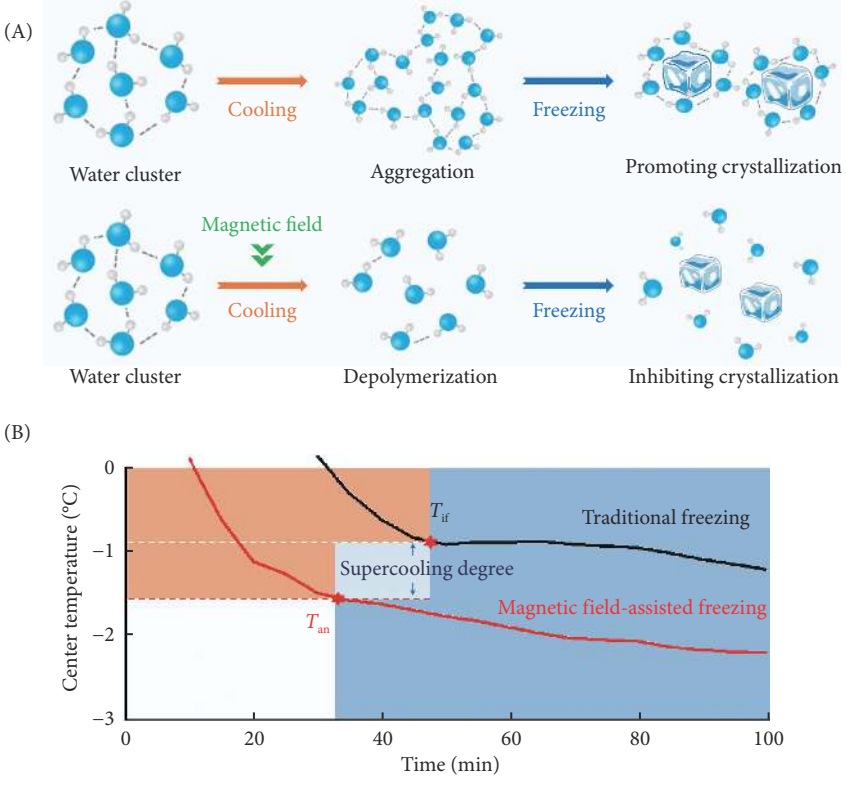

Figure 3 Magnetic field-induced supercooling effect in muscle foods. (A) Molecular mechanisms of ice crystallization inhibition by magnetic field. (B) Supercooling degree of muscle foods induced by magnetic field. Traditional freezing, center temperature variation of pork loins (approximately 100 g) at an initial temperature of 4 °C in a –18 °C environment recorded at 1 min intervals. Magnetic field-assisted freezing, a 5 mT stastic magnetic field exerted on the condition of the traditional freezing.

sorbitol, mannitol, gum arabic, and carrageenan to minced beef and revealed that the T_g of beef increased to approximately −13 °C, and could significantly inhibit the increase in total volatile basic nitrogen (TVB-N) content and thiobarbituric acid reactive substances (TBARS) value within 6 months of storage at −9 °C. Kovačević et al.[42] observed that T_g of minced chicken can be significantly increased by polydextrose with a positive concentration dependence. Hydrophilic hydroxyl groups are usually enriched in the molecular chains of polysaccharides, such as sodium alginate, konjac gum and sucrose. In their mutual binding with MP of muscle food through covalent force, on the one hand, it can protect the stabilized structure of MP from extrusion and destruction by ice crystals. On the other hand, it can form a large variety of hydrogen bonds with water molecules to improve the WHC of MP, which avoids the drip loss caused by the massive moisture migration. Thus, a sugar-based cryoprotectant can be used as an additive ingredient in the incomplete freezing and preservation process of muscle foods. Therefore, cryoprotectants represented by polysaccharides can be utilized as an additive component in the incomplete freezing of muscle foods. However, it is more suitable for the application of the minced muscle foods system due to the adequate interactions, but is restricted to the regular integral muscle.

3.3 Mitigating the microbial contamination and oxidative stress

Incomplete freezing mainly provides a favorable environment for muscle foods preservation, indeed, and a large amount of regulatory space can also be imposed on the muscle surface. Some antimicrobial and antioxidant approaches have the potential to further extend the shelf life of muscle foods, especially for the lower ones including superchilling and micro-freezing. Physical field-assisted techniques can also be realized to inhibit microbial activities in muscle foods by affecting cellular respiration and membrane permeability. We can conclude that it is meaningful for physical fields to play their roles in the full scope of incomplete freezing. Besides, a variety of packaging modes are progressively being adopted for superchilling or micro-freezing storage of muscle foods. It mainly comprises conventional packaging methods dominated by modified atmosphere packaging and vacuum packaging, as well as functional active packaging prepared by encapsulating antimicrobial or antioxidant active agents, sometimes in direct contact with the muscle foods, in some suitable substrates. Bellés et al.[6] developed an O_2-enriched and an anaerobic atmosphere for superchilling storage of lamb slices. Pei et al.[16] prepared an epigallocatechin gallate (EGCG) active coating for micro-freezing storage of large yellow croaker, which effectively inhibited the MP oxidation by lowering H_2O_2 generation and protecting secondary and tertiary structures of MP.

In summary, the regulatory approaches of incomplete freezing for muscle foods mainly involves several aspects as illustrated in Figure 4. 1) Exerting the assistance of physical fields. 2) Adding cryoprotectants, antimicrobials, and antioxidants. 3) Implementing suitable packaging modes.

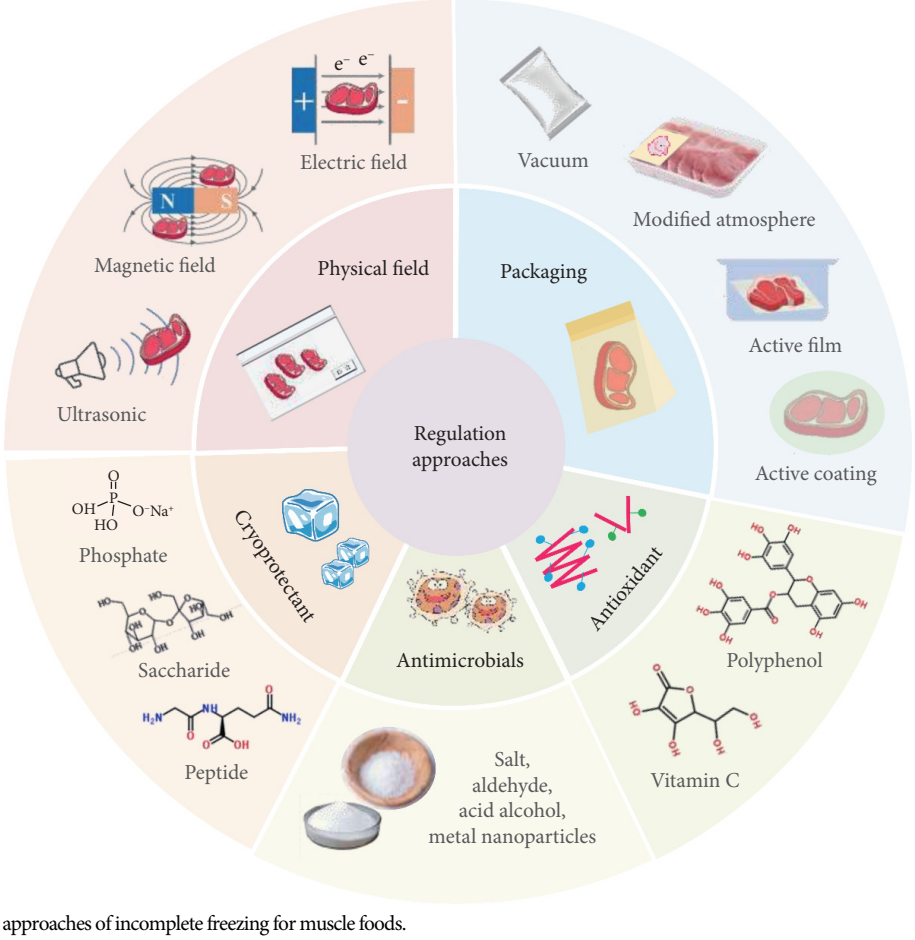

Figure 4 Main regulatory approaches of incomplete freezing for muscle foods.

4 Quality maintenance of muscle foods by incomplete freezing

For the maintenance of freshness, edible value, and sensory properties of muscle foods, a minimum level of processing is progressively demanded by consumers. As a compromise strategy between traditional chilling and freezing, incomplete freezing has been applied to muscle foods with varying degrees of preservation requirement[9]. To harmonize the language, the incomplete freezing degree consistent with the introduction of the present review will be used to describe the various studies, which may results to some differences from themselves. Compromise strategies were first contributed to the preservation of aquatic products due to their superior nutritional value and susceptibility to spoilage, while incomplete freezing of meat appeared later.

Earlier, Duun et al.[43] reported that micro-freezing storage at −2.2 °C delayed the growth of microbial synthesis to the upper limit of Atlantic cods by approximately 4 weeks relative to normal ice chilling. Additionally, 44.44% of drip loss was conserved compared to −20 °C freezing, although the difference was not statistically significant when freezing at −40 °C. These findings supported the substantial advantages of the micro-freezing in terms of extending freshness and reducing energy consumption. Subsequently, Liu et al.[44] proposed that although microbial activity and MP degradation in grass carps were suppressed by −3 °C micro-freezing, the intra- and extra-cellular ice crystals generated after 10 d led to deterioration of the WHC and texture of fish. Sun et al.[45] demonstrated a marked MP oxidative denaturation in *Litopenaeus vannamei* after 4 weeks of micro-freezing storage at −3 °C, as evidenced by the elevated carbonyl group content and surface hydrophobicity, as well as the decreased sulfhydryl group content and Ca^{2+}-ATPase activity. Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) results also showed a clear degradation of α-actinin and troponin I, indicating that the storage quality of muscle foods was also considerably decided on the ice crystal behavior even in the micro-freezing state. The tactics of raising the storage temperature could not entirely avoid it, as a phenomenon of intra- and extra-cellular ice crystals leading to tissue protease leakage from lysosomes were observed in −1.5 °C micro-freezing storage of Atlantic salmon by Bahuaud et al.[46]. Hence, regulatory approaches of ice crystal behavior is necessary, and acceleration is the most intuitive way. Kaale et al.[22] adjusted the heat transfer rate at different temperature by an Impingement Advantec Lab Freezer and rapidly cooled salmon fillets to a center temperature of −1.7 °C at −30 °C environment with a higher cooling rate of 227 W/(m^2·K). They found that the equivalent diameter of ice crystals in salmon fillets shrank by 23.39% after 1 d at this condition compared to cooling at −20 °C with a slower cooling (153 W/(m^2·K)). During the subsequent growth phase, moreover, ice crystals also remained relatively stable in their size. In another study, the drip loss of pork at −3 °C micro-freezing storage was even lower than −2 °C, which directly reversed our common knowledge about the relationship between ice crystal quantity and drip loss (20.85% and 37.21% ice crystals in pork at −2 and −3 °C storage, respectively)[8]. Furthermore, the deeper micro-freezing storage at −3 °C also notably prevented the elevation of colony counts, TVB-N contents, and oxidation of MP/lipids in pork compared to −1 and −2 °C storage. It followed that greater cooling rate prior to achieving the target temperature is crucial for efficient storage.

Although the incomplete freezing of meat was developed later because of the pervasiveness of conventional freezing both in factories and at home, it has also received more investigations in recent years owing to the emerging requirements of cold chain preservation and transportation. Liu et al.[47] and Pomponio et al.[48] demonstrated that superchilling storage at −1 °C prolonged the freshness of beef and pork for 12 d and 8 weeks, respectively. This dramatic disparity is attributed to the vacuum hypoxic packaging practiced in the latter one. For cooked meat products, incomplete freezing is also an efficient preservation strategy. Duun et al.[49] discovered that roasted boneless pork shanks stored at −2 °C maintained lower colony counts throughout the 16 weeks storage period, whereas traditional chilling at 3.5 °C maintained it for only about 2 weeks. Moreover, they simulated temperature fluctuations and electricity outages during cold chain storage, and frontally suggested that temperature fluctuations should be avoided in micro-freezing storage because the crystallization degree of products is closely related on temperature. In view of that, Tao et al.[50] investigated the impact of temperature fluctuations centered at −3 °C on the micro-freezing storage of pork tenderloin. The outcomes indicated that both (−3 ± 3) °C and (−3 ± 5) °C placed pork loins in an iterative state of freezing-thawing cycles, leading to WHC decrease, myofibrillar rupture, and lipid oxidation, and the deterioration was positively correlated with the fluctuation amplitude. Moreover, Cui et al.[27] performed a more refined temperature fluctuation using −3.5 °C as a benchmark, and they revealed that (−3.5 ± 2) °C also led to similar quality deterioration of pork loins and salmon at 15 d. But no noticeable difference in quality parameters appeared between (−3.5 ± 1) °C and a constant temperature. These provide a technical reference for the development of micro-freezing and partial freezing equipment, which must stabilize the environment temperature inside the equipment within a range of ± 1 °C. Deeper incomplete freezing is less affected by fluctuations in ambient temperature since it rarely involves the thawing of ice crystals and already exhibits the characteristics of frozen foods for long-lasting preservation. For instance, partial freezing at −4 °C extended the shelf life of rabbit meat to 36 d, much longer than at −2.5 °C (20 d) and 4 °C (6 d)[51]. However, drip loss from ice crystals was not considered in this study. Lu et al.[15] also observed that partial freezing at −4 °C prolonged the shelf life of Chinese yellow beef by 2.4 times in comparison with at 2 °C, but the 8-week storage sample's drip loss was twice as much as the frozen sample (−18 °C). Although the troponin T and desmin were better protected, the myofibrillar gap gradually enlarged by the growth of ice crystals during the 12 weeks storage period[26]. Li et al.[33] showed that sub-freezing (−7 °C) caused more drip loss and cooking loss compared to superchilling (−1 °C) during short-term storage (6 d), but it could be improved by accelerating the freezing rate.

In conclusion, incomplete freezing is an effective, pervasive, energy-efficient, and flexibly adjustable approach for the storage and preservation of muscle foods (Table 2). But low degree of incomplete freezing is unable to fully inhibit microbial growth and oxidative denaturation, resulting in a shelf life mostly limited for 20 d. Although higher degree of incomplete freezing can substantially extend the shelf life, overgrowth of ice crystals lead to an inevitable drip loss. Thus, maintaining the storage quality of muscle foods depends critically on establishing a balance that suppresses microbial activity and MP denaturation, and avoids the overgrowth of ice crystals. But it is quite difficult to realize in theory and apply in practice. Relatively, exerting some regulatory approaches to adjust the relevant factors is a feasible solution.

Table 2 Methods, materials, conditions and effectiveness of incomplete freezing on the shelf life of muscle foods.

Category of incomplete freezing	Environment temperature (°C)	Category of muscle foods	Shelf life (extended (day), total (day), and multiple)	Period of quality stabilization (day)	Other meaningful condition	Reference
Micro-freezing	−2.2	Atlantic cod	34, 42, 5.25		Vacuum packaging	[43]
Micro-freezing	−3.0	Grass carp	About 6, 21, about 1.4			[44]
Micro-freezing	−3.0	*Litopenaeus vannamei*		32		[45]
Micro-freezing	−1.5	Atlantic salmon		32		[46]
Micro-freezing	−1.7	Salmon fillet		14	Rapid freezing	[22]
Superchilling, micro-freezing	−3	Pork loin	About 10, 35, about 1.4			[8]
Superchilling	−1	Beef	12, 20, 2.5			[47]
Superchilling	−1	Pork loin	56, 84, 3.0		Vacuum packaging; rapid freezing	[48]
Micro-freezing	−2	Pork roast	98, 112, 8		Vacuum packaging	[49]
Micro-freezing/ partial freezing	−2.5/−4	Rabbit meat	14, 20, 3.33/30, 36, 6			[51]
Partial freezing	−4	Beef loin	49, 84, 2.4		Vacuum packaging	[15]
Sub-freezing	−7	Beef loin		294	Vacuum packaging; rapid freezing	[33]

5 Quality maintenance of muscle foods by combination of incomplete freezing and regulatory approaches

To further ameliorate the potential negative effects of incomplete freezing, it is profitable and convenient to exert appropriate regulations in storage systems where cryogenic environment as the main technology factor (Table 3).

The addition of cryoprotectants, antimicrobials, and antioxidants is the most intuitive and economical manner, as it does not involve too complex techniques and parameters. Even a simple treatment of brine immersion (2.5% for 2 d before storage) can extend the storage period of cod loins by 6 d at −2 °C, which is enough to prove its effectiveness[52]. For cryoprotectants, sucrose and sorbitol mixtures are the most common type of commercial cryoprotectant, which was used in the micro-freezing storage of carp by Liu et al.[53]. They found that the addition of 4% sucrose and sorbitol mixture (1:1) reduced the moisture activity of carp surimi, prevented the MP oxidative denaturation and mitigated the mechanical damage, thus protecting the storage quality of surimi at −3 °C. However, only 2 impact factors (oxidation and ice crystal) were examined but microbial behavior was ignored. ε-Polylysine is a peptide preservative consisting of 25–35 *L*-lysine units that exhibit inhibitory effects on the colonization of both Gram-positive and Gram-negative bacteria[58]. Jia et al.[54] confirmed that the presence of 0.1 g/100 mL ε-polylysine significantly suppressed *Pseudoalteromonas* and *Psychromonas*, which were identified as the dominant spoilage organisms in Pacific white shrimp at 5 d of superchilling storage (0 °C). The decline in microbial activity retarded the biochemical reaction rate in shrimp and inhibited the elevation of TVB-N contents, putrescine, cadaverine and TBARS values, resulting in prolonged shelf life of 2 d compared to the control. Further, Cao et al.[1] compounded 0.3% ε-polylysine with 2 natural antioxidants (0.75% *Portulaca oleracea* extract and 0.03% luteolin) and discovered that it markedly mitigated the deterioration of physicochemical properties, freshness, and oxidization of beef, resulting 24 d of shelf life occurred at −1.5 °C. Similar findings were presented in the study of Luan et al.[21]. They showed that parceling 6 g/L tea polyphenols aqueous solution was able to reduce endogenous autolysin activity and prevented lipid oxidation in micro-frozen hairtail at −3 °C. If the storage period reached 20 d, however, the TVB-N content of micro-freezing hairtail at −3 °C exceeded that of −18 °C frozen. It indicated that tea polyphenol could not singly achieve long-lasting preservation of hairtail, but a powerful preservation effect can be ensured within 20 d. While Wei et al.[55] investigated that 4 different types of polyphenols could protect the MP structure stability of tilapia fillets under −4 °C storage by lowering protein hydrophobic interactions and enhancing disulfide bonds. Procyanidin was most beneficial in protecting the quality of tilapia fillets compared to carnosic acid, quercetin, and resveratrol as a 25 d extension period was modeled by kinetic equations. Taken together, cryoprotectants, antimicrobials, and antioxidants are capable of achieving further enhancement of incomplete freezing. However, a single or complex substance that can simultaneously modulate ice crystals, oxidation, and microbial behavior is still a lack, which provides a huge space in the regulatory approaches of incomplete freezing.

Appropriate packaging modes will also enhance the protection of muscle foods from incomplete freezing, especially superchilling and micro-freezing with preliminary cooling stages. Packaging prevents oxidation of MP and lipid and the growth and multiplication of aerobic microorganisms by regulating the amount of O_2 exposure to muscle foods in confined spaces, such as vacuum packaging and specific ratios of modified atmosphere packaging we mentioned earlier. A modified atmosphere (60% CO_2 + 40% N_2) was employed by Rosnes et al.[56] in the superchilling storage of farmed spotted wolffish at −1 °C. This anaerobic environment significantly diminished ($P < 0.001$) the microbial activity of spotted wolffish in a high-density polyethylene semi-rigid trays, thus prolonging the shelf life by 5–7 d. Analogous phenomena were observed by Wang et al.[57]. A modified atmosphere package with 50% CO_2, 5% O_2, and 45% N_2 extended the shelf life of cod loin by about 2.33 times, and the characteristic fresh and sweet taste could also be maintained during storage. Bellés et al.[6] systematically analyzed the effects of O_2-enriched atmosphere and vacuum packaging on the superchilling storage. Both were effective in reducing colony counts of lamb slices within 28 d, but the vacuum packaging was more beneficial in limiting lipid oxidation and maintaining the color stability. In spite of the common vacuum and modified atmosphere packaging, functional active packaging based on some antimicrobial

Table 3 Methods, materials, conditions and effectiveness of incomplete freezing combined with regulatory approaches on the shelf life of muscle foods.

Category of incomplete freezing	Environment temperature (°C)	Category of muscle foods	Shelf life (extended (day), total (day), and multiple)	Period of quality stabilization (day)	Regulatory approach and other meaningful condition	Reference
Micro-freezing	−2	Cod	6, 21, 1.4		Modified atmosphere packaging (50% CO_2, 5% O_2, 45% N_2), 2.5% NaCl solution	[52]
Micro-freezing	−3	Common carp		35	4% sucrose/sorbitol (1:1) rapid freezing	[53]
Superchilling	0	Pacific white shrimp	2, 8, 1.33		0.1 g/100 mL ε-polylysine	[54]
Micro-freezing	−1.5	Beef loin	4, 24, 1.2		0.03% luteolin, 0.75% *Portulaca oleracea* extract, 0.30% polylysine	[1]
Micro-freezing	−3	Hairtail block		30	6.0 g/L tea polyphenol	[21]
Partial freezing	−4	Tilapia fillet	25, 102, 1.32		2.0 g/L carnosic acid/ procyanidin/quercetin/resveratrol	[55]
Superchilling	−1	Farmed spotted wolf-fish	5–7, 15, 1.5–1.88		Modified atmosphere packaging (60% CO_2, 40% N_2)	[56]
Superchilling	−0.9	Cod	12, 21, 2.33		Modified atmosphere packaging (50% CO_2, 5% O_2, 45% N_2)	[57]
Micro-freezing	−3	Large yellow croaker		42	Gum tragacanth-sodium alginate active coatings containing EGCG	[16]
Regulated supercooling	−3.5	Yellowfin tuna	About 7, 10, 3.33		7 V, 20 kHz pulsed; electric field; 15 mT, 1 Hz oscillating magnetic field	[19]
Regulated supercooling	−4	Beef loin	6, 14, 1.75		7.98–8.15 mT static magnetic field	[20]

or antioxidant agents also has the potential to applied in the incomplete freezing of muscle foods. As against direct contact, active packaging encapsulates functional ingredients inside macromolecules and releases gently over time to ensure the sustained effects till the later storage period. As Pei et al.[16] embedded EGCG in a carrier of sodium alginate and xanthan gum to form a coating film with antioxidant activity, which remarkable maintains the α-helix content of MP in large yellow croaker during storage at −3 °C and thus stabilizing the secondary structure from oxidative degradation. The tight binding of water molecules with myofibrils was observed, also, which allowed the stable storage for 42 d. However, a large quantity of excellent functional active packaging is still being researched and applied in the context of traditional chilling rather than superchilling or micro-freezing as described in this review, suggesting that the shift to incomplete freezing range is the meaningful trend in functional active packaging. Moreover, the functional active packaging is unavailable to directly regulate and influence the ice crystals behavior and the drip loss may become a weak link. In this case, physical field-assisted techniques to increase supercooling degree are necessary to be introduced to present system. Lee et al.[19] determined that the combined action of a pulsed electric field (7 V, 20 kHz) and an oscillating magnetic field (15 mT, 1 Hz) could reduce the initial T_{if} of tuna from −1.7 to −3.5 °C and keep it unfrozen at −3.5 °C for 10 d. And no visible growth in the colony counts was noted during 7 d of storage. Similarly, Lin et al.[20] revealed that a static magnetic field of 7.98–8.15 mT dropped the T_{if} of beef below −4 °C, keeping the beef in an ice crystal-free state for 14 d. Drip loss from the beef (21.9% and 47.8% less than 4 °C chilling and −18 °C freezing, respectively) was dramatically diminished, consequently, a less lipid oxidation was also detected in the experimental results. Researches together revealed that magnetic field had the potential to achieve the co-regulation of ice crystals, microbial, and oxidative behaviors, which might be closely linked to the water molecule clusters depolymerization, microbial charge perturbation, and enzymatic reaction retardation.

6 Conclusion and prospect

Based on the variation in moisture/ice-crystal behaviors during the cooling of muscle foods, this review classified incomplete freezing technology as superchilling, micro-freezing, partial freezing, and sub-freezing along with the depth of cooling stage. No noticeable distinction exists between sub-freezing and traditional freezing except for the reduction of energy consumption, leading to more researches focusing on initial cooling stages including superchilling, micro-freezing, and partial freezing. As a compromise strategy between chilling and freezing, incomplete freezing occupies cryogenic environment to prevent microbial growth and reproduction in muscle foods without forming large amounts of ice crystals to destory muscle tissue. Supplementing by vacuum packaging can also considerably attenuate the MP/lipid oxidation. All 3 main types of quality deterioration factors are suppressed by incomplete freezing, contributing in varying extensions of muscle food freshness. Furthermore, adding cryoprotectants or other acitve substances, selecting suitable packaging modes, and exerting physical field-assisted techniques can further enhance the preservation capacity of incomplete freezing by varying mechanisms. As illustrated in Figure 5A, incomplete freezing has been most abundantly studied in fish and slightly less in meat, especially mutton. In terms of timeline, incomplete freezing research of muscle foods has tended to break through the previous decade within a 4-year period in 2020s, which confirms the growing recognition and requirement of its potential. During the extremely rapid development, yet, only superchilling storage is more closely correlated with the residual literature in the search engines as depicted in Figure 5B, since most of the incomplete

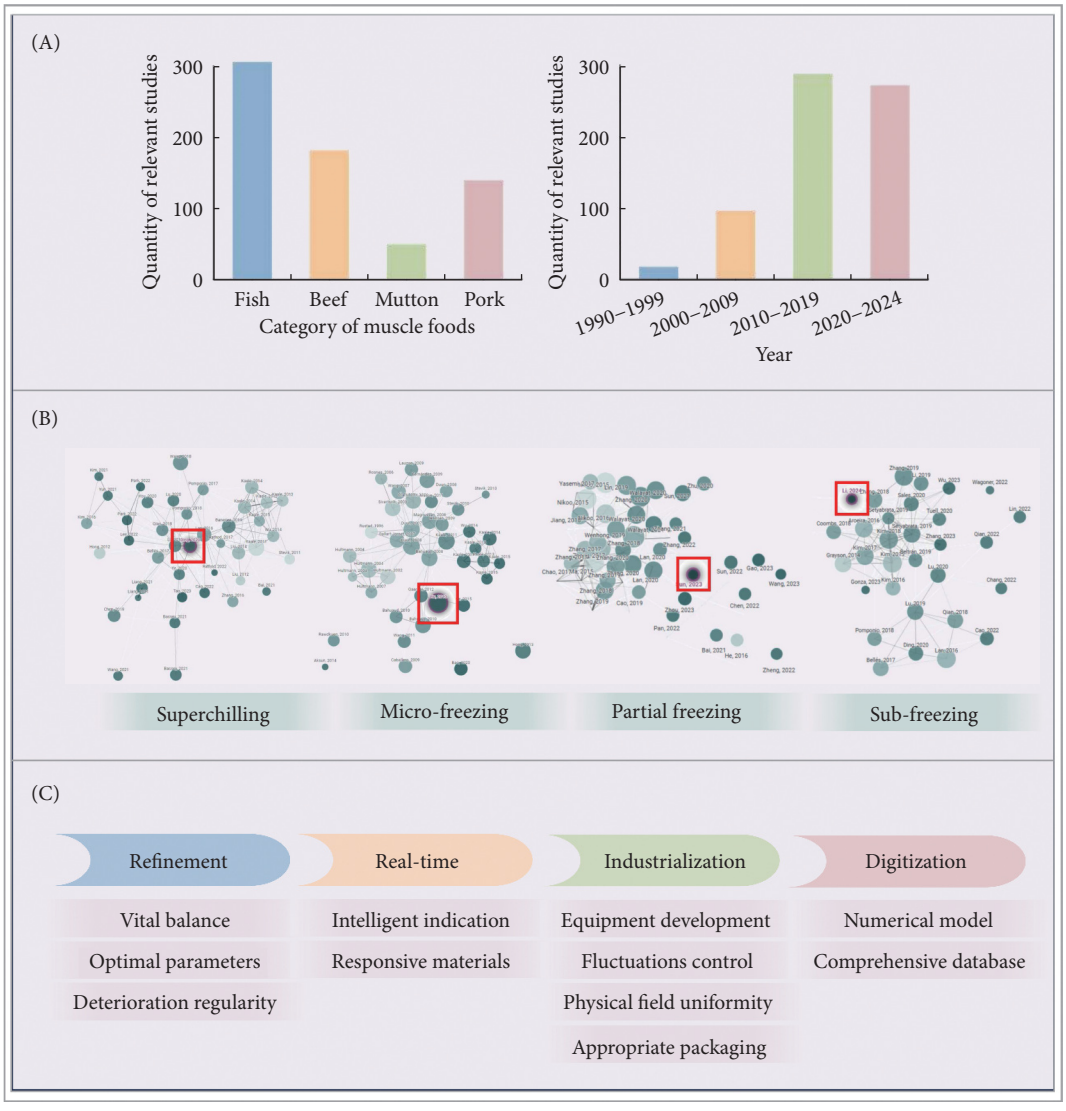

Figure 5 Current progress and future perspectives for incomplete freezing of muscle foods. (A) Relative study quantities of incomplete freezing respectively summarized by muscle food categories and eras from www.ScienceDirect.com. (B) The visualization of literature association strength was obtained by separately entering 4 keywords into www.connectedpapers.com, where the depth in green indicates the association strength. (C) Several future perspectives for incomplete freezing of muscle foods.

freezing category is vaguely claimed to be superchilling. The lack of standardization in the nomenclature and application process is disconcerting, and the systematic categorization in this review is an effort to eliminate it. Overall, the incomplete freezing technology is an effective, flexibly adjustable, energy-saving, and promising preservation strategy for various requirements, which possesses the potential to be applied to the cryogenic storage and cold-chain transportation of muscle foods. Despite the categorization, decades of research progress on various types of incomplete freezing is still insufficient to fulfill the demands of building a modern cold chain logistics system in the future. Several aspects still requires investigation and improvement as summarized in Figure 5C.

1) Incomplete freezing for muscle foods ought to move toward refinement. Incomplete freezing, as previously introduced, is a compromise strategy between chilling and freezing. Since the term "compromise" has been described, a crucial equilibrium must exist between them. This equilibrium involves microbial activity, oxidation reactions, and ice crystals formation. A lower freezing degree allows it difficult to sufficiently inhibit microbial growth and reproduction as well as oxidative enzyme activity in muscle foods. While a higher freezing degree is possible to cause structure damage and the subsequent drip loss in muscle foods due to the large-scale formation of ice crystals. In specific muscle foods, therefore, an optimal temperature parameter can simultaneously control the 3 main deteriorating factors to an acceptable level. The critical temperature is probably present in the micro-freezing range, and perhaps needs to be accurate to the ± 0.1 °C level or even below. Hence, more refined environment temperature conditions are meaningful to be explored rather than the existing wider gradient differences such as −1, −2 and −3 °C. A considerable research on refined storage parameters might provide us with pervasive theories on micro-freezing storage of muscle foods, such as the methodology for calculating or obtaining the optimal temperature. Additionally, information regarding the succession pattern of dominant spoilage bacteria and ice crystal formation during each incomplete freezing storage of muscle foods are also necessary to be determined to provide a clear theoretical basis to guide the exact implementation. 2) Incomplete freezing for muscle foods ought to move toward real-time. The objective of storage performance studies of incomplete freezing is mainly the comparison of

differences in muscle food quality before and after storage. However, real-time quality information during storage is also important to be reacted and monitored for factories, cold chains, and consumers. In fact, convenient and non-destructive techniques that enable real-time monitoring of freshness are currently proposed by several researchers. Some intelligent indicators (such as anthocyanins, etc.) were prepared as films or labels and attached to the packaging of muscle foods, which can translate certain condition variations in the environment into color changes by their greater sensitivity. As storage time prolongs, microbial and enzymatic activities in muscle foods trigger variations in terms of pH, humidity, and small molecule content, which are captured by indicators and produce specific color signals. Frustratingly, the study object for these smart indications remains the traditional chilling muscle foods. The development of advanced technologies or materials for real-time monitoring of muscle food freshness under incomplete freezing is of major significance for the timely adjustment of business models and storage methods, as well as for consumer safety. 3) Incomplete freezing for muscle foods ought to move toward industrialization. Transferring incomplete freezing technology from the laboratory to production and transportation is challenging. Complete equipments and proven systems enable traditional chilling, freezing, and thawing to still be widely practiced in factories, transportation, shelves, and household although some obvious drawbacks exist. During the process of applying incomplete freezing technology to the industrial processing of muscle foods and the whole logistics chain, the development of suitable large-scale equipments is a necessary and fundamental part. Primary requirements for such equipment is controlling the constant environment temperature and reducing the fluctuations. Some categories of incomplete freezing are subject to relatively narrow temperature ranges, especially for superchilling and micro-freezing which are divided by the T_{if}. Only slightly fluctuations are possible to push the center temperature of muscle foods beyond the threshold value, thus leaving it in a freeze-thaw cycle during storage and transportation and destroying the quality maintenance. Although physical field-assisted technologies can highly reinforce the benefits of incomplete freezing, some critical researches should be carried to guarantee the distribution uniformly of the physical field parameters in the relevant equipment space, even in storage warehouses. It is more adapted for recent development of incomplete freezing to searching some suitable additives or packaging modes from an economic view. Certainly, the relevant considerations should depend more on various aspects such as consumption scenarios, groups, costs, and edible values. 4) Incomplete freezing for muscle foods ought to move toward digitization. Mathematical modeling and computer simulation of the incomplete freezing process is an attractive area that relates to the intelligent construction of future cold chain logistics. It seems that environment temperature is the only major parameter exists in incomplete freezing technology, although, the actual conditions (including muscle food type, size, shape, components, stacking method, equipment space, heat transfer rate, storage time, transportation distance, etc.) will seriously affect the ice fraction, microbial activity, and oxidative state of muscle foods. Therefore, it is meaningful to establish a mathematical model that can obtain the optimal storage temperature and other parameters by inputting information such as product properties, storage conditions and freshness requirements. Furthermore, a database containing the diverse strategies and effects of incomplete freezing should also be proposed and established to provide information reference for national cold chain logistics.

Conflict of interest

There is no conflict of interest associated with authors.

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