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COMPREHENSIVE REVIEW

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Effects of osmotic dehydration pretreatment on freezing characteristics and quality of frozen fruits and vegetables

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Abstract

Osmotic dehydration (OD) is a process of soaking products in an aqueous solution containing salt or sugar, which is normally applied to fruits and vegetables. The combination of OD pretreatment with freezing, or osmotic dehydrofreezing (ODF), is a novel technology to shorten the freezing process and prolong the preservation of fruits and vegetables. However, the effectiveness of ODF is affected by process parameters and nature of the product, thus information on freezing characteristics and quality of osmotically dehydrated frozen fruits and vegetables is useful to the food industry. This review intends to provide an overview of the effects of OD pretreatment on freezing characteristics such as freezing rate, thermal properties, and quality of frozen fruits and vegetables. Fundamentals of ODF technology, including significance of OD to freezing, and mechanism and factors affecting ODF are summarized. In addition, hurdle technologies comprising of ODF and other innovative nonthermal techniques, such as ultrasound and pulsed electric field (PEF) are presented, and future trends of the combined technology are briefly discussed. ODF can accelerate the freezing process and enhance the quality of osmotically dehydrated frozen fruits and vegetables. The novel ultrasound and PEF techniques, which can provide cryoprotection from in situ interference, were proposed for the production of product with many-functional characteristics, by incorporating bioactive compounds like plants sterols, probiotics, and dietary fibers, into the matrix of cellular tissues during ODF process. However, these techniques can enhance the performance of the ODF to promote fast freezing, produce small ice crystals, and raise glass transition temperature of cellular tissues. The future trends of ODF technology should mainly focus on controlling the mass and heat transfer processes, improving quality stability during glassy state storage condition and development of product with many-functional characteristics.

Practical Applications

Fruits and vegetables are subject to freezing damage, particularly tissue softening and drip loss when thawing, thus reducing their quality and market value. OD pretreatments to freezing or ODF has great potentials in preservation of fruits and

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vegetables, with the advantage of minimum quality loss due to the reduction in freezing loads. Currently, innovative studies have been carried out on the combined use of OD pretreatments and emerging freezing techniques to improve the freezing process, achieve better quality with extended shelf life, and produce products with many-functional characteristics. However, the findings presented in this review work can provide detail insights on the quality of fruits and vegetables that were frozen by ODF and give some guidance for further developments of ODF technology.

1 | INTRODUCTION

Like drying (Alabi, Olaniyan, & Odewole, 2016; Pragati & Preeti, 2014; Sagar & Suresh Kumar, 2010) and cooling (McDonald & Sun, 2000; Olunloyo, Olunloyo, & Ibiyeye, 2019), freezing is a widely used technique to preserve some quality attributes of fruits and vegetables, such as color, minerals, and vitamins. However, freezing can also cause physical and chemical changes, which could lead to a loss in quality (Chassagne-Berces et al., 2009; Silva, Gonçalves, & Brandão, 2009). This loss is more apparent in tissues of fruits and vegetables due to high water content and ice crystals formation (Li, Zhu, & Sun, 2018). In addition, recrystallization during frozen storage potentially causes mechanical damage, promoting drip loss when thawing (Li et al., 2016). Therefore, other techniques that can improve the freezing process and enhance the quality of frozen fruits and vegetables have been developed.

Among the techniques, osmotic dehydration (OD) as a pretreatment to freezing emerges as a novel technology. This technology involves partial moisture removal from products before freezing (Ben, Said, Bellagha, & Allaf, 2015; James, Purnell, & James, 2014; Yadav & Singh, 2014) and is thus also known as osmotic dehydrofreezing (ODF). By reducing the moisture and increasing the solid content of products, improvement in structural characteristics, reduction in drip loss, and better retention of sensory and nutritional properties have been reported in thawed fruits and vegetables that were frozen by ODF (Cao, Zhang, Zhu, Zhao, & Liu, 2018). Furthermore, a reduction in moisture content lowers the refrigeration load during freezing, and the cost of packaging, distribution, and storage (Li & Sun, 2002). With these advantages, the ODF technology has been investigated to preserve fruits and vegetables including mango (Zhao et al., 2017), tomato (Chottanom & Srisa-Ard, 2011), grape (Cao et al., 2018), strawberry (Talens, Escriche, Martinez-Navarrete, & Chiralt, 2002), muskmelon (Maestrelli, Scalzo, Lupi, Bertolo, & Torreggiani, 2001), pineapple (Ramallo & Mascheroni, 2010), and apple (Ben et al., 2015; Bunger, Moyano, Vega, Guerrero, & Osorio, 2004).

During ODF, samples are first dipped in an aqueous solution, mostly in concentrated sugar (i.e., sucrose, trehalose, glucose, or sorbitol) or salt (i.e., sodium chloride or calcium chloride) solution, inducing two main mass transfer processes: (a) water moving from samples into osmotic solution and (b) osmotic solutes flowing from osmotic solution into the samples. In addition, some leaching of soluble compounds such as minerals, acids, and vitamins can occur, which may affect the organoleptic and nutritional properties of the final products (Talens, Escriche, Martínez-Navarrete, & Chiralt, 2003). After the OD treatment, samples are put inside a freezing system to lower their temperatures to below the freezing point, changing the remaining water into ice. Figure 1 shows the successive stages of ODF and their effects on process parameters and quality attributes of fruits and vegetables. However, the effectiveness of ODF is based on the product, osmotic agent, and process parameters. A high osmotic rate is mostly preferred to prevent excessive leaching of soluble compounds, which is determined by the size and shape of samples, affecting the surface area and resistance to mass transfer. On the other hand, the freezing method also plays important roles in the effectiveness of ODF, as it affects the freezing rate and final product quality.

There are few relevant reviews published in the past. Yadav and Singh (2014) reviewed the importance of OD pretreatment to extend the shelf life of fruits and vegetables. James et al. (2014) provided an overview of innovations in the dehydrofreezing research, including the comparison of the effect of dehydrofreezing with conventional freezing and the commercial application of dehydrofreezing technology. Moreso, for a better understanding of mass transfer process, Ramya and Jain (2016) detailed the mathematical modeling of mass transfer during OD of foods for enhancing energy saving and quality of the final product. Despite the above reviews, to the best of our knowledge, no review about the effect of OD pretreatment on freezing characteristics and quality of frozen fruits and vegetables is available. Therefore, in the current review, the fundamentals of ODF technology are introduced, effects of OD pretreatment on the characteristics during freezing of fruits and vegetables are discussed, and methods to further improve ODF process by combining other novel techniques such as ultrasound or pulse electric field (PEF) are presented. It is hoped that the current review could provide useful information on the development of ODF techniques and the improvement on the quality of osmotically dehydrated frozen fruits and vegetables for the food industry.

2 | FUNDAMENTALS OF ODF

2.1 | Significance of osmotic dehydration to freezing

The significance of OD to freezing of fruits and vegetables includes microbial inhibition (Akritidou & Koutsoumanis, 2018), fast freezing,

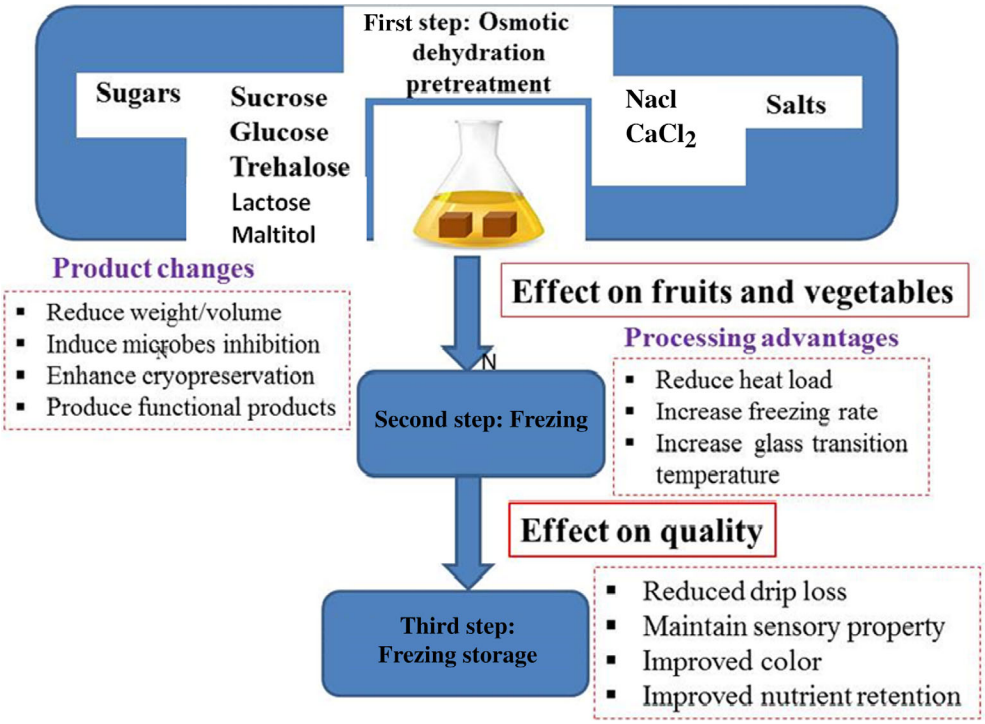


FIGURE 1 Successive stages of osmotic dehydrofreezing and their effects on process parameters and quality attributes of fruits and vegetables

cryoprotection, and development of products with many-functional characteristics (Li et al., 2016; Velickova, Tylewicz, Dalla, & Winkelhausen, 2011). Fresh fruits and vegetables contain high moisture content that allows microorganisms to survive or interact (although with difficulty at a low temperature), thus affecting quality (Al-Kharousi, Guizani, Al-Sadi, Al-bulushi, & Shaharoona, 2016). However, controlling moisture to a certain level, as in the case of OD, inhibits the activity of microorganisms and produces unalter quality.

In addition, by reducing the moisture content in fresh fruits and vegetables, OD pretreatment lowers the refrigeration load and promotes fast freezing. It can also fortify pectin substance in cells of fruits and vegetables, enhancing cryoprotection against freezing damage (Alabi, Zhu, & Sun, 2020). The cryoprotection is possible because solutes in the osmotic solution can be introduced into the cells of samples, and it has shown to maintain the cell structure of thawed kiwi fruit that was frozen by ODF (Talens, Martinez-navarret, Fito, & Chiralt, 2001). Essentially, OD pretreatment introduces bioactive compounds (like plant sterols, prebiotics, and dietary fibers) into the tissues of frozen fruits and vegetables, leading to the development of products with many-functional characteristics (Chavan & Amarowicz, 2012). For instance, osmotic agents like oligofructose have been used as fruit additive with many benefits, including the support for the beneficial gastrointestinal flora and reduction of infectious diarrhea (Egea, Borsato, dos Santos Ferreira da Silva, & Yamashita, 2012).

Table 1 presents the effects of OD pretreatment on freezing process and quality of fruits and vegetables.

2.2 | Mechanism of ODF

The mechanism of ODF can be expressed in two processes, namely (a) OD pretreatment and (b) freezing. In the OD pretreatment process, samples are dipped in a concentrated sugar or salt solution, leading to a flow of water from the samples mass into the solution and solutes flow from the solution into the samples. This mass exchange continues until the water activity of the sample, and the solution is at equilibrium (James et al., 2014; Ramya & Jain, 2016). However, the mass exchange normally takes place through a semipermeable cell membrane and depends on the osmotic pressure difference between the cell of the sample and the solution. When the osmotic solution concentration is high, solute penetrates, and water leaves the cell, causing cell shrinkage. However, low osmotic solution concentration causes water to flow into the cell, making the cell to swell up to a level the cell wall can withstand. Notwithstanding, when solutes penetrate into a sample, its first flow into the extracellular environment and later diffuse into the intracellular environment (Ferrando & Spiess, 2001, 2003). Normally, the mass exchange in plant cells follows two major pathways, namely apoplasmic and symplasmic (Ahmed, Mabood, & Jamal, 2016). The former is made possible by the connection between the cell components (cell wall and middle lamella), while the latter occurs via linked protoplasm of the surrounding cells, thus allowing cell to cell mass transport. In addition, pores and capillary system in plant cells allow the flow of water, and solutes of different molecular weight, shape, and size as they vary with main fruits and vegetables (Ramya & Jain, 2016).

In the freezing process, the remaining water in the sample is cooled from the initial temperature until it reaches the initial freezing point, and further cooling causes the water molecule to separate, forming ice crystals. The type of ice crystals depends on the freezing methods. Generally speaking, slow freezing induces a slow rate of mass transfer and causes the formation of large extracellular ice crystals, while fast freezing normally induces a high rate of mass transfer, leading to the formation of intracellular and extracellular small ice crystals (Alabi et al., 2020). Hence, the mechanism of ODF of fruits

TABLE 1 Effects of osmotic dehydration pretreatment on freezing process and quality of fruits and vegetables

Samples	Osmotic solution treatments	Freezing conditions	Observations	Reference
Papaya	Sucrose solution (40, 55, 60, and 65°Bx at 20, 25, 30, and 40°C for 30, 45, 60, and 90 min)	Air blast slow freezing at −28°C, 0.55 m/s for 1.5 hr and cryogenic fast freezing at −63°C for 10 min	Texture quality improves with increase in concentration due to solid intake and water loss from the fruit tissue	Moyano, Vega, Bunger, Garreton, and Osorio (2002)
Kiwi fruit	Sucrose solution (45 and 65°Bx)	Air freezing at −40°C, 4°C/min for 122 min	Osmotic treatment promotes notable changes in the volatile compounds: a significant decrease in *trans*-2-hexenal, *trans*-2-hexen-1-ol and 1-hexanol and slight increase in some ethyl ester compounds	Talens et al. (2003)
Apple	Sucrose solution (40, 55, 60, and 65°Bx at 25, 35, 40, and 45°C for 30, 45, 60, and 90 min) plus ascorbic acid (1%) and citric acid (0.2%)	Air blast freezing at −28°C and 0.55 m/s for 1.5 hr followed by conventional storage at −18°C for 15 days	Higher osmotic concentration increases firmness and preserves color and sensory properties	Bunger et al. (2004)
Pear, apple, strawberry, and kiwi	Sucrose (69°Bx), glucose (47°Bx), and fructose (69°Bx) solution at 30°C for 24 hr	Air blast freezing at −40°C	Size of solute molecules influences dehydration rate for the different tissues, leading to divergence in drip loss and color change	Marani, Agnelli, and Mascheroni (2007)
Strawberry	Sucrose solution (65°Bx for 3.5 and 8.5 hr)	Air blast freezing at −40°C, 24 hr and stored at 18°C, for 30 and 180 days	Osmotic treatment causes slight decrease in vitamin C content and offers long time preservation of the sample	Moraga, Martinez-Navarrete, and Chiralt (2006)
Strawberry	Glucose, oligofructose, and HDM solution (56.5% w/w, 35°C, 150 min) $CaCl_2$ (1.5% w/w) and NaCl (3.5% w/w)	Chest freezer at −40°C, 24 hr and stored at −5, −8, −12, and −15°C, for 180 days	Sugar enrichment and partial moisture removal improve firmness, vitamin C, and sensory characteristics for prolong storage life and less water loss during thawing, maintaining tissue integrity	Dermesonlouoglou, Giannakourou, and Taoukis (2016)
Rambutan	Sucrose, trehalose, and maltitol solution (50% w/w, 30°C, 1 hr)	Cryogenic freezing at −40°C for 25 min and stored at −18°C for 3, 60, and 120 days	Samples pretreated with sucrose solution has improved sensory characteristics and highest value of firmness than the other treatments and untreated samples	Lowithun and Charoenrein (2009)
Strawberry	Sucrose solution (60% w/w, 5 and 30°C)	Immersion freezing at −19°C for 24 hr followed by conventional storage at −18°C for 1 month	Sample pretreated at high temperature has a slight depletion of phenolic compounds	Blanda et al. (2009)
Tomato	Salt (NaCl: 10% w/v) and sugar (sucrose: 25% w/v) solutions at 30°C, 5 hr	Air freezing at −18°C and stored (−18°C for 30 days)	Samples treated with sucrose and salt solution are significantly more acceptable than untreated samples	Olatidoye, Sobowale, and Akinlua (2010)
Pineapple	Sucrose solution (60°Bx, 40°C, for 30, 60, 120, 180, and 240 min	Air blast freezing at −31.5 ± 2°C for 2 hr	Impregnation of solute in treated samples reduce the freezing time and drip loss and improve vitamin C content when compared with the untreated ones	Ramallo and Mascheroni (2010)

TABLE 1 (Continued)

Samples	Osmotic solution treatments	Freezing conditions	Observations	Reference
Tomato	Maltose (35 and 50%), sucrose (35 and 60%), and sorbitol (35 and 60%) solutions at 35°C for 2 and 6 hr	Air blast freezing at −35°C	High concentration of sucrose and sorbitol (60%) solution causes slight changes in the cell structure and induces oxidation of lycopene, although with unalter color in treated samples as compared with the ones treated in high concentration of maltose (50%) solution	Chottanom and Srisa-ard (2011)
Carrot	Sucrose solution [50% (w/w), 10°C for 5 hr]	Freezing at −18°C and stored at −18°C, for 1 week	Osmotic treatment prevents cell membrane degradation and maintains firmness after freezing–thawing process	Ando, Kajiwara, Oshita, and Suzuki (2012)
Mango	Mixed solutions (sucrose: glucose:fructose in a ratio of 3.6:1:3) of different concentrations [30, 40, and 50% (w/w) for 2 hr at 30°C] plus $CaCl_2$ (1.5% w/w)	Freezing at −18 ± 2°C and stored at −18°C and −55°C for 6 months	Osmotic dehydration in all sugar solutions reduces drip loss and increases hardness, vitamin C content, and total soluble solids of frozen samples more significantly in glassy state than in rubbery state	Zhao et al. (2017)
Banana	Sucrose solution (65°Bx for 4 hr)	Air blast freezing at −34°C and stored at −18°C for 17 hr	The process of osmotic dehydration and freezing improves the quality of banana slices in terms of color and texture	Jariyawaranugoon (2015)

Abbreviations: $CaCl_2$, calcium chloride; HDM, high dextrose maltodextrin; NaCl, sodium chloride.

and vegetables is hinged on the product, osmotic process parameters, and the freezing methods.

2.3 | Factors affecting ODF

The performance of ODF depends on several factors including those related to the products (i.e., geometry and nature of the products) and those related to the process parameters (such as composition, concentration and temperature of the osmotic solution, osmotic process time, level of agitation in the solution, sample to solution ratio, and freezing methods). Several publications have described the roles of these factors on the effectiveness of ODF of common fruits and vegetables (Cao et al., 2018; Chottanom & Srisa-ard, 2011; Dermesonlouoglou et al., 2016; Giannakourou & Taoukis, 2003; Li et al., 2016; Maestrelli et al., 2001; Sirijariyawat & Charoenrein, 2012; Talens et al., 2001).

The geometry (size or shape) of sample affects ODF because of the different in the length of mass transport as it varies with main fruits and vegetables. Typically, a big sample allows slow ODF, due to a long distance required for mass transport through the sample mass when compared with a small sample (Dermesonlouoglou et al., 2016). Also, the nature (cell components) of the product affects ODF process. However, the components of cellulose fibers including cellulose, hemicellulose, and pectin substances, depending on plant cultivars, prevent the cell from failing during ODF, aid structural stability, and cause less damage to quality. Maestrelli et al. (2001) studied the effect of cultivar and osmotic dehydration pretreatment on the freezing process and some quality parameters of two muskmelon cultivars (i.e., Rony cultivar and Mirado cultivar). The results ascertain that Rony cultivar has good quality retention due to the higher water permeability of its cell membranes, and it is more suitable for ODF than the Mirado cultivar.

Similarly, osmotic process parameters such as composition and concentration of osmotic solution affect ODF of fruits and vegetables. Chottanom and Srisa-ard (2011) reported that the quality characteristics and mass transfer during ODF of tomatoes are influenced by the types of osmotic agents and the concentration of osmotic solution. Among other osmotic agents applied, maltose (at 50%w/w solution concentration) is recommended for the ODF of tomatoes because of its positive effects on water loss, solid gain, color, lycopene retention, and melting temperature. Talens et al. (2001) observed the changes in the optical and mechanical properties of kiwi frozen by ODF. The findings reveal that among other treatments applied, samples treated in 45°Bx sucrose solution prolong the preservation of mechanical properties. In the same way, depending on the osmotic solutes applied, improvement in freezing process, and better retention of quality in thawed grapes (Cao et al., 2018), peas (Giannakourou &

Taoukis, 2003) and mangoes (Zhao, Hu, Xiao, et al., 2014) that were frozen by ODF have been reported. These diverse studies indicate that osmotic solutes have potentials to influence the ODF of fruits and vegetables.

Moreover, the temperature of osmotic solution affects the rate of mass transport during the ODF of fruits and vegetables. Although the rate increases with temperature, it is limited to a maximum temperature of about 60°C, because higher temperature can cause damage to cell membrane (Chavan & Amarowicz, 2012). Dermesonlouoglou et al. (2016) reported that the increase in temperature of the osmotic solution markedly affects the water loss and solid gain values in frozen strawberry.

Time is another important factor that affects ODF process. Li et al. (2016) examined the cell integrity and evaluated some quality parameters of frozen tomatoes pretreated in 55% (w/w) maltodextrin at 35°C for 24 hr. The results show that the cell structure of the pretreated tomatoes exhibit less shrinkage than the untreated ones, and lycopene content in the treated tomatoes shows no significant different from the fresh ones, owing to the long time (24 hr) of diffusion of maltodextrin into the tomatoes mass that enabled a strong binding force between the lycopene and the tomatoes mass.

Likewise, agitation affects the ODF process of fruits and vegetables. The higher the speed of agitation of samples inside the osmotic solution, the faster the rate of mass exchange and vice versa (James et al., 2014). However, agitation can cause damage to sample. Therefore, it is a challenge to prevent or minimize damage of sample. A low-speed magnetic stirrer is commonly used for safe agitation.

In the case of the effect of sample to solution ratio on ODF, any increase in the sample to solution ratio will lead to an increase in osmotic flow rate. Majorly, an optimum ratio of 1:10 is used for effective flow (Yadav and Singh, 2014).

In addition, freezing conditions such as freezing temperature influence the formation of ice crystals during the ODF process. Ice crystal is a critical factor that affects the cell structure of frozen fruits and vegetables. Ice crystal can be large or small, depending on freezing methods. The combination of OD pretreatment and conventional freezing methods like air blast and chest storage freezer (with most common operating temperature of −18°C) promotes fast freezing and produces small ice crystals in tissues of fruits and vegetables (James et al., 2014). These relatively small ice crystals cause less texture deterioration and consequently retain quality. However, only few studies have combined OD pretreatment with cryogenic freezing (Blanda et al., 2009; Bunger et al., 2004).

3 | EFFECTS OF OSMOTIC DEHYDRATION PRETREATMENT ON FREEZING CHARACTERISTICS OF FRUITS AND VEGETABLES

3.1 | Effect of osmotic dehydration pretreatment on freezing rate

Osmotic dehydration pretreatment affects the freezing rate of fruits and vegetables like banana (Jariyawaranugoon, 2015), apple (Ben et al., 2015; Bunger et al., 2004), and tomato (Chottanom & Srisa-Ard, 2011; Li et al., 2016). Specifically, the effect occurs at phase change region and depends on the amount of freezable water and solid content present in the sample tissue when freezing (Li et al., 2016). Li et al. (2016) observed the freezing process of fresh (untreated) and osmotically dehydrated tomato under three distinct phases (i.e., precooling, phase change, and subcooling) and reported that the treated and untreated samples were characterized with rapid temperature drop at the precooling stage. But at phase change, the treated samples have temperature decrease at a shorter time (3.13 min), indicating a fast-freezing rate (16.53°C/min), while untreated samples have temperature drop at a longer time (4.48 min), indicating a slow freezing rate (11.58°C/min). The effect is made possible because of the influence of the osmotic solids on the supercooling phenomenon of water, thus accelerating nucleation process in the treated samples.

Similarly, Ben et al. (2015) studied the relationship between moisture content and freezing rate during ODF of apple. The results reveal that the lower the moisture content in the sample, the higher the freezing rate and vice versa. However, no study has been identified on the effect of osmotic process parameters on the freezing rate of osmotically dehydrated frozen fruits and vegetables.

3.2 | Effects of osmotic dehydration pretreatment on thermal properties

Thermal properties (i.e., enthalpy or heat capacity) can favorably change during the ODF of fruits and vegetables (Agnelli, Marani, & Mascheroni, 2005). A modulated temperature differential scanning calorimetry by Baroni, Sereno, and Hubinger (2003) shows a reduction in enthalpy values during osmotic dehydration process of tomato. Tocci and Mascheroni (2008) reported that the osmotic dehydration process (in sucrose solution) reduces the values of enthalpy, heat capacity, and the initial freezing temperature of kiwifruit.

Likewise, a change in temperature and/or moisture content within samples' structure that occurs during OD pretreatment process leads to a change of glass transition temperature (Tg') of products (Lowithun & Charoenrein, 2009; Rosas-mendoza, Fernandez-Munoz, & Arjona-Román, 2011; Zhao et al., 2018). The modification of rambutan (Lowithun & Charoenrein, 2009) and mango (Rosas-mendoza et al., 2011) by osmotic syrups confirms that osmotic agents can raise the Tg' of plant tissue. For instance, the Tg' values of untreated and treated rambutan (in maltitol, sucrose, and trehalose solution) are −48.6, −47.4, −46.7, and −42.1°C, respectively (Lowithun & Charoenrein, 2009). The increase in Tg' provides a safe condition for glassy state storage because solid mass movement occurs at a very slow rate and causes minimal physical and chemical changes in tissues of fruits and vegetables (Mahato, Zhu, & Sun, 2019; Torreggiani & Bertolo, 2001). Bunger et al. (2004) studied the effect of OD pretreatment on the Tg' and the advantages of glassy state storage of apple frozen by ODF. As compared with the Tg' value (−37.12°C) of fresh samples, the Tg' of apple, maximally treated in sucrose solution (at 55°Bx, 35°C, 60 min) is −41.89°C and produces a good and

TABLE 2 Glass transition temperature (Tg') of some concentrated fruits

Samples	Osmotic agents and process conditions	Tg' (°C)	Product stability and acceptability	Reference
Papaya	Control Sucrose:55°Bx, 20°C, 30 min 55°Bx, 20°C, 60 min 65°Bx, 20°C, 60 min	−45.52 −36.64 −34.67 −33.74	Optimum treatment with Tg' value of −33.74°C gives a lower water loss and better stability of the product	Moyano et al. (2002)
Apple	Control Sucrose: 55°Bx, 35°C, 60 min 65°Bx, 20°C, 60 min 65°Bx, 45°C, 60 min	−44.45 −41.89 −38.87 −37.12	Optimum treated sample with Tg' value of −41.89°C has a less severe osmotic treatment based on quality retention	Bunger et al. (2004)
Rambutan	Control Sucrose: 50% (w/w), 30°C, 60 min Trehalose: 50% (w/w), 30°C, 60 min Maltitol: 50% (w/w), 30°C, 60 min	−48.6 −47.6 −42.1 −47.4	Study on product response at Tg' not yet conducted	Lowithun and Charoenrein (2009)

extended storage life. In another study, Zhao et al. (2017) demonstrated that OD pretreatment and glassy state storage (at −55°C) of mango frozen by ODF produces excellent quality when compared with the untreated ones. Therefore, OD pretreatment constitutes a promising technique to achieve Tg', particularly for samples whose Tg' is not practically achievable, thus prolonging the preservation of main fruits and vegetables. Table 2 lists the Tg' values of some concentrated fruits.

3.3 | Effects of osmotic dehydration pretreatment on quality

Osmotic dehydration as a pretreatment to freezing protects cell structure against freezing injury and reduces texture softening in broccoli (Ohnishi & Miyawaki, 2005), kiwis (Talens et al., 2003), and peas (Lim, Wu, Breckell, & Birch, 2006). However, for better understanding of the protective effect of OD pretreatment on frozen tissues, Ando et al. (2012) used pulsed field gradient-nuclear magnetic resonance measurement to observe two mechanical texture parameters, namely fracture stress related to cell wall and initial modulus related to cell membrane of osmotically dehydrated frozen carrot. The results reveal that OD pretreatment has effect on only the fracture stress with values close to the raw samples. Surprisingly, this is not so for broccoli (Ohnishi & Miyawaki, 2005) and strawberry (Ferrando & Spiess, 2001). The differences in cellular response are as a result of the osmotic agents used (Ando et al., 2012) and an uncontrolled mass transfer that occurs during the OD process (Ferrando & Spiess, 2001).

Moreso, OD pretreatment improves the firmness of frozen fruits and vegetables. An Instron Universal Testing machine shows that the firmness increases as moisture content decreases during the ODF of apple (Ben et al., 2015). The compression test on pineapple frozen by ODF clearly shows a greater failure resistance in osmotically treated samples when compared with the untreated ones (Ramallo & Mascheroni, 2010). Interestingly, Cryo-SEM micrographs of fresh (untreated) and osmotically treated frozen strawberry show that, although there is a relative cell alteration in the treated samples, the cell structure is much better than the untreated samples (Moraga et al., 2006). Likewise, OD pretreatment protects rheological properties, thus lessens plasma membrane injury during freezing of fruits and vegetables. The optical micrographs of some frozen agricultural materials by Ohnishi and Miyawaki (2005) show that the pretreated samples have less membrane injury when compared with the untreated ones.

In the same vein, OD pretreatment has been applied for limiting drip loss in frozen–thawed fruits and vegetables like pears (Giannakourou & Taoukis, 2003; Marani et al., 2007), kiwis (Marani et al., 2007; Talens et al., 2001), apples (Marani et al., 2007), strawberry (Dermesonlouoglou et al., 2016; Marani et al., 2007), and grapes (Cao et al., 2018). Marani et al. (2007) demonstrated the potential of OD pretreatment in reducing the drip loss in some frozen–thawed fruits. The findings reveal that the osmotically treated samples have lower drip loss, which vary according to the sample types and the osmotic agents used (see Figure 2).

Many findings have also indicated that OD pretreatment can enhance the nutritional properties of frozen fruits and vegetables (Dermesonlouoglou, Chalkia, & Taoukis, 2018; Dermesonlouoglou, Giannakourou, & Taoukis, 2007a, 2007b; Jariyawaranugoon, 2015; Moraga et al., 2006; Moyano et al., 2002). The results by Moraga et al. (2006) show that OD pretreatment can increase the total soluble solids in frozen strawberry. Osmotic dehydration pretreatment has also been reported to retain vitamin C in frozen tomato (Olatidoye et al., 2010) and mangoes (Zhao et al., 2017, 2018). Zhao et al. (2017) show that the rate of vitamin C loss in osmotically dehydrated frozen mangoes is slightly lowered when compared with the untreated ones after 6 months of storage. Likewise, OD pretreatment offers good and acceptable sensory property (i.e., color, flavor, and texture) in common frozen fruits and vegetables like banana (Jariyawaranugoon, 2015), tomato (Dermesonlouoglou et al., 2007a), and apple (Bunger et al., 2004) and shows improvement in polyphenols and volatile compounds (i.e., esters and furaneol) in frozen strawberry and kiwi (Blanda et al., 2009; Talens et al., 2002, 2003). Studies on the use of combined osmotic solutes that do not alter the final quality of osmotically

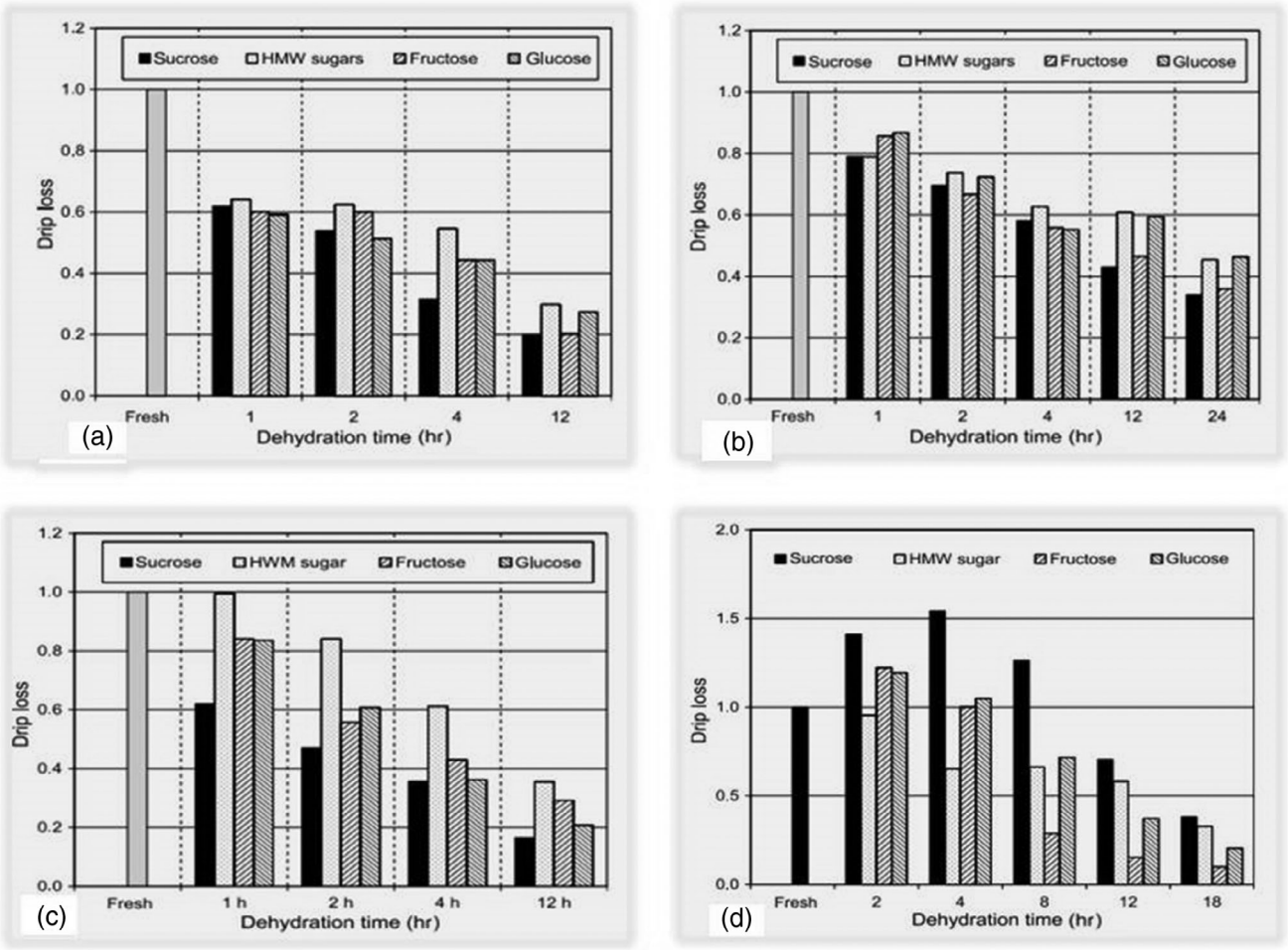


FIGURE 2 Drip loss (relative to the fresh sample) during thawing of (a) kiwis, (b) apples, (c) pears, and (d) strawberries that are frozen by osmotic dehydrofreezing (ODF, with different osmotic agents; Marani et al., 2007)

dehydrated frozen fruits and vegetables have also been reported (Giannakourou & Taoukis, 2003; Monnerat, Pizzi, Mauro, & Menegalli, 2010). In comparing osmotic solutes, Cao et al. (2018) reported that trehalose is more effective than sucrose and glucose in maintaining color parameters like a* and L* values of grapes. All these studies indicate that the amount of moisture content in fresh samples is enough to cause damage when freezing. Hence, partial moisture removal constitutes a promising method to prevent the freezing damage of fruits and vegetables.

4 | HEAT AND MASS TRANSFER MODELING

The modeling of heat and mass transfer during the ODF of fruits and vegetables allows for an effective process control and optimization. It is a complex task because it involves two processes, namely (a) a mass transfer of soluble solids (including small quantities of organic acids, minerals, and vitamins), and water between the product and the osmotic solution, and (b) heat transfer during freezing, and can be classified into successive mass and heat transfer models, which are developed based on numerical method (Agnelli et al., 2005; Agnelli, Marani, Spiazzi, & Mascheroni, 2001). The mass transfer operation occurring in the OD process is based on the concentration gradient that exists between the product and the osmotic medium, which depends on the nature of the treatment (i.e., solute concentration and its molecular weight), operating conditions (i.e., temperature and time of treatment), and also the cellular structure (i.e., size and shape) of the product (Goula & Lazarides, 2012; Zhao, Yuan, Li, et al., 2014). Goula and Lazarides (2012) used numerical approach, particularly finite volume, to model mass transfer in the ODF of tomato fruits. The authors reported that concentration gradient can effectively predict mass balance by analyzing the diffusion of solutes across intercellular spaces, based on the microstructural properties of the product, as expressed using the mass balance with a homogenous cellular volume shown in Equation (1).

$$\frac{\partial V_c C^{\text{int}}}{\partial t} = \nabla\left(V_c D_{\text{eff}}^{\text{int}} \nabla C^{\text{int}}\right) - A_m J, \tag{1}$$

where V_c is the cellular volume (m^3), C^{int} is the cellular molar concentration, $D_{\text{eff}}^{\text{int}}$ is the effective diffusion coefficient, A_m is the surface area (m^3), and J is the molar flux through the cell membrane.

On the other hand, the heat transfer during subsequent freezing is based on temperature gradient between the product and the freezing medium, which also depends on the thermal diffusivity, composition, size, and shape of the product (Agnelli et al., 2001). The modeling of the freezing step was also achieved via numerical methods, which involves a phase change in the thermal balance and enthalpy, as expressed in Equation (2).

$$\rho\frac{\partial h}{\partial t}=\nabla(k\nabla T), \tag{2}$$

where ρ is the product density, k is the thermal conductivity, h is the enthalpy of the product (J/kg), and T is the temperature. Agnelli, Marani, & Mascheroni (2005) used the explicit finite-differences approach on thermal balance equation to develop a model that effectively predict thermal histories from previously dehydrated apple and pears, and the results showed that the model can predict quite precisely the thermal evolution during freezing. The finite volume approach has also been used for modeling heat transfer during ODF with successful prediction similar to experimental results (Goula & Lazarides, 2012; Zhao et al., 2014).

So far, numerical methods developed still lack the capability to analyze quality loss including soluble solids degradation.

5 | INNOVATIVE TECHNIQUES TO ENHANCE ODF PROCESS

To promote the effectiveness of ODF technology, innovative techniques such as ultrasound and PEF have been applied. These innovative techniques are nonthermal treatments that are normally applied before and/or during ODF process, enhancing mass transfer. The advantages and limitations of these techniques are presented in Table 3.

The ultrasound-assisted osmotic dehydrofreezing (UODF) technique involves partial and fast dehydration under ultrasound waves. The ultrasound waves incite comprehensive effects, including acoustical cavitation, sponge effect, and internal microstreaming, influence the cell wall permeability, and increase the mass transfer rate, thus maintaining the final quality (Cheng, Sun, Zhu, & Zhang, 2015; Qiu, Zhang, Chitrakar, & Bhandari, 2020). The findings of Baoguo, Zhang, Bhandari, and Cheng (2014) indicate that UODF technique has positive effect on firmness, color, and drip loss value of red radish when compared with untreated and osmotically dehydrated samples. Similar results were reported for kiwi (Fan, Zhang, Wang, & Bhandari, 2020) and broccoli (Xin, Zhang, & Adhikari, 2014) that were frozen by UODF.

In theory, the ultrasound waves cause thermolysis reaction, and degradation of ascorbic acid content in plant tissues, thus placing UODF at a disadvantage (Fernandes, Gallão, & Rodrigues, 2009). But, Baoguo et al. (2014) have uncovered an evidence that suggests otherwise, having studied the ascorbic acid contents influenced by UODF of red radish. The findings show that UODF causes less ascorbic acid leaching from the red radish, due to the small drip loss. However, UODF creates free radicals and causes oxidative damage, thus affecting phenols content in fruits and vegetables (Awad, Moharram, Shaltout, Asker, & Youssef, 2012).

TABLE 3 Advantages and limitations of innovative techniques for promoting osmotic dehydrofreezing process

Techniques	Advantages	Limitations
UODF	Energy saving and short dehydration and subsequent freezing time	Oxidative damage affects preservation of phenols
PEF-assisted ODF	Can be used for different types of fruits and vegetables, increases heat and mass transfer, and preserves bioactive compounds, phytochemicals, and phenolic	Irreversible electroporation disrupts plasmolemma in cells of fruits and vegetables

Abbreviations: ODF, osmotic dehydrofreezing; PEF, pulsed electric field; UODF, ultrasound-assisted osmotic dehydrofreezing.

UODF can also influence the Tg' of fruits and vegetables. The results obtained from the differential scanning calorimeter, low field nuclear magnetic resonance, and magnetic resonance imaging show the effectiveness of ultrasound-assisted osmotic dehydration (in trehalose solution) in raising the Tg' of broccoli through a change in the state of the cellular water (Xin, Zhang, & Adhikari, 2013).

In the same way, normally, PEF-assisted ODF makes use of short pulses of high electric fields with duration of micro to milliseconds and intensity in the order of 0.5–80 kV/cm, induces small pores in cells of fruits and vegetables through electroporation, a process which is applied to promote mass transfer and thus assist ODF process (Parniakov, Lebovka, Bals, & Vorobiev, 2015). Electroporation depends on the process conditions and can be reversible or irreversible. Whereas irreversible electroporation causes plasmolemma disruption and disturbs cells from its normal functions, reversible electroporation allows cells to revive its functions, because it does not cause total damage to the cells. The PEF-assisted ODF do not only promotes mass transfer rate, but as well maintains the cell wall of fruits and vegetables. Shayanfar, Chauhan, Toepfl, and Heinz (2014) reported that PEF-assisted osmotic treatments by cryoprotectants (such as calcium chloride, glycerol, and trehalose solutions) lead to better accessibility of intracellular materials to freezing and thus reduce the freezing time, leading to better maintaining of texture after thawing of carrot. The firmness results show that the PEF-assisted ODF gives higher value of 6.63 N, whereas PEF alone and control samples give lower values of 5.84 and 3.46 N respectively. The SEM studies also support the firmness results and show that the cell walls of the PEF-assisted osmotically dehydrated frozen samples are intact. In addition, PEF-assisted osmotic treatments (at time 180 min and concentration of 20 wt%) allow prevention of apple tissue softening after defrosting (Parniakov et al., 2015) and high freezing tolerance in spinach tissue after thawing (Phoon, Federico, & Anthonio, 2008).

By and large, the few studies available in literature show that the combination of ODF and innovative techniques like ultrasound or PEF has greater advantages, including the support for the process improvement and quality stability.

6 | CHALLENGES AND FUTURE WORK

ODF is a novel technology that can accelerate the freezing process and prolong the preservation of fruits and vegetables. Specifically, ODF technology has great potentials to reduce the enthalpy and heat capacity and increase the freezing rate and glass transition temperature of fruits and vegetables. However, the mass exchange that occurs during ODF introduces active solutes like plant sterols into sample mass, aids cryoprotection, and potentially causes the development of products with many-functional characteristics. In addition, hurdle technology combining ODF with either ultrasound or PEFs is an innovative technique that assists ODF process.

Although, the combined innovative-assisted ODF techniques have made great impacts on preservation of fruits and vegetables, challenging issues still remain and should be considered in future studies.

To promote ODF technology, efforts should be made to understand or control mass transfer process in products. One method that can be explored is the use of analytical techniques such as Fourier transform infrared spectroscopy, and nuclear magnetic resonance (H-NMR) spectroscopy, due to their sensitivity to water and solid exchange between osmotic solution and plant-based food materials. In addition, efforts should be made to ensure stability of polyphenols and volatile compounds such as esters and furaneol in frozen tissues. Since ODF technology favorably changes glass transition temperature, future studies should also focus more on the effect of osmotic treatment and glassy state storage on the quality of main fruits and vegetables.

Similarly, the combined innovative-assisted ODF techniques are still at the laboratory stage, and only few studies are reported on freezing characteristics, thus making experimental reproducibility a major concern. Therefore, to apply these technologies, efforts should be made to check the effect of these techniques on the freezing characteristics of fruits and vegetables and also check the feasibility of transferring laboratory results to industrial application.

Despite good number of research on the combined innovative-assisted ODF techniques, few studies are reported on thawing process. Information on the thawing process would enhance complete comprehension; therefore, more study should focus on the effect of ultrasound and PEF on the characteristics during thawing of fruits and vegetables.

In regard to modeling, there are limited research on the effect of osmotic dehydration pretreatment on freezing of cellular tissues; there is a need to further research on the development of accurate models that would include mass transfer across cellular tissue and heat transfer over a range of temperature. Although modeling of cellular dehydration, thermal expansion, and volumes changes are reported, other effects caused by ODF processes including cell deformation, soluble solids degradation, ice nucleation, and crystal growth are much neglected. More insightful study that focuses on these effects is required for comprehensive and effective prediction.

In conclusion, the results available have shown that ODF technology can achieve fast freezing for fruits and vegetables, making it a promising technology in the food industry. However, most of the freezing methods applied during ODF are conventional and are becoming unsatisfactory to modern frozen market. The availability of fast freezing technique such as high-pressure shift freezing (HPSF) can be a platform to achieve a superfast freezing, with excellent product quality. Therefore, future work should focus on the use of HPSF technique during the ODF of fruits and vegetables.

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