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Research Article

Application of Freeze-Drying in Food Processing and Storage - A Review

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Abstract

Freeze-drying is a significant processing unit operation in food processing and packaging production. It offers dehydrated products with extended shelf life and high quality. The technique of freeze-drying, often referred to as lyophilization, is a process that involves melting ice crystals in order to remove water from frozen materials. When compared to items dried using conventional techniques, the best quality products can be produced using the right process parameters. Various food products, including meats, coffee, juices, dairy products, pumpkin, strawberries, guava, spices, tomatoes, etc. have successfully been freeze-dried. In this study, the effect of the freeze-drying process on quality attributes, such as structural changes, the influence of glass transition during food processing and storage, morphological changes in the drying process as a result of temperature and drying time were discussed A general overview of freeze-drying principles, procedures, freeze-dryer parts, and how freeze-drying circumstances affect particular materials' physical qualities is also given. Currently, the demand from consumers for high-quality, minimally processed items is growing along with the market for "natural" and "organic" foods. This perspective suggests that the freeze-dried processed food sector is growing and diversifying.

Keywords: *Drying, Fruits & Vegetables, Sublimation, Lyophilization, Processing*

Introduction

Drying is one of the vital and widely reported methods of food preservation. There are numerous artificial drying technologies available. Bacteria that cause food to deteriorate and decay cannot grow and multiply in the absence of sufficient water. Water is necessary for the majority of enzymes that promote undesirable changes in the chemical composition of food (Ghimire, 2017; Liu et al., 2018). According to Khan et al. (2020), the drying process is a phenomenon of heat and mass transfer; moisture moves from the inside of the product to the surface, where it diffuses to vaporize. Different food processors use different drying procedures. However, all methods are driven to achieving an extended storability by reducing the water activity from food products which can slow down the rate of deterioration, extent shelf life and maintain its quality. Drying of food products is advantageous as it extends shelf life of various food items, minimizes packaging, storage, and transportation costs (Afolabi, 2014). Dalmau *et al*., (2019), stated that the conventional method for drying food in the majority of underdeveloped countries has been sun-drying. However, technology such as freeze-drying, vacuum drying, hot air drying, and spray drying could enhance this procedure.

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Freeze-drying also known as Lyophilization is a method of water elimination from a frozen product and placed under a vacuum, allowing the ice to change directly from solid to vapor without passing through a liquid phase. Lyophilization is further defined as a drying process in which the crystallization of the solvent (often water) or the suspension media occurs at a low temperature and thereafter sublimated from the solid state directly into the vapor phase (Remington, 2000 & Liu *et al*., 2008).

Its ability to maintain the soft texture of dried food, especially those consumed in dried form like dried apple fruit, and its ability to prevent compression are the reasons this method is so widely accepted (Deng et al., 2014; Moreira et al., 2014). It involves freezing of all available moisture, reducing deterioration by low-temperature effect, maintaining the quality, and retaining the solid structure. Thus, during freeze-drying procedures, the rate of heat transfer is influenced by the food's thermal properties, such as specific heat and thermal conductivity (Gupta & Bhagyashree, 2014). The thermal properties of the food are taken into account in the design of food storage and refrigeration equipment as well as in the assessment of processing times for cooling, freezing, heating, or drying of meals (Timilehin & Won, 2020).

Principle of Freeze Drying

The primary idea behind freeze drying, according to Kunal *et al*., (2015), is that it is a process known as sublimation, in which water moves straight from its solid state (ice) to its vapor state. According to Welti-Chanes *et al*., (2005), freezing is the process by which internal temperature of food is lowered below the freezing point and a portion of the moisture content changes to form ice crystals. Freeze drying is the process of sublimating ice crystals. Phase sublimation occurs when a frozen liquid undergoes a phase change from solid to vapor. Food stuff is dried by being exposed to temperatures and pressures below triple point. Temperature and pressure are the main determinants of the phase in which a material occurs (Kunal *et al*., 2015). There are several stages to this procedure, and each one is plainly important.

The temperature and pressure at which the solid, liquid, and vapor phases of a pure substance (water) can coexist in equilibrium is called triple point T in Figure1 and this depicted the phase diagram where the hot air drying occurs in gas and liquid phase, while vacuum drying takes place under reduced pressure in gas and liquid phase and freeze drying occurs in the phases of solid and gas by sublimation (Welti-Chanes *et al.*, 2005).

Freeze-Drying Processes

Pre-freezing, primary drying, and secondary drying are the three steps that make up the freeze-drying process (Sagar et al., 2020).

Pre-freezing

Pre-freezing is the initial separation step in the freeze-drying process, which solidifies the food ingredients, according to Sagar et al., (2020). Ice crystal size and formation are influenced by the pace of freezing; a slow rate of freezing results in larger crystals, and vice versa. As a result, the size of the crystals influences the rate of drying; larger ice crystals are easier to sublimate and so hasten primary drying (Ratti, 2013).

Primary Drying or sublimation stage

Patel (2010) and Tang (2004), noted that primary drying stage also known as sublimation stage entails applying a vacuum and raising the shelf temperature to initiate sublimation so that the product temperature is 2 to 30℃ below the collapse temperature Tc. According to Tang (2004), the collapse temperature is the point above which a product runs the risk of losing its macroscopic structure during the freeze-drying process. A freeze-drying microscope could be used to measure Tc, although it can alternatively be inferred from the glass transition temperature (Tg). It should be noted that Tc may range from 20 to 200 degrees Celsius higher than Tg, mostly dependent on the makeup of the sample (Patel, 2010; Tang, 2004). However, extremely cautious estimations of the collapse temperature may simply lead to a significantly lengthier freeze-drying process; as a result, they should only be utilized in extreme circumstances where freeze-drying the sample is problematic. In each step of the freeze-drying process, Figure 2 shows the usual temperature profile of a product. It is clear from Figure 2 that during primary drying, the product temperature should be lower than the collapse temperature (shown in Figure 2 as a dotted line T1).

Secondary Drying or Absorption Stage

Secondary drying, a slow part in the freeze-drying process that may take at least 30% longer to complete than the completion of sublimation, begins while sublimation is still taking place. This final stage could be carried out at a higher shelf temperature, but below the glass transition temperature of dry materials (shown as dotted line T2 in Figure 2), to more effectively remove the remaining unfrozen or bound water by desorption. The beginning of the secondary drying phase or the conclusion of primary drying are both difficult to pinpoint. Prior to the completion of the primary drying process, when the temperature is raised, the product may collapse and the ultimate quality may be impacted (Patel et al., 2010).

Components of a Freeze Dryer

Freeze-dryers typically include four main parts: a drying chamber, a vacuum pump, a heat source, and a condenser, Figure 3 (Garcia-Amezquite, 2016).

The drying chamber – although the freezing process could be initiated inside the chambers as a first step, the system has to have a freezing system (see Figure 2 above). The drying chamber is where the frozen product is deposited. Given that heating and cooling operations take place inside the chamber, the chamber must be designed to be vacuum-tight, and the shelves inside need to be kept at a certain temperature.

The vacuum pump - in order to achieve the desired vacuum level, which is below 0.61kPa (4.58 mm Hg or 0.006 atm), the non-condensable gases must be removed from the chamber using a vacuum pump.

The heat sources – the glass transition temperature (Tg) and the moisture content of the food are the two main factors that determine the temperature of the heating source, which may range from 243.15K to 423.15K (- 30℃ to 150℃).

Condenser - the condenser's job is to collect the water vapor that is emitted when ice melts inside a product. It needs to have enough surface area and cooling power to completely condense all of the steam produced during the sublimation process. When water vapor comes into touch with the condenser surface, it transforms into ice crystals that release energy before being evacuated from the system.

Freeze-Drying of Food Produce

Timilehin and Won (2020), holds the view that freeze-drying is an industrial method that involves the dehydration of food molecules by the sublimation of frozen ice. Since it functions at low temperatures and in a high vacuum, it is a recommended method for drying foods containing chemicals that are thermally sensitive and prone to oxidation. According to Timilehin and Won (2020), it has been used on a variety of food items, including strawberries, apples, tomatoes, potatoes, asparagus, and pumpkins.

Its disadvantages, though, include the inevitable shrinkage and collapse that may occur during the drying process when it isn't done correctly. In the last three decades, freeze-drying has been the subject of extensive research. Due to recent assumptions that product quality performs well at low temperature, a decrease in injuries caused to liable bio-products that drying at high temperature or ambient temperature would have caused, and subsequently due to its approval by the food standard bodies, freeze-drying is gradually becoming a well-utilized processing technique in the food industries. As freeze-drying is reported to be accompanied by several complex interactions that may prove to be a problem at different processing stages, it is necessary that we look beyond the surface when choosing the type of processing methods to be used for a specific product (Harper, 1957; Franks, 1998; Livesey, 1987). Consequently, freezing, heating, and mass transfer inside the equipment may also occur in conjunction with chemical and physical changes.

5.1 Application of Freeze-Drying

5.1.1 *Fruits and Vegetables*

Vegetables are rich sources of essential nutrition, to achieve long term consumption; dehydration is usually a good choice of preservation method.

There are several ways to use freeze-dried pumpkin in the production of formulated foods such soups, noodles, breads, and cakes. In order to describe the nutritional and physicochemical characteristics of pumpkin for the aforementioned food applications, several authors have examined the freeze drying of pumpkin (Ciurzy' nska, 2014; Guiné, 2012; Que, 2008). According to Guiné et al. (2012), freeze drying reduced the moisture content of pumpkin from 90% to 8%, yet this softening effect resulted in a decrease in the pumpkin's hardness from 19.37 N (fresh) to 1.59 N (dried/rehydrated). Additionally, the color change (total change in color, DE = 12) was significant. According to research on the effects of the sun, oven, vacuum-oven, and freeze-drying on the phenolic content, antioxidant capacity, and ascorbic acid content of tomatoes, freeze-dried tomatoes had a phenolic content that was about two times higher than that of other drying methods (654.60 mg gallic acid equivalent/100 g dm vs. 314.27-355.79 mg/100 g dm) (Gümü¸say *et al.*, 2015)

New industrial uses of the freeze-drying method are being developed as a result of constant innovation and process improvement (Rey & May, 2001). It appears to be a viable method for dehydrating materials that are sensitive to heat, including fruits (Marques et al., 2007). Both the freeze-drying duration and the quality standards used to assess fruits that have been frozen-dried are affected by processing circumstances. Rehydration and texture are actually two criteria that are intimately related to the final use of the freeze-dried product and cannot be viewed as absolute standards. Fruits that have been dehydrated are typically meant to be added to foods like corn flakes, cereal bars, ice cream, pastry sauces, etc. 2011 (Ciurzyska)

Makhlouf et al. (2002), establishes that the fresh fruits with high moisture content are difficult to dehydrate using conventional drying procedures since doing so causes substantial physical damage, including collapse and serious bleeding from skin rupture. Under varied freeze-drying shelf temperatures (30℃, 40℃, 50℃, 60℃, and 70℃), under varied freeze-drying shelf temperatures (30℃, 40℃, 50℃, 60℃, and 70℃), Shishehgarha et al. (2002) studied the various quality metrics (drying kinetics, color, and volume variation) of sliced and whole strawberries. Whole and sliced strawberries saw an average volume reduction of 8% and 2%, respectively, after freeze drying at shelf temperature. This level of shrinkage was shown to be independent of shelf temperature. On the other hand, it was discovered that the chance of collapse rose exponentially after the freeze- drying shelf temperature surpassed the dried strawberry glass transition temperature. Makhlouf and others, 2002.

Shrinkage and collapse of fruits are often encountered during drying, mainly by air-drying techniques and compare the quality of guava obtained by heat pump dryers (RH = 10%, v = 0.7 m/s, T = 45℃, 8 h), vacuum (vacuum pressure = 15,000 Pa, T = 45℃, 8 h), and freeze-dryers (freezing at – 20℃ for 24 h, and less than 613.2 Pa vacuum pressure, 10℃ shelf temperature, 24 h for freeze-drying). In comparison to powder made by vacuum and heat pump dryers, freeze dried guava had greater porosity, color, rehydration, and vitamin C retention. As a result, it was the most preferred powder. Compared to heat pump dryers, freeze drying was able to preserve 63% of the vitamin C (Hawlader et al., 2006).

5.1.2 *Additional Special Foods*

Freeze-drying has been used to manufacture dried specialty foods including coffee, tea, and spices (An et al., 2016; Ding et al., 2012; Fante & Norea, 2015; Gümü say et al., 2015; Chan et al., 2009; Cheng et al., 2019; Dong et al., 2019). It is not only used for fruits and vegetables.

Coffee and tea are currently the two most consumed liquids worldwide. Because freeze drying can preserve volatile components, it has been utilized to manufacture instant tea. According to Kraujalyte et al. (2016), freeze-dried instant tea had a volatile component concentration of 318.65 ng/g, which was much greater (by a factor of two to five) than instant tea made using conventional drying techniques (68.60 to 143.33 ng/g). In the case of coffee, Chan et al. (2009), reported that the amount of phenolic acids in coffee beans increased by 41% following freeze drying compared to fresh green coffee beans. In order to determine how freeze-drying techniques affected odor components and the aromatic profile of roasted coffee beans, Dong et al. (2019) carried out a study. Interestingly, they discovered that the main organic acid quinic acid, which is linked to the quality of coffee, was only identified in the sample dehydrated using the freeze-drying method.

The functional qualities of egg yolk, devoid of additives, can be kept through freeze-drying, which includes pre-crystallization and fast freezing. Freeze-dried egg yolk can be produced even at commercial costs because full contact quick freezing eliminates the need for liquid nitrogen (Jaekel et al., 2008).

There have also been reports of freeze drying being used to dehydrate spices like ginger and garlic. Sablani et al. (2007) investigated the impact of freeze-drying shelf temperatures on the development of garlic pores. They discovered that lesser open pore porosity came from drying garlic at a higher shelf temperature. Additionally, as garlic dried, its apparent porosity grew considerably more porous. The impact of freeze drying on the capacity for allicin production was examined by Ratti et al. in 2007. The amount of allicin in the material reduced as the drying temperature rose, and the material dried at 20℃ retained more of its ability to generate allicin. Gingerols, phenolic content, flavonoids, antioxidant activity, and certain volatile components were all highly retained after freeze drying (An et al., 2016). Other products than food, such as flowers, microbes, pharmaceuticals, medical equipment, and cosmetics, particularly chemicals and pigments, enzymes, and ceramic powders, can be used (Pan et al., 2008; Chan et al., 2009).

Effect of Freeze-Drying Conditions of the Selected Physical Properties of Materials

The final product quality of food products may be considerably impacted by the physicochemical and structural changes that occur during processing. Important issues that arise during food handling and storage include color alterations and a lack of color stability. The processing techniques have an impact on porosity, texture, taste, the preservation of nutrients, and the sorption of components, according to Khalloufi and Ratti (2003). Foods' physical, chemical, and nutritional characteristics are significantly altered by the drying process (Bhatta et al., 2020). Adrieu and Vessot (2018), established that freeze-drying is less harmful than air-drying and spray-drying. Lyophilization is regarded as the best method for food dehydration as a result (Hammami et al., 1999). To produce a freeze-dried product of sufficient quality, it is necessary to regulate the freezing rate, temperature level, total gas pressure, and final mean moisture content (Adrieu & Vessot, 2018).

The Shelf Temperature

Many of the qualitative characteristics of foods and other materials that are submitted to this type of dehydration may be strongly impacted by the freeze-drying process parameters. One of the factors that is crucial in the formation of the material structure during the freeze-drying process is the temperature of the heating plate. According to Duan et al. (2007), using an inappropriate temperature during the procedure can lead to unintended changes in the material's structure. According to Patel et al. (2010) and Tang et al. (2004), an excessive collapse of the structure during secondary drying can reduce the freeze-drying rate and worsen many product characteristics such as texture, porosity, volume, shape, stickiness, rehydration capacity, and stability.

The freeze-drying process parameters may have a significant impact on a number of the qualitative traits of foods and other materials that are subjected to this method of dehydration. The temperature of the heating plate is one of the elements that is essential in the development of the material structure during the freeze-drying process. Duan et al. (2007) claim that doing the operation at the incorrect temperature can result in undesired modifications to the material's structure. An extensive collapse of the structure during secondary drying, according to Patel et al. (2010) and Tang et al. (2004), can lower the freeze-drying rate and deteriorate many product properties, including texture, porosity, volume, shape, stickiness, rehydration capability, and stability.

The primary and secondary stages of freeze-drying have different mechanisms for drying and pore formation, as well as for product stability. The longest stage of drying is the sublimation of ice, which uses more energy than the subsequent drying stage (Ratti, 2001; Assegehegn et al., 2020; Malik et al., 2020). For this reason, significant work has been done to design the appropriate freeze-drying cycles, particularly primary drying, for various food products (Patel et al., 2010; Malik et al., 2020; Barresi et al., 2009).

At the initial stage of the freeze-drying of gum Arabic solutions with concentrations of 20–60%, Malik et al. (2020) used varied shelf temperatures (–20, –30, and –40℃). With a constant chamber pressure of 0.1 mbar, the secondary drying was carried out at 20℃. The experiment revealed that when drying took place at shelf temperatures of - 30℃ and - 20℃, the puffing effect was significant for the sample's 60% content of Arabic gum. When primary drying took place at the higher temperatures of the shelf, the porosity of freeze-dried hydrocolloid was likewise higher. Because these temperatures were over the melting point, the sample could not be sufficiently cooled at - 20°C or - 30℃.

Wu et al. (2019) also note that increasing the process temperature from 40 to 70℃ resulted in a substantial 37% reduction in drying time while drying the mushroom Cordyceps militaris. Although material dried at high temperatures can collapse and lose the pore structure produced by the freezing process, the sublimation rate is typically faster at higher temperatures (Antelo et al., 2012).

For heat-sensitive materials, the temperature of the product should be restricted to between 10 and 35℃, and for less heat-sensitive materials, the temperature can be higher than 50℃, in order to control product stability, especially during the secondary drying stage (Duan et al., 2016 & Liapis et al., 2014). Higher temperatures of freeze-drying at the secondary stage, according to Wu et al. (2019) and Nireesga et al. (2013), should speed up the drying process because more energy is needed to remove the material's surplus water. However, a temperature that is too high may result in shrinkage or the melting of ice during the sublimation stage of drying (Duan et al., 2016; Sadikoglu et al., 2016). The balance between the input and the necessary heat should be taken into consideration when choosing an appropriate shelf temperature (Wu et al., 2019). Additionally, when designing the freeze-drying process, the final product's quality is an important consideration.

According to Egas-Astudillo et al. (2020), they were able to produce a product with improved quality and a more efficient procedure by using greater temperatures during the freeze-drying of fruit puree. The porosity of freeze-dried grapefruit puree increased slightly from 0.81 to 0.83 during a shelf temperature increase from ambient to 40℃. Additionally, pores' average surface area increased. According to the findings of Egas-Astudillo et al. (2020), not only was the structure of the material altered, but it also dried with less mechanical resistance (fracture force) at a lower heating plate temperature.

The physical characteristics of food include aspects like shape, volume, color, and texture that are particularly significant to consumers. A key criterion for judging the quality of a freeze-dried product is its porosity. The texture of foods, particularly their crispness and crunchiness, is significantly influenced by the size and distribution of pores in the material.

Some studies on the connection between freeze-dried product density, shrinkage, and porosity and shelf temperature have been published in the literature (Sabalni et al., 2006; Rahman et al., 2007). For abalone, potatoes, and brown dates, Sabalni and Rahman (2007) observed a decreasing tendency of apparent porosity and an increase in apparent density with the rise in shelf temperature in the range from -45℃ to 15℃. Krokida et al. (1995; Sabalni et al. (2006)) showed a similar tendency for freeze-dried potatoes, carrots, and bananas. When the temperature of the plate was raised for freeze-dried fruits like apples and yellow dates, however, the apparent porosity rose and the substance shrank less.

All dried products cannot be included in the glass transition idea, which claims that major changes in the apparent porosity (decrease in pore formation) and the collapse of the structure occur at or near Tg (Sabalni et al., 2006; Rahman, 2001). Foods can differ in their structure, composition, initial porosity of materials, variety, ripeness, size, shape, pre-treatment prior to drying, and process conditions, which can affect the mechanism of pore formation and shrinkage during drying (Sabalni et al., 2006; Hussain et al., 2002). According to Sabalni et al. (2006), some structures may also be more resilient to collapsing during the drying process. The studies conducted by Sablani et al. (2007) demonstrated that the ultimate porosity and apparent density of freeze-dried garlic were unaffected by the applied shelf temperatures of - 5℃, - 15℃, and - 25℃. However, the study found that during drying at a shelf temperature of -5℃, porosity increased continuously as water content in the material decreased, whereas at lower shelf temperatures, the general tendency was similar but there was a fluctuation in porosity (drop) when the critical moisture content was reached. The effect of temperature on pore development was not seen at that point since it was presumed there was no longer any ice in the dried material.

The material's composition and kind may have an impact on how much the freeze-dried product shrinks. According to Khalloufi and Ratti (2003) and studies by Shishehgarha et al. (2002) for freeze-dried whole strawberries under different temperatures in the range of from 30℃ to 70℃, the material's shrinkage did not significantly differ under the different shelf temperatures of 20℃, 40℃, and 70℃ for apples (13%) and strawberries (8%). This investigation shown that although the quantity of collapsed fruits increased with the heating temperature, the value of fruit shrinkage remained independent of shelf temperature. In the instance of pears, a high shelf temperature (70℃) caused the sample to shrink by a maximum of 12%; however, at lower temperatures, this parameter decreased to about 6%. It was determined that the pear's glass transition may be connected to the sample's propensity to shrinkage at high freeze-drying temperatures (Khalloufi & Ratti, 2003).

Due to the existence of air gaps and pores, the porous structure of dried materials may impact color descriptors, particularly the lightness of material. The determination of dried product color parameters is essential since the product's color is one of the primary quality criteria that consumers consider. The unintended heat destruction of several beneficial chemicals can be detected by changes in the color of dried foods. In some papers (Krzykowski et al. 2018; Rudy et al. 2015), the impact of shelf temperature on the color of various items has been examined. Different shelf temperatures (20℃, 40℃, and 60℃) were used by Krzykowski et al. (2018) to freeze-dry red pepper puree. By increasing the shelf temperature in the range of 20℃ to 60℃, the process time was reduced by more than half. When the heating plate's temperature was raised from 30℃ to 70℃ while drying whole and pulped cranberries, a similar tendency was noticed. About 40% less drying time was required (Rudy et al., 2015). When compared to fresh material, pepper puree's lightness and yellowness enhanced after freeze-drying. At 20℃, redness was reduced, but at 40℃ and 60℃, it was enhanced. In general, the degradation of carotenoids caused by the prolonged drying time of pepper at 20℃

and the application of a high temperature of 60℃ led to a decrease in the color intensity (Rudy et al., 2015). When freeze-drying orange puree, Silva-Espinoza et al. (2019) did not notice any changes in lightness as the process temperature increased from 30℃ to 50℃, but they did notice that the chroma was enhanced at the higher shelf temperatures of 40 and 50℃ and the hue angle decreased for temperatures below 50℃.
The color variations of apple, pear, and strawberry following freeze-drying at shelf temperatures of 20℃, 40℃, and 70℃ were examined by Khalloufi and Ratti in 2003. For lower heating temperatures of 20℃ and 40℃, there were no appreciable differences in the color characteristics of apple and pears. In the instance of strawberries, the freeze-drying procedure, not the degree of heating, was directly responsible for the rise in the b* value in contrast to the raw material. The browning of apples and pears was impacted by the greater temperature. As a predictor of potential color changes, the glass transition temperature was used.

Strawberry was found to have the greatest Tg value, whereas pear had the lowest. It was determined that under the identical freeze-drying circumstances, strawberry should be less susceptible to color fading than pear. According to Shishehgarha et al. (2002), the color and volume of freeze-dried strawberries were unaffected by raising the heating shelf temperature to 70℃. According to Egas-Astudillo (2020), heating the substance to 40^{o}C during the freeze-drying of grapefruit puree had no impact on the color of the finished product. Zghal et al., 2002; Agbisit et al., 2007; Le-Bail et al., 2009) Semi-empirical models have been used to characterize the mechanical properties of porous foods based on density changes during processing.
When evaluating the quality of food products, texture is among the most crucial factors. A few studies have looked at how shelf temperature affects the texture of products that have been freeze-dried. According to Silva-Espinoza et al. (2019), freeze-dried orange puree compacted into cylinders that behaved similarly to materials with higher rigidities when stored at higher shelf temperatures. The slope of the fracture curve's values was also correlated with sample resistance and an increase in deformation with shelf temperature. Before it broke, the freeze-dried product had a mechanical rigidity due to the high temperature of 50℃. It was a significant characteristic of the dried material since it might be connected to the product's higher mechanical resistance during transportation. The texture of rehydrated freeze-dried strawberries was assessed using penetration tests. The textural characteristics of rehydrated strawberries were shown to be unaffected by the heating plate's temperature (Dorota and Ewa, 2020). The shelf temperature of 15℃ and a rate of temperature increase of 1.6℃/min or a shelf temperature of 45℃ and a heating rate of 0.4℃/min were found to have the least texture degradation of freeze-dried strawberries.

The freeze-dried mandarin snack's mechanical attributes were measured using the puncture test. The research revealed that the texture was significantly altered when the shelves were heated from room temperature to 40℃. With a rise in shelf temperature, the fracture force and area under the puncture curve decreased, while the number of peaks rose. Despite being characterized as a crunchy product with every delicate structure, the sample without biopolymer integration, freeze-dried at 40℃, was shown to be more durable during storage in terms of mechanical parameters than the snack prepared at a lower heating temperature (Martinez-Navarrete et al., 2019). During secondary drying, Mawilai et al. (2017) looked into the impact of shelf temperature (30℃, 40℃, and 50℃) on the texture of freeze-dried dragon fruits. The lowest hardness and best crispness were found in the pulp during its 40℃ drying process. However, the dried peel's hardness did not noticeably change as the temperature rose, whereas its crispness did.

Lewieki and Lukaszuk (2004), noted that the water content and water activity of a dried material have a significant impact on its textural characteristics. While it has been observed that many researchers do not always monitor and manage the values of the water content and water activity after freeze-drying, despite the fact that these parameters are crucial for a proper evaluation of many other features of freeze-dried foods.

The Pressure Chamber

According to Martinez-Navarrete et al. and Silva-Espinoza et al. (2019), the application of proper working parameters during lyophilization, particularly the working pressure, may have a substantial impact on both the process' progress and the quality of the end products. At various pressures (5 and 100 Pa), the orange puree was freeze-dried inside the chamber. On the characteristics of color, a considerable impact of pressure was seen. Lightness L* values increased under low pressure, whereas chroma C* values decreased. According to Silva-Espinoza et al. (2019), samples dried at a higher working pressure were darker and had richer colors.
Papaya slabs were freeze-dried by Udomkun et al. (2018) at three different chamber pressure levels and a constant shelf temperature of 20℃. For samples dried at working pressures of 28 and 77 kPa, all color indices were comparable. The L*, b*, and DE (total color difference) values increased while the a* value decreased when a lower pressure of 9 kPa was applied. For freeze-dried strawberries, Hammami and Rene (1997) likewise noted a decline in the L* value at a higher pressure, which was accompanied by a sizable shrinking of the sample. To lessen the shrinking of sample fruits, such as strawberries, the applied pressure during freeze-drying should be lower than 50 Pa.

The apparent density, solid density, and porosity of the freeze-dried papaya were unaffected by the working pressure. Samples dried at the lowest pressure of 9 kPa showed a somewhat increased porosity. SEM micrographs demonstrated that the pressure applied during freeze-drying had a discernible impact on the modifications to the product's surface and structural makeup. Compared to papaya samples dried at 9 and 77 kPa, which had structures with dense dry layers and substantial cavities, the samples obtained at 28 kPa were characterized by a less collapsed, more homogenous, and porous structure. In addition, Oikonomopoulou et al. (2011) found that freeze-dried strawberry, mushroom, and potato had increased porosity and a greater number of big holes when lower working pressure was used. These freeze-dried materials' bulk density dropped as the applied pressure (from 1.5 to 0.06 mbar) decreased.

The sublimation process, particularly the temperature of ice sublimation, is strongly influenced by pressure. Ice is sublimated away, leaving behind pores and gaps with various properties. Therefore, by adjusting the freeze-drying settings, the desired porosity, density, and ultimate water content can be achieved (Oikonomopoulou, 2011; Hamkamsujarit & Charoenrein, 2012).

The texture of the dried products may be described by structural characteristics like density and porosity. Additionally, one may tailor the drying process and affect many various aspects, such as the textural characteristics of meals, by controlling how pores form and are distributed in items during drying (Rahman, 2001; Regier et al., 2007).

Although the effect was statistically significant, the fracture force of dried orange puree was very slightly affected by various operating pressures. According to the authors, a lower process pressure might lead to the development of a dry product with a texture that is more fracture-resistant (Silva-Espinoza et al., 2019). A lower pressure resulted in a reduced penetrating force, according to Domin et al. (2020). The structure collapsing during freeze-drying was the cause of the increased force seen for the kiwi samples acquired at a higher pressure. Without heating the plate, the operation was completed. The samples collapsed as a result of the increase in pressure, which also increased the temperature at which freeze-drying occurs.

The Freezing Rate

Another crucial step in the production of items that have been freeze-dried is the freezing of raw materials before the sublimation procedure. Both dried and frozen materials' structures are impacted by the freezing rate. Similar mean values could be found in the color properties of freeze-dried orange puree that was frozen at both a slow rate (-45℃ in a conventional freezer) and a fast rate (-38℃ in a blast freezer). Texture was also not considerably impacted by the freezing rates (Silva-Espinoza et al., 2019). The texture and color indices of the freeze-dried carrot samples were unaffected by either gradual freezing or rapid freezing. However, the shrinkage of freeze-dried carrot samples was decreased from 3.2% to 2.2% when fast freezing in liquid nitrogen was used in place of gradual freezing (a household freezer at - 15℃) (Reyes et al., 2007). The initial structure and composition of the materials may have an impact on the qualities of freeze-dried goods. The texture, level of ripeness, and moisture content of plant tissue have a significant impact on the freeze-drying process, according to Genin and Rene (2017).

Hammami and Rene (1997) reported that other factors that may impact the freeze-drying rate include the loading density, the height of the product layer, the product's surface, and the condenser capacity. Apple samples were freeze-dried after being cooled to - 25℃ at various rates of 0.5, 2, and 3℃/min. Comparing slow freezing to the fastest freezing rate resulted in an 8.3% reduction in drying time. The cell wall was damaged by the delayed freezing, which aided in the evacuation of moisture. Apples' texture softened and their ability to rehydrate was increased as a result of the cooling rate's reduction (Antal et al., 2013).

Storage of Freeze-Dried Foods

Although high porosity of dried materials has a detrimental impact on storage stability, Ciurzyska and Lenart (2011) identify time, temperature, and pressure as the most crucial parameters in the freeze-drying process. If these parameters are well defined, they may in fact affect the quality of the final product. Therefore, it is necessary to keep freeze-dried items in a hermetic container.

Food products that have been freeze-dried need to be sealed in airtight containers to stop oxygen and moisture from escaping. For bulk packing, laminated foil pouches, metal, and plastic cans are employed. For freeze-dried food products, vacuum packing and inert gas packaging are also appropriate in order to prevent food oxidation and spoilage (Ciurzyska & Lenart, 2011).

Advantages and Disadvantages of Freeze-Dried Food

According to Dincer (2000), the main advantages of freeze-drying over other traditional methods of food preservation (such as conventional drying and others) are the following: preservation of morphological, biochemical, and immunological properties; high levels of viability and activity; lower temperatures and shear conditions than other drying methods; high recovery of volatiles; preservation of structure, surface area, and stoichiometric ratios; high yield; and long shelf life.

Equipment for freeze-drying is very expensive and might not be economical for some goods. The equipment is not small since it needs a lot of room and operates for a long period to freeze-dry food. Not all foods can be freeze-dried, and some foods may require additions. Compared to freeze-drying, canning or dehydration are more economical.

Conclusions

A particular drying technique called freeze-drying enables the production of dried products with characteristics unique to the raw material. Typically, it is used to dehydrate a variety of items, including fruits, vegetables, spices, and even some unusual ones. The greatest standards of control and reliability are required when using freeze-drying to safely preserve a wide range of heat-sensitive items. When compared to other dehydration techniques, freeze-drying is the best at preserving nutritional properties, even though some vitamin and other valuable bio-compound losses can be observed. This is especially true when the process is carried out under vacuum.

Freeze-drying is expensive; hence its use in the food business is still not very widespread. To decrease the amount of time and energy required for this process, further research should be done in the areas of high energy requirement reduction, pretreatment of raw materials, and equipment innovation. This is due to the fact that decreasing the time and energy required for freeze-drying will lower production costs and boost its widespread use in the food sectors.

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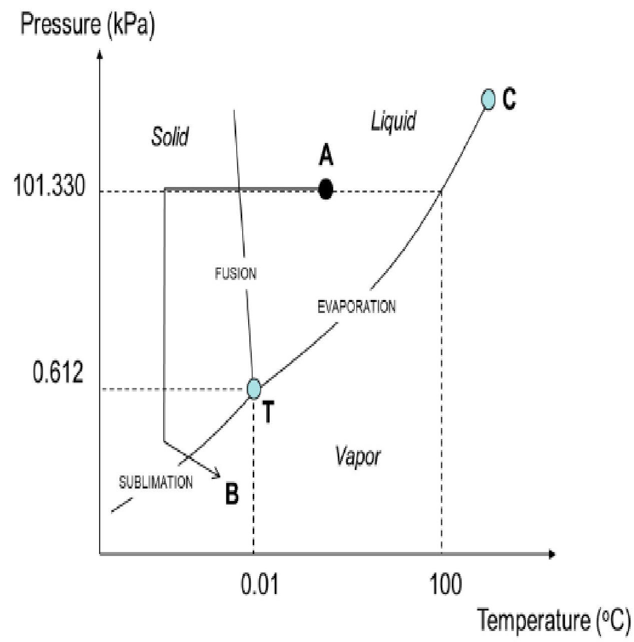

Figure 1. Phase diagram of water (T: triple point of water, C: critical point of water). "A" represents the starting point prior to freeze-drying (atmospheric pressure and ambient temperature), while "B", the desired final conditions during sublimation (below the triple point T). Sagar Bhatta *et al.,* 2019

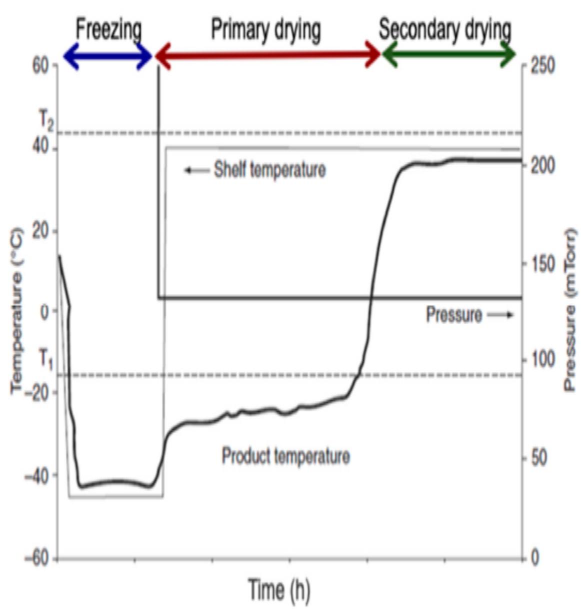

Figure 2. Temperature profile of product during freeze-drying process, where T1 (dotted line) is the collapse temperature and T2 (dotted line) is the glass transition temperature of dry solids (Ratti, 2013).

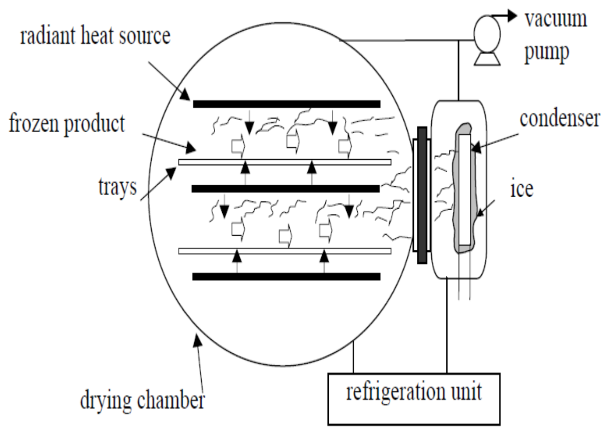

Figure 3. Schematic representation of a freeze-dryer system (Sagar Bhatta *et al.*, 2019).