Journal of Food Process Engineering

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Journal of Food Process Engineering

ORIGINAL ARTICLE

Effects of Osmotic Dehydration-Assisted Freezing at Different Pressure Rates on Mass Transfer and Quality of Fresh-Cut Apple

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Received: 4 December 2024 | **Revised:** 22 April 2025 | **Accepted:** 30 April 2025

Funding: This work was supported by Tertiary Education Trust Fund (KWASUIBR/CRIT/270921/VOL1/TETF2020/0019).

Keywords: apple | food industry | high pressure freezing | microstructure | osmotic dehydration | sensory

ABSTRACT

This study aims to enhance the preservation of fresh-cut apple slices by applying osmotic dehydration in sucrose solutions prior to high-pressure shift freezing (HPSF). Apple slices (1 × 1 × 1 cm) were osmotically dehydrated under varying sucrose concentrations (45°Bx, 55°Bx, 65°Bx), temperatures (25°C, 35°C, 45°C), and durations (30, 60, 90 min) before freezing at pressures of 200 and 240 MPa. Mass transfer (water loss, solid gain), drip loss, total soluble solids (TSS), sensory qualities (color, sweetness, flavor, texture, acceptability), and microstructural changes (via light microscopy) were assessed using standard methods, with statistical analysis applied to evaluate differences. Optimal pretreatment at 65°Bx, 35°C, and 30 min followed by freezing at 240 MPa increased TSS and reduced drip loss by 93% compared to untreated samples. Sensory qualities and microstructure were significantly better preserved in treated samples ($p \leq 0.05$). The study demonstrates that combining osmotic dehydration and HPSF under optimized conditions enhances fresh-cut apple preservation, offering valuable applications for the food industry.

1 | Introduction

The demand for high-quality fresh or processed fruits has increased tremendously, mainly due to their numerous health benefits and guidelines pointed out by food regulatory bodies. This motivated food engineers to study the most effective methods for their preservation (Sivakumar and Fallik 2013). Freezing is commonly applied for fruit preservation (Alabi et al. 2020). However, freezing can alter tissue integrity, leading to cell structure failure which affects final quality (Chassagne-Berces et al. 2009; Silva et al. 2009). The effect is typically common in the tissue of fruit products due to the high moisture content, fragile nature of fruit cells and the crystallization process (Li et al. 2018). Hence, innovative methods that can improve the crystallization process are thus preferred. Among the techniques available, freezing in conjunction with osmotic dehydration (OD), also referred to as osmotic dehydrofreezing (ODF) emerges as the most promising technique for achieving fast freezing and producing products with high quality (Alabi et al. 2022; Hasan et al. 2022; Aroua et al. 2023). ODF is the partial removal of moisture content from samples prior to freezing, resulting in the reduction of refrigeration load, promoting freezing rate, and glass transition temperature, which are conditions required for the preservation of cellular foods (Cheng et al. 2015). In addition, ODF increases the solid content of products, maintains physicochemical properties, reduces drip loss (DL) value, and produces acceptable sensory properties of thawed fruits (Moyano et al. 2002; Lowithun and Charoenrein 2009; Jariyawaranugoon 2015). More so, ODF makes use of compatible solutes like sucrose, glucose, or trehalose that aid cryoprotection of cell structure against freezing injury (Ando et al. 2012; Velickova et al. 2013;

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Zhao et al. 2014; James et al. 2014). All these benefits make the ODF technique an effective method for preserving tomato (Chottanom and Srisa-ard 2011), apple (Lewicki and Porzecka-Pawlak 2005), and pineapple (Ramallo and Mascheroni 2010).

Chottanom and Srisa-ard (2011) studied the effect of osmotic solutions including maltose solution (35, 50 v/v), sucrose (35, 60 v/v) solution, and sorbitol (35, 60 v/v) solution on mass transfer, melting temperature, lycopene content, and color of tomato. The study revealed that the reduction of melting temperature and retention of color depend on osmotic agents and the solid mass fraction. The osmotic solids were reported to influence supercooling of water in the sample and prompted instantaneous nucleation (Asghari et al. 2024); Lewicki and Porzecka-Pawlak (2005) reported that OD at 61.5% sucrose solution slightly affected the microstructure and changed the shape and dimension of intercellular spaces of apple. Ramallo and Mascheroni (2010) evaluated the combined effects of OD pretreatment and air blast freezing (at −31.5°C ± 0.2°C) on some quality parameters of pineapple slices. The study showed that OD pretreatment reduces the freezing time and significantly lowers DL values of samples.

So far, the ODF technique has not completely solved the problem of quality loss. Even when the OD pretreatment process gives rise to a cellular structure that is the same or stronger than that in fresh samples, the most common conventional (such as air blast and contact plate) freezing technique causes a slight loss in firmness, as well as a pronounced diminution of breaking resistance, leading to an additional loss of soluble compounds (like minerals and vitamins) after the freezing–thawing process (Talens et al. 2002). However, some emerging freezing techniques like high-pressure shift freezing (HPSF) are available (Fernandez et al. 2006; Otero et al. 2008; Chevalier et al. 2000). The HPSF process has unique properties under pressure and takes advantage of the phase diagram of water, inducing extensive supercooling on products (Sanz and Otero 2014). Typically, the process comprises three successive stages: (i) samples are cooled under pressure at sub-zero temperatures to induce extensive supercooling throughout the samples mass without ice crystal formation provided adequate pressure and temperature are maintained, (ii) fast pressure release induces supercooling and initiates instantaneous nucleation and growth throughout the sample mass, and (iii) crystal growth at atmospheric pressure, with no further nucleation occurring (Sanz and Otero 2014). The principles and main applications of HPSF have been reported (Sanz and Otero 2014). HPSF has been applied for the preservation of food models and fruit tissues (Chevalier et al. 2000; Fernandez et al. 2006). For instance, broccoli frozen by HPSF (at 210 MPa and −20.5°C) displayed firmness and color similar to the fresh ones (Fernandez et al. 2006). Other studies by Otero et al. (2008) revealed that HPSF enhances quality, whereas air blast freezing (−40°C) negatively affected the final quality of peach and mango. In the case of certain minimally processed fruits like apple, which have delicate cells with high nutritional and commercial value, the HPSF process is not satisfactory due to "pressure" effect and texture degradation, promoting DL when thawing (Kotwaliwale et al. 2012).

Meanwhile, the supercooling effect of osmotic solutes, especially sugars, affects ice nucleation, crystal growth, and cell structure at given pressure (Thiebaud et al. 2002), making osmotic solutes have huge advantages in the HPSF process. However, the study on the combined effect of OD pretreatment and HPSF of fruits is still lacking in the literature. Also, to the best of our knowledge, there are scant studies on the cell structures of apples that were frozen under osmo-dehydrofreezing. Therefore, the present study investigated the joint impact of OD pretreatment and HPSF on mass transfer, quality, sensory properties, and cell structures of apples. The qualities were optimized based on the best combination of the pretreatment conditions, and the microstructures of the fresh, untreated, and maximally dehydrated frozen samples were evaluated.

2 | Materials and Methods

2.1 | Sample Preparation

Fresh apples (*Malus domestica*) were acquired from a local market at Malete and transported to the Food and Agricultural Engineering Laboratory at Kwara State University (KWASU). The samples were cleaned using absorbent paper and put in a refrigerated storage (at 10°C) before use. The samples were washed, peeled, and diced into cubes measuring dimensions of 1 × 1 × 1 cm.

2.2 | Osmotic Dehydration

The apple slices were immersed in sucrose solution (at 45°Bx, 55°Bx, and 65°Bx) in a thermostatically controlled water bath (HH-S4 Shanghai, China). According to Moyano et al. (2002) and Lewicki and Porzecka-Pawlak (2005), the sucrose solutions were prepared by adding sucrose (commercial sugar) to distilled water that contained 1% ascorbic acid and 0.5% citric acid (relative to the water content) to prevent enzymatic spoilage. The sucrose solution and apple slices were combined in a 2:1 weight-to-weight ratio. The duration and temperature for osmotic dehydration were 30, 60, and 90 min and 25°C, 35°C, and 45°C, respectively. Dehydrated apple slices were blotted with tissue paper to eliminate the remaining syrup and weighed. Afterwards, the dehydrated samples were vacuum-sealed in a low density polyethylene bags prior to HPSF.

2.3 | Mass Transfer

2.3.1 | Water Loss, Solid Gain, and Drip Loss

The water loss (WL), solid gain (SG), and DL were expressed according to Alabi et al. (2016), as described in Equations (1–3), respectively:

$$\mathrm{WL} = \frac{\left(M_o - m_o\right) - (M - m)}{m_o} \tag{1}$$

$$\mathrm{SG} = \frac{m - m_o}{m_o} \tag{2}$$

$$\mathrm{DL} = \frac{W_o - w}{W_o} \times 100 \tag{3}$$

where:

M_o = Initial mass of the sample before osmotic treatment.

M = Mass of the sample after an osmotic treatment duration of time t.

m_o = Dry mass of the sample before osmotic treatment.

m = Dry mass of sample after time t of osmotic treatment.

W_o = Weight of the sample after freezing.

w = Weight of the sample after thawing.

2.4 | Freezing and Thawing Process

Freezing of the samples (untreated or osmotically dehydrated) was carried out at −20°C (freezing time: 7200 s) in a high pressure freezing chamber (Pressure of 200 and 240 MPa (HPM 010 basic 3 × 380/220 V, 50 Hz) Zurich, Switzerland), and thereafter stored at −20°C for 15 days. Thawing was carried out at room temperature for 8 h before the analysis. Fresh, untreated, and osmotically treated frozen samples were analyzed based on their quality and microstructure changes using standard methods. Figure 1 shows the experimental procedure of the osmotic dehydration-assisted freezing of apple under different pressures.

2.5 | Total Soluble Solids (TSS)

The TSS values were measured according to Bartz and Brecht (2003). The treated and untreated juice samples were extracted, and a small quantity of the juices was placed on the handheld refractometer (HRB32-T Kruss Optronic Co. Ltd., Germany) and the total soluble solid values displayed were recorded.

2.6 | Sensory Property

Apple slices were assessed for color, appearance, sweetness, flavor, mouth feel, and overall acceptability using a nine-point hedonic scale test (1 = extremely dislike, 9 = extremely like). Twenty-one trained assessors were selected based on their interest and product familiarity. As part of the training, the assessors cleansed their palates with distilled water before tasting the sample and anytime during the test as prescribed by Lim (2017).

2.7 | Microstructure

The light microscope (LM) used in this study was based on the method of Dong (2024) with slight modifications. The internal zone (about 4 mm^3) of fresh and maximally dehydrated frozen–thawed samples was fixed with a 3% glutaraldehyde solution for 24 h and dehydrated using a graded ethanol series (50%, 56%, 80%, 95%, and 100% v/v) and washed with xylene to remove alcohol and allow infiltration. The samples were infiltrated with resin for polymerization and embedded in paraffin. The polymerized samples were cut into 5 μm sections by using an ultramicrotome. The sections were stained with 1% Toluidine blue and examined under a LM (LED 134-CLED, National optical & scientific Instrument Inc. Schertz, TX, United States).

2.8 | Statistical Analysis

All measurements taken from the experiments were analyzed in terms of the effect of OD pretreatment and HPSF on the mass transfer and physicochemical properties of thawed apple slices. The process parameters were selected as fixed factors. The mass transfer parameters, such as WL and SG, and other qualities, including DL, TSS, and sensory properties, were regarded as response variables. Analysis of variance (ANOVA) was employed using the design expert (6.0) statistical package, and the significance was

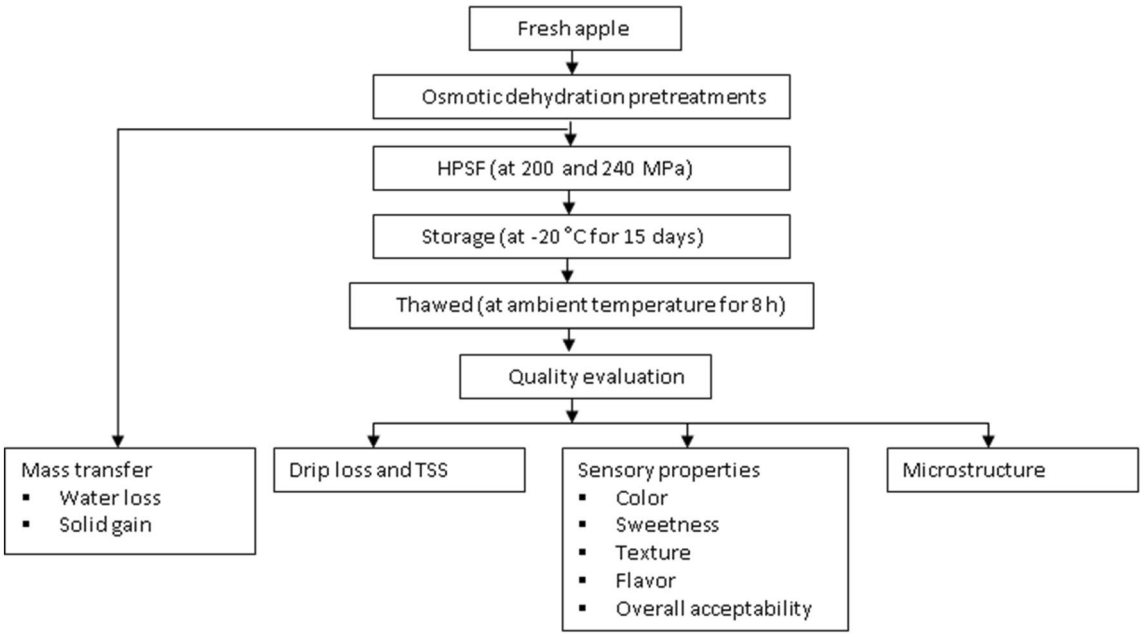


FIGURE 1 | Experimental procedure of the osmotic dehydration-assisted freezing of apple under different pressures.

set at the level of 0.5, considering the main effects and two-factor interactions to arrive at the best results of the treatments.

3 | Results and Discussion

3.1 | Water Loss

WL is a key factor in plant-based foods, influencing the remaining soluble mass after processing. As shown in Figure 2a–c, WL has a linear relationship across all treated samples. As duration increases from 30 min to 60 min, the WL increases. The lowest WL (0.90 g/g) occurred at 25°C, 45°Bx, and 30 min, while the highest (2.39 g/g) was at 45°C, 65°Bx, and 90 min. These results indicated that increasing concentration and processing time lead to greater WL. Additionally, the temperature of the osmotic solution significantly impacts moisture movement during osmotic dehydration, with WL rates increasing with temperature, up to 45°C. This finding aligns with Dermesonlouoglou, Giannakourou, et al. (2016), who also observed that higher osmotic solution temperatures significantly influence WL.

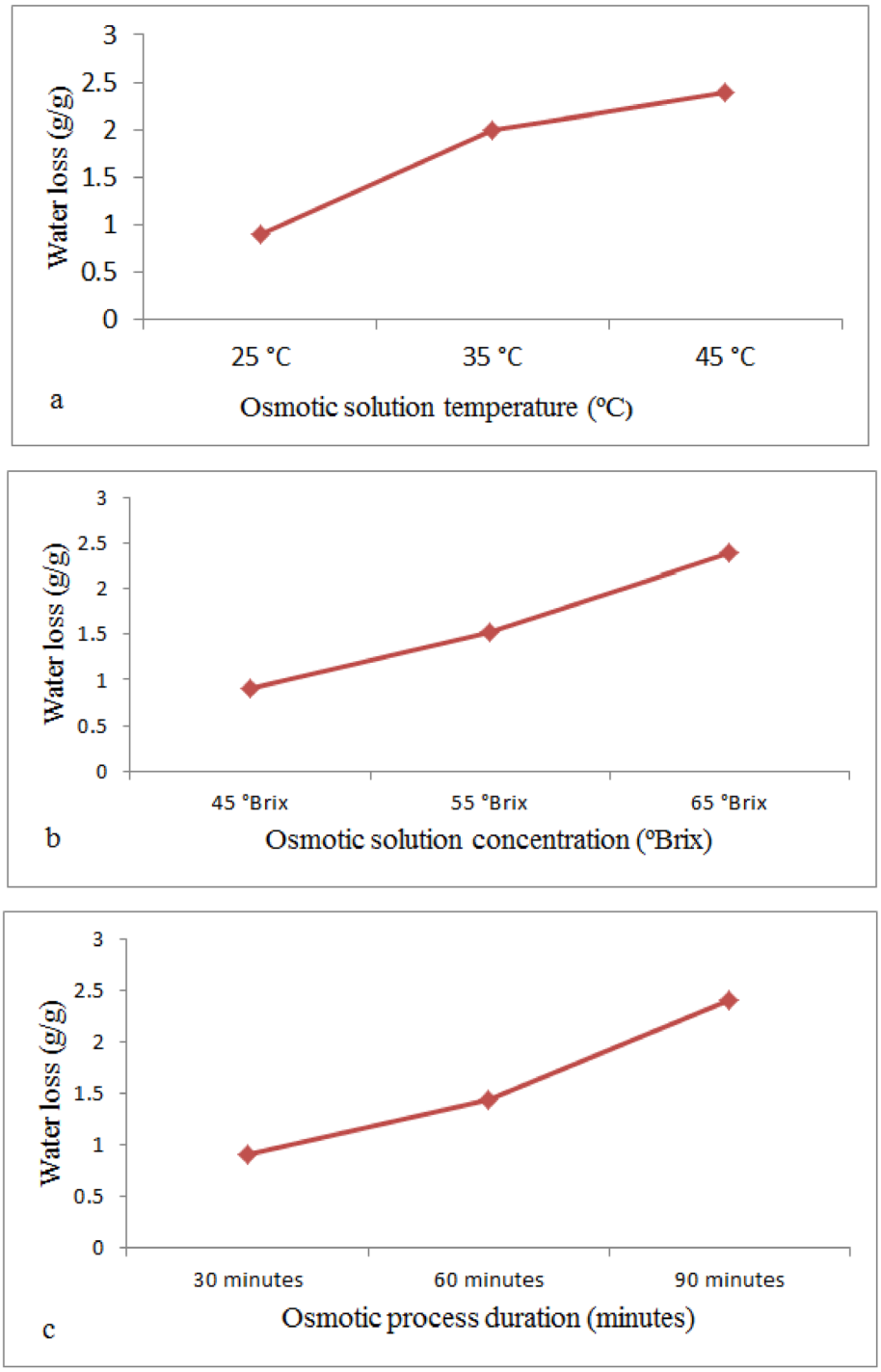


FIGURE 2 | Effect of process variables on water loss of apple: (a) Effect of osmotic solution temperature on water loss of apple, (b) Effect of osmotic solution concentration on water loss of apple, and (c) Effect of osmotic process duration on water loss of apple.

The observed increase in WL with higher concentrations and longer processing times is consistent with findings from prior studies. Osmotic dehydration, a process that removes water by immersing plant tissues in hypertonic solutions, relies heavily on solute concentration and time to drive WL from cells (Silva et al. 2014). High solute concentrations create a stronger osmotic pressure gradient, which accelerates water migration out of the tissue (Kowalska and Lenart 2001). Temperature also played a crucial role in enhancing WL during osmotic dehydration. Some studies showed that higher temperatures increase the diffusion coefficient of water, facilitating faster moisture removal (Torreggiani 1993). Dermesonlouoglou, Tsigkourakou, et al. (2016) similarly found that raising the temperature of the osmotic solution leads to greater WL, due to enhanced molecular activity and membrane permeability at elevated temperatures. As temperature rises, water molecules are more mobile, leading to an increased rate of water migration (Kowalska et al. 2017). Thus, the results in this study aligned well with the broader body of literature on osmotic dehydration of plant tissues, reinforcing the key roles of solute concentration, time, and temperature in WL during processing (Asghari et al. 2024).

3.2 | Solid Gain

The SG in all treated samples showed significant differences ($p \leq 0.05$) across the various process variables. The minimum SG of 0.12 g/g was recorded when the sample was treated at 25°C, 45°Bx, and a processing time of 90 min, while the maximum SG reached 0.41 g/g under the same concentration and temperature but with a shorter processing time of 30 min (see Figure 3a–c). These findings indicated that a longer osmotic process time, such as 60 min and 90 min, led to lower SG. This phenomenon can be attributed to the prolonged diffusion of osmotic solutes, allowing more soluble solids to dissolve into the osmotic solution (Yadav and Singh 2014). As the process continues, the osmotic pressure creates more significant concentration gradients and enhances the movement of water out of the plant tissue. Consequently, this led to excessive loss of solids, as the osmotic solutes diffuse into the solution, reducing the overall concentration within the sample mass (see Figure 3c).

The observed relationship between processing time and SG in osmotic dehydration is supported by recent literature. Most of these studies have consistently shown that increasing processing time can lead to a decrease in SG due to enhanced diffusion of osmotic solutes from the food matrix into the osmotic solution. For instance, Prakash et al. (2020) demonstrated that longer osmotic dehydration times resulted in a significant reduction in SG for apple slices, attributing this phenomenon to the extended diffusion of sugars and acids into the osmotic solution. Similarly, Zare et al. (2019) found that as processing time increased during the osmotic dehydration of strawberries, the SG decreased, correlating with greater leaching of soluble solids into the osmotic solution. Furthermore, Zheng et al. (2021) reported that prolonged osmotic treatment times can lead to cell shrinkage in fruits and vegetables, primarily due to the excessive loss of soluble solids and water migration. They highlighted that maintaining an optimal processing time is critical for preserving the structural integrity and quality of the food products. These studies collectively emphasize the idea that while osmotic dehydration is an effective method for reducing moisture content, careful consideration of processing time is essential to achieve a favorable balance between solid retention and the physical characteristics of the food.

3.3 | Drip Loss

DL typically refers to the liquid exuded from frozen and thawed food products, which is often a result of cell membrane damage caused by the formation of large ice crystals during freezing. When tissues are frozen without adequate protection, the intracellular and extracellular water forms large ice crystals, which puncture the cell walls and membranes, leading to higher DL upon thawing (Zhu et al. 2018; Yu et al. 2019). Figure 4 shows the effect of osmotic dehydration pretreatments and HPSF on the percentage DL of apple after thawing. As shown in Figure 4, the significant reduction in DL observed in the treated samples (0.33%) compared to the untreated frozen samples (4.36%) is a notable outcome of the osmotic pretreatment. This reduction, amounting to 93%, suggests that the application of osmotic pretreatment at specific operating parameters (65°Bx OSC, 35°C OST, and 30 min OPD) plays a crucial role in enhancing the structural integrity of the apple tissue during freezing and thawing processes. The reduction in DL in OD-treated samples can be attributed to the ability of the osmotic solute to alter the freezing dynamics. OD treatment influenced the size and distribution of ice crystals during freezing. Studies by Delgado and Rubiolo (2021) and Xu et al. (2022) demonstrated that applying OD lowers the amount of water in the fruit tissues, leading to smaller ice crystals during the freezing process. This contributes to the preservation of cell integrity, which is essential for reducing DL upon thawing.

Furthermore, Jan et al. (2021) reported that osmotic pretreatment increased the ability of fruits to retain moisture during thawing, further lowering DL. This aligns with the findings of 93% reduction in DL, as the combination of OD pretreatment and PMF likely helped to preserve water-binding compounds in the apple tissue, reducing the extent of moisture loss during the freezing process. The use of ODF at an optimal setting (at 65°Bx OSC, 35°C OST, 30 min OPD and 240 MPa HPSF) contributed to the balance of osmotic pressure, thereby preserving the microstructure of the apple tissues, reducing the cellular DL during thawing.

3.4 | Total Soluble Solids (TSS)

The observed increase in total soluble solids (TSS) in osmotic dehydrated apples (ranging from 16.70°Bx to 25.70°Bx) compared to untreated apples (12.1°Bx) at a significance level of $p \leq 0.05$ (as shown in Figure 5) underscores the effectiveness of osmotic dehydration as a pretreatment prior to freezing. This significant enhancement in TSS can be attributed to the infusion of soluble solids from the osmotic solution into the apple matrix, facilitated by the osmotic pressure gradient between the sample and the hypertonic solution of 65°Bx concentration. Recent studies have reinforced the benefits of high osmotic dehydration concentrations in enhancing the TSS of fruits. For instance, a study by Aroua et al. (2023) demonstrated that high osmotic

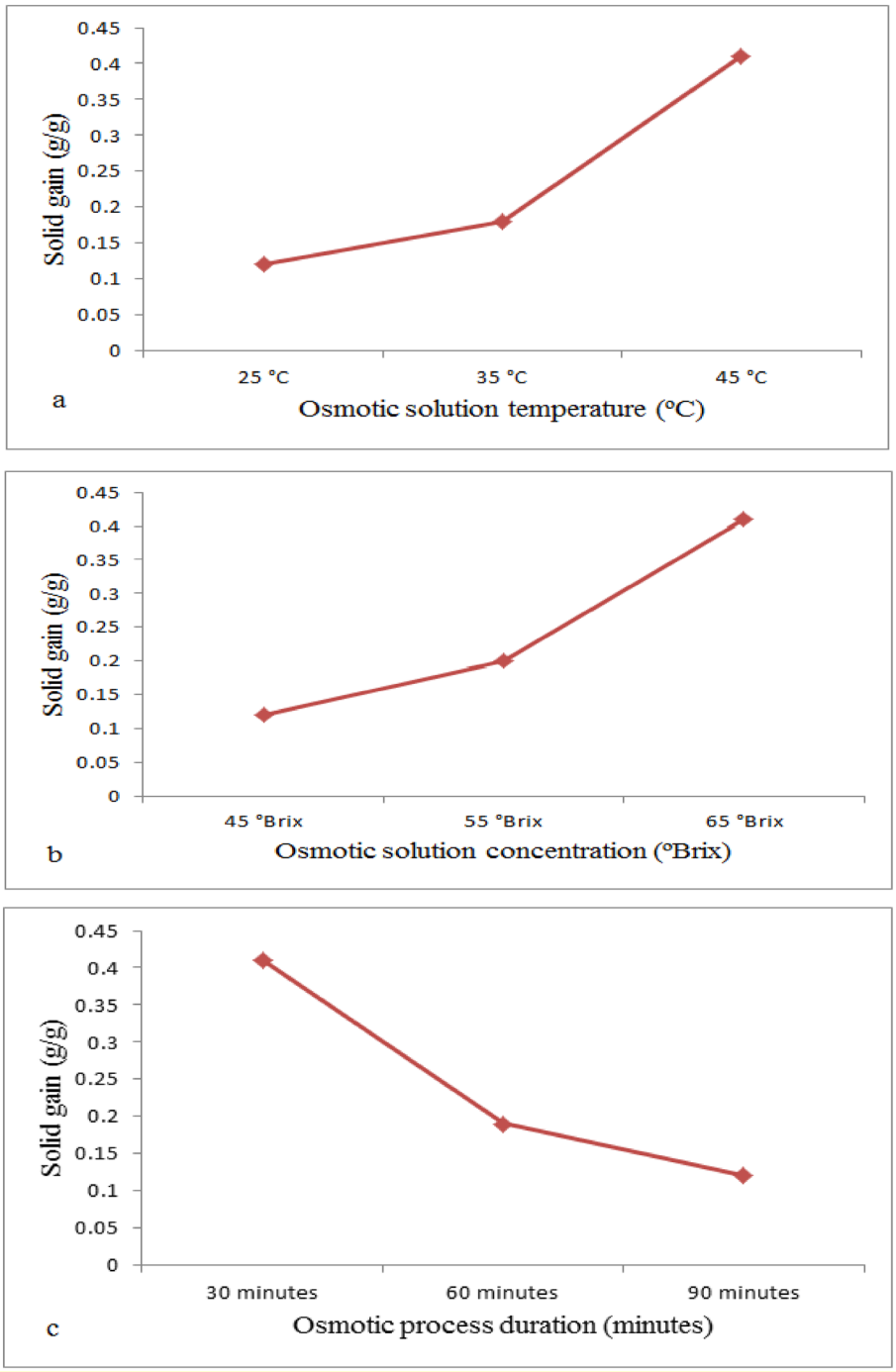
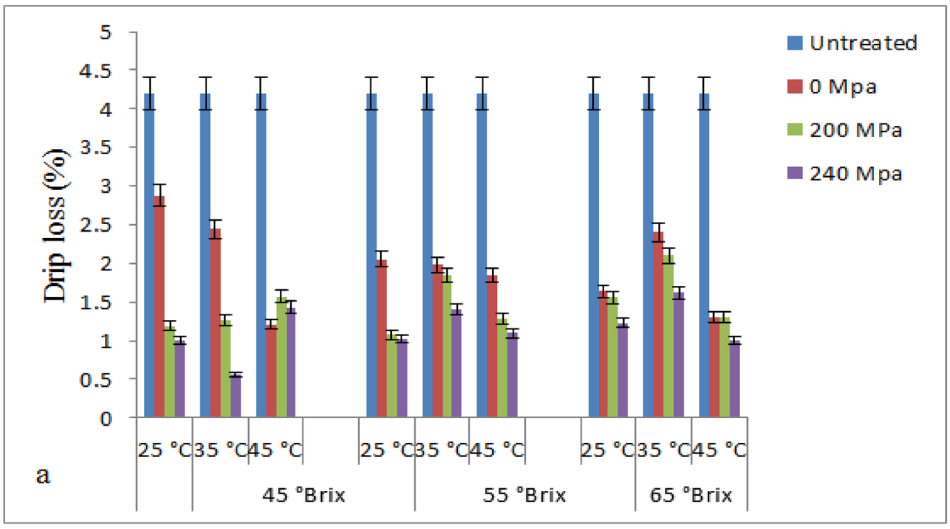


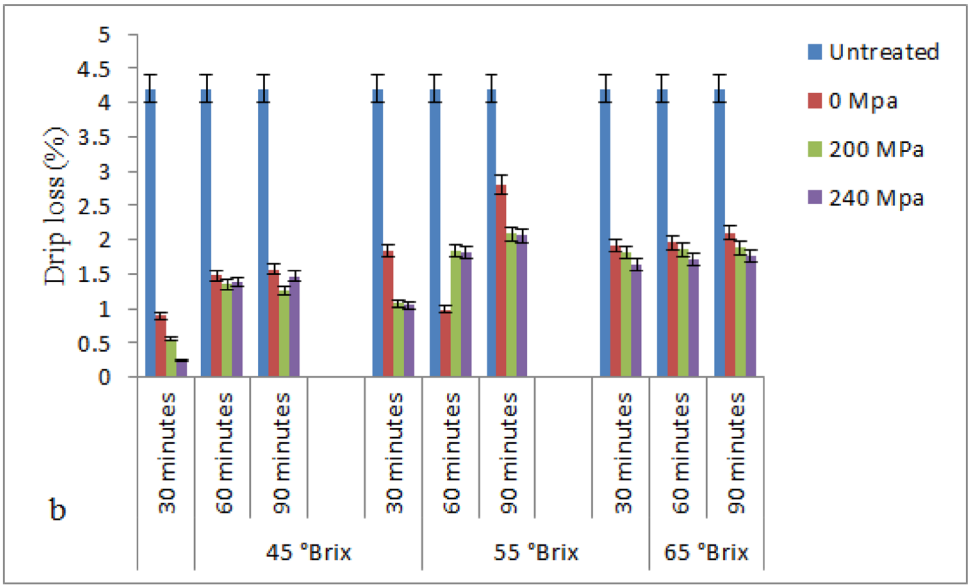
FIGURE 3 | Effect of process variables on solid gain of apple: (a) Effect of osmotic solution temperature on solid gain of apple, (b) Effect of osmotic solution concentration on solid gain of apple, and (c) Effect of osmotic process duration on solid gain of apple.

concentration up to 60°Bx did not only increase the TSS of apples but also improved their flavor profile and overall sensory quality. The researchers noted that the osmotic treatment leads to an increase in sugar concentration within the fruit, enhancing sweetness and palatability, which aligns with the findings of this study.

Moreover, Hasan et al. (2022) examined the effects of various osmotic agents, such as sugar and salt, on the TSS of mangoes and reported similar trends. They found that fruits treated with high osmotic concentration exhibited significantly higher TSS values, confirming the mechanism of solid impregnation through osmotic processes. This indicates that the choice of osmotic solution is crucial in determining the extent of solid uptake and the resultant quality of the fruit. According to Dumont et al. (2023), osmotic treatment assists in cell wall modification, leading to enhanced permeability and increased retention of soluble solids during subsequent freezing processes of fruits.

The significant elevation in TSS values observed in osmotic dehydrated apples reinforces the efficacy of this pretreatment method in enhancing the final quality of samples. The synergistic effects of osmotic dehydration, including solid impregnation





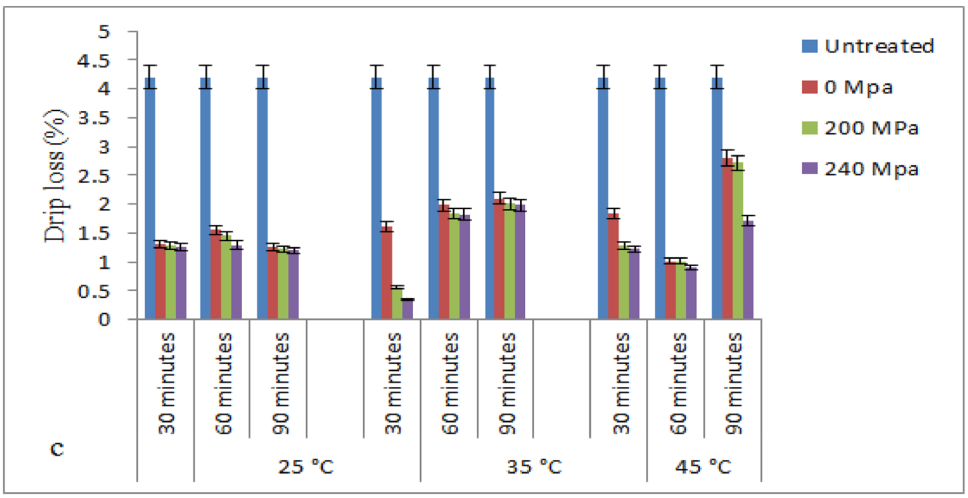


FIGURE 4 | Combined effect of osmotic dehydration pretreatments and high pressure shift freezing; (a) Effect of OSC, OST, and HPSF, (b) Effect of OSC, OPD, and HPSF, (c) Effect of OST, OPD, and HPSF on drip loss of apple slices.

and improved fruit structure, highlight its potential as a valuable technique in fruit processing, meriting further exploration in the context of other fruit varieties and different osmotic solutions. Table 1 show the analysis of variance (ANOVA) of the effect of process input variables on process output variables of frozen apple.

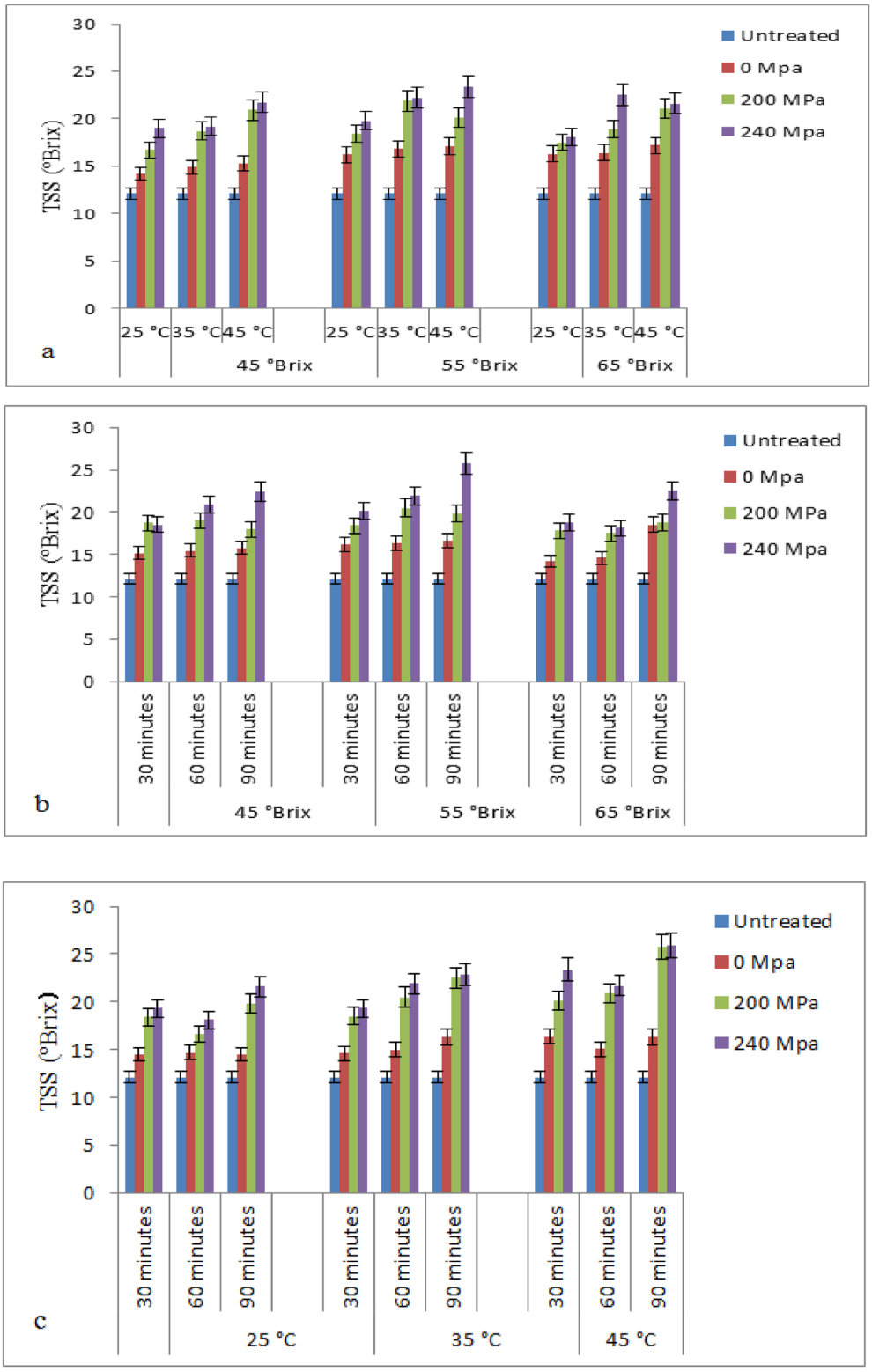


FIGURE 5 | Combined effect of osmotic dehydration pretreatments and high pressure shift freezing; (a) Effect of OSC, OST, and HPSF, (b) Effect of OSC, OPD, and HPSF, (c) Effect of OST, OPD, and HPSF on TSS of apple slices.

3.5 | Sensory Properties

Osmotic dehydration is a well-established technique in food processing that significantly improves the sensory properties of various fruits and vegetables. Figure 6 was given in codes to illustrate the effect of OSC coded as "A," OST coded as "B," OPD coded as "C," and HPSF coded as "D," on sensory properties including color, sweetness, flavor, texture, and overall acceptability of the samples. From Figure 6, samples treated with a concentration of 65°Bx (A3), a temperature of 35°C (B2), a duration of 30 min (C1) and frozen under 240 MPa (D2) HPSF exhibited the highest scores for all sensory properties, particularly for color and sweetness. This

TABLE 1 | Analysis of variance (ANOVA) of the effect of process input variables on process output variables of frozen apple.

Process inputs					Interaction									
Process outputs	**A**	**B**	**C**	**D**	**AB**	**AC**	**BC**	**AD**	**BD**	**CD**	**ABC**	**ABD**	**ACD**	**BCD**
Water loss (g/g)	0.0000[a]	0.0377[a]	0.0159[a]		0.8762	0.0205[a]	0.8202		0.9922		0.0000[a]			
Solid gain (g/g)	0.0507[a]	0.0084[a]	0.0970		0.0159[a]	0.0382[a]	0.0117[a]		0.0016[a]		0.0000[a]			
Drip loss (%)	0.0000[a]	0.0084[a]	0.0997	0.0150[a]	0.2972	0.0000[a]	0.0923	0.4147	0.0002[a]	0.0016[a]	0.0001[a]	0.0020	0.0835	0.0000[a]
TSS (°Bx)	0.3949	0.0001[a]	0.0000[a]	0.0035[a]	0.3652	0.8627	0.0419[a]	0.0039[a]	0.2515	0.5708	0.0000[a]	0.1266	0.0006[a]	0.0063[a]

[a]Significantly different at $p \leq 0.05$ (A = OSC; B = OST; C = OPD; D = HPSF).

result can be attributed to the effective concentration gradient created during the osmotic dehydration process, which facilitated the infusion of solute into the apple tissue. The high solute content resulted in more vibrant color retention, sweetness enhancement, and overall improved sensory appeal. The lower temperature and moderate duration ensured that the natural texture and volatile flavor compounds were not excessively altered or degraded. Color is one of the most critical attributes in consumer acceptance, and it is often closely linked to the perception of freshness and quality. The superior color in the samples treated with 65°Bx, 35°C, and 30 min can be attributed to the protective role that the sucrose solution played in preserving the natural pigments in the apple tissues that were frozen under 240 MPa HPSF. This observation is supported by previous studies, such as the work of Santagapita et al. (2018), which demonstrated that osmotic dehydration can effectively preserve the visual appeal of fruits by stabilizing their anthocyanin and carotenoid pigments, especially when processed under optimal conditions of solute concentration and time. In terms of sweetness, the osmotic dehydration process introduced sucrose into the apple matrix, which enhanced the sweet flavor of the sample. Torres et al. (2020) reported that the higher the concentration of the osmotic solution, the greater the transfer of sugar into the food product. This explains why the sample treated at 65°Bx achieved the highest score in sweetness, as it had the highest solute infusion.

More so, the flavor that is closely linked to both the retention of natural aromatic compounds and the enhancement provided by the osmotic solutes, the moderate temperature (35°C) helped in retaining the natural volatile compounds responsible for the fruit's flavor, as excessive heat can result in the loss of these volatile components. Izli et al. (2022) demonstrated that osmotic dehydration at moderate temperatures is more effective in preserving the natural flavor profiles of fruits compared to higher temperatures, where flavor compounds tend to degrade.

The texture of the samples was also positively influenced by osmotic dehydration. The introduction of sucrose solute helped in maintaining cell turgidity, leading to firmer and more desirable textures. Moreover, the dehydration process (at 65°Bx, 35°C, and 30 min) removed water content faster, preventing excessive softening or mushiness that occurred in untreated samples after thawing. This result is in agreement with Fernandes et al. (2019), who reported that osmotic dehydration significantly improved the firmness of fruits by promoting structural integrity through solute absorption and partial dehydration.

Overall, the acceptability of the samples treated under 65°Bx, 35°C, and 30 min was the highest, indicating that the panelists (consumers) preferred the samples that exhibited a balance of vibrant color, enhanced sweetness, preserved flavor, and improved texture. These findings are consistent with the conclusions of Giovanelli et al. (2021), who highlighted the positive impact of osmotic dehydration on the sensory quality of fruits, especially when processed under optimal conditions of time, temperature, and solute concentration.

In summary, the osmotic dehydration treatment gave the highest acceptable sensory properties of the apple. The enhanced sensory attributes can be largely attributed to the solute uptake and WL dynamics that preserved color, intensified sweetness,

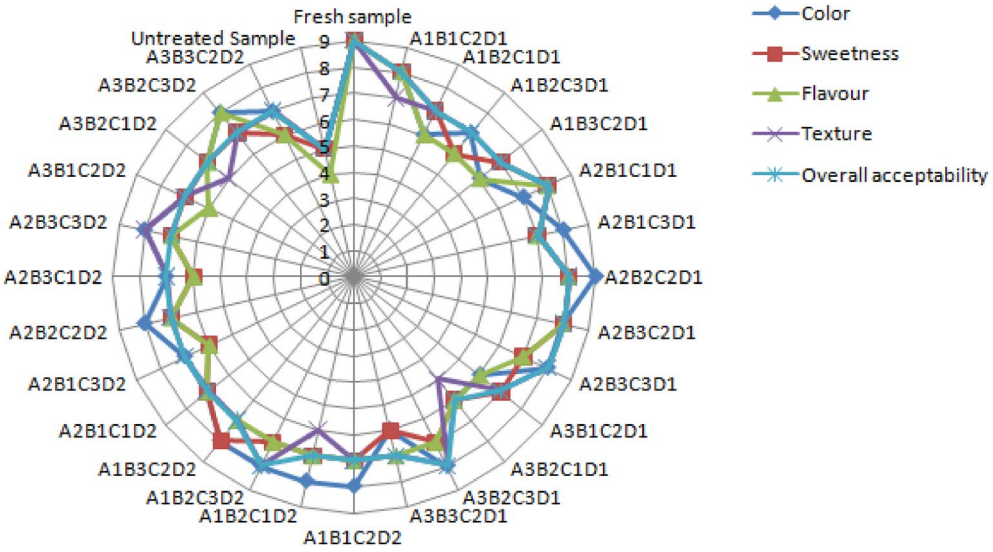


FIGURE 6 | Effect of process input variables on sensory properties.

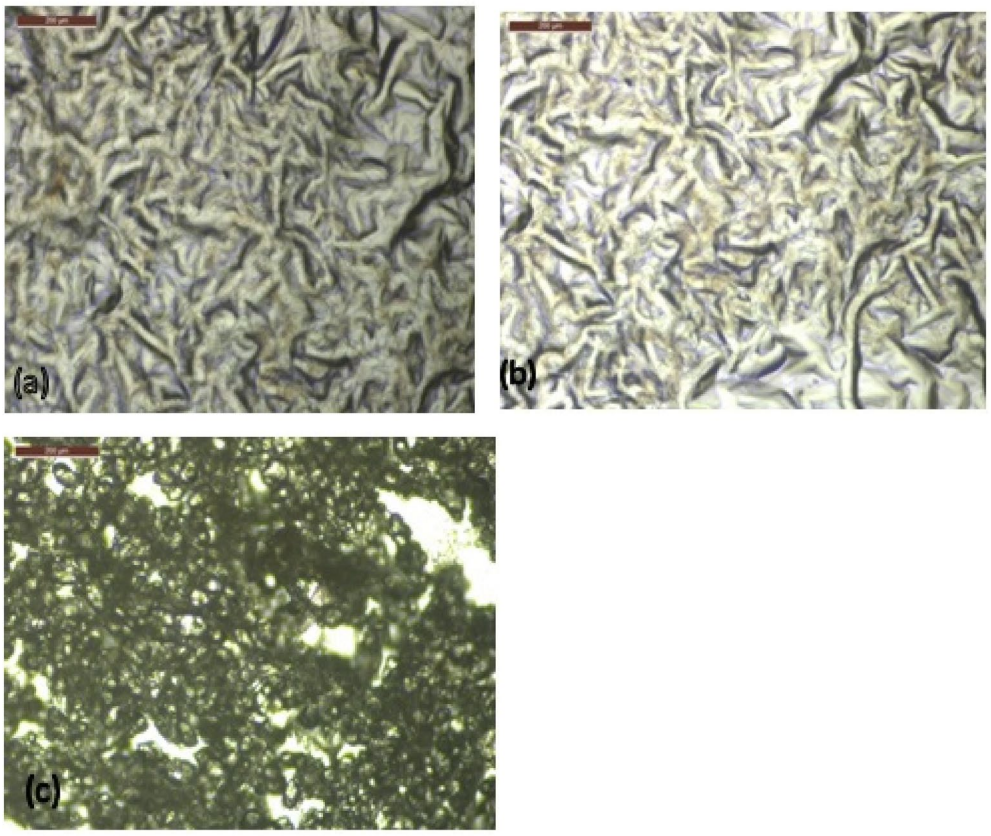


FIGURE 7 | Effect of osmotic dehydrofreezing on morphological changes of apple (a) fresh sample; (b) maximally treated frozen sample; (c) untreated frozen sample. Scale bar = 500 μm.

retained flavor, and improved texture—all of which contributed to higher consumer acceptability.

3.6 | Microstructure Observation

A sequential organization of plant tissues at the microscopic level plays a crucial role in facilitating plant moisture movement, and it is also a basic channel for heat and mass transfer during the ODF process (Alabi et al. 2020). The microstructure changes, according to the optimized ODF of the apple slices, are shown in Figure 7. Figure 7a–c showed the microscopic image of fresh, treated, and untreated samples, respectively. The microscopic analysis showed that the apple microstructure undergoes changes from smooth surfaces to degradation of the cell outer layer. Fresh microstructure, as shown in Figure 7a, displayed unaltered and linked cell structure closely to the treated frozen sample. Slight cell breakage marked with rupture characterized the untreated frozen sample

(see Figure 7c). However, the damage to the treated-frozen cell was minimized due to a low freezing load and the integration of cryoprotectants (see Figure 7b). The result was in agreement with Lewicki and Porzecka-Pawlak (2005) who reported that the integration of solutes via OD reduced freezing damage to the apple structure. Moreover, with rigid tissue, higher HPSF (at 240 MPa) increased the freezing point and caused large openings of apple stomata, leading to faster heat and mass transfer with preserved microstructure. The image texture analysis that quantifies the freezing effect on cellular structure and ice crystal size has been determined on apple tissue (Chassagne-Berces et al. 2009). It was reported that freezing at −20°C and after immersion in liquid nitrogen induced cell membrane breakage, resulting in cell wall collapse and tissue breakage, respectively, which accounted for the mechanical behavior of samples, showing that the microstructure preservation is critical during the freezing process.

By using direct methods such as cryo-scanning electron microscopy (C-SEM), X-ray microtomography, cryo-confocal laser scanning microscopy (CCLSM), and cold stage fluorescence microscopy, and indirect methods like scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray tomography, confocal laser scanning (CLSM) imaging, hyperspectral imaging, nuclear magnetic resonance (NMR) spectroscopy, and magnetic resonance imaging (MRI), further microstructure examinations of frozen fruits and vegetables have been carried out and discussed (Jha et al. 2018).

4 | Conclusion

The effect of osmotic dehydration-assisted freezing at different pressure rates on mass transfer, quality, sensory properties, and microstructure of treated and untreated apple was investigated. The apple slices were pretreated in sucrose solution concentration at 45°Bx, 55°Bx, and 65°Bx, temperatures of 25°C, 35°C, and 45°C, and durations of 30, 60, and 90 min, before freezing at 200 and 240 MPa using HPSF. The results showed that the optimally pretreated (at 65°Bx, 35°C, 30 min) samples that were frozen under 240 MPa exhibited the most favorable outcomes, including a 93% reduction in DL, higher SG, and enhanced total soluble solids when compared to untreated frozen samples. Sensory evaluation confirmed the superiority of the osmotically dehydrated frozen samples in terms of color, sweetness, flavor, texture, and overall acceptability. In addition, maximally treated (at 65°Bx, 35°C, and 30 min) samples exhibited well-preserved microstructure when compared to the untreated ones. These findings revealed the potential of osmotic dehydration pretreatment and HPSF to improve the quality and storage stability of frozen apple.

Author Contributions

K.P.A. conceived and developed the HPSF device, carried out the experiment and performed data analysis, and wrote the initial version. A.F. performed data analysis. K.R.A. conducted editing. L.O.G. acquired experimental materials, journals, books, and conference proceedings.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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