Trends in Food Science & Technology 101 (2020) 63–72

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Transport phenomena and their effect on microstructure of frozen fruits and vegetables

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ARTICLE INFO

Keywords:
Fruits and vegetables
Freezing
Transport phenomena
Microstructure stability
Phase change
Cellular water

ABSTRACT

Background: Fresh fruits and vegetables have a short shelf life. Freezing offers a solution to their long-term preservation. However, transport phenomena during freezing of fruits and vegetables pose significant changes in microstructure, affecting quality stability, shelf-life extension, and market value. Therefore, information on the microstructure of frozen fruits and vegetables is very critical for process design and quality control.

Scope and approach: In this review, transport phenomena and their effect on the microstructure of frozen fruits and vegetables are considered at the cell level. The effect of cell structure, freezing rates, and heat and mass transfer characteristics on the texture of cellular tissues are presented. Emerging techniques for controlling ice crystal growth are also discussed.

Key findings and conclusions: The quality of frozen fruits and vegetables is hinged on the microstructure stability, which is highly dependent on phase change processes and the size of ice crystals. The proportion and characteristics of cellular water, heat and mass transfer parameters, freezing rate and thermal property of cells are considered as the main drivers for moisture migration and ice crystal formation. To produce frozen fruits and vegetables with high quality, more insightful study and accurate understanding of transport phenomena in cellular space and their corresponding effects on the microstructure is necessary. It is hoped that this review should provide critical information on preserving the microstructure and quality of fruits and vegetables as affected by moisture migration for future studies.

1. Introduction

Fruits and vegetables are important sources of nutrients such as vitamins, minerals, and antioxidants (Hoffmann, Boeing, Volatier, & Becker, 2014) with a wide range of health benefits (Veerman, Barendregt, & Mackenbach, 2006). However, fruits and vegetables are highly perishable and they are thus often cooled or frozen after harvest. For ensuring the supply of high quality, shelf-stable and safe products, cooling or freezing processes should be optimized or novel cooling or freezing techniques should be employed (Zhu, Geng, & Sun, 2019; Zhu, Li, Sun, & Wang, 2019; Zhu, Zhang, & Sun, 2020; Zhu et al., 2018; Kiani, Sun, Delgado, & Zhang, 2012; McDonald & Sun, 2001; Wang, Li, Sun, & Zhu, 2019; Zhan, Zhu, & Sun, 2019a). Among fruits and vegetables, the consumption of frozen fruits and vegetables has reached millions of tons per year in many countries (Herath, 2019; Hughes et al., 2012).

The main component of fruits and vegetables is water, with a content of up to 80–90% (Khan et al., 2017). This high water content favours microbial activity and enzymatic reactions within the cells, resulting in chemical degradation and quality loss. On the other hand, the microstructure is crucial to the quality and can change due to freezing (Karim, Rahman, Pham, & Fawzia, 2018; Li, Zhu, & Sun, 2018; Li & Sun, 2002; Oikonomopoulou, Krokida, & Karathanos, 2011; Peng et al., 2018; Voda et al., 2012). Therefore, it is a challenge to prevent or minimize quality changes of frozen fruits and vegetables through the preservation of their microstructures.

Freezing is a popular method for long-term preservation of fruits and vegetables, during which, the cellular solution present in the food

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https://doi.org/10.1016/j.tifs.2020.04.016
Received 6 December 2019; Received in revised form 26 March 2020; Accepted 18 April 2020
Available online 27 April 2020
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matrix is cooled to its initial freezing point, and further cooling causes the water molecule to separate, forming ice crystal. The migration of water molecules during crystallization led to an increase in osmotic pressure, further enhancing the water permeability of the cell membranes. This transport of water molecules, if not controlled, can eventually affect the microstructure of the frozen produce.

Generally speaking, slow freezing can result in damages to the microstructure due to the formation of large extracellular ice crystals (Buggenhout et al., 2006; Chassagne-Berces et al., 2009; Delgado & Rubiolo, 2005; Kotwaliwale, Curtis, Othman, Naganathan, & Subbiah, 2012), while fast freezing normally induces a high rate of heat and mass transfer, minimal water migration and low osmotic pressure, leading to the formation of intracellular and extracellular small ice crystals, and thus less damage to microstructure (Li & Sun, 2002; Zhu, Luo, & Sun, 2020a). In addition, cell components (cell wall and middle lamella) and cell morphology including cell sizes and pores can also significantly affect the quality of frozen foods as they vary with plant-based food materials.

As fast freezing remains the focus of the frozen food industry in preserving the original structure and maintaining the shelf-stable quality of frozen fruits and vegetables, it is therefore important to understand moisture migration within the cellular compartments during freezing since both intracellular and extracellular crystallization can lead to different microstructural changes of frozen products. In addition, a better understanding of the formation of ice nuclei and the growth of ice crystals in the cellular environment during freezing is also useful for controlling the freezing process.

Therefore, the aim of the current review is to provide detailed information on the transport phenomena and their effect on the microstructure of frozen fruits and vegetables. In this context, the cellular water and their classifications and transport mechanisms are presented, factors affecting cell structure and moisture transfer are discussed, and emerging techniques for controlling the growth of ice crystals are highlighted.

2. Cellular water and transport mechanisms

2.1. Classification of cellular water

Cellular water of fruits and vegetables can be classified into free and bound water based on physical property and molecular bonding (Khan et al., 2016, 2017; Ambastha & Tiwari, 2015). The bound water exists as loosely bound water (LBW) or as strongly bound water (SBW) based on strength. Fig. 1 shows a generalized cell of plant-based food materials containing different categories of cellular water. Free water (FW) is freely contained between two or more cells, LBW is contained in the intracellular space, while SBW is entrapped within the cell wall and cell rupture moves such water across the cell membrane (Khan and Karim, 2017). The proportion of water in the cell of main fruits and vegetables including apple, kiwifruit, cucumber, and eggplant is significant in transport, with about 80–92% of LBW, 6–16% of FW and only about 1–6% of SBW (Khan et al., 2016). Meanwhile, these proportions are highly dependent on cell size, porosity, and solid contents. For instance, kiwifruit contains the lowest percentage of LBW when compared with apple, whereas eggplant contains a higher amount of LBW as compared with cucumber (Khan et al., 2016). These variations are attributed to the size of intracellular space, i.e., smaller in kiwi and cucumber and larger in apple and eggplant. Also, the proportion of SBW increases as solid content increases. Khan, Kumar, et al. (2016) and Khan, Wellard, et al. (2016) found that SBW was higher (about 5%) in kiwifruit as compared with apple (about 2.5%) due to the high proportion of solid contents present in kiwifruit.

However, the movement of cellular water during the freezing of fruits and vegetables depends on several factors, such as cell size, cell composition including water and gases, freezing conditions and pressure gradient generated within the cell. As such, these factors can influence the quality of frozen samples. Meanwhile, little has been done to relate the cell composition of fruits and vegetables to microstructural changes in frozen samples by considering the proportion of cellular water and its respective transport property (Silva, Gonçalves, & Brandão, 2008).

2.2. Transport mechanisms

Based on the thermodynamic principle, transport mechanisms during freezing of cellular tissue of fruits and vegetables often occur in precooling and phase change. During precooling, the liquid solution in cells is cooled from the initial temperature until it reaches the initial freezing point and sensible heat is removed, while during phase change, latent heat is removed and ice is formed, which takes place first extracellularly, causing higher solute concentration in the intracellular space due to the presence of minerals and sugar. This leads to the creation of an osmotic pressure difference between intracellular and extracellular spaces, making intracellular water to diffuse across the cell membrane and deposit on the growing extracellular crystals. The possibility of intracellular nucleation mainly depends on the freezing rate (Luo, Sun, Zhu, & Wang, 2018; Mahato, Zhu, & Sun, 2019; Tian, Zhu, & Sun, 2020; Zhan, Sun, Zhu, & Wang, 2018). A fast freezing rate can make the freezing point of the cell to fall much more rapidly than the local temperature. This allows the intracellular solution to separate markedly from the equilibrium concentration, and thus increases the probability of intracellular nucleation (Zaritzky, 2012). After some high degrees of supercooling, nucleation is formed and the temperature increases sharply to the initial freezing point, producing numerous

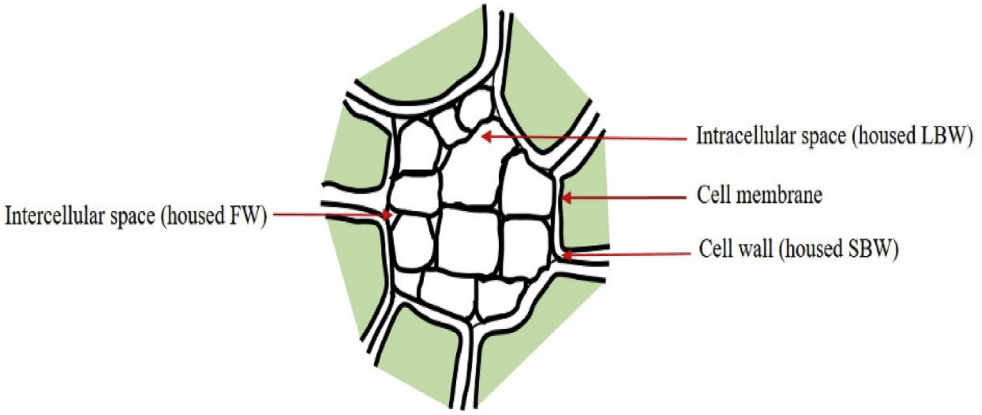


Fig. 1. A general cellular environment with different water components for plant-based food materials (FW = free water, LBW = loosely bonded water, SBW = strongly bonded water) (redrawn from Karim et al., 2018).

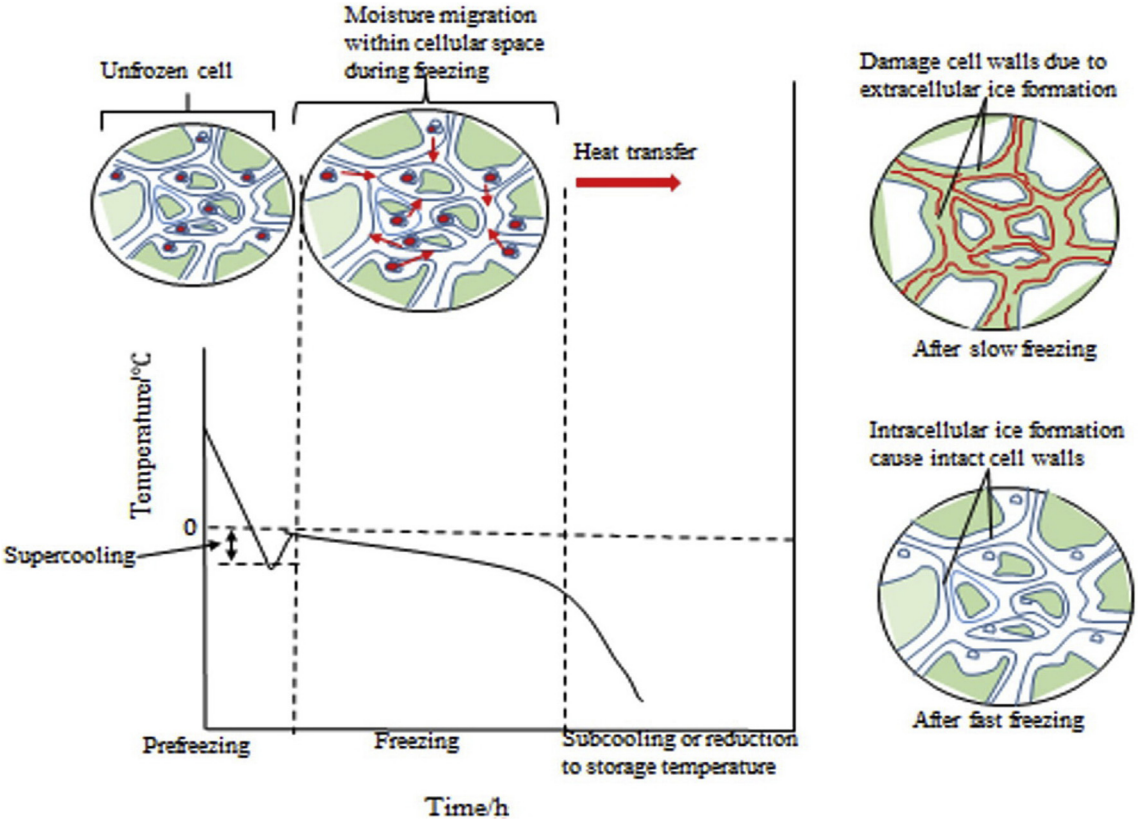


Fig. 2. A typical freezing and moisture migration process showing the impact of freezing rates on the cell structure of plant-based food materials.

smaller ice crystals.

Upon nucleation, crystal growth becomes the only mechanism and no further supercooling is required.

As ice crystal grows, three phases including ice already formed, crystallized solute, and unfrozen solution co-exist at a constant temperature under an ideal situation. The rate or extent of ice crystal growth depends solely on the rate of latent heat removal. Once the interphases between frozen and unfrozen completely disappear, the temperature freely falls and then releases the latent heat from the surface of the ice.

The subcooling stage takes place after the completion of the phase change, during which, some further cooling proceeds to keep the ice in equilibrium with the external environment or storage temperature. On the other hand, at a later stage of subcooling or frozen storage, intracellular and extracellular ice crystals sublime, leaving void spaces on the cell surface. The formation of large extracellular ice crystals affects cell structure. Fig. 2 illustrates a typical freezing and moisture migration process, showing the impact of freezing on the cell structure of plant-based materials.

3. Factors affecting cell structure and moisture transfer

3.1. Cell wall modification and freezing rates

The cell is a unit component of plant tissue, whose structure contributes to the mechanical and structural integrity of plant materials (Joardder, Kumar, & Karim, 2017). Different plant cell shows a significantly different structure. In fruits and vegetables, the cell structure is closed such as those found in parenchyma cells of the grape berry. A sequential arrangement of cells with integrated cell walls and the assistance of cellulose fibres form a stabilized plant tissue. However, the components of cellulose fibres including cellulose, hemicellulose and pectin substances are important in preventing the cell from failing under stress. During freezing, cellulose provides the cell wall with structural rigidity and tearing resistance required for stability, while hemicellulose and pectin substances enhance the ability of cell wall to withstand elasticity or plasticity occurrence (Jha, Xanthakis, Chevallier, Jury, & Le-Bail, 2018). Though some plant species exhibit high cell wall rigidity, the inability of the cell wall to stress conditions resulted mainly from large extracellular ice crystals can lead to cell wall modification (Khudyakov, Kuleshova, & Zaitseva, 2018).

Cell wall modification, depending on temperature, aids in the release of degradable enzymes and causes cell disintegration (Ochoa-Jiménez, Berumen-Varela, Fernández-Valle, Martín-Ernesto, & Hernández, 2018). Chassagne-Berces et al. (2009) studied the changes in texture, cellular structure and cell composition in apple tissue after freezing at three different temperatures of −20 °C, −120 °C and −196 °C, and as shown in Fig. 3, the cell wall modification provoked a high amount of cell wall damage, larger extracellular spaces and tearing of the tissue after freezing at a temperature of −20 °C as compared with freezing at temperatures of −120 °C and −196 °C. Generally, cell structure with small extracellular space allows minimum moisture movement and produced compact texture, while that with large extracellular space can cause more moisture movement and produce coarse texture (Jha et al., 2018). The structural damage accompanying cell wall modification shows that turgor pressure preservation remains critical during the freezing process.

The cell wall integrity of frozen fruits and vegetables can be significantly maintained by fortification of pectin substances using dehydration and texturing agents such as sugar (sucrose and trehalose) and salts (calcium chloride and sodium chloride) (Cichowska & Kowalska, 2018; Suutarinen, Heiska, Moss, & Autio, 2000; Velickova, Tylewicz, Dalla, & Winkelhausen, 2011). This method is known as osmotic treatment or water removal process that involves soaking fruits and vegetables in hypertonic sugar or salt or combined solution before freezing, to reduce water content while increasing soluble solid content,

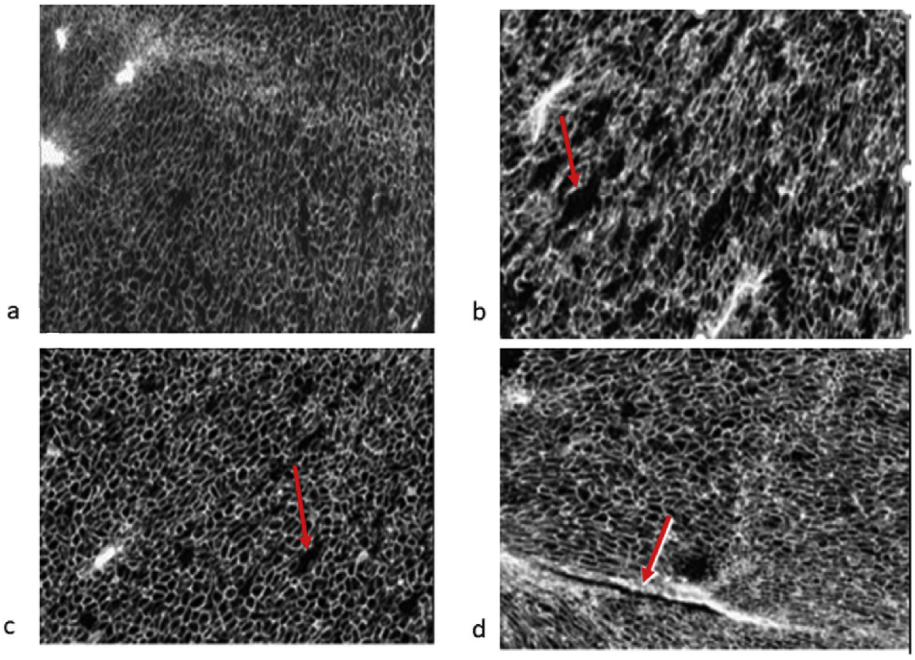


Fig. 3. Macroscopic images of apple parenchyma tissue sections before and after freezing (a) fresh apple, (b) thawed apple after freezing at – 20 °C, (c) thawed apple after freezing at – 80 °C, and (d) thawed apple after freezing in liquid nitrogen at – 196 °C. The field of view was 5.5 × 7.25 mm. The arrows show tissue cracks (Chassagne-Berces et al., 2009).

thereby, minimizing the negative modification of the cells of frozen fruits and vegetables.

According to Suutarinen et al. (2000), calcium ion has a great potential to maintain and protect the cell wall of the strawberry against softening and disintegration, due to the interaction of calcium with the presence of pectic acid to form calcium pectate.

Similarly, the freezing rate affects cell structure of fruits and vegetables. Different freezing rates show varying degrees of mass transport in cells and can induce significant changes in the microstructure of fruits and vegetables. Typically, slow freezing rates have been reported for slowing down moisture movement in cells and cause damage to cell structures of strawberry (Delgado & Rubiolo, 2005; Kobayashi & Suzuki, 2018), cucumber (Nachiket et al., 2012) carrot (Voda et al., 2012), and apple (Chassagne-Berces et al., 2009), as compared with fast freezing rates (Zhu et al., 2020a). Roy, Taylor, and Kramer (2001) studied textural and ultrastructure changes in the cell wall and middle lamella of carrot tissue under different freezing conditions and reported that fast freezing rates of −4.5 °C/min and −2.4 °C/min led to less structural damage than slow freezing rates of −0.19 °C/min and −0.05 °C/min due to the pattern of growing ice crystals and substantial loss of pectin material.

Blanching prior to freezing can lead to better preservation of microstructure (Zhan, Zhu, & Sun, 2019b). The maintenance of microstructure was reported for carrot tissues that were subjected to cryogenic freezing coupled with blanching (at 60 °C) (Ando et al., 2016; Buggenhout et al., 2006). Meanwhile, tissues exposed to different time-temperature protocols show varying textural and structural characteristics (Roy et al., 2001).

Voda et al. (2012) hypothesized that cells were preserved upon blanching due to the homogeneous distribution of sugar within intracellular space. However, this hypothesis needs more studies for scientific justification.

Apart from blanching, applications of the electric field, microwave, ultrasound, and high pressure to freezing have also been demonstrated to be effective in preserving cell wall integrity and maintaining cell membrane with undamaged microstructure (Cheng et al., 2015; Dalvi-Isfahan, Mamdami, Xanthakis, & Le-Bail, 2017; Li & Sun, 2002; Tylewicz et al., 2016; Wang, Li, Sun, & Zhu, 2018).

The above observations indicate that fast freezing rates result in well-preserved cell structures in fruits and vegetables since moisture movement is faster and minimal, while low freezing rates slow down moisture movement and cause damages to cell structures. Table 1 shows the microstructural changes during the freezing of fruits and vegetables.

3.2. Ice crystal type, size and distribution

Ice crystal is also one of the critical factors that affect cell structure of fruits and vegetables. This can be large, small, intracellular, and extracellular, round and dendritic shaped and may partially depend on cell types (Celli, Ghanem, & Brooks, 2016). For numerous and small ice crystals that are evenly distributed within the intracellular and extracellular environment of cells, they cause little cell disintegration and less cell damage, while for few and large ice crystals that are distributed in the extracellular environment of cells, they can cause cell collapse and rupture (Ashworth & Pearce, 2002; Chassagne-Berces et al., 2009; Jha et al., 2018; Voda et al., 2012).

Vicent, Verbonen, Ndoye, Alvarez, and Nicolai (2017) studied and quantified the distribution of ice crystals in apple tissue frozen using different freezing rates including slow freezing of 2.0 °C/min, intermediate freezing of 12.6 °C/min, and fast freezing of 18.5 °C/min and showed that ice crystals size distributions with mean equivalent diameters of about 45 ± 3.5 μm, 55 ± 7.4 μm, and 71 ± 9.6 μm were obtained for the fast, intermediate and slow freezing rates, respectively. Although the preference of crystal size depends on the purpose of freezing. In cellular tissue of frozen fruits and vegetables, the ice crystals must be as small as possible and evenly distributed in the cell so as to maintain the integrity of the cell wall as much as possible. For instance, many smaller ice crystals were reportedly distributed in the cellular region in apple subjected to fast freezing at 8.1 °C/min (about 3 μm) with little changes to the cellular structure as compared with irregular large extracellular ice crystals (mainly between 10 and 30 μm) formed under slow freezing at 0.9 °C/min, which induced large changes in the cellular structure and caused cell collapse in the frozen samples (Chassagne-Berces et al., 2009).

Sman, Voda, Dalen, and Duijster (2013) reported ice crystal interspacing in frozen carrot tissue subjected to four different temperatures in cold air at −28 °C, immersion in dry ice at −80 °C, in aqueous nitrogen at −150 °C and in liquid nitrogen at −196 °C and concluded that the cell structure of the frozen carrot was a function of the size and

Table 1
Microstructure changes during freezing of fruits and vegetables.

Target change	Samples	Freezing type/conditions	Observations	References
Microstructure	Peach and mango	PSF (200 MPa, −20 °C), air blast freezing at −40 °C and 5.5 m/s, and cryogenic freezing in liquid N_2	PSF maintained the original structures of both samples to a greater extent than air blast freezing and cryogenic freezing	Otero et al. (2000)
Texture and Firmness	Carrot tissue	Air blast freezing at −174, −60, −23 and −20 °C with different freezing rates ranges from −0.05 °C/min to −4.5 °C/min	Rapid freezing rates (−4.5 °C/min, −2.4 °C/min) retained better texture and a high degree of cellular integrity while slow freezing (−0.19 °C/min, −0.05 °C/min) gave an opposite effect	Roy et al. (2001)
Hardness	Carrot tissue	Air blast freezing at −18 °C, PSF (200 MPa, −15 °C) and cryogenic freezing in liquid N_2 and with pretreatments (thermal, soaking in 0.5% $CaCl_2$ for 1 h, and high pressure)	The hardness and tissue were affected remarkably by the pretreatment methods for both freezing at −18 °C and freezing in liquid N_2, depending on the freezing rate. PSF with pretreatment improved the hardness and reduced tissue damage	Buggenhout et al. (2006)
Texture and cell structure	Apple tissue	Air blast freezing at −20 and −80 °C and by immersion freezing in liquid N_2 (−196 °C)	Freezing at −20 °C led to damaged vacuoles and cell walls, resulting in overall structural degradation, but freezing at −80 °C and immersion in liquid N_2 maintained the cell structure.	Chassagne-Berces et al. (2009)
Cell structure	Banana	Freezing in a microwave freezer (at −30 °C for 5 h)	The cellular walls of the frozen samples disappeared as compared with the fresh samples due to changes in osmotic pressure tenable to the extracellular concentration of solutes and drastic sublime reaction	Jiang, Zhang, Mujumdar, and Lim (2014)
Porosity, bulk density, and true density	Strawberry	Vacuum freezing at −30 °C for 72 h (at 0.06–1.50 mbar)	The bulk density significantly affected by freezing time and pressure, leading to changes in structural properties. Bulk density decreased and porosity increased at a decreased applied pressure	Oikonomopoulou et al. (2011)
Texture	Cucumber	Air blast freezing at −18 °C for 150 min	The firmness of the frozen samples was significantly higher than the control due to high moisture loss causing hardening of the tissues	Kotwaliwale et al. (2012)
Microstructure and rehydration properties	Carrot	Air blast freezing at −28, −80, −150, and −196 °C with blanching	The growth of ice crystals ruptured and compressed the cells. The blanched sample showed a fine microstructure with less cell damage and collapse	Voda et al. (2012)
Microstructure, firmness, and drip loss	Brocolli	UAF at 20 kHz and 30 kHz frequency and power of 150 W–175 W and IF (at −25 ± 0.5 °C)	The microstructure and firmness of the frozen samples were adequately preserved and drip loss was significantly reduced by the optimized application of UAF compared with the immersion freezing	Xin et al. (2014)
Texture and cell structure	Red radish	SF, IF (in 30 w/v $Cacl_2$, at −20 °C), and UAF (at 20 kHz and power intensities of 0.09, 0.17, 0.26, and 0.37 W/cm^2)	IF and UAF samples showed better textural preservation than SF. The frozen samples exhibited better cellular structures under ultrasonic power intensities of 0.17 and 0.26 W/cm^2 with less cell separation and disruption	Xu et al. (2015)
Textural change	Carrot	Air blast freezing at −18, −40, and −80 °C with instant DIC and with osmotic pretreatment in sucrose solution (at 98 ± 2 °C, 40 °Brix, for 20 min) and freezing in liquid N_2 at −196 °C	The carrot tissue was severely damaged at freezing temperature −18 and −40 °C with freezing times of 84.2 and 45.0 min, respectively, while samples frozen at −80 and −196 °C were adequately preserved	Peng et al. (2018)
Texture, drip loss and microstructure	Strawberry	Supercooled freezing in a cryo-chamber at −6.5 °C with a freezing rate of 0.0375 °C/min, and conventional air blast rapid (at −85 °C) and slow freezing (at −10 °C)	Supercooled freezing method caused greater damage to the cell membrane and cell walls than the conventional rapid freezing, resulting in high drip loss and texture degradation	Kobayashi and Suzuki (2018)

Note: PSF = pressure shift freezing, UAF = ultrasound-assisted freezing, SF = slow freezing, IF = immersion freezing, DIC = controlled pressure drop.

distribution of ice crystals.

In another study, Kobayashi and Suzuki (2018) demonstrated that fast freezing has a great potential to form smaller intracellular ice crystals in strawberry tissue, although the quality of frozen strawberry was not fully sustained as compared with samples frozen under slow freezing. It was assumed that high and instantaneous ice nucleation accompanying supercooling promoted drastic water migration and consequently caused significant degradation of strawberry cells. This study shows that not only the size but also the type of ice crystals potentially affects the cell structure.

In addition, Trelea, Passot, Marin, and Fonseca (2009) revealed that the thermal properties of cellular tissues of plant-based materials including viscosity, specific heat, internal heat transfer resistance as well as internal mass transfer resistance contributed to the size of ice crystals and integrity of cells. However, it is evident that cell structure degradation is strongly related to ice crystals and predominantly depends on the freezing rates and type of cells.

Besides cell structure degradation, there is a tendency of physic-chemical changes such as a change in colour, and loss of water holding capacity resulting in drip loss. These changes normally occur at the ice/liquid interphase and increasingly depend on water-phase solute concentration (Jha et al., 2018; Silva et al., 2008). An increase in water-phase solute concentration changes pH level, most often towards acidic, thereby impacting on the micronutrients of frozen produce (Oliver & Palou, 2000). Andres-Bello, Barreto-Palacious, Garcia-Sergovia, Mir-Bel, and Martinez-Monzo (2013) demonstrated the significant effects of pH on plant pigments (e.g. chlorophyll, carotenoids, and anthocyanin) that are responsible for the colour of fruits and vegetables. Therefore, the process of ice formation can affect the microstructure and quality of frozen fruits and vegetables, thus making control of the freezing process essential.

4. Heat and mass transfer modeling

The modelling of moisture transport phenomena during the freezing of fruits and vegetables has great practical importance for process control and optimization. The freezing models can be classified into heat transfer models and coupled heat and mass transfer models, and they are broadly based on numerical (finite difference, finite element, and finite volume) and empirical methods (Delgado & Sun, 2001; Pham, 2006; Singha & Muthukumarappan, 2016). The empirical models are simple and approximate for practical applications, while numerical models are complicated but accurate, which normally includes effects of changes in boundary conditions, phase change over a range of temperature, and variation in thermal properties (Delgado & Sun, 2001).

In the heat and mass transfer during freezing, the temperature difference between the product and freezing medium is the driving force, which depends on many intrinsic and extrinsic factors. The intrinsic factors are those related to product size (particularly thickness), shape and composition, while extrinsic factors are those related to the freezing systems including cooling medium, relative humidity and heat transfer coefficient between the cooling medium and the products (Campanone, Viviana, & Rodolfo, 2005).

Blija, Beitane, Aboltins, & Boca, 2017 used a numerical approach to model heat and mass transfer in freezing a layer of berries and showed the role of freezing temperature in predicting freezing times.

Mass transfer occurs during freezing, where moisture transfer is paramount, however, the solute transfer also happens in some cases like immersion freezing. Therefore, changes can be analyzed through the diffusion of substance (Pham, 2006). This is mostly expressed using a thermal energy transport equation in an enthalpy form with the mass flux being assumed to follow the Fick's law of diffusion:

$$\frac{\partial(\rho H)}{\partial t} = \nabla(k\nabla T) + \nabla(H_w \dot{m}_w) \quad (1)$$

where $\dot{m}_w$ is the mass flux (kg/s m^2), H_w is the enthalpy of diffusing substance (J/kg), ρ is density (kg/m^3), t is freezing time (s), T is the temperature (K), k is thermal conductivity (W/m K), and H is specific enthalpy (J/kg K).

Campanone et al. (2005) and Kouznetsova, Brekelmans, and Baaijens (2001) proposed to solve the Fick's law based on numerical methods and modelled the mass transfer successfully in cellular tissues. However, due to lack of adequate data, most previous studies on moisture transport-related modelling of frozen cellular tissue assumed plant cell as a unit and that moisture movement followed a single diffusion-equation with an effective diffusivity as shown below (Pham, 2016):

$$\frac{\partial w}{\partial t} = \nabla(D_w \nabla w) \quad (2)$$

where w is the mass ratio of total moisture to dry solids (kg/kg dry solid) and D_w is the effective diffusivity constant.

Meanwhile, plant-based food materials are heterogeneous in nature, having cells with different water compositions and morphology, each of which has its own diffusion rate (Khan et al., 2016). Therefore the above assumption of a single unit cannot accurately depict the true moisture movement if the cell nature is to be considered. For example, mass transfer is much faster in porous fruits such as pear and apple than in dense fruits such as raspberries and broccoli (Nakagawa & Ochiai, 2015; Pham, 2006).

It should be also noted that at phase change, where the liquid-solid stage and solid-vapour stage are recognized, the part of sample close to coolant where solidification first starts has a low mass diffusivity value, while the mass diffusivity value increases along with the distance away from coolant and reaches the maximum close to the surface where water vapour transport occurs. The differences in water composition and mass diffusivity in cellular tissues make the surface close to the coolant to be the only portion to have undergone any deformation after freezing (Pham, 2006). However, few studies have reported the significant changes in moisture diffusivity values on the entire cell during freezing.

Attempts have also been made to consider the heterogeneity of plant-based foods and the effects on the accuracy of modelling moisture movements, normally using the numerical method. Campanone et al. (2005) used the finite difference method to simulate the heat and mass transfer during freezing. The model enabled the evaluation of temperature and moisture movements, leading to the prediction of mass losses for different products. However, the finite-difference approach was not suitable for products with large latent heats over a wide range of temperatures (Pham, 2006). On the other hand, apparent specific heat and enthalpy values are normally be used to account for the sharp changes in these values during phase change.

Norton, Delgado, Hogan, Grace, and Sun (2009) used the finite difference approach on enthalpy formulation to predict temperature profile and freezing times during high-pressure shift freezing for cellular tissues and results showed that the model could satisfactorily describe the freezing process.

The finite volume approach has also been used for model heat and mass transfer during freezing with successful prediction similar to experimental results (Nicolaï, Verboven, Scheerlinck, & Leuven, 2001). However, numerical methods developed up till now still lack the capability to analyze large deformation of cells, thereby such modelling relies on many assumptions (Delgado & Sun, 2001; Rahman, Joardder, Khan, Pham, & Karim, 2017).

5. Emerging techniques for controlling the formation and growth of ice crystals

As discussed previously, transport phenomena during freezing of cellular tissue of fruits and vegetables induce nuclei formation and growth, thereby producing ice crystals of different sizes, which affect

Table 2
Advantages and limitations of emerging freezing techniques.

Freezing techniques	Mechanisms	Advantages	Limitations
Microwave freezing	Dipole polarization of water molecules due to electromagnetic field effect	Energy-saving and flexible, temperature and weight loss can be measured while freezing	Poor rehydration property
Electric field freezing	Same as microwave, but with the electric field component	Short nucleation time, on-line measurement of changes in products	Corona discharge affects nucleation and freezing capability
Ultrasonic freezing	Ultrasound propagates to the molecules of cellular water	Energy-efficient and short nucleation time, capable of facilitating crystallization and recrystallization	High intensity leads to heating effects
High-pressure freezing	Samples are cooled under pressure at sub-zero temperatures to induce extensive supercooling throughout the sample	Large supercooling promotes instantaneous crystallization, high nucleation rate	It cannot be used for products with high porosity or high air content

cell walls, microstructures and the quality of frozen products. The control of ice formation and growth is therefore crucial to optimize quality preservation.

Although widely used in the food industry, conventional freezing techniques including immersion, air blast, and plate contact freezing could produce large ice crystals that cause cell rupture and affect the microstructure of fruits and vegetables. To better preserve cell structures and maintain the microstructure of frozen products, innovative freezing techniques have been developed (Cheng et al., 2015; Zhu, Zhou, & Sun, 2019), which include microwave-assisted, ultrasound-assisted, electric field-assisted, high-pressure freezing (HPF), and isochoric freezing. The mechanisms, advantages, and limitations of some of these techniques are summarized in Table 2.

Microwave-assisted freezing involves low energy consumption and much less freezing time. By influencing the characteristics of cellular water in plant tissue, the microwave field attempts to reorient the water molecules and break the hydrogen bonds connecting the water network, thus controlling ice formation in cells and tissues of fruits and vegetables (Dalvi-Isfahan et al., 2017; Jiang, Zhang, Mujumdar, & Lim, 2015, 2010, 2014). Jiang, Zhang, and Mujumdar (2010a, 2010b) examined the variation of structure and some physicochemical changes during different stages of microwave-assisted freezing of banana chips and showed that ice crystals size was directly correlated to the number of nuclei formed during nucleation stage, which consequently influenced microstructure. They further reported that different times and temperatures of the cold trap significantly affected the freezing rate and microstructure.

In other studies, Wang, Zhang, and Mujumdar (2012) and Jiang et al., (2014, 2015) applied pulse-spouted microwave-assisted freezing for lettuce slices and banana cubes, respectively and revealed that the pulse-spouted microwave assisted freezing improved the uniformity of temperature distribution with minimal moisture movement as compared with the steady freezing mode.

In ultrasound-assisted freezing, the ultrasound waves can generate uniform bubbles following sponge effect, leading to the creation of microscopic channels in products (Islam, Zhang, & Adhikari, 2017; Khandpur & Gogate, 2015; Xu, Zhang, Bhandari, Cheng, & Islam, 2015). The technique can be applied to preserve the cell structure of frozen products through the initiation of ice nucleation, control of ice crystal size, and acceleration of the freezing process (Zhang, Zhu, & Sun, 2018). Several studies have reported the effects of ultrasound on preserving the cell structures of strawberry (Cheng, Zhang, Adhikari, Islam, & Bao-guo, 2014, 2015), broccoli (Xin, Zhang, & Adhikari, 2014), and red radish (Xu et al., 2015), showing the formation of microscopic channels in the cell structures that reduced the adhesion among cells and increased cell interspaces, consequently resulting in an increase in the diffusion of water. Thus, ultrasound-assisted freezing can induce faster ice formation with preserved cell structures.

For electric field-assisted freezing, an electric voltage is applied to control the size of ice crystals by realignment of water molecules present in the cells. The realignment of water molecules causes spontaneous nucleation through the breakage of the hydrogen bonds, making the water less structured and polarized (Woo & Mujumdar, 2010). However, when dissolved solutes in the water solution are considered, the field-effect in controlling ice crystal growth is influenced by the amount of the dissolved solute (Woo & Mujumdar, 2010). For instance, additives such as sodium chloride (NaCl), sucrose, trehalose, glycerol, and glucose can significantly influence the nucleation temperature and ice crystal sizes under direct current (DC) electric field application (Petersen, Schneider, Rau, & Glasmacher, 2006). Jha, Sadot, et al. (2017) and Jha, Xanthakis, et al. (2017) categorically stated that the use of electric field-assisted freezing through either alternating current (AC) or DC electric field applications in an aqueous solution containing ionic solutes was able to interfere with ice crystal growth, due to the potential difference generated between the forming ice and solution.

While the electric current sustained in the growing interphase can reduce the diffusion coefficient of water, the formation of ice crystals is suppressed depending on the nature of solute in terms of concentration and the freezing rate. Apart from solute concentrations, other factors like strength of the applied electric field and the properties of the electrode (i.e. electrode type, ionization tendency, polarity, surface roughness and shape of electrode materials) can also contribute to nuclei formation and ice crystal growth during electric field-assisted freezing (Jha et al., 2017).

For HPF, pressure decreases the freezing point (0 °C) of water to a minimum of −22 °C at 208 MPa (Sanz & Otero, 2014). This implies that when cellular tissue of fruits and vegetables is kept in a liquid state at sub-zero temperatures combined with high pressure, upon pressure release, a large degree of supercooling is achieved, promoting rapid ice nucleation. The method is safe and energy-efficient, which supports the uniform distribution of pressure over the sample, resulting in homogenous nucleation throughout the sample. The number and size of ice crystals formed during HPF are directly proportional to the extent of supercooling reached in the sample before nucleation and the subsequent growth of ice crystals. So far, three strategies have been identified for HPF including pressure shift freezing (PSF), pressure-assisted freezing (PAF) and pressure-induced freezing (PIF). The comparative differences among each process are extensively discussed by Cheng, Sun, et al. (2015) and Cheng, Zhang, et al. (2015). The first two methods (i.e. PSF and PAF) are commonly studied in literature due to their easy operation, mainly about their effects on the texture, appearance, microstructure, and colour of fruits and vegetables. Meanwhile, the PSF technique has the advantage over PAF because it accelerates the rate of nucleation, and consequently promotes the formation of small ice crystals (Sanz & Otero, 2014).

Study on PSF (at 210 MPa and −20.5 °C) of cellular tissue of broccoli as shown Fig. 4, indicates a well-preserved microstructure, with no major changes on colour, and lower drip losses and better texture as compared with samples frozen under conventional freezing in atmospheric conditions (Fernandez & Prestamo, 2006).

On the other hand, Otero, Martino, Zaritzky, Solas, and Sanz (2000) evaluated the microstructure modifications of peach and mango under PSF (at 200 MPa and −20 °C) as compared with samples frozen under conventional air blast (−40 °C) and cryogenic freezing in liquid

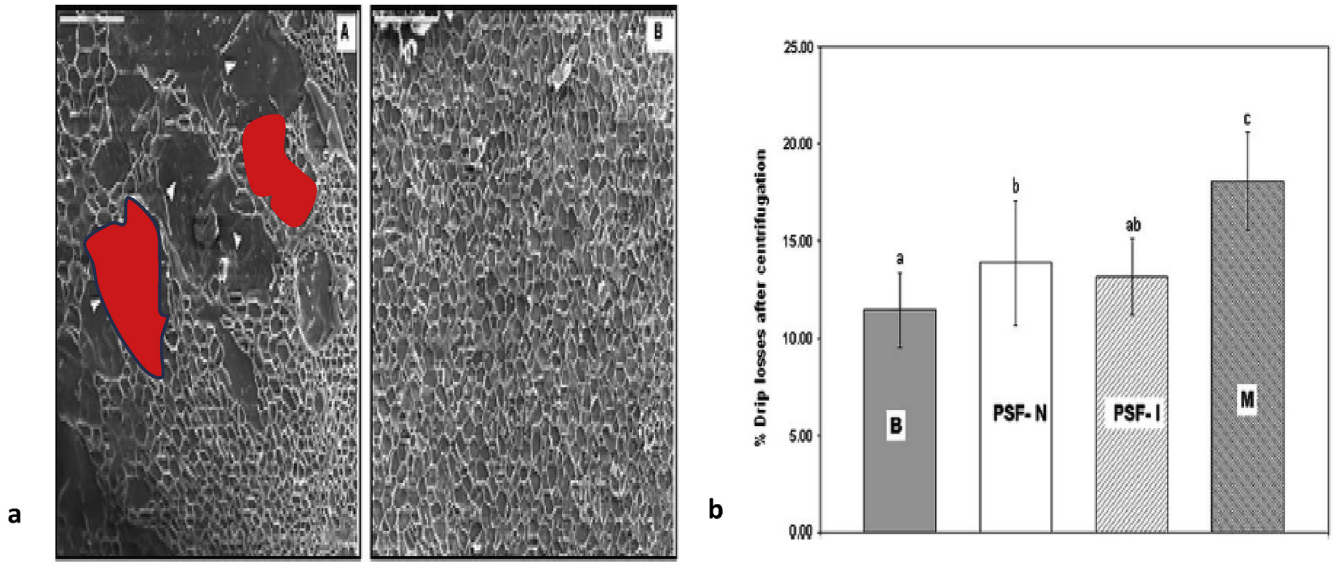


Fig. 4. Assessment of cell damages on broccoli frozen by high pressure-shift freezing, (a) Cryo-SEM micrographs (A: frozen broccoli at atmospheric condition with large irregular ice crystals, B: pressure-shift frozen broccoli at 210 MPa and −20.5 °C with the white bar = 200 μm), and (b) comparison of drip losses (%) with different freezing processes (B: non-frozen blanched sample, PSF-N: sample frozen by pressure-shift freezing followed by freezing in liquid N2, PSF-I: pressure-shift frozen sample, M: frozen sample in atmospheric conditions) (Fernandez & Prestamo, 2006).

nitrogen, and showed that PSF prevented the quality loss, whereas air blast freezing formed large ice crystals and negatively influenced the cell structure and the final quality. However, the most challenging issue in applying HPF is the substances or mixtures including silicon oil, propylene glycol, glycol/water, ethylene/glycol ethanol/glycol, and ethanol/water used in the pressure vessel (Sanz & Otero, 2014) as liquids are unhygienic, and pre-vacuum packing of the samples in a polythene bag is needed.

Another novel freezing technique reported by Preciado and Rubinsky (2010), called isochoric freezing, preserves fruits and vegetables at subfreezing temperatures without ice damage. In isochoric freezing, produce is immersed in a solution in osmotic equilibrium with the produce processed inside a pressure chamber. This technique has been demonstrated for producing less damaging ice crystals and better-preserved texture, structure and nutritional property of sweet cherry and spinach (Bilbao-Sainz et al., 2018, 2019).

6. Conclusions and future prospects

Transport phenomena can greatly influence the cell walls and microstructure of fruits and vegetables during freezing. However, the occurrence of phase change during the freezing process allows the diffusion of cellular water across the cell membrane, thereby producing ice crystals of different sizes.

The formation of large ice crystals causes damage to cell structure, which normally occurs due to slow moisture movement in cells with conventional freezing techniques. On the other hand, emerging freezing techniques can potentially produce small ice crystals throughout the sample, thus maintaining the integrity of cells and microstructure of the frozen product.

So far, the emerging techniques used in controlling the size of ice crystals have not yet completely solved the problems of degrading the microstructure of fruits and vegetables caused by conventional freezing methods. This is mainly due to the ionic composition of fruits and vegetables, leading to high osmotic stress achievable at low temperatures and causing an increase in the diffusion coefficient of cellular water. Although it was hypothesized that the application of the electric field during freezing of a food system could reduce the diffusion coefficient of water and thus has the capability of producing small ice crystals, it has not been demonstrated in the cellular tissue of fruits and vegetables. In addition, the presence of intracellular space and variation in cellular water plays a significant role in moisture transport in fruits and vegetables, however, there is not yet any study available that considers the effects of intracellular space and cellular water on cellular tissues during freezing, therefore, more studies should be conducted at the cell level.

In regard to modelling, the effects of heat and mass transfer on the freezing process have been widely studied, however, other phenomena accompanying the freezing process including ice nucleation, crystal growth, thermal expansion, and volume changes, and cellular dehydration, stress, and crack are much neglected. Future studies should thus focus on combining the modelling of heat and mass transfer with these phenomena so that the model can not only predict the freezing process but also the overall product quality. One possibility is to use multiphase modelling with the capability of analyzing cell deformation, which should provide a better understanding of moisture transport to ensure adequate preservation of microstructure.

For microwave-assisted, ultrasound-assisted, electric field-assisted, and high-pressure freezing, most of the studies are still at the experimental stage, while their potentiality in preserving the microstructure of plant-based materials have been demonstrated, more studies should focus on the effect of different freezing parameters on ice crystal size distribution and the microstructure of fruits and vegetables in order to optimize the freezing processes.

Acknowledgement

The authors are grateful to the Key R&D Program of Ningxia Hui Autonomous Region (2018BCF01001) for its support. This research was also supported by the National Key R&D Program of China (2017YFD0400404), the Agricultural Development and Rural Work of Guangdong Province (2018LM2170, 2018LM2171, 2017LM4173), the Contemporary International Collaborative Research Centre of Guangdong Province on Food Innovative Processing and Intelligent Control (2019A050519001), the Common Technical Innovation Team of Guangdong Province on Preservation and Logistics of Agricultural Products (2019KJ145) and the Innovation Centre of Guangdong Province for Modern Agricultural Science and Technology on Intelligent Sensing and Precision Control of Agricultural Product Qualities. In addition, Kehinde Peter Alabi is in receipt of a SCUT International

Scholarship for Excellence from the South China University of Technology.

References

Ambastha, V., & Tiwari, B. S. (2015). Cellular water and anhydrobiosis in plants. *Journal of Plant Growth Regulation, 34*(3), 665–671.

Ando, Y., Maeda, Y., Mizutani, K., Wakatsuki, N., Hagiwara, S., & Nabetani, H. (2016). Impact of blanching and freeze-thaw pretreatment on drying rate of carrot roots in relation to changes in cell membrane function and cell wall structure. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 71*, 40–46.

Andres-Bello, A., Barreto-Palacious, V., Garcia-Sergovia, P., Mir-Bel, J., & Martinez-Monzo, J. (2013). Effect of pH on color and texture of food products. *Food Engineering Reviews, 5*, 158–170.

Ashworth, E. N., & Pearce, R. S. (2002). Extracellular freezing in leaves of freezing-sensitive species. *Planta, 214*, 798–805.

Bilbao-Sainz, C., Sinrod, A., Dao, L., Takeoka, G., Williams, T., Wood, D., et al. (2019). Preservation of spinach by isochoric (constant volume). *International Journal of Food Science and Technology, 55*(5), 2141–2151.

Bilbao-Sainz, C., Sinrod, A., Powell-Palm, M., Dao, L., Takeoka, G., Williams, T., et al. (2018). Preservation of sweet cherry by isochoric (constant volume). *Innovative Food Science & Emerging Technologies, 52*, 108–115.

Blija, A., Beitane, I., Aboltins, A., & Boca, S. (2017). Heat-mass transfer in layer of berries during freezing process. Paper No. 16/172, *Paper presented at the International Conference of Engineering for Rural Development. Jelgava, Latvia,* 700–705 Date 24-26, 05 2017.

Buggenhout, S. V., Lille, M., Messagie, I., Loey, A. V., Autio, K., & Hendrickx, M. (2006). Impact of pretreatment and freezing conditions on the microstructure of frozen carrots : Quantification and relation to texture loss. *European Food Research and Technology, 222*, 543–553.

Campanone, L. A., Viviana, O. S., & Rodolfo, H. M. (2005). Food freezing with simultaneous surface dehydration : Approximate prediction of freezing time. *International Journal of Heat and Mass Transfer, 48*, 1205–1213.

Celli, G. B., Ghanem, A., & Brooks, M. S.-L. (2016). Influence of freezing process and frozen storage on the quality of fruits and fruit products. *Food Reviews International, 32*(3), 280–304.

Chassagne-Berces, S., Poirier, C., Marie-Francoise, D., Fernada, F., Marc, L., Giuseppe, P., et al. (2009). Changes in texture, cellular structure and cell wall composition in apple tissue as a result of freezing. *Food Research International, 42*(7), 788–797.

Cheng, L., Sun, D.-W., Zhu, Z., & Zhang, Z. (2015). Emerging techniques for assisting and accelerating food freezing processes - a review of recent research progresses. *Critical Reviews in Food Science and Nutrition, 57*(4), 769–781.

Cheng, X.-F., Zhang, M., Adhikari, B., Islam, N., & Bao-guo, X. (2014). Effect of ultrasound irradiation on some freezing parameters of ultrasound-assisted immersion freezing of strawberries. *International Journal of Refrigeration, 44*, 49–55.

Cheng, X.-F., Zhang, M., Bao-guo, X., Adhikari, B., & Sun, J. (2015). The principles of ultrasound and its application in freezing related processes of food materials : A review. *Ultrasonics Sonochemistry, 27*, 576–585.

Cichowska, J., & Kowalska, H. (2018). Effect of osmotic pre-treatment and temperature storage conditions on water activity and colour of dried apple. *International Journal of Food Engineering, 14*(2), 1–11.

Dalvi-Isfahan, M., Mamdami, N., Xanthakis, E., & Le-Bail, A. (2017). Review on the control of ice nucleation by ultrasound waves, electric and magnetic fields. *Journal of Food Engineering, 195*, 222–234.

Delgado, A. E., & Rubiolo, A. C. (2005). Microstructural changes in strawberry after freezing and thawing processes. *LWT Food Science and Technology, 38*(2), 135–142.

Delgado, A. E., & Sun, D.-W. (2001). Heat and mass transfer models for predicting freezing processes - a review. *Journal of Food Engineering, 47*, 157–174.

Fernandez, P. P., & Prestamo, G. (2006). Assessment of cell damage in high-pressure-shift frozen broccoli: Comparison with market samples. *European Food Research and Technology, 224*(1), 101–107.

Herath, U. S. (2019). Fruit consumption, its determinants and attitudes among undergraduates. *International Journal of Agriculture, Environment and Food Sciences, 3*(1), 50–53.

Hoffmann, K., Boeing, H., Volatier, J., & Becker, W. (2014). Evaluating the potential health gain of the World Health Organization' s recommendation concerning vegetable and fruit consumption. *Public Health Nutrition, 6*(8), 765–772.

Hughes, R. J., Edwards, K. L., Clarke, G. P., Evans, C. E. L., Cade, J. E., & Ransley, J. K. (2012). Childhood consumption of fruit and vegetables across england: A study of 2306 6 - 7-year-olds in 2007. *British Journal of Nutrition, 108*, 733–742.

Islam, N., Zhang, M., & Adhikari, B. (2017). Ultrasound-assisted freezing of fruits and vegetables: Design, development, and applications. In G. V. Barbosa-cánovas,, P. María,, G. Candoğan,, K. Medina,, I. G. Meza,, & C.da S. Lannes, (Eds.). *Global food security and wellness* (pp. 457–487). New York: Springer.

Jha, P. K., Sadot, M., Vino, S. A., Rouaud, O., Havet, M., Le-bail, A., et al. (2017). A review on effect of DC voltage on crystallization process in food systems. *Innovative Food Science & Emerging Technologies, 42*, 204–219.

Jha, P. K., Xanthakis, E., Chevallier, S., Jury, V., & Le-Bail, A. (2018). Assessment of freeze damage in fruits and vegetables. *Food Research International, 12*(2), 1–18.

Jha, P. K., Xanthakis, E., Jury, V., & Le-Bail, A. (2017). An overview on magnetic field and electric field interactions with ice crystallisation; application in the case of frozen food. *Crystals, 7*(10), 299–321.

Jiang, H., Zhang, M., & Mujumdar, A. S. (2010a). Physico-chemical changes during different stages of MFD/FD banana chips. *Journal of Food Engineering, 101*(2), 140–145.

Jiang, H., Zhang, M., & Mujumdar, A. S. (2010b). Microwave freeze-drying characteristics of banana crisps. *Drying Technology, 28*(12), 1377–1384.

Jiang, H., Zhang, M., Mujumdar, A. S., & Lim, R. (2014). Comparison of drying characteristic and uniformity of banana cubes dried by pulse-spouted microwave vacuum drying, freeze drying and microwave freeze drying. *Journal of the Science of Food and Agriculture, 94*(9), 1827–1834.

Jiang, H., Zhang, M., Mujumdar, A. S., & Lim, R. (2015). Drying uniformity analysis of pulse-spouted microwave freeze drying banana cubes. *Drying Technology, 34*(5), 539–546.

Joardder, M. U. H., Kumar, C., & Karim, M. A. (2017). Food structure: Its formation and relationships with other properties. *Critical Reviews in Food Science and Nutrition, 57*(6), 1190–1205.

Karim, A., Rahman, M. M., Pham, N. D., & Fawzia, S. (2018). Food microstructure as affected by processing and its effect on quality and stability. In S. Devahastin (Ed.). *Food microstructure and its relationship with quality and stability* (pp. 43–56). United Kingdom: Woodhead Publishing Limited.

Khandpur, P., & Gogate, P. R. (2015). Understanding the effect of novel approaches based on ultrasound on sensory profile of orange juice. *Ultrasonics Sonochemistry, 27*, 87–95.

Khan, I. H., & Karim, M. A. (2017). Cellular water distribution, transport and investigation methods for plant-based food materials. *Food Research International, 99*, 1–14.

Khan, I. H., Kumar, C., & Karim, M. A. (2016). Mechanistic understanding of cellular level of water in plant-based food material. *Paper No. 01000-1, paper presented at the 7th BSME international conference on thermal engineering Dhaka, Bangladesh* Date 22-24 December 2016.

Khan, I. H., Nagy, S. A., & Karim, M. A. (2017). Transport of cellular water during drying : An understanding of cell rupturing mechanism in apple tissue. *Food Research International, 105*, 772–781.

Khan, I. H., Wellard, R. M., Nagy, S. A., Joardder, M. U. H., & Karim, M. A. (2016). Investigation of bound and free water in plant-based food material using NMR T 2 relaxometry. *Innovative Food Science & Emerging Technologies, 38*, 252–261.

Khan, I. H., Wellard, R. M., Nagy, S. A., Joardder, M. U. H., & Karim, M. A. (2017). Experimental investigation of bound and free water transport process during drying of hygroscopic food material. *International Journal of Thermal Sciences, 117*, 266–273.

Khudyakov, A. N., Kuleshova, L. G., & Zaitseva, O. O. (2018). The effect of pectins on water crystallization pattern and integrity of cells during freezing. *Biopreservation and Biobanking, 66*, 3–8.

Kiani, H., Sun, D.-W., Delgado, A., & Zhang, Z. (2012). Investigation of the effect of power ultrasound on the nucleation of water during freezing of agar gel samples in tubing vials. *Ultrasonics Sonochemistry, 19*, 576–581.

Kobayashi, R., & Suzuki, T. (2018). Effect of supercooling accompanying the freezing process on ice crystals and the quality of frozen strawberry tissue. *International Journal of Refrigeration, 99*, 94–100.

Kotwaliwale, N., Curtis, E., Othman, S., Naganathan, G. K., & Subbiah, J. (2012). Magnetic resonance imaging and relaxometry to visualize internal freeze damage to pickling cucumber. *Postharvest Biology and Technology, 68*, 22–31.

Kouznetsova, V., Brekelmans, W. A. M., & Baaijens, F. P. T. (2001). An approach to micro-macro modeling of heterogeneous materials. *Computational Mechanics, 27*(1), 37–48.

Li, B., & Sun, D.-W. (2002). Novel methods for rapid freezing and thawing of foods— A review. *Journal of Food Engineering, 54*, 175–182.

Li, D., Zhu, Z., & Sun, D.-W. (2018). Effect of freezing on cell structure of fresh cellular food materials: A review. *Trends in Food Science & Technology, 75*, 46–55.

Luo, W., Sun, D.-W., Zhu, Z., & Wang, Q.-J. (2018). Improving freeze tolerance of yeast and dough properties for enhancing frozen dough quality - a review of effective methods. *Trends in Food Science & Technology, 72*, 25–33.

Mahato, S., Zhu, Z., & Sun, D.-W. (2019). Glass transitions as affected by food compositions and by conventional and novel freezing technologies: A review. *Trends in Food Science & Technology, 94*, 1–11.

McDonald, K., & Sun, D.-W. (2001). Effect of evacuation rate on the vacuum cooling process of a cooked beef product. *Journal of Food Engineering, 48*, 195–202.

Nakagawa, K., & Ochiai, T. (2015). A mathematical model of multi-dimensional freeze-drying for food products. *Journal of Food Engineering, 161*, 55–67.

Nicolaï, B. M., Verboven, P., Scheerlinck, N., & Leuven, K. U. (2001). The modelling of heat and mass transfer. In L. M. M. Tijskens, L. A. T. M. Hertog, & B. M. Nicolai (Eds.). *Food process modelling, 60–86*. U S A: Woodhead Publishing Limited and CRC Press.

Norton, T., Delgado, A., Hogan, E., Grace, P., & Sun, D.-W. (2009). Simulation of high pressure freezing processes by enthalpy methods. *Journal of Food Engineering, 91*, 260–268.

Ochoa-Jiménez, V. A., Berumen-Varela, G., Fernández-Valle, R., Martín-Ernesto, & Hernández, T. (2018). Rhamnogalacturonan lyase: A pectin modification enzyme of higher plants. *Emirates Journal of Food and Agriculture, 30*(11), 910–917.

Oikonomopoulou, V. P., Krokida, M. K., & Karathanos, V. T. (2011). The influence of freeze drying conditions on microstructural changes of food products. *Procedia Food Science, 1*, 647–654 *11th International Congress on Engineering and Food*. May 22-26, 2011, Athens, Greece.

Oliver, J., & Palou, A. (2000). Chromatographic determination of carotenoids in foods. *Journal of Chromatography A, 881*(1–2), 543–555.

Otero, L., Martino, M. A., Zaritzky, M. E., Solas, M., & Sanz, P. D. (2000). Preservation of microstructure in peach and mango during high pressure shift freezing. *Journal of Food Science, 65*(3), 466–470.

Peng, J., Yi, J., Bi, J., Chen, Q., Wu, X., Zhou, M., et al. (2018). Freezing as pretreatment in instant controlled pressure drop (DIC) texturing of dried carrot chips: Impact of freezing temperature. *LWT-Food Science and Technology, 89*, 365–373.

Petersen, A., Schneider, H., Rau, G., & Glasmacher, B. (2006). A new approach for freezing of aqueous solutions under active control of the nucleation temperature. *Journal of Cryobiology, 53*(2), 248–257.

Pham, Q. T. (2006). Modelling heat and mass transfer in frozen foods : A review.

International Journal of Refrigeration, 29(6), 876–888.
Pham, Q. T. (2016). Freezing theory. In B. Caballero, P. M. Finglas, & F. Toldra (Eds.). *Encyclopedia of food and health* (pp. 1717–1725). New York: Academic Press.
Preciado, J. A., & Rubinsky, B. (2010). Isochoric preservation: A novel characterization method. *Cryobiology, 60*, 23–29.
Rahman, M. M., Joardder, M. U. H., Khan, M. I. H., Pham, N. D., & Karim, M. A. (2017). Multi-scale model of food drying: Current status and challenges. *Critical Reviews in Food Science and Nutrition, 58*(5), 858–876.
Roy, S. S., Taylor, T. A., & Kramer, H. L. (2001). Textural and ultrastructural changes in carrot tissue as affected by blanching and freezing. *Journal of Food Science, 66*(1), 176–180.
Sanz, P. D., & Otero, L. (2014). High-pressure freezing. In D.-W. Sun (Ed.). *Emerging Technologies for food processing, 515–538*. United Kingdom: Academic Press.
Silva, C. L. M., Gonçalves, E. M., & Brandão, T. R. S. (2008). Freezing of fruits and vegetables. In J. A. Evans (Ed.). *Frozen food science and Technology* (pp. 165–183). United Kingdom: Blackwell Publishing.
Singha, P., & Muthukumarappan, K. (2016). Quality changes and freezing time prediction during freezing and thawing of ginger. *Food Sciences and Nutrition, 4*(4), 521–533.
Sman, R. V. D., Voda, M. A., Dalen, G. V., & Duijster, A. J. (2013). Ice crystal interspacing in frozen foods. *Journal of Food Engineering, 116*(2), 622–626.
Suutarinen, J., Heiska, K., Moss, P., & Autio, K. (2000). The effects of calcium chloride and sucrose prefreezing treatments on the structure of strawberry tissues. *LWT-Food Science and Technology, 33*(2), 89–102.
Tian, Y., Zhu, Z., & Sun, D.-W. (2020). Naturally sourced biosubstances for regulating freezing points in food researches: Fundamentals, current applications and future trends. *Trends in Food Science & Technology, 95*, 131–140.
Trelea, I. C., Passot, S., Marin, M., & Fonseca, F. (2009). Model for heat and mass transfer in freeze-drying of pellets. *Journal of Biomechanical Engineering, 131*(7), 9–12.
Tylewicz, U., Aganovic, K., Vannini, M., Toep, S., Bortolotti, V., Dalla, M., et al. (2016). Effect of pulsed electric field treatment on water distribution of freeze-dried apple tissue evaluated with DSC and TD-NMR techniques. *Innovative Food Science & Emerging Technologies, 37*, 352–358.
Veerman, J. L., Barendregt, J. J., & Mackenbach, J. P. (2006). The European common agricultural policy on fruits and vegetables: Exploring potential health gain from reform. *The European Journal of Public Health, 16*(1), 31–35.
Velickova, E., Tylewicz, U., Dalla, M., & Winkelhausen, E. (2011). Effect of vacuum infused cryoprotectants on the freezing tolerance of strawberry tissues. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 52*(2), 146–150.
Vicent, V., Verbonen, P., Ndoye, F. T., Alvarez, G., & Nicolai, B. (2017). A new method developed to characterize the 3D-microstructure of frozen apple using X-ray micro-CT. *Journal of Food Engineering, 212*, 154–164.
Voda, A., Homan, N., Witek, M., Duijster, A., Dalen, G. V., Van Der Sman, R., et al. (2012). The impact of freeze-drying on microstructure and rehydration properties of carrot. *Journal of Food Research International, 49*(2), 687–693.
Wang, Q., Li, Y., Sun, D.-W., & Zhu, Z. (2018). Enhancing food processing by pulsed and high voltage electric fields: Principles and applications. *Critical Reviews in Food Science and Nutrition, 58*(13), 2285–2298.
Wang, Q., Li, Y., Sun, D.-W., & Zhu, Z. (2019). Effects of high-voltage electric field produced by an improved electrode system on freezing behaviors and selected properties of agarose gel. *Journal of Food Engineering, 254*, 25–33.
Wang, Y., Zhang, M., & Mujumdar, A. S. (2012). Microwave-assisted pulse-spouted bed freeze-drying of stem lettuce slices- Effect on product quality. *Food and Bioprocess Technology, 6*(12), 3530–3543.
Woo, M. W., & Mujumdar, A. S. (2010). Effects of electric and magnetic field on freezing and possible relevance in freeze drying. *Drying Technology, 28*(4), 433–443.
Xin, Y., Zhang, M., & Adhikari, B. (2014). The effects of ultrasound-assisted freezing on the freezing time and quality of broccoli (Brassica oleracea L. var. botrytis L.) during immersion freezing. *International Journal of Refrigeration, 41*, 82–91.
Xu, B., Zhang, M., Bhandari, B., Cheng, X., & Islam, N. (2015). Effect of ultrasound-assisted freezing on the physico-chemical properties and volatile compounds of red radish. *Ultrasonics Sonochemistry, 27*, 316–324.
Zaritzky, N. (2012). Physical-chemical principles in freezing. In D.-W. Sun (Ed.). *Handbook of frozen food processing and packaging* (pp. 9–32). (2nd ed.). USA: CRC Press.
Zhang, P., Zhu, Z., & Sun, D.-W. (2018). Using power ultrasound to accelerate food freezing processes: Effect on freezing efficiency and food microstructure. *Critical Reviews in Food Science and Nutrition, 58*, 2842–2853.
Zhan, X., Sun, D.-W., Zhu, Z., & Wang, Q.-J. (2018). Improving the quality and safety of frozen muscle foods by emerging freezing technologies: A review. *Critical Reviews in Food Science and Nutrition, 58*, 2925–2938.
Zhan, X., Zhu, Z., & Sun, D.-W. (2019a). Effects of extremely low frequency electromagnetic field on the freezing processes of two liquid systems. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 103*, 212–221.
Zhan, X., Zhu, Z., & Sun, D.-W. (2019b). Effects of pretreatments on quality attributes of long-term deep frozen storage of vegetables: A review. *Critical Reviews in Food Science and Nutrition, 59*, 743–757.
Zhu, Z., Geng, Y., & Sun, D.-W. (2019a). Effects of operation processes and conditions on enhancing performances of vacuum cooling of foods: A review. *Trends in Food Science & Technology, 85*, 67–77.
Zhu, Z., Li, Y., Sun, D.-W., & Wang, H.-W. (2019b). Developments of mathematical models for simulating vacuum cooling processes for food products – a review. *Critical Reviews in Food Science and Nutrition, 59*(5), 715–727.
Zhu, Z., Luo, W., & Sun, D.-W. (2020a). Effect of liquid nitrogen quick freezing on polyphenol oxidase and peroxide activities, cell water states and epidermal microstructure of wolfberry. *LWT- Food Science and Technology, 120*, 108923.
Zhu, Z., Wu, X., Yi, G., Sun, D.-W., Chen, H., Zhao, Y., et al. (2018). Effects of modified atmosphere vacuum cooling (MAVC) on the quality of three different leafy cabbages. *LWT-FOOD SCIENCE AND TECHNOLOGY, 94*, 190–197.
Zhu, Z., Zhang, P., & Sun, D.-W. (2020b). Effects of multi-frequency ultrasound on freezing rates and quality attributes of potatoes. *Ultrasonics Sonochemistry, 60*, 104733.
Zhu, Z., Zhou, Q., & Sun, D.-W. (2019). Measuring and controlling ice crystallization in frozen foods: A review of recent developments. *Trends in Food Science & Technology, 90*, 13–25.