Texture of freeze-dried intact and restructured fruits: Formation mechanisms and control technologies

Shuhan Feng[1], Jinfeng Bi[*1], Timo Laaksonen[2], Patrick Laurén[2], Jianyong Yi[*1]

[1] Institute of Food Science and Technology, Chinese Academy of Agriculture Sciences (CAAS) / Key Laboratory of Agro-Products Processing, Ministry of Agriculture and Rural Affairs, Beijing 100193, China

[2] Division of Pharmaceutical Biosciences, Faculty of Pharmacy, University of Helsinki, P.O. Box 56, 00014 Helsinki, Finland

* **Corresponding author at.** P.O. No. 2, Yuanmingyuan West Road, Haidian District, Beijing, 100193, China

Tel: 86-010-62812584

Email address: bjfcaas@126.com (J.Bi) ; yijianyong515@126.com (J.Yi)

Abstract

Background:

Owing to the growing demand for ready-to-eat food and the expanding food-processing sector, consumption of freeze-dried fruit food is increasing globally, holding significant market value. Texture is critical in determining the overall quality and consumer acceptance of freeze-dried fruit products. However, texture formation and control remain one of the least well-described quality attributes due to challenges from complex fruit matrices and testing methodologies, impeding advancements within the freeze-drying industry.

Scope and approach:

Focusing on the two main types of freeze-dried fruit products (*i.e.*, freeze-dried intact and restructured fruits), this review elaborates on the formation mechanisms and control technologies of the texture properties, primarily analyzing from the perspective of carbohydrates in fruits. Try to establish a porous scaffold model to clarify the dominant attributes of texture formation during freeze-drying, thereafter explain and compare the formation and control principles governing the texture of these two types of freeze-dried fruits.

Key findings and conclusions

The porous scaffold of freeze-dried fruit is built by a polysaccharide network and small molecule sugars within glassy amorphous at sufficiently low water content, showing various macroscopic porous characterization. Three dominant attributes of texture formation are summarized, namely pore/cellular morphology, solids, and water content in the final freeze-dried fruit matrix. Most texture control techniques are based on the modification of these three dominant attributes. Furthermore, freeze-dried restructured fruits exhibit a greater texture enhancement potential than intact fruits due to the loss of cellular structure, providing new inspiration for the future development of personalized multi-functional freeze-dried snacks.

Keywords: Freeze-drying, Fruit, Texture property, Restructure, Control technologies.

1. Introduction

Fruits are considered an indispensable source of dietary fiber and bioactive compounds in healthy human diets, which are associated with various benefits in preventing chronic diseases (Kubola, Siriamornpun, & Meeso, 2011). However, due to the high moisture and sugar content, plant-based foods continue to respire during storage, making them prone to browning and decay. This poses challenges for long-term storage, long-distance transportation, and year-round consumption. In this situation, drying technology that can transform such fresh foods into dried products with an extended shelf life is gaining attention. Among them, the emergence of freeze-drying (FD) technology has enabled the production of high-quality dried fruit products by directly removing water in the form of vapor via sublimation, without a liquid phase, which greatly preserves the initial properties of raw materials. Despite the above advantages, FD has always been regarded as one of the most expensive operations for manufacturing dehydrated products owing to its extensive time consumption and high energy for operation (Duan, et al., 2015). Therefore, in industrial settings, process parameters are usually adjusted to shorten time-consuming and minimize costs. Nonetheless, inappropriate parameters can lead to product thawing and structural collapse, consequently deteriorating the overall quality of the FD products (Nowak & Jakubczyk, 2020). Another way to reduce the energy consumption of FD is to eliminate vacuum limitations by operating at atmospheric pressure. Many studies have demonstrated that FD is possible to performe under atmospheric pressure if the partial pressure of water in the chamber is maintained sufficiently low, referred to as atmospheric freeze drying (Bantle, Kolsaker, & Eikevik, 2011; Meryman, 1959). However, the drying rate of atmospheric freeze drying is too slow to be industrially feasible (Duan, et al., 2015; Ishwarya, Anandharamakrishnan, & Stapley, 2015).

In general, texture, appearance, flavor, and nutritional value are summarized as the four major factors used to evaluate the overall quality of foods (Mercado, Matas, & Posé, 2019). Among them, the textural factor significantly influences consumer acceptance, as it directly affects sensory appreciation and enjoyment during chewing.

Unlike fresh fruits with a water content of up to 80-90%, freeze-dried fruits lose almost all free water and part of bound water, resulting in significant differences in their textural characteristics (Nowak & Jakubczyk, 2020). After FD, the removal of frozen water creates porous spaces, which leads to the formation of special porous or sponge-like structures, conferring the lyophilized fruits a remarkably crispy texture. During this process, the frozen water acts as a porogen. After water removal, most of the solid matter in the fruit matrix is retained, which can be divided into water-insoluble fractions (WIF) and water-soluble fractions (WSF). The WIF mainly consists of certain cell wall polysaccharides, proteins, and some macromolecular storage substances (Mercado, et al., 2019). The WSF can be described as the low molecular compounds present in the watery dispersing medium of plants, such as salts, sugars, organic acids, water-soluble bioactive ingredients, *etc*. In this case, the final freeze-dried fruits could be regarded as a porous plant-based structure built by the combination of WIF and WSF with trace moisture, giving them a unique sense of texture. Given the compositional complexity of fruit matrices, the present review will specifically focus on the role of carbohydrates in the freeze-dried texture formation process.

Currently, freeze-dried fruit products are widely processed by many manufacturers (including Nestle, General Mills, Kellogg's, *etc*.) due to their storage stability, high nutrient retention, and convenience in consumption. Based on our survey of online and offline products, as shown in Fig. 1, the freeze-dried fruit products currently circulating in the food market could be divided into two categories: (i) Freeze-dried intact fruits (FDi), which are manufactured by directly performing FD without damaging the cell-tissue morphology of raw materials, or by mere slicing. (ii) Freeze-dried restructured fruits (FDr), which are produced with various pretreatments (such as grinding, crushing, pulping, homogenizing, *etc*.), frequently coupled with the incorporation of various additives. Compared to FDi, FDr products available in the current food market represent a category of FD snacks derived from one or several raw materials that are generated by grinding, homogenizing, mixing, and subsequently reshaping. For example, Hnin et al. (2019) developed freeze-dried restructured rose powder-yam snack chips by blending ground yam paste with rose powder. Huang et al. (2011) created freeze-dried restructured apple chips by mixing apple with potato paste. Ciurzyńska et al. (2020) produced freeze-dried restructured fruit and vegetable bars by combining broccoli, cauliflower, green pepper, and carrot pulp. In a word, restructured fruits are a fruit state that needs to undergo a thorough process to fully disrupt the plant tissue morphology. Hence, in this review, we define freeze-dried fruit products with an intact tissue structure as FDi, and those with a disrupted tissue structure as FDr. Due to the different processing procedures for FDi and FDr, these two categories of FD fruit products display contrasting porous structures, implying variations in their final textural properties. Given the substantial market potential of freeze-dried fruits, a comprehensive understanding of the texture formation mechanisms and control technologies in these two types of products is crucial for the future development of the FD industry.

In recent years, the application and development of FD technology in food processing have been comprehensively reviewed (Bhatta, Stevanovic Janezic, & Ratti, 2020; Nowak & Jakubczyk, 2020). Nevertheless, texture is one of the least well-described food quality attributes, which is probably attributed to the challenges from complex fruit matrices and testing methodologies. To the best of our knowledge, a comprehensive review of the texture formation and control technologies of FDi and FDr is currently lacking. To address this gap, the current review will provide a systematic introduction to the formation mechanisms and control technologies of the freeze-dried texture properties within FDi and FDr based on the FD process (i.e., freezing and drying), primarily analyzing from the perspective of carbohydrates in fruits. Furthermore, the definition and development prospects of freeze-dried fruit texture are also discussed.

2. Fundamental Principle of Freeze Drying

During FD process, the removal of solid-state free water and some bound water in fruits generally falls into three phases: freezing (completely solidification), the primary drying phase (ice sublimation), and the secondary drying phase (desorption of remaining unfrozen water), as illustrated in Fig. 2a. These three phases of the FD involve five essential physical phenomena to ensure the overall quality of the obtained products, namely freezing, sublimation, desorption, vacuuming, and vapor condensation (Waghmare, Perumal, Moses, & Anandharamakrishnan, 2021). This review will focus on three stages of freezing, sublimation, and desorption stages that significantly influence the texture properties of lyophilized products.

2.1 Freezing Phase

As the first separation step, up to 95% of the water in fruit systems is completely solidified, so the morphology and size distribution of pure solid ice crystals are fixed at this stage (Assegehegn, Brito-de la Fuente, Franco, & Gallegos, 2019). If no collapse occurs during the subsequent drying stage, the morphology of the ice crystals will remain consistent with the final pore structure of the dried products, which, in turn, impacts the textural properties of the lyophilized fruits. Through pre-cooling and ice crystallization, the majority of the water at this stage solidifies into an ice phase network (Waghmare, et al., 2021). During solidification, the availability of free water decreases, causing dissolved solute molecules to be excluded from pure ice crystals, and subsequently accumulate in residual liquid water, which is also referred to as cryo-concentrated. Along with cryo-concentration, the frozen food system gradually transforms into a two-phase mixture consisting of ice crystals and concentrated amorphous solution, eventually yielding the concentrated amorphous solution with the maximum concentration, resulting in a rubber-like texture. As the temperature continues to drop, the concentrated amorphous solution will transition from a rubbery state to a solid amorphous glassy state, which is usually denoted as glassification or vitrification. The temperature at which this transition occurs is referred to as glass transition temperature (Tg). For preservation, the freezing step should be performed at or below the Tg of freeze-dried fruits, as the frozen food products are in an unstable rubbery or liquid state when the temperature is above the Tg (Ohkuma, et al., 2008).

2.2 Primary Drying Phase

During primary drying, a vacuum is applied, and the shelf temperature is raised to induce the sublimation of ice in the frozen products. In order to maintain the sublimation process, there are two basic conditions that must be met. Firstly, the sublimation vapor needs to be constantly removed from the sublimation area without hindrance. Secondly, continuous heat supply to the material is necessary for ice sublimation, maintaining the vapor pressure difference, and removing water vapor from the chamber. Here, it is crucial to carefully balance the heat added to the materials with the energy extracted from the drying materials as water vapor. Otherwise, excessive heat leads to an increase in sublimation temperature above the *Tg*, resulting in the ice melting into a solute phase, allowing the system to stay sufficiently mobile to flow under the forces operating within the food structure. In this state, unexpected structural phenomena may occur, such as irreversible softening, bulging, shrinking, and collapse (Assegehegn, Brito-de la Fuente, Franco, & Gallegos, 2020). Unfortunately, these structural phenomena usually represent the loss of structure, reduction of pore size and number, and the shrinkage of volume, restricting the vapor transfer rate and effectively ending the drying operation, while making freeze-dried materials lose their crunchiness and become texturally unacceptable (Levi & Karel, 1995). Therefore, to avoid structural collapse, the pressure must be low enough for the free water in the materials to remain in a solid state (Fig. 2b). Theoretically, the pressure in the chamber should be below 610 Pa (the triple point pressure of water), but plant material frequently needs to be maintained at around 63-124 Pa under a lower temperature of at least -25 to -20 °C (Genin & Rene, 1996). However, in the industrial production of freeze-dried fruits, the collapse temperature (*Tc*) of the specific material seems as a more practical and precise temperature for determining the collapse during FD. *Tc* is the temperature above which the macroscopic structure of freeze-dried products undergoes collapse and the shelf temperature of freeze-dried fruits ideally should be maintained at 2-3 °C below the *Tc* to prevent or retard structural collapse (Levi & Karel, 1995; Merivaara, et al., 2021).

2.3 Secondary Drying Phase

The last stage is termed "secondary drying", during which unfrozen water is removed by desorption from the concentrated amorphous solution. Depending on the composition and content of the solids in the fruits, various amounts of residual water still adsorbed in the amorphous matrix after primary drying, potentially affecting the storage stability of the final products. Basically, the residual water content after primary drying accounts for 5-20% of the initial water content of fresh raw materials (Assegehegn, et al., 2020). Therefore, the purpose of secondary drying is to limit the residual water content of freeze-dried products to the recommended level for long-term storage. In essence, the secondary drying phase determines the final moisture content or water activity (*Aw*) of freeze-dried fruits, which in turn influences their *Tg* values. Yi, et al. (2016) have indicated that in the range of low water content, an increase in the *Aw* of the dried sample caused a decrease in the *Tg* value of the system. In other words, the lower the moisture content, the higher the *Tg* of the dried product, and the more stable the glass state of the system is. Hence, *Aw* and *Tg* are two broadly accepted concepts that elaborate on the storage stability of freeze-dried fruit systems. Generally, the final moisture content of freeze-dried cellular materials is between 0.5 to 3%, as higher values can damage long-term storage stability, while lower values can affect the activity of the active ingredients (Merivaara, et al., 2021).

3. Texture Characteristics of Freeze-dried Fruits

3.1 Texture Definition of Freeze-dried Fruits

The study of texture could be traced back to the end of the 19th century and the beginning of the 20th century, but a general agreement on the definition of texture was not reached until nearly the 21st century (Szczesniak, 2002). Brennan (1989) defined the sensory perceived texture as '*The attribute of a substance resulting from a combination of physical properties and perceived by the senses of touch (including kinaesthesis and mouthfeel), sight and hearing*'. Szczesniak (2002) later supplemented these physical properties, describing texture as '*the sensory and functional manifestation of the structural, mechanical and surface properties of foods*'. Based on elaborated on the definition of texture, three clear concepts can be derived:

(i) Texture is a sensory property, and the physical parameters quantified by texture analyzers (TA) must be interpreted in terms of sensory perception.

(ii) It is a multi-parameter attribute derived from the molecular, microscopic, and macroscopic structure of the food.

(iii) Humans perceive texture through multiple senses, most notably the senses of touch and pressure.

According to Civille and Szczesniak's description of the solid and semi-solid foods, to which freeze-dried fruits belong, the classification of textural terms mainly includes hardness, cohesiveness, viscosity, springiness, and adhesiveness (Civille & Szczesniak, 1973). The aforementioned textural characteristics have been systematically described and defined by Szczesniak (2002). Specifically, hardness refers to the force required to compress and deform a material; cohesiveness represents the extent to which the material can be deformed before breaking; viscosity is defined as the rate of flow per unit force; springiness is described as the rate at which a deformed material returns to its undeformed state after the deforming force is removed; and adhesiveness is related to the force required to remove substances that adhere to the oral cavity.

For the dynamic aspects, the above descriptions of texture characteristics can be divided into two stages: before or after the freeze-dried fruits enter the oral cavity. As presented in Fig. 3a, before entering the oral cavity, the unique porous structure and extremely low water content of freeze-dried fruits endow their texture with hardness, cohesiveness, and springiness as the main characteristics. Their hardness is usually described as firm, cohesiveness as brittleness, and springiness as plastic. After entering the oral cavity, the rehydration of freeze-dried fruits imparts them with the properties of semi-solid food and irreversibly reduces the brittleness of the structure, showing the characteristics of viscosity and adhesiveness. The texture of freeze-dried products is mainly influenced by tactile and pressure sensations that arise during chewing in response to the compressive force of teeth. As visualized in Fig. 3b, the porous structure suffers from the fracture or rupture of the pore wall under compression force, leading to wide fluctuations in force as the structure disintegrates (Peleg, 2016). At the initial stage of chewing, porous materials were broken down into big particles due to the bite force of teeth and the squeeze force of the tongue. After extensive chewing, the large particles are further broken into small particles, and the viscosity and adhesiveness of the dried texture are gradually triggered by saliva immersion. Therefore, the hardness and brittleness of dried materials dominate at the beginning of oral processing, while the perception of viscosity and adhesiveness dominates at the end of oral processing.

Once entering the oral cavity, most of the water is re-absorbed by single fibers during the first three seconds, and the air in pores becomes a major obstacle to complete rehydration (Amos, 1967). Notably, incomplete saliva impregnation of the solids in the system may contribute to the lyophilized product becoming viscous and tacky in the oral cavity. After oral processing, freeze-dried fruit products will completely lose their porous structure as well as the dry sensation, becoming a mixed semi-solid matrix containing WIF, WSF, and saliva. For clarity, more attention in this review will be focused on the texture characteristics of freeze-dried fruit products before entering the oral cavity, namely the hardness and brittleness.

Generally, the hardness of the dried materials is defined as the maximum yield force under compression which is associated with the maximum force detected by TA. However, there are dozens of different definitions of crunchiness and crispness (brittleness). Here, we believe that the brittleness of freeze-dried fruits is better described as *"desirably firm and brittle, and easily crumbled"*, as defined by Tunick et al. (2011). As shown in Fig. 3b, the brittleness of freeze-dried fruits is closely related to the sudden yielding of the pore wall under an applied mechanical load which is reflected by the number of fracture peaks of force-distance TA curves (Lammerskitten, Wiktor, et al., 2019; Silva-Espinoza, Salvador, Camacho, & Martinez-Navarrete, 2021).

3.2 Basis of Texture Formation of Freeze-dried Fruits

The textural characteristics of freeze-dried materials are qualitatively determined by the mechanical oscillations generated within the porous scaffold. As depicted in Fig. 4a, this review tries to explain the texture formation by building a three-dimensional (3D) porous model. It discerns that this process involves the stability of the glassy state, the mechanical resistance of the pore walls to chewing as well as the physical characteristics of pore spaces. Thus, three dominant attributes of freeze-dried fruits that control their oral sense of touch and pressure could be basically classified as follows:

(i) Pore or cellular morphology, representing the basic properties of the pore space on a macroscopic 3D freeze-dried scaffold. It includes pore shape, size, number, and distribution, which are simultaneously determined by the ice habits and the drying process.

(ii) Solids, which consist of all solid matter in fruits that are aggregated and concentrated within the glassy amorphous matrix, eventually form the pore walls of freeze-dried fruits.

(iii) Water content or A_w. Sufficiently low moisture content, or A_w, is a crucial factor in maintaining the glass state of freeze-dried fruit, which is the basis of all freeze-dried textures.

3.2.1 Pore morphology

The formation of pore characteristics is a continuous process controlled by both the freezing stage and drying stage. As mentioned before, the final pore characteristics of the freeze-dried products are theoretically determined by the ice habits in the freezing stage. For example, pores with greater diameters tend to be formed by larger ice crystals at a slow freezing rate, while smaller pore sizes tend to be created at a faster freezing rate. However, unexpected structural collapse under inappropriate processing conditions during drying can destroy the initial porous structure by causing the loss of pores. Therefore, any factor that may interfere with ice crystal growth behavior during freezing and *Tg* (or *Tc*) of the system during FD could alter the pore morphology of freeze-dried products. Here, it is worth mentioning the opening and closing of pores in the fruit matrix also affect the occurrence of collapse. Briefly, the more open pores, the weaker the resistance to water vapor overflow, and the lower the degree of collapse. This is also the core reason for the difference in texture between FDi and FDr, which will be elaborated upon in section 3.3.2.

The porous characteristic or cellular structure is closely related to the hardness and brittleness of freeze-dried products. Regarding hardness, it has been confirmed that there is an obvious negative correlation between pore size (50-1000 μm) and compressive strength of porous structure (Zhao, Li, Ding, Liu, & Ai, 2018). This means that the smaller the pores, the greater the hardness of the freeze-dried fruits. Furthermore, Zhao et al. (2018) also found that a more regular pore arrangement could enhance the mechanical resistance of the porous structure. As for brittleness, it has been revealed that dried fruits with more and larger pores were crispier, while chips with fewer and smaller pores were harder and less crisp (Léonard, Blacher, Nimmol, & Devahastin, 2008). Based on the determination of brittleness, the number of fracture peaks is greatly contributed by the mechanical fracture strength of the pore walls. In other words, brittleness is closely related to hardness, as greater rigidity could bring about stronger oral perception of the mechanical oscillations from products, showing a crunchy perception. Nevertheless, Silva-Espinoza et al. (2021) found that there was a significant negative correlation ($r = -0.7109$) between the maximum force and the number of fracture peaks on force-displacement curves, indicating that crispier products break more easily when eaten. The above contradiction between hardness and brittleness predicts that exclusively prioritizing one attribute over the other might not be a prudent strategy for optimizing texture quality. Instead, aiming for a balanced and appropriate combination of both suitable hardness and brittleness appears to be a more dependable approach. This speculation will be exemplified in detail in section 3.3.

3.2.2 Solids

Differing from the pore morphology, solids are determined by the material basis of the original fruits. Normally, carbohydrates dominate the solid matter of common fruits. As support, the components of different fruits mainly include water, small molecular sugars, and dietary fiber (Fig. 4b). Carbohydrates in fruits basically exist in the form of complex sugars such as cellulose, pectin, and hemicellulose and simple sugars such as glucose, fructose, and sucrose (Sethi, Joshi, Arora, & Chuanhan, 2022). In other words, carbohydrates could be mainly divided into two classes: (i) the polysaccharide within WIF, and (ii) the mono-/disaccharides within WSF. These two classes play different roles during the FD texture formation. As visualized in Fig. 4a, the spatial cross-links of polysaccharides are retained as attachable 3D pore walls, while the remaining small molecule solids are stacked in the amorphous matrix and gradually cover the lyophilized porous scaffolds. To prove this, the textural properties of cell wall polysaccharide mixtures (pectin and cellulose) after FD was tested, and the results showed that pure pectin-cellulose sample exhibited a weakly sponge-like structure with almost no hardness and brittleness (Du, et al., 2023). Hence, during texture formation, polysaccharides may only tend to play as a 3D scaffold lacking mechanical strength, offering attachment places for the amorphous matrix. Furthermore, Feng et al. (2022) confirmed that the degree of cross-linking of polysaccharides affects the hardness and brittleness of porous scaffolds. In detail, the pectin-xyloglucan porous structure with ionic interactions exhibited stronger hardness and brittleness than the one with hydrogen bond interactions.

The incorporation of small molecule sugar, *i.e.* fructose, into the non-rigid pectin-cellulose system substantially increased the mechanical resistance and fluctuation, highlighting the indispensable role of mono-/disaccharides on freeze-dried texture formation (Du, et al., 2023). Numerous studies have indeed confirmed the structural reinforcing role of additional mono/disaccharides in polysaccharide porous systems (Ciurzyńska, Mieszkowska, Olsiński, & Lenart, 2017; Harnkarnsujarit, Charoenrein, & Roos, 2012). As reported, there is a positive correlation between the mono/disaccharides content and the hardness as well as the brittleness of freeze-dried fruits (Feng, Bi, Yi, Li, Li, et al., 2022). Upon freezing, simple sugars in fruits concentrate within the unfrozen phase and subsequently form stacked amorphous sugars during high-speed FD (Imamura, et al., 2008). These amorphous sugars then adhere to the non-rigid 3D scaffold of polysaccharides, imparting the distinctive texture characteristic of freeze-dried products. As evidence, a previous report has demonstrated that amorphous sugars are generally stronger than their crystalline counterparts, which may be better able to support, encapsulate, and/or stabilize unstable active macromolecular components (Hancock & Shamblin, 1998). Moreover, different small molecular sugars exhibited various effects on the mechanical properties of freeze-dried products (Amos, 1967). It has been found that when adding 10 kinds of small molecules (*e.g.* fructose, glucose, sucrose, maltose, trehalose, *etc.*) in the pectin-carboxymethyl cellulose mixed system, fructose exhibited the highest ability to enhance hardness (as shown in S-Fig. 1).

Here, it is worth mentioning that mono-/disaccharides can also influence texture qualities by accelerating structural collapse. It is well-known that mono-/disaccharides could promote the collapse of freeze-dried materials by reducing the Tg in the matrix (Roos, 1993). Harnkarnsujarit et al. (2012) confirmed that the presence of mono-

/disaccharides reduces the average molecular weight of the system, which corresponds to a lower *Tg*. In such instances, the storage temperature (*Ts*) can more easily surpass *Tg*, leading to porosity loss, dry matter accumulation, lower brittleness, and an undesired increase in hardness. Additionally, fruit systems abundant in fructose and glucose exhibited greater susceptibility to structural collapse compared to sucrose than sucrose, possibly due to their lower *Tg* value (Feng, Bi, Yi, Li, Li, et al., 2022; Roos, 1993).

3.2.3 Water content or Aw

Regardless of polysaccharides or small molecular sugars, they eventually reside in the amorphous matrix and confer dry texture characteristics to the lyophilized system in a glassy state, determined by the difference between the *Ts* and the *Tg*. As stated earlier, *Tg* values are dependent on the final moisture content and the *Aw* of dried products. An increase in water content or *Aw* causes the freeze-dried system to transition from the glassy state to the rubbery state, directly resulting in the softening of their texture quality (Moraga, Talens, Moraga, & Martínez-Navarrete, 2011). For example, it has been confirmed that the lower the water content, the more brittle the dried banana sample was (Boudhrioua, Michon, Cuvelier, & Bonazzi, 2002). Correspondingly, the hardness and brittleness of freeze-dried persimmon slices also significantly decreased as *Aw* increased, which was associated with the continuous loss of plasticity in the dried product (González, Llorca, Quiles, Hernando, & Moraga, 2020). Indeed, it has been indicated that maximum compression force and brittleness perception decreased as a function of water content while *Ts* remained below their *Tg* (Farroni, Matiacevich, Guerrero, Alzamora, & Buera, 2010). In addition, Silva-Espinoza et al. (2020) observed a sharp increase in the maximum force of freeze-dried orange snacks during the transition from the glassy to the rubbery state, followed by a sharp decrease upon achieving the rubbery state. This increase in maximum force at the lowest *Aw* was also observed in other studies (Moraga, et al., 2011). This phenomenon is related to the anti-plasticizing effect of water, which is also considered a ‘toughening’ or mere hardening effect. It is attributed to the enhanced cohesiveness of the glassy food matrix, providing greater resistance to compressive forces and thus increasing the rigidity and hardness of freeze-dried products.

3.3 Differences in Texture Formation between FDi and FDr

The formation mechanism of freeze-dried fruit texture is a complex process determined by multiple factors. Any conditions that interfere with pore morphology, solids, or water content in the fruit systems could lead to a dramatic change in freeze-dried texture characteristics. Among the above three dominant attributes, the transformation of pore morphology is the core reason for the diverse texture characteristics between FDi and FDr. Apparently, the essential difference between intact and restructured fruits is the presence or absence of cellular structures (Fig. 5a). For FDi, the parenchyma cells with intact physical anatomy of the tissue could be preserved under a fast freezing rate and a perfect drying process. In detail, the cellular structure that affects the mechanical properties of dry solid foods can be categorized as (i) open or closed cells; (ii) flexible or rigid cell walls; (iii) cell size distribution; and (v) cell wall thickness and shape (Peleg, 2016). On the contrary, the above intact cellular structure has been completely or partially destroyed in FDr, leading to the loss of integrity of the cell membranes, loss of turgor, and deterioration of cell wall structure. This disintegration of cellular structure influences the texture formation of freeze-dried fruit products as a continuous process, which could be classified into the freezing phase and the drying phase.

3.3.1 Freezing stage

3.3.1.1 Freezing stage of intact fruits

In general, it is accepted that the cell wall/membrane barrier on ice propagation must be taken into account when fruits with intact cell structures are frozen (Tolstoguzov, 1999). As a typical thermodynamic process, the freezing stage of cellular food is explored by previous studies by assuming them as capillary-porous materials, which implies that their heat transfer is much more complicated than that of non-porous materials (Datta, 2007). In fruits, the main structural factors affecting heat transfer basically can be summarized into two categories. Firstly, the presence of the cell wall/membrane of the plant matrix not only acts as a semipermeable barrier to water and solutes but also hinders the transfer of heat and mass during freezing. Studies have reported that the cell membrane can prevent the seeding of the transiently supercooled intracellular fluid by extracellular ice (Tolstoguzov, 1999). The complex tissue matrix formed by the cell wall/membrane linked with various plant components would impede the heat transfer during freezing, thus resulting in supercooling of the intracellular regions with nucleation temperatures much lower than the surrounding extracellular space. However, a previous study by Dorota Nowak et al. (2016) found that the internal cellular structure influenced the temperature pattern of the freeze-dried samples only in the case of a slow freezing rate. Secondly, the physical characteristics of plant tissue, involving the cell size and intercellular space within fruit tissues, should also be considered (Schudel, Prawiranto, & Defraeye, 2021). Fruit materials with small cells are generally tightly packed, while large cells are embedded in large intercellular gaps (Feng, Bi, Yi, Li, Li, et al., 2022). As reviewed by Li et al. (2018), these large gaps can provoke internal stress, thereby affecting the heat transfer during freezing while favoring the formation of extracellular ice. the continuous growth of extracellular ice crystals indicates severe cellular structural damage, such as rupture of cell membranes and deterioration of cell walls and above damages consecutively affect the drying behavior, thereby altering the pore structure and textural quality. The impact of extracellular ice crystals on cellular structure during freezing is schematically illustrated in Fig. 5b, and it results in intracellular dehydration and eventually forms the shrunken intact cellular structure shown in SEM images.

3.3.1.2 Freezing stage of restructured fruits

During the restructuring process, the destruction of the original tissue and intact cell structure will inevitably occur. The sophisticated cell wall crosslinked by polysaccharides is disorganized, and the interaction of pectin with cellulose, hemicellulose, and metal ions is subsequently disrupted. Then, the free water and loosely bound water delimited by the endomembrane system are released along with the watery dispersing solute, forming a complex system mixed with intracellular liquid, cell wall polysaccharides, and other plant components. When it occurs, some water-soluble cell wall polysaccharides (*e.g.* pectin and hemicellulose) will re-dissolve in the intricate fruit system. After freezing begins, these re-dissolved polysaccharides would be physically crosslinked with other insoluble cell wall fragments within the concentrated amorphous solution under cryo-concentration during ice crystal growth (Zhang, Liu, Chen, & Dai, 2019). In a simplified manner, we can assume that when all cell wall polysaccharides in concentrated amorphous solution are present as isolated chains rather than cell wall fragments, they would be trapped by the moving water-ice front and further accumulated into the cryo-concentrated solution in the intergranular space of ice crystals, following the direction of the temperature gradient during freezing (Grenier, et al., 2019; Zhang, et al., 2019). As shown in Fig. 5b, during this process, polysaccharide chains close to the ice-solution interfaces spontaneously self-assembled and intercrosslinked via non-covalent interaction, serving as scaffolds for subsequent lyophilized products. Back to a matter of fact, since the traditional food restructuring process cannot wholly decompose the sophisticatedly interacted cell wall, there is a high probability that cell wall fragments in restructured fruits are linked to form pore walls through physical cross-linking of partially redissolved water-soluble polysaccharides, as shown in Fig. 5b. In this case, the pore morphology of FDr essentially represents the fingerprint of the ice crystals shapes and sizes during freezing stage. Therefore, any changes that control the ice crystal habits would ultimately affect the pore morphology and, consequently, alter the textural properties of the FDr.

3.3.2 Drying stage

3.3.2.1 Drying stage of intact fruits

Undoubtedly, the presence of cellular structures in fruits affects heat and mass transport during the drying stage. Several models have been developed to measure the influences of the cell structure on the transport properties of cellular food materials during drying (Araki, Sagara, Abdullah, & Tambunan, 2001; Crapiste, Whitaker, & Rotstein, 1988). However, the integrity of the cellular structures during the drying stage is highly influenced by the ice crystal growth behavior in the previous freezing stage. Thus, here we temporarily assume that the integrity of the cellular structure in fruits is not damaged by water crystallization. Under this assumption, considerable resistance against the molecular transfer of water vapor by the cellular structure still remains in the frozen fruit materials (Araki, et al., 2001). Nowak et al. (2016) have established the influence of plant tissue structure during the drying stage and found that the disruption of cell walls accelerated the water vapor transportation to the surface of the sample for sublimation. Conversely, when the cellular structure is intact, its limitation of mass transfer rate results in a weaker vapor flow and the accumulation of water vapor during drying, which may cause the chamber pressure to rise above the saturation vapor pressure of the ice. As shown in Fig. 2b, when the intracellular pressure increases sharply, the water molecules in the vapor state transform into the liquid state. Thereafter, the plasticizing effect of water on the vitrified state is strengthened, leading to melting in the surrounding regions (Roos, 2010). In other words, the presence of tissue cell structure promotes the collapse of structure and the unexpected accumulation of pore walls, which directly deteriorates the texture quality by undesired hardening. This texture deterioration phenomenon is more prone to occur in fruit tissues with smaller cell sizes. It has also been found that fruits with smaller cell sizes are more susceptible to structural shrinkage and collapse than those with larger cell sizes, implying that the smaller pores and denser pore structure bring higher resistance to vapor flow during FD (Feng, Bi, Yi, Li, Li, et al., 2022).

3.3.2.2 Drying stage of restructured fruits

Unlike intact fruits, ice crystals of restructured fruits tend to form an interconnected ice phase throughout the product during freezing due to the absence of cell wall interference, implying the formation of a large number of open pores (Wang, et al., 2019). This means the water molecules in the frozen fruits can smoothly escape in the form of vapor, and the interconnected pores within restructured systems serve as the main path of vapor flow during drying, contributing to the FD rate and quality. Yang et al. (2023) have revealed that the negative effects of cellular tissue barriers and epidermal waxes on water sublimation could be inhibited when the original fruit was crushed to a homogeneous pulp form, thereby improving the overall quality of the freeze-dried product. Actually, when comparing intact and restructured apples, strawberries, and mangoes, it was found that damaging the cell structure not only lowered the final *Aw* and inhibited shrinkage, but also improved consumers' overall acceptance of freeze-dried products (Feng, Yi, Wu, Ma, & Bi, 2023). The disintegration of the cell structure results in a large number of open-pore structures throughout the restructured fruits. When this occurs, barrier-free vapor transfer effectively inhibits collapse and ensures the integrity of the porous structure, leading to better texture quality. Based on this, we can infer that the formation of pore morphology in restructured fruits is more dependent on ice crystal growth without considering the impact of unpredictable collapse. Therefore, it is possible to produce FDr with a variety of pore morphologies and textural qualities only by changing ice habits during freezing. This also inspired us regarding the high controllability and predictability of freeze-dried texture quality in FDr.

Considering the definition of freeze-dried texture, theoretically, better texture characteristics with excellent hardness and brittleness would be presented when the restructured system is designed as a porous structure with a large pore size and greater mechanical solid strength. However, an excessive pursuit of large pores with high hardness may negatively impact the evaluation of texture by consumers. Fig. 6 shows the typical force-displacement curves for four restructured apple samples with various texture characteristics. All samples exhibited highly jagged curves with many force peaks, which are described as crispy or crunchy. Once the hardness and oscillating behaviors of the samples (sample 1 and sample 2) are too strong or too weak, it will actually reduce the subject's perception of brittleness and the acceptability of the product. However, samples (sample 3 and sample 4) with suitable hardness and moderate mechanical fluctuations allowed subjects to perceive greater brittleness and higher acceptability, which demonstrated the significance of a well-suited balance of hardness and brittleness in influencing texture perception, as previously mentioned in section 3.2.1.

4. Control technologies of the Texture of FDi and FDr

Based on the FD process, texture modification of freeze-dried fruit products mainly occurs in the physical pretreatment, the freezing stage, and the drying stage. Among them, texture control that occurs during freezing and drying tends to have common laws on both FDi and FDr. However, in the pretreatment stage, due to the significant diversity in the internal structure of the system, intact and restructured fruits have different methods of textural control.

4.1 Pretreatment

Among the three dominant attributes of freeze-dried texture summarized earlier, pore morphology and solids offer greater flexibility for us to modify the texture properties of lyophilized produces, while water content must be kept sufficiently low to ensure prolonged storage and the maintenance of the glassy amorphous matrix. Supported by the facts, much attention has been devoted in recent decades to the study of texture control by altering pore or cellular morphology as well as solid content and composition, as described below.

4.1.1 Pretreatment for intact fruits

Various pretreatment methods for texture control of FDi are illustrated in Table 1, including ultrasonic (US), high pressure (HP), pulsed electric fields (PEF), freeze-thaw cycles (FTC), and osmotic dehydration (OD), and other pretreatment methods. Most of them achieve the purpose of improving texture by changing the integrity of the cellular structure to accelerate the heat and mass transfer during the freezing and drying process. Essentially, the principle of these methods to change the texture properties is similar to that of restructure treatment. Still, the destruction of cell structure through these methods is more invisible, which preserves the cellular morphology in the original fruit tissue.

4.1.1.1 Ultrasonic (US) pretreatment

As an essential and widely known pretreatment method of FD, the impact of US on the texture quality of freeze-dried fruit has been reported in numerous studies (Waghmare, et al., 2023). During the US process, surface tensions and cavitation effects will be generated in capillaries, forming micro-channels to accelerate water loss from the sample during drying. Due to the creation of microchannels, the cell size of US-treated materials was somewhat large, promoting mass transfer during drying (Li, Zhang, & Wang, 2020). In this case, the resistance against water vapor by the cellular structure is weakened, implying better structural preservation without severe structural collapse. Hence, Yildiz and Izli (2019) found that untreated freeze-dried samples exhibited a more compact and denser porous structure with higher hardness than US-assisted freeze-dried samples. Even though the US reduces the hardness of the lyophilized fruits, the cell outlines of US-treated fruits were more uniform and visible when compared with directly freeze-dried fruits, inducing greater brittleness sensory scores of US-assisted products (Fan, Chitrakar, Ju, & Zhang, 2020). Similar findings were reported by Yuan et al. (2022), who found that US treatment resulted in a greater brittleness of freeze-dried jujube slices. However, improper ultrasonic penetration would disrupt the continuity of the cellular structure, leading to structural collapse and accumulation of solid matter, causing an undesirable increase in hardness.

4.1.1.2 High pressure (HP) pretreatment

As another pretreatment that enhances the mass transfer of water during FD, HP treatment of foodstuffs is normally carried out in ranging from 50 to 600 MPa for the desired dwell time and temperature (Dziki, 2020). Application of HP increases the cell membrane permeability by disrupting the integrity of the cell structure in structurally fragile materials, thereby enhancing diffusion and increasing the mass transfer during drying (Witrowa-Rajchert, Wiktor, Sledz, & Nowacka, 2014; Zhang, et al., 2020). It was observed that the hardness values of HP-treated samples were higher than those of the untreated samples, which is attributed to the lower water content within HP samples (Yuan, et al., 2022). Similarly, Hulle et al. (2015) also found that the hardness of dehydrated aloe vera enhanced with increasing pressure. In comparison, no significant brittleness improvement was found in the HP-pretreated samples (Yuan, et al., 2022). This may be due to the substantial increase in average pore area and diameter after HP treatment, which may reduce the number of pores (Zhang, et al., 2020). In this way, the freeze-dried fruits after HP treatment may be closer to the structural characteristics of sample 4 in Fig. 6, corresponding to a lower score for brittleness in the sensory evaluation.

4.1.1.3 Pulsed electric fields (PEF) pretreatment

PEF treatment is a pretreatment that can significantly enhance FD efficiency, depending on permeabilization (electroporation) of cell membranes under electric pulses with an electric field strength (ranging from 1 to 10 kV/cm) in a short period of time (from nanoseconds to milliseconds) (Barba, et al., 2015). Besides, when PEF is applied for food processing, the plasmolysis of biological cells is also induced by the electric pulses (Witrowa-Rajchert, et al., 2014). The disruption of the cellular structure reduces mass transfer barriers in the product, ultimately altering the textural properties. Expressly, Faustera et al. (2020) have stated a significant reduction of the structural shrinkage for both PEF-treated bell peppers and strawberries when compared to directly freeze-dried samples, with 30% and 50% lower volume losses, respectively. The above protection of the porous structure by PEF application will induce higher porosity. For instance, it has been reported that PEF treatment increased the porosity of freeze-dried apples by 86 times (Parniakov, Bals, Lebovka, & Vorobiev, 2016). Due to the increase in the number of pores, PEF reduced the hardness of freeze-dried strawberries and bell peppers even up to 60% (Fauster, et al., 2020). The noticeable softening of structure mechanical strength was also detected in freeze-dried PEF pretreated apples (Lammerskitten, Mykhailyk, et al., 2019). In terms of brittleness, PEF-treated freeze-dried samples were crispier in comparison to untreated ones, which is ascribed to more porosity in their structure as well as their desirable hardness improved by PEF (Lammerskitten, Mykhailyk, et al., 2019). However, due to the limitation of the number of publications on this topic, more extensive works should be developed in the future.

4.1.1.4 Freeze-thaw cycles (FTC) pretreatment

Two steps constitute FTC preprocessing: freezing materials to their freezing points and thawing the frozen materials at higher temperatures. During this process, the transformation of water into ice crystals in plant cells causes damage to the intact cell structure, and the degree of damage is related to the number of freeze-thaw cycles and the speed of freezing (Phothiset & Charoenrein, 2014). Unlike US, HP, and PEF, FTC is more damaging to plant cells as almost no cells in the whole tissue can survive freeze and thaw cycles (Charoenrein & Owcharoen, 2016). Unfortunately, the effect of freeze-thaw treatment on texture after FD has been poorly reported. Limited studies found that the destruction of the 3D scaffold in the freeze-dried material can be clearly observed in the FTC pretreated samples, which is due to the expansion force generated by the liquid-solid transition of water (Feng, et al., 2020). This would subsequently lead to

FTC-treated lyophilized samples forming porous structures containing considerable pores, implying weaker hardness and poorer brittleness characteristics (Ando, et al., 2016; Feng, et al., 2020).

4.1.1.5 Osmotic dehydration (OD) pretreatment

Different from the previous four pretreatments that mainly change the cell structure, OD treatment could increase the solute content while removing water from the material in the system (Dziki, 2020). In other words, OD not only affects the cellular structure but also changes the solids of the food. Based on the properties of the material, different osmotic agents are used for OD, such as maltodextrin, maltose, fructose, sucrose, sodium chloride, calcium chloride, *etc* (Ahmed, Qazi, & Jamal, 2016; Yadav & Singh, 2014). Compared to the osmotic agents with higher molecular weight, osmotic agents with lower Mw could easily penetrate the cells of fruits, so various small molecular sugars are more commonly used in freeze-dried fruit products as osmotic agents (Ahmed, et al., 2016). For example, Prosapio and Norton (2017) selected fructose from four saccharide osmotic agents (maltodextrin, maltose, fructose, and sucrose) to explore the texture changes of freeze-dried strawberries. Their results exhibited that the samples that underwent OD maintained a better porous structure and greater hardness than untreated freeze-dried strawberries. Furthermore, our previous studies showed that different saccharide osmotic agents have diverse hardness improvements in FD apple slices, among which fructose and glucose were the most outstanding (Ma, et al., 2022). The above finding is consistent with previously described content in this review that small molecular sugars strengthen the hardness of freeze-dried systems. However, the saccharide osmotic agents application also promotes structural collapse and shrinkage, which increases the pore wall thickness and reduces the pore volume, suggesting a reduction in the brittleness of the samples (Ma, et al., 2022). Unlike saccharide osmotic agents, salt osmotic agents (*e.g.* calcium chloride and calcium lactate) could minimize the structural collapse and shrinkage, while increasing the porosity of FD products (Prosapio & Norton, 2018). Notably, the US is usually used to assist in the conduction of OD to shorten operating time. Prosapio and Norton (2018) observed that the OD-treated strawberries with ultrasounds for 30 min exhibited the highest hardness preservation, comparable to that of the fresh material. Nevertheless, US-assisted OD lyophilized yams using higher US power levels could reduce the porosity due to the local collapse, inducing an undesirably high hardness and low brittleness in the overall textural properties (Li, et al., 2020).

4.1.2 Pretreatment for restructured fruits

4.1.2.1 Polysaccharides additives

During the pretreatment stage, the texture of the freeze-dried restructured product can be precisely regulated by adding specific ratios of various food additives (Yang, et al., 2023). Building on our earlier description, externally added additives regulate the final texture quality by altering the composition and content of the solid matters in fruit system. Amongst the diverse range of additives, natural polysaccharides garner continuous attention due to their accessibility and renewability, non-toxicity, and diverse health benefits. Most of them are extensively applied in the food industry as stabilizers, thickeners, viscoelastic regulators, and gelling agents to modify the texture of food, including agar, gellan gum, locust bean gum, pectin, carrageenan, and xanthan gum, *etc.*(Dille, Draget, & Hattrem, 2015; Sun, Wu, Song, & Chen, 2022). However, most studies on the effect of polysaccharide additives on texture primarily focus on undehydrated materials, while limited reports on dehydrated materials. Notwithstanding, we summarize the dominant effects of polysaccharide additives concerning the texture formation mechanism of FDr as follows:

(i) Impact on ice crystal growth during the freezing phase. Several studies have demonstrated that the hydration behavior, crosslinking, gelation, and interaction of polysaccharides with ice crystals may influence their ice interference capability to vary extents (Feng, Yi, Ma, & Bi, 2023; Sun, et al., 2022). The effect of polysaccharides on ice crystal can be divided into two processes, *i.e.* nucleation and ice growth. Regarding ice nucleation, high-molecular-weight polysaccharides generally have minimal impact on the freezing point, while some can promote nucleation through a heterogeneous mechanism (Guerreiro, et al., 2020; Pummer, Bauer, Bernardi, Bleicher, & Grothe, 2012). Previous reports suggest that water molecules enclosed by surrounding polysaccharides may eventually evolve into active sites for nucleation processes (Zachariassen & Kristiansen, 2000). Regarding ice growth, the addition of polysaccharides increases the micro-viscosity of the cryo-concentrated micro-domain surrounding the ice crystals, thereby reducing water diffusion to the ice core surface (Maity, Saxena, & Raju, 2018). In this scenario, restructured fruits enriched with polysaccharides tend to form a porous structure with small pore size and increased pore number, which means the higher hardness of the system. As support, Egas-Astudillo et al. (2020) found that polysaccharide-supplemented grapefruit purees exhibited higher hardness compared to non-supplemented ones, implying a better textural characteristic.

(ii) Effects of interactions between polysaccharides. Before freezing, the added additive may crosslink the polysaccharides originally existed in the puree through non-covalent interactions, strengthening the matrix mechanically. For instance, the mechanical strength of lettuce/pectin matrixes was exhibited to be positively influenced by the concentration of exotic pectin (Vancauwenberghe, et al., 2019). After freezing, the polysaccharide additive crosslinks with the polysaccharide accumulated in the concentrated amorphous solution via non-covalent interactions. As support, Yang et al. (2023) explored the addition of edible gum cross-linking polysaccharides or cellulose in strawberries during processing, resulting in a tighter structure. Similarly, Martínez-Navarrete et al. (2019) also observed increased hardness in freeze-dried mandarin snacks containing added gum Arabic.

(iii) Inhibition of structural collapse through reduces *Tg* values. Since *Tg* decreases with increasing Mw provided by polysaccharides, fruit systems rich in polysaccharides could exhibit lower overall *Tg* values (Feng, Bi, Yi, Li, Li, et al., 2022; Roos & Karel, 1991). For instance, Marilu Andrea Silva-Espinoza et al. (2020) found that the freeze-dried orange pulp without polysaccharides had lower *Tg* values than freeze-dried pulps with added polysaccharides. Consequently, the polysaccharide additive prevents collapse and shrinkage by raising the *Tg* value of the fruit puree system, thereby maintaining the integrity of the porous structure and enhancing the mechanical properties, brittleness, chewiness, and sensory evaluation score of the restructured fruit products (Martínez-Navarrete, et al., 2019; Silva-Espinoza, et al., 2020; Yang, et al., 2023).

4.2 Freezing Stage

As mentioned earlier in this review, freezing conditions dictate the ice habit (size, number, and morphology), which not only affects the integrity of the cell structure in intact fruits but also determines the pore morphology in restructured fruits, impacting the subsequent drying process, such as water vapor flow resistance. A crucial factor influencing various ice behaviors is the freezing temperature and time combination, known as the freezing rate (Schudel, et al., 2021). The freezing rate (ice crystal growth rate) depends on the degree of supercooling (Shibkov, Golovin, Zheltov, Korolev, & Leonov, 2003). At low degrees of supercooling, the supercooled system absorbs only a limited amount of heat for crystallization due to the small difference between nucleation and freezing point temperatures, leading to the formation of a small number of large ice crystals at a slow growth rate (Assegehegn, et al., 2019). In this case, water molecules have enough time to arrange into regular hexagonal crystals (*i.e.* dendrites). Conversely, at a higher degree of supercooling, a lower ice nucleation temperature indicates a greater temperature difference with nucleation temperature, resulting in a faster ice crystal growth rate (Petzold & Aguilera, 2009). In this case, water molecules are arranged randomly around the ice core, generating irregular dendrites or needle-like crystals (Assegehegn, et al., 2019; Petzold & Aguilera, 2009). The above different ice habits control the freeze-dried texture quality of intact and restructured fruits in different ways, which are described as follows.

4.2.1 Effect of freeze rate on the texture of FDi

Damage to the cellular structure during ice crystal growth usually occurs in two ways, including physicochemical damage caused by ice development, as well as intracellular dehydration due to changes in local osmotic pressure (Mazur, Leibo, & Chu, 1972). Among these, the former refers to a series of adverse biochemical reactions after the rupture of the endomembrane system caused by the volume expansion during water crystallization, which obviously has a greater impact on the formation of freeze-dried texture. The above damages caused by the ice crystal growth are highly related to the ice habit, which can be divided into two cases according to the freezing rate. When the freezing rate is slow, intracellular water leaves the cell to form large extracellular ice, resulting in cell dehydration and deformation (Moore, Vicre-Gibouin, Farrant, & Driouich, 2008). When the freezing rate is fast, smaller and more uniformly distributed ice crystals grow both intracellularly and extracellularly, reducing cell shrinkage and deformation (Schudel, et al., 2021). As confirmed by Charoenrein and Owcharoen (2016), mango cells remained a similar round shape to those of fresh tissue after fast freezing, whereas slow freezing resulted in a dramatic change in cellular structure and a degradation in cellular uniformity. Hence, compared to slow-frozen samples, fast-frozen samples exhibited a more open structure due to less shrinkage of cellular structures, suggesting faster-drying efficiency and better porosity preservation. In this way, FDi produced by a fast freezing rate will exhibit better brittleness and more suitable hardness in comparison to the slow freezing rate.

4.2.2. Effect of freeze rate on the texture of FDr

If the effect of freezing rate on intact fruits primarily concerns the damage to cell structure integrity, its effect on restructured fruits is more evident in controlling pore morphology. As stated earlier, the final pore morphology of the restructured fruit products depends more on the ice habit during the freezing process. Therefore, when the freezing rate is slower, larger ice crystals are formed within the fruit puree, which means that the freeze-dried products will show more expanded gas pores in their structure. This result was confirmed by Silva-Espinoza et al. (2019) in the freeze-dried orange puree system. Conversely, when the freezing rate is fast, more uniform and smaller pores are present in the internal structure of the restructured fruits. In theory, controlling the size, shape, and distribution through freezing rate could be a well-established method for modulating the textural quality of restructured fruit products. However, a study exploring the effect of FD conditions on sensory perception in freeze-dried puree products found no significant relationship between freezing rate and brittleness or sensory perception (Silva-Espinoza, et al., 2021). This indicates that further research is necessary to confirm the possibility of designable regulating the texture quality of restructured fruit products by altering the freezing rate.

4.3 Drying Stage

The drying stage mainly depends on two parameters during the operation of the freeze dryer: shelf temperatures and working pressures. These two parameters determine the collapse or shrinkage rate during the FD process, thereby controlling the pore shape and *Aw* of final products, implying changes in the freeze-dried texture. In terms of shelf temperature, it has been revealed that a higher shelf temperature could increase the mechanical rigidity of the freeze-dried orange samples (Silva-Espinoza, et al., 2019). At a lower shelf temperature (low drying rate), the water gradient within the dried product is small, thereafter resulting in low internal stresses that promote uniform shrinkage towards the solid core (Ratti, 1994). At a higher shelf temperature (high drying rate), rapidly falling surface moisture leads to a 'casehardening phenomenon' at the surface, limiting subsequent shrinkage and thus increasing porosity formation (Sablani & Rahman, 2007). Furthermore, the increasing trend in pore formation of high-shelf temperature samples is also confirmed in apples, yellow date, oranges, and grapefruits (Egas-Astudillo, et al., 2020; Sablani & Rahman, 2007; Silva-Espinoza, et al., 2019). Regarding working pressures, products freeze-dried at the lowest pressure displayed a higher number of fracture peaks ($P<0.05$), indicating a crispier texture (Silva-Espinoza, et al., 2021). Unlike shelf temperature, pressure primarily affects lyophilized texture by influencing water content rather than porous structure (Silva-Espinoza, et al., 2019). At present, commonly used FD assistance methods mainly include infrared-assisted freeze drying (IAFD), microwave-assisted freeze drying (MAFD), and ultrasonically-assisted freeze drying (UAFD). The original purpose of the above methods is to accelerate heat and mass transfer during FD to overcome the high energy consumption. However, they will inevitably have various effects on the texture quality of the final products, as illustrated in Table 1 and elaborated upon in the following sections.

4.3.1 Infrared-assisted freeze drying (IAFD)

Infrared radiation is a frequently considered candidate that can be combined with FD for rapid drying time and low energy efficacy. It has been reported that IAFD-treated banana products showed increased hardness and better brittleness than FD bananas, possibly related to the crust/dense layer formation and internal structural changes (Pan, Shih, McHugh, & Hirschberg, 2008). After infrared radiation assistance, Khampakool et al. (2019) indicated that FD presented a dense surface structure and large pores in the central region. The application of infrared radiation provides energy during FD for rapid heating, accelerating lyophilization rates and stiffening the surface to inhibit shrinkage. Meanwhile, its energy increases the force of water vapor on the cell wall, which leads to the formation of macropores within the material, resulting in higher brittleness (Kang, Hwang, Chung, & Park, 2021). Moreover, Antal et al. (2017) observed that pears that were dehydrated by mid-infrared FD methods exhibited significantly lower hardness values than freeze-dried pears ($p < 0.05$), which was attributed to the large size pores in the central region inside the product structure. The above results were also found in the FDr products that long exposure to infrared light promoted the collapse of the central structure within freeze-dried restructured material, resulting in a less dense structure and larger pores (Hnin, Zhang, Devahastin, & Wang, 2019; Oliveira, Silva, Figueiredo, Norcino, & Resende, 2021).

4.3.2 Microwave-assisted freeze drying (MAFD)

Compared with conventional FD, MAFD can provide a better heat and mass transfer rate, resulting in a quick-drying rate at low temperatures. Obviously, the greater the microwave power density, the higher the drying rate and the shorter the drying time. It has been found that with the increase in microwave powers, MAFD-treated yam chips exhibited excellent resistance to damage and higher average hardness and brittleness (Duan, Duan, & Ren, 2019). Similarly, Wang et al. (2010) also observed that MAFD potato slices exhibited high hardness and lower shrinkage ratio than that of FD slices. The impact of microwave assistance on textural properties is also found in FDr products. For instance, Liu et al. (2012) revealed that MAFD-restructured sweet potato granules exhibited desirable brittleness and volume expansion (puffing). This may be due to the protection of the porous structure in the material due to the rapid drying rate. As supported, Zhang et al. (2006) have reviewed that combining the microwave with FD could reduce the non-uniform shrinkage of fruit and vegetable materials. However, if the microwave power becomes too high, the possibility of overheating within the products would increase, resulting in non-uniform temperature distribution, serious shrinkage, and texture deterioration (Chen, Lin, Amani, & Yan, 2023; Wu, Zhang, Mujumdar, & Wang, 2010).

4.3.3 Ultrasonically-assisted freeze drying (UAFD)

Power ultrasound has been proven to be an effective and environment-friendly technology to speed up the FD process. Unlike the previous two assistance methods, ultrasound functions are not thermal but mainly mechanical, which avoids the risk of overheating the freeze-dried fruits and consequently reduces the deterioration of texture quality (Garcia-Perez, Carcel, Riera, Rosselló, & Mulet, 2012). During UAFD, the acoustic waves of ultrasound could create cycles of periodically repeated mechanical compression and expansion stresses, which generate natural channels and other micro-pathways, promoting vapor flow out of the dried materials. According to existing literature, ultrasound assistance is primarily employed in atmospheric freeze-drying, with a focus on drying kinetics and changes in bioactive substances. Unfortunately, the current texture data on UAFD fruits are minimal, suggesting that more research is still needed. Based on limited data, it was found that with the higher applied ultrasonic power, the greater the ultrasonic effect, the lower the hardness and chewiness of the rehydrated FD sample (Carrión, Mulet, García-Pérez, & Cárcel, 2018). Similar results were also observed in atmospheric freeze-dried apples (Santacatalina, Contreras, Simal, Carcel, & Garcia-Perez, 2016). This result is attributed to the mechanical damages caused by the high-power ultrasound that affects the internal structure integrity, softening the structure of final freeze-dried products (Cárcel, García-Pérez, Riera, & Mulet, 2017). As evidence, Rodriguez et al. (2014) found more cell disruption in ultrasonically assisted dried apple samples than in control samples.

5. Conclusions and Future Prospects

The texture quality of freeze-dried products is primarily determined by three main attributes: pore/cellular morphology, solids, and water content. Pore or cellular morphology refers to the macroscopic characterization of the freeze-dried scaffolding network composed of solid matter in the fruit matrix, which plays a crucial role in determining the final texture quality of the freeze-dried fruit product. Different carbohydrate solids have distinct roles in constructing the scaffold network. Precisely, the interconnected polysaccharide scaffolds within the amorphous matrix act as 'steel bars' despite lacking mechanical strength, which is then overlaid by a cement-like layer of small molecule sugars in an amorphous state, ultimately leading to the exceptional hardness and brittleness characteristics of freeze-dried products. Simultaneously, maintaining a sufficiently low moisture content (or *Aw*) is crucial as it forms the foundation for the amorphous matrix to remain in a stable glassy state, thereby preserving the plasticity and porosity stability of the product.

The presence of cellular structure is the core reason for the disparity in texture formation between FDi and FDr. The pore morphology of FDi is influenced by the cellular structure of the original fruit, whereas the pore morphology of FDr is predominantly governed by the ice crystal habits (*e.g.* size, number, and morphology) during freezing. This difference directly leads to distinct regulatory technology of texture for FDi and FDr. When handling FDi, the current technology primarily focuses on either destroying the cell structure or providing additional heat, which accelerates heat and mass transfer during the drying process, thereby inhibiting shrinkage while maintaining low *Aw* and brittleness. When dealing with FDr, various techniques could be employed to enhance their texture, such as controlling the freezing rate, incorporating polysaccharide additives, increasing the heat during drying, *etc*.

Compared to FDi, FDr offers the following advantages, which inspire promising future prospects for the texture of freeze-dried fruit snacks:

(i) As a personalized functional freeze-dried snack: freeze-dried restructured fruit snacks can be tailored to meet the specific dietary and texture preferences of consumers by combining various raw materials and nutritional ingredients, such as functional polysaccharides and fiber-rich fruits and vegetables.

(ii) As a potentially low-energy freeze-dried snack: To achieve this, further research and innovation are required to develop techniques that create a homogeneous pulp and mitigate the adverse effects of cell-tissue barriers on vapor sublimation during drying. By doing so, the drying time of products can be reduced, leading to higher drying efficiency and better preservation of product brittleness.

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Figure caption:

Fig. 1 Comparison and product pictures of two dominant categories of freeze-dried fruit products on the market. Red arrows indicate SEM images of cross-sections of these two products, which show significant differences in porous structure.

Fig. 2 a) Kinetics of changes in the material weight and material temperature (underside) measured along the freezing, primary drying, and secondary drying stages, using apples as an example. b) Phase diagram of water in glassy state and molten state. *Tg* represents the glass transition temperature, and *Tm* represents the melting temperature. The red arrows represent the inflection point in the sample weight curve for the primary drying beginning and the inflection point on the shelf temperature curve corresponding to the secondary drying beginning.

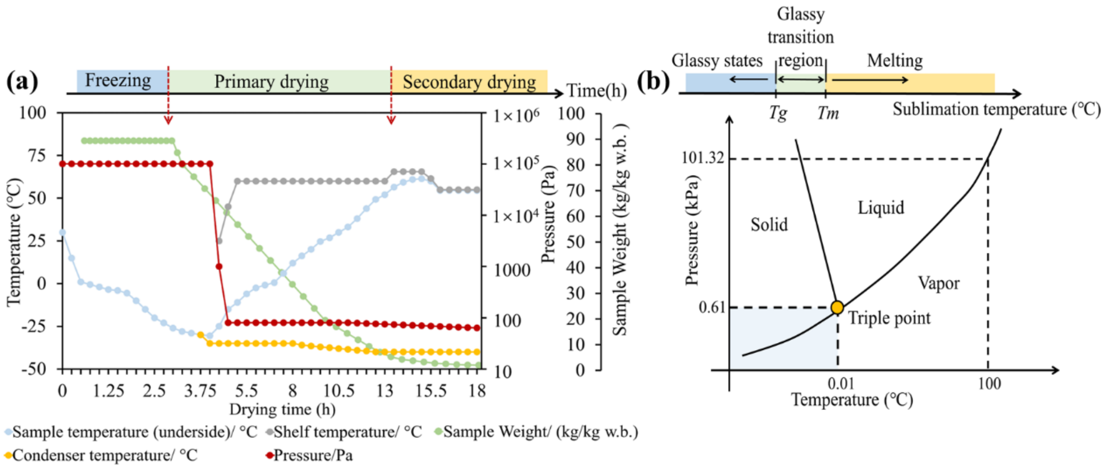
Fig. 3 Changes in textural properties and quantitative characterization of freeze-dried fruits during oral consumption. a) Simplified representation of the main textural characteristics of the porous scaffold before and after entering the oral cavity. Arrows list key attributes and manifestations. b) Schematic diagram of the structural changes of porous scaffold under the compression of chewing forces and standardization of textural properties into measurable units by texture analyzer. The arrows point to the fracture peaks and maximum force on the force-distance curve, which are related to brittleness and hardness, respectively.

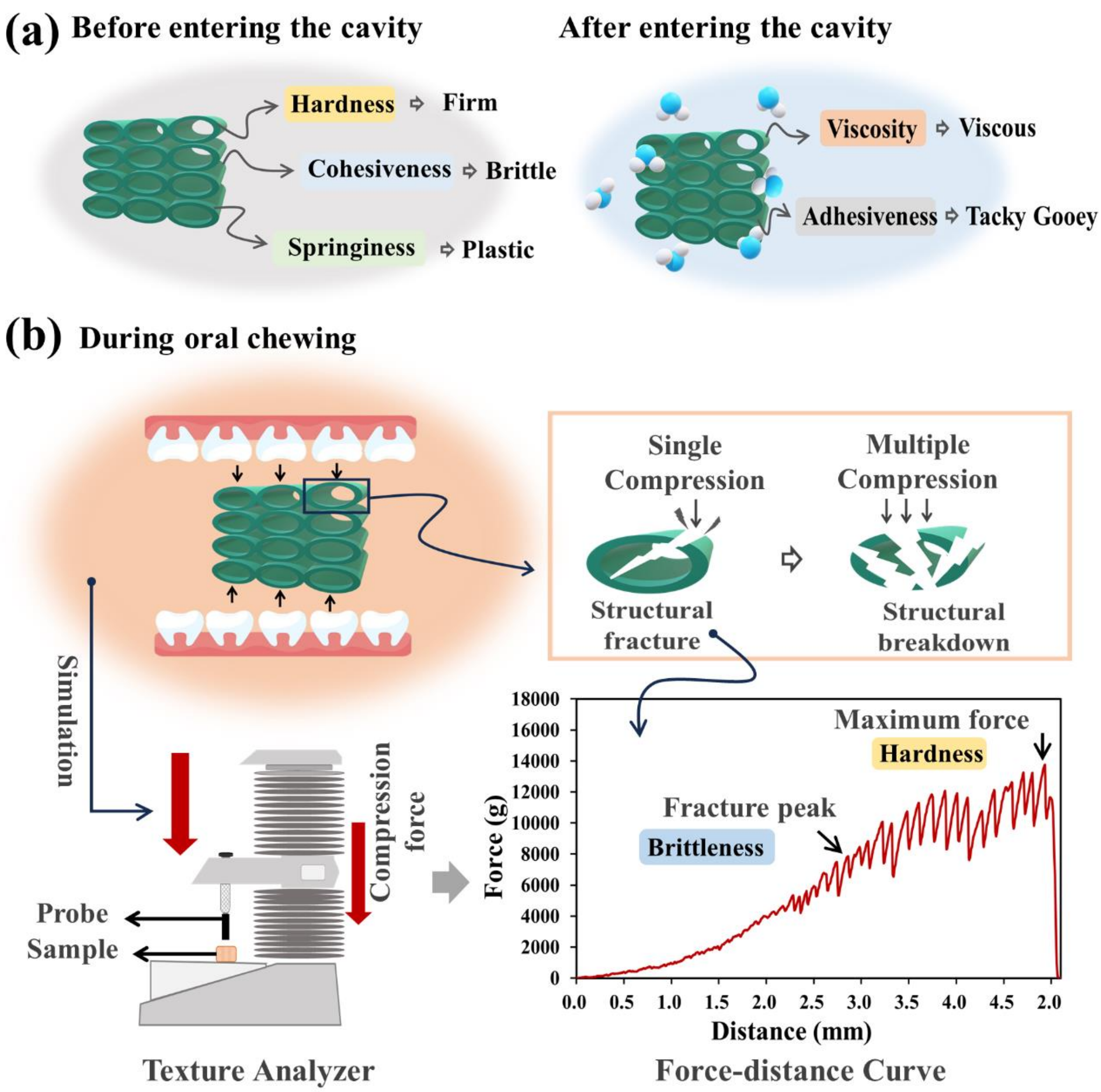
Fig. 4 Schematic illustration of three-dimensional (3D) porous model solid components and their roles. a) Schematic diagram of the three-dimensional (3D) porous model and three dominant attributes of the texture formation of freeze-dried fruits. Inside the red box is an enlarged schematic diagram of the pore wall compositions and their corresponding main functions. b) Percentage of basic chemical composition in 5 fruits. Modified from: Feng et al. (2022)

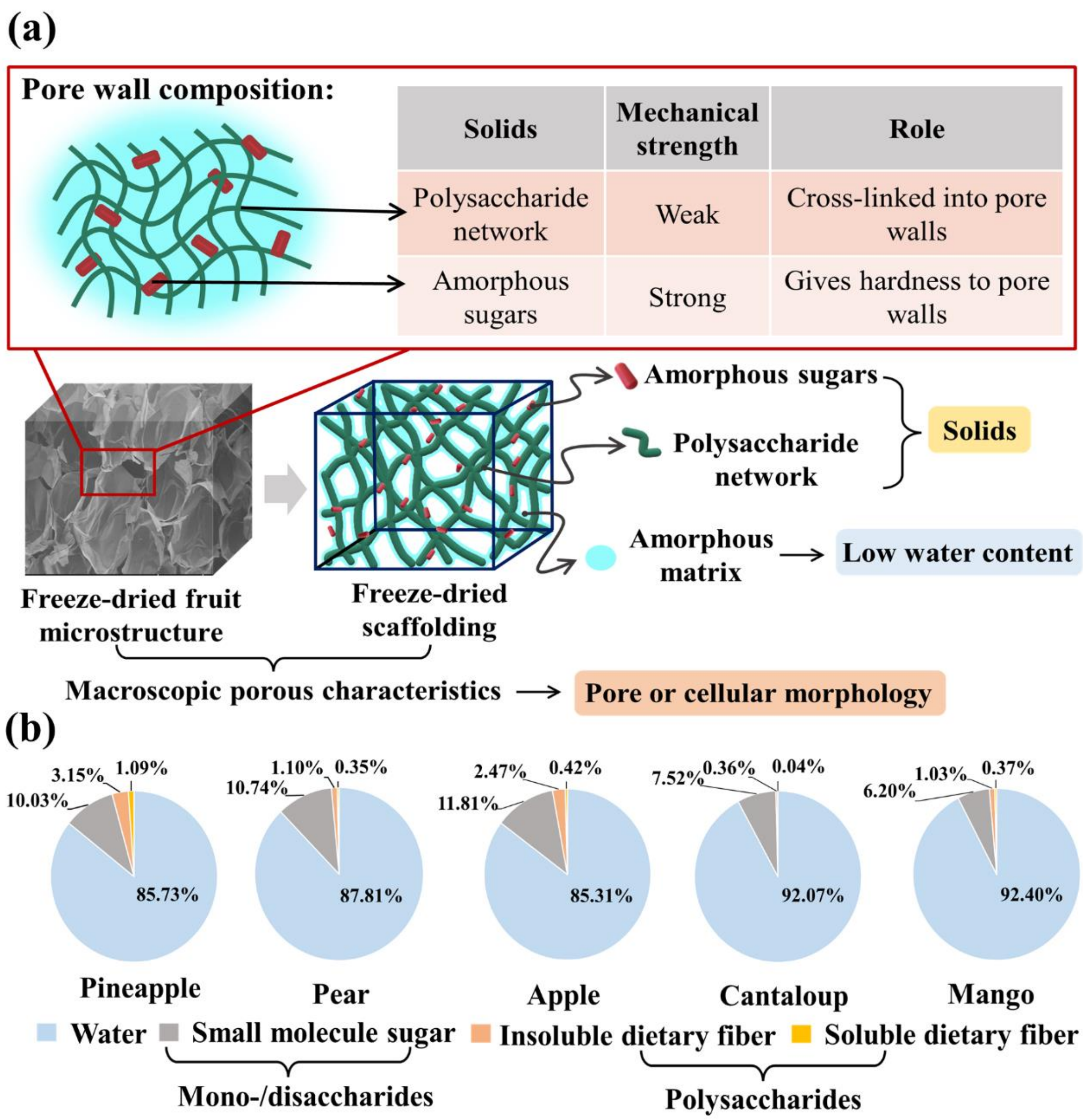
Fig. 5 Comparison of the texture formation mechanisms of freeze-dried intact fruits (FDi) and freeze-dried restructured fruits (FDr). a) Table summarizing the core differences between FDi and FDr in freezing and drying processes. b) Schematic representation of pore formation due to ice crystal growth during the FDi and FDr freezing stage. The red arrows in SEM images indicate the boundaries of pores.

Fig. 6 a) Typical force-distance curve for four restructured apple samples with various texture characteristics. b) Radar chart of sensory evaluation for corresponding four restructured apple samples (unpublished data). Sample 1 is the restructured apples with pectin calcium-induced gel network, sample 2 is the restructured apples with gelatinized starch, sample 3 is the restructured apples without other additives, and sample 4 is the restructured apples with gelatinized starch and calcium-induced gel network (unpublished data).

Products	Pretreatments	Processed status	Tissue morphology
Freeze-dried intact fruits (FDi)	No treatment, mere slicing	Natural fruit flesh	yes
Freeze-dried restructured fruits (FDr)	Grinding, crushing, pulping, homogenizing, etc.	Fruit puree	No

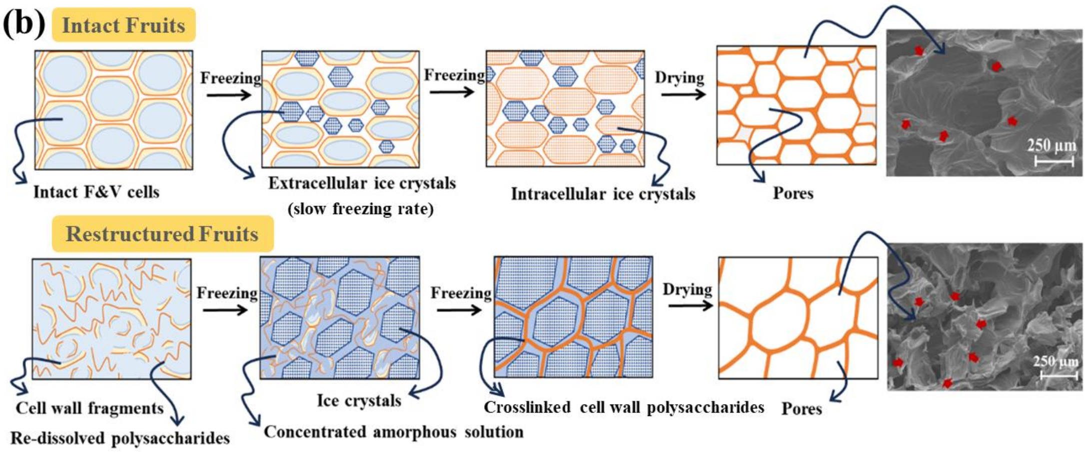



(a) Before entering the cavity
After entering the cavity
Hardness ⇨ Firm
Cohesiveness ⇨ Brittle
Springiness ⇨ Plastic
Viscosity ⇨ Viscous
Adhesiveness ⇨ Tacky Gooey
(b) During oral chewing
Single Compression
Multiple Compression
Structural fracture
Structural breakdown
Simulation
Compression force
Probe
Sample
Maximum force
Hardness
Fracture peak
Brittleness
Force (g)
Distance (mm)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
2.0
Texture Analyzer
Force-distance Curve


(a)
Pore wall composition:
Solids
Mechanical strength
Role
Polysaccharide network
Weak
Cross-linked into pore walls
Amorphous sugars
Strong
Gives hardness to pore walls
Amorphous sugars
Polysaccharide network
Solids
Amorphous matrix
Low water content
Freeze-dried fruit microstructure
Freeze-dried scaffolding
Macroscopic porous characteristics
Pore or cellular morphology
(b)
3.15%
1.09%
10.03%
85.73%
1.10%
0.35%
10.74%
87.81%
2.47%
0.42%
11.81%
85.31%
7.52%
0.36%
0.04%
92.07%
1.03%
0.37%
6.20%
92.40%
Pineapple
Pear
Apple
Cantaloup
Mango
Water
Small molecule sugar
Insoluble dietary fiber
Soluble dietary fiber
Mono-/disaccharides
Polysaccharides

(a)

		Freeze-fried intact fruits (FDi)	Freeze-fried restructured fruits (FDr)
	Intact cellular structure	Yes	No
Freezing	Cell morphology influence on ice	Yes	No
Freezing / Drying	Determinants of porous characteristics	Cell morphology	Ice habit
Drying	Pore wall composition	Original cell wall	Spontaneously self-assemble re-dissolved polysaccharides and cell wall fragments



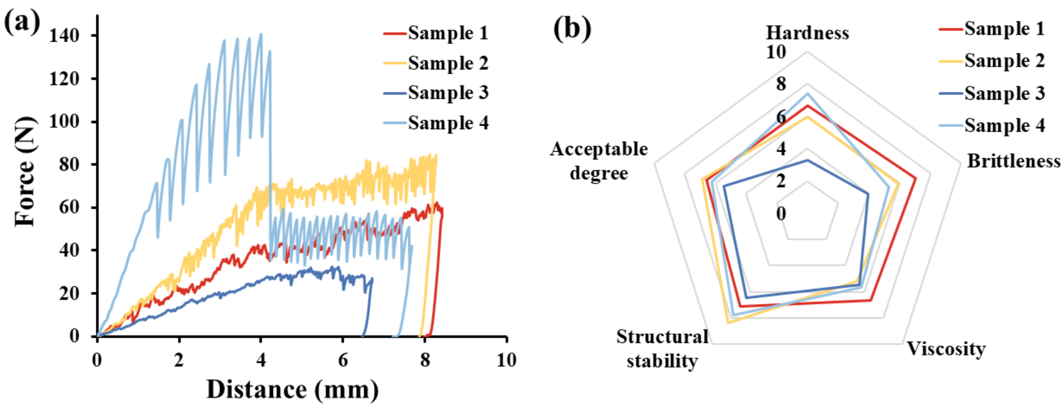


Table 1 Summary of textural control technologies in the physical pretreatment and drying stage.

chnologies	Processing Conditions	Products	Type	Main Findings	Reference
	Frequency: 28 kHz US Power: 50 W Time: 10, 20, and 30 min	Freeze-dried quince slices	FDi	US pretreatment reduced the *Aw*, shrinkage ratio, and hardness of the freeze-fried quince sample.	Yildiz and Izli (2019)
	Frequency: 40 kHz US Power: 200 W Time: 25 min	Freeze-dried strawberry slices	FDi	US pretreatment promoted lower moisture content, greater hardness, and a more uniform and visible porous structure of freeze-dried strawberries.	Zhang et al. (2020)
rasonic (US)	Frequency: 40 kHz US Power: 180 W Time: 5 and 10 min	Freeze-dried red beets	FDi	US pretreatment lowered Aw and increased porosity of freeze-dried materials.	Ciurzynska et al. (2021)
	Frequency: 45 kHz US Power: 150, 240, and 300 W Time: 30 min	Freeze-dried carrot slices	FDi	The brittleness of freeze-dried carrot slices increased with increasing US power.	Fan et al. (2020)
	Frequency: 40 kHz Time: 20 min	Freeze-dried jujube slices	FDi	Freeze-dried jujube slices with US pretreated showed a lower Aw, higher hardness, and greater brittleness.	Yan et al. (2022)