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ORIGINAL ARTICLE

Mass transfer kinetics and process optimization of osmotic dehydration of Kinnow mandarin (*Citrus reticulata*) peel

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Abstract

Kinnow mandarin (*Citrus reticulata*) peel, an agricultural solid waste of the Kinnow juice processing industry, was studied to understand the mass transfer kinetics during osmotic dehydration and its process optimization. The experiments were conducted in sucrose (40, 50, and 60° Brix) at different temperatures of 40, 50, and 60°C and process duration of 0–240 min. The Central Composite Design was used for the optimization of the osmotic dehydration process with the variables, such as blanching time (3–6 min), solute concentration (40–60° Brix), process temperature (40–60°C), and process duration (120–150 min). Increased water loss (28.70 g/100 g) and solid gain (12.90 g/100 g) were observed at 60° Brix and 50°C in 240 min. The Penetration model was the best-fitted model for water loss and solute gain. The osmotic dehydration process at 60° Brix and 48°C for 150 min with blanching (3.60 min) yielded water loss (32.40 g/100 g), solute gain (14.60 g/100 g), ascorbic acid (17.50 mg/100 g), and overall acceptability (6.50). Overall, the findings concluded that the understanding of process parameters can be used as the basis for the sustainable valorization of Kinnow peel using osmotic dehydration.

Practical applications

Currently, valorization of agri-food waste becomes a major challenge and thus we studied to understand the mass transfer kinetics during the osmotic dehydration and its process optimization of Kinnow mandarin (*Citrus reticulata*) peel. The findings suggested that the optimization of osmotic dehydration process parameters and kinetic modeling may be useful for the valorization of Kinnow peel in the development of food products.

1 | INTRODUCTION

Kinnow mandarin (*Citrus reticulata*) is a hybrid citrus cultivar of 'King' and 'Willow leaf' mandarin and received much scientific attention in terms of nutrition, health benefits, and economic value (Singla, Panesar, et al., 2021). Kinnow is the major fruit crop predominantly grown in the northern region of India and an important biological resource to be comprehensively utilized. Globally, the citrus industry has developed in more than 140 countries with an annual output of >146 million tons (Chen et al., 2019) and contributes >18% of total fruit production in the world. Most Kinnow fruits were mainly used for juice production and its processing. Kinnow peel and pulp residues are the most significant by-products generated from Kinnow juice manufacturing process, which accounts for 55–60% of the original fruit weight (Singla, Singh, et al., 2021). This is the major concern associated with the disposal of Kinnow juice processing waste that led to various environmental hazards due to its unpleasant and unhygienic nature. Thus, sustainable approaches to utilize or convert this "waste" into value-added products should be necessary through circular engineering models.

A plethora of research has been conducted to investigate the valorization approaches of Kinnow peel waste, such as extraction of functional compounds by green novel strategies (Putnik et al., 2017), production of biosugars (Cho et al., 2020), and development of peel paste food products, such as jam, cookies, and madeleines (Tsurunaga et al., 2021). Nonetheless, these methods for processing of Kinnow peel are relatively high cost and require the use of specific chemicals. Thus, finding alternative technologies for the efficient and long-term sustainable management of Kinnow by-products is a crucial component in the Kinnow juice processing industry. One of the simplest and cheaper methods to utilize the overall Kinnow peel is the mechanistic understanding and optimization of process parameters for the valorization of Kinnow peel waste by energy-saving methods, such as osmotic dehydration.

Osmotic dehydration is one of the most reliable energy-saving methods for the partial removal of water from food products by immersion in a hypertonic solution to improve the quality attributes of food products (Tsironi & Taoukis, 2019). This technology is simple, affordable, and uses low temperature to preserve the nutritional, quality, and mechanical properties of foods. However, several parameters, such as solute concentration, temperature, time, pre-treatment, solute to sample ratio, nature, and size of the sample may influence the quality attributes of the product (Brochier et al., 2019). To overcome these problems, engineering methods (process optimization and control) are necessary that describe the mechanistic behavior of osmotic dehydration and mass transfer kinetics to study the effects of process variables and optimization (Assis et al., 2017). To date, only a limited number of studies have been identified on the utilization of Kinnow peel through green extraction and food production development (Putnik et al., 2017; Tsurunaga et al., 2021). However, the complete use of Kinnow peel through long-term energy-saving methods coupled with optimization techniques has not yet been investigated. Hence, we hypothesized that the osmotic dehydration coupled with mathematical modeling can be a sustainable approach for the long-term valorization of Kinnow peel and development of value-added food products.

Therefore, the present study aimed to study mass transfer kinetics during the osmotic dehydration of Kinnow peel and to optimize the Kinnow peel osmotic dehydration process. The findings are expected to provide optimized parameters that can be used to predict the mass transfer kinetics of osmotic dehydration at different process conditions and serve as the basis for the sustainable valorization of Kinnow peel using osmotic dehydration.

2 | MATERIALS AND METHODS

2.1 | Sample collection and preparation

Kinnow mandarin (*Citrus reticulate* Blanco) fresh peel with a thickness of 0.60 cm was procured from the local commercial market of Sangrur, Punjab, India and transported to the Department of Food Engineering and Technology, Sant Longowal Institute of Engineering Technology, Longowal, India. The moisture content of the peel was found to be 75 ± 1% (w.b.). The peel samples were manually cut into sheets (2 × 2 cm^2) using a food-grade knife and blanched for 3 min (Mann & Aggarwal, 2013).

2.2 | Osmotic dehydration of Kinnow peel

Osmotic dehydration was performed in sucrose osmotic solution at different concentrations (40, 50, and 60° Brix) with different solution temperatures of 40, 50, and 60°C for 0–240 min. Peel to solution ratio was maintained at 1:5 (w/v). The temperature of the osmotic solution was maintained by a thermostatized water bath (LE110, GPC Medical Ltd., New Delhi, India). Agitation (50 rpm) was performed to reduce the mass transfer resistance at the surface of the fruit and to mix thoroughly (Moreira et al., 2007; Tortoe, 2010). Approximately 150 ml stain-less steel food-grade containers were filled with osmotic solution and kept in a hot water bath until they attained the desired solution temperature. Then, the Kinnow peel (10 g) was placed into the solution.

2.3 | Mass transfer kinetics

The samples were withdrawn after a regular interval between 0–240 min and were immediately rinsed with tap running water to remove the solute adhered to the sample surface. Free surface water was removed by absorbent paper and placed in the pre-weighed Petri dish for the determination of the dry matter by the oven-drying method. The water loss (WL) and solute gain (SG) were calculated according to the following Equations 1 and 2 as described by Islam et al. (2019).

$$\text{Water loss (g/100 g sample)} = \left[\frac{\text{Weight reduction (g)} + \text{solute gain (g)}}{\text{Initial weight of peel } (W_0, \text{g})} \times 100\right] \quad (1)$$

$$\text{Solute gain (g/100 g sample)} = \left[\left(\frac{S_t - S_0}{W_0\,(g)}\right) \times 100\right]. \quad (2)$$

Here, weight reduction (g) was determined by initial weight of peel before (W_0), while solute gain (g) was determined by initial dry matter of peel before (S_0) and after osmotic dehydration at time t (S_t).

2.4 | Mathematical modeling

The six mathematical models were validated by the non-linear regression technique to predict the kinetics of moisture ratio, SG ratio, WL, and SG of the osmotic dehydration process (Table 1). The validity of Magee, Peleg, and Penetration models was used to predict WL and SG. Power law was validated for SG ratio, whereas Page and Newton models were validated for moisture ratio.

TABLE 1 Selected empirical models for osmotic dehydration[1]

Model	Equation
Page	$MR = \frac{M_t - M_e}{M_o - M_e} = \exp(-kt^N)$
Newton	$MR = \frac{M_t - M_e}{M_o - M_e} = (\exp - kt)$
Power law	$MR = \frac{M_t - M_e}{M_o - M_e}$ or $SGR = \frac{C_t - C_e}{C_o - C_e} = kt^N$
Penetration	$WL \text{ or } SG = k\sqrt{t}$
Peleg	$WL \text{ or } SG = K_1 + K_{2\,t}$
Magee	$WL \text{ or } SG = a + Kt^{1/2}$

[1]MR represents the moisture ratio, SGR, solute gain ratio; and WL, water loss. M_o is the initial moisture content, M_t is the moisture at any time t during drying, M_e is the equilibrium moisture content, k is the drying rate constant, and *N*, *c*, *a*, and *b* are parameters in empirical models.

2.5 | Optimization of osmo-convective dehydration process

The Central Composite Design with four variables at five levels was used for the optimization of the osmotic dehydration process (Supporting Information Table S1) using Design-Expert version 7.01 (State-Ease Inc., Minneapolis, USA). The independent variables were blanching time (3–6 min), solute concentration (40–60° Brix), process temperature (40–60°C), and process duration (120–150 min) (Mann & Aggarwal, 2013). The fruit to solution ratio was kept at 1:5 (w/w) during all the experiments. The experiments were conducted as described above and the dried sample was cooled to room temperature and stored in an air-tight polycarbonate vacuum desiccator.

2.6 | Ascorbic acid content

The ascorbic acid content was measured by the visual titration method (Gao et al., 2020) with modifications. Samples were blended with 3% HPO_3 and make up to 10 ml with 2% HCl and then filtered. After filtration, sample (5 ml) was thoroughly mixed with 0.50 ml potassium iodide (10 g/L), 2 ml of starch (5 g/L), and 2.50 ml double distilled water. The aliquot (10 ml) was titrated against potassium iodate (1 mM/L) until it turned to faint blue color for 15 s. The ascorbic acid content was calculated according to Equation (3) and expressed as mg/100 g sample,

$$\text{Ascorbic acid}\left(\frac{\text{mg}}{100\,\text{g}}\right) = \left[\left(\frac{\text{Titer value} \times K_{AA} \times \text{volume of sample}}{\text{Amount of aliquot} \times \text{sample weight}} \times 100\right)\right], \quad (3)$$

K_{AA} = mass of ascorbic acid that 1 ml of 1 mM/L potassium iodate solution equal to, 0.10 mg.

2.7 | Overall acceptability

Overall acceptability of samples was evaluated by 10 trained voluntary panel members (aged between 25–35 years with equal number of males and females), Department of Food Engineering & Technology, Sant Longowal Institute of Engineering and Technology, Longowal, Punjab, India, based on 9-point hedonic scale (9 = like extremely and 1 = dislike extremely) according to Pellizzeri et al. (2020). The dried samples (coded with 3-digit numbers) were randomly provided to panelists and requested to rate overall acceptability. The results were collected and calculated using the mean scores.

2.8 | Optimization and statistical analysis

The second order polynomial function was used to fit dependent variable according to Equation 4.

$$Y_k = \left[B_{k0} + \sum_{i=1}^{n} B_{ki}X_i + \sum_{i=1}^{n} B_{kii}X_i^1 + \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} B_{kij}X_iX_j + e\right], \quad (4)$$

where Y_k = response variable; Y_1 = water loss (g/100 g sample); Y_2 = solute gain (g/100 g sample); Y_3 = ascorbic acid (mg/100 g sample); Y_4 = overall acceptability; X_i represent the coded independent variables (X_1 = blanching time, X_2 = solution concentration, X_3 = process duration, and X_4 = process temperature); where B_{ko} was the value of the fitted response at the center point of the design, i.e., point (0, 0, 0), B_{ki}, B_{kii}, and B_{kij} were the linear, quadratic, and cross-product regression coefficients, respectively, and the e is relative error.

The optimized process variables, such as osmotic solution concentration, temperature, blanching time, and process duration may yield high WL, SG, and ascorbic acid, and overall acceptability of dehydrated Kinnow peel. Response graphs and contour plots were constructed using the Design-Expert version 7.01. All the experiments were conducted with triple replicates and were presented or plotted as mean values. Optimization of osmotic dehydration process was performed with Design-Expert version 7.01 (State-Ease Inc., Minneapolis, USA). The model parameters, coefficient of determination (R^2), chi-square (χ^2), the average percentage error (E %), and root-mean-square errors (RMSE) were determined using CurveExpert 1.4 (Hyams Development, USA).

3 | RESULTS AND DISCUSSION

3.1 | Mass transfer kinetics

3.1.1 | Effect of immersion time and solute concentration on water loss and solute gain

The total amount of water loss (WL) and solute gain (SG) increased with increase of time at all different concentrations and temperatures (Figure 1A). The total WL and SG values were 28.70 g /100 g and 12.90 g/100 g, respectively, at 60° Brix and 50°C in 240 min. Out of the total WL and SG in 4 hr, 20.77 g/100 g as well as 8.71 g/100 g of WL and SG, respectively, were observed during initial first hour. Therefore, 72.37% of the total value of WL was reported during the

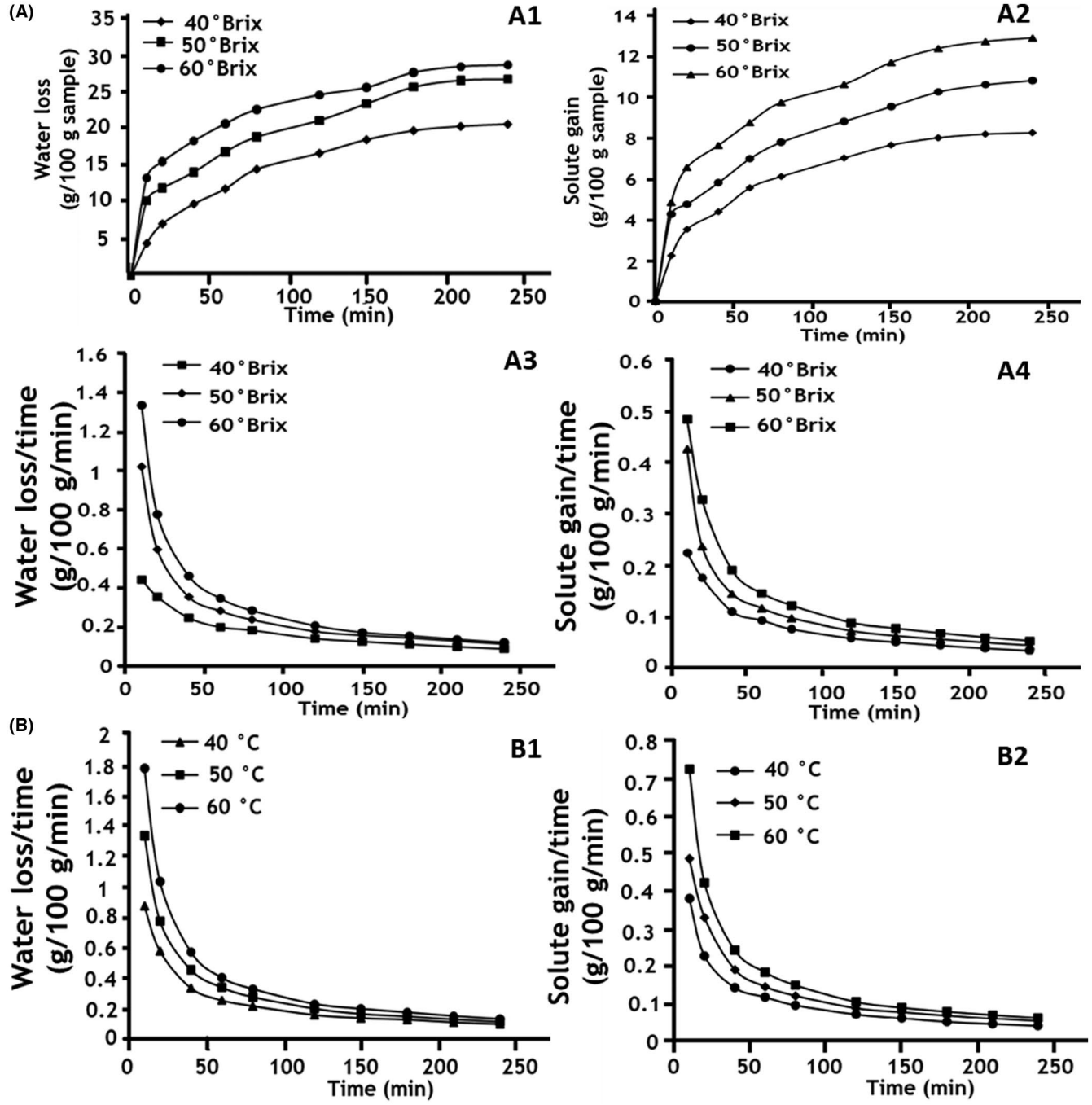

FIGURE 1 Water loss and solute gain as affected by solute concentration, process time, and temperature. (A) effect of immersion time and solute concentration on water loss and solute gain at 50°C: Water loss (A1), solute gain (A2), rate of water loss (A3), and rate of solute gain (A4); (B) effect of osmotic solution temperature and immersion time at 60° Brix: rate of water loss (B1) and rate of solute loss (B2)

initial first hour of the process. Likewise, 67.52% of the total value of SG was noticed in the first hour of the process, indicating that the 27.63% WL and 32.48% SG were reported during the last three hours of osmotic dehydration. Therefore, it was clear from the above findings that WL and SG were rapid in the initial process and then decreased after 1 hr. Similar findings were observed by Cortellino et al. (2011), in which authors reported the increase in WL and SG within the first hour of osmotic dehydration of citrus peels. The high WL and SG were attributed to the internal structure of pith and intercellular spaces. Thus, this process is an efficient way to limit solute uptake and obtain a large WL and SG ratio.

On the other hand, an increase in WL and SG was observed with an increase of osmotic solution concentration at all the process temperatures (Figure 1A). The values of WL at 60, 50, and 40° Brix solution concentration at 50°C after 240 min were 28.70, 26.80, and 20.60 g/100 g, respectively. Similarly, the values of SG at 60, 50, and 40° Brix solution concentration at 50°C after 240 min were 12.90, 10.80, and 8.20 g/100 g, respectively.

Therefore, an increase in solution concentration resulted in an increase in WL and SG. Comparable findings were observed in watermelon slabs and apricots when immersed in different solute concentrations from 40, 50, and 60° Brix (Falade et al., 2007; İspir & Toğrul, 2009). The increase in SG and WL with the solute concentration might be due to the high concentration difference between the fruit sample and osmotic solution. Two independent studies investigated by Azoubel and Elizabeth (2004) and Phisut (2012) reported that the increased solution concentration resulted in the increase in the osmotic pressure gradients and higher WL. The findings also reported a higher rate of WL compared to SG, which may be associated with a higher molecular weight of sucrose (342.30 g/mol) than water (18.01 g/mol). Thus, the water molecules can easily move out of the sample, while sucrose molecules enter at lower rate. Similar results were also reported for sweet potato (Antonio et al., 2008). Low molecular weight osmotic agents may penetrate easily into the fruit cells compared to high molecular weight osmotic agents (Phisut, 2012).

The rates of WL and SG during osmotic dehydration are illustrated in Figure 1B. The decrease in WL and SG rates might be related to time. The gradual decrease in water outflow and solid inflow was that the system reached a state of dynamic equilibrium of molecule transfer (Harati et al., 2011).

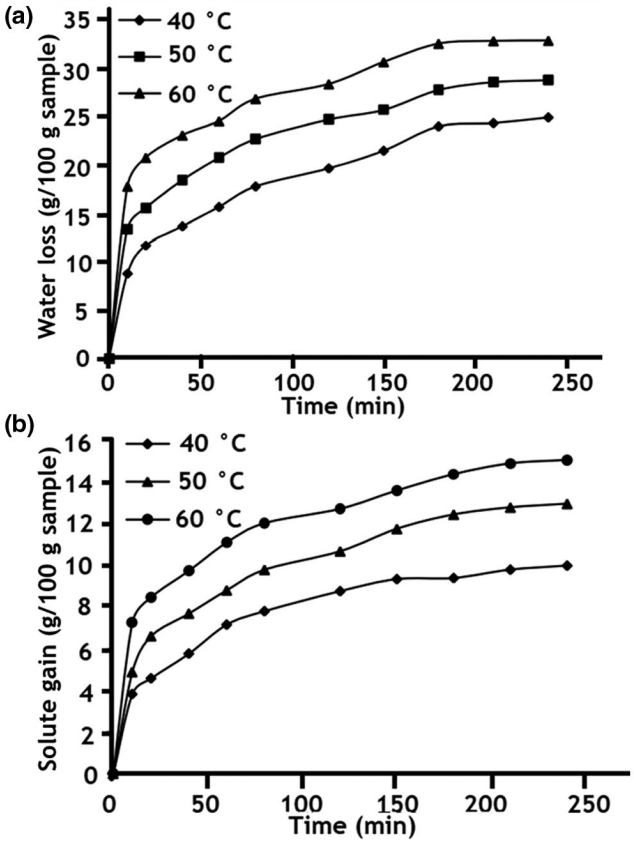

FIGURE 2 Effect of osmotic solution temperature at 60° Brix. (a) water loss and (b) solute gain

3.1.2 | Effect of osmotic solution temperature on water loss and solute gain

An increase in WL and SG was observed with the increase in temperature for all concentrations of the solution (Figure 2). Higher values of WL and SG were observed at 60°C than 50°C and 40°C. Values for SG and WL at 60°C and 50° Brix after 240 min were 15 g/100 g and 32.80 g/100 g, respectively; while in case of 40°C at 50° Brix, values for SG and WL were decreased to 9.90 g/100 g and 24.90 g/100 g, respectively. The result demonstrated that the WL increased over the time, which was influenced by a higher temperature. This might be contributed to a higher temperature that increased the WL through cell plasticization and swelling in the membrane. This further allowed the water into samples due to the high mass transfer rate and lower viscosity of osmotic solution at higher temperatures (Phisut, 2012). Devic et al. (2010) investigated the mass transfer kinetics and the effect of temperature at 45°C and 60°C using apple cultivars. Another study focused on the effect of temperature on WL and SG of watermelon slabs immersed into sucrose solution at 50° Brix (Falade et al., 2007). In both the studies, authors reported an increase in WL and negligible change in SG as affected by temperature.

3.2 | Validation of empirical models for osmotic dehydration

In all osmotic dehydration experiments, the best suitable models were selected based on higher coefficient of determination (R^2), root-mean-square error (RMSE), average percentage error (E %), and lower chi-square (χ^2).

3.2.1 | Water loss

The Penetration model showed the best fit for the WL during the osmotic dehydration with accepted statistical values. The values of WL during osmosis at different concentrations and temperatures over time were determined experimentally and predicted as shown in Figure 3a. The Penetration model reported a good statistical fit for WL during osmotic dehydration with higher R^2 > 0.96, RMSE (0.574), and χ^2 (0.367) (Supporting Information Table S2), which were comparatively lower than other model values. The results agreed with the findings concluded for the osmotic dehydration of ripe papaya (Islam et al., 2019). This fact also confirmed that the model equation is a good representation of the process and can be used for process development purposes (Manivannan & Rajasimman, 2011). In contrast to our findings, Azarpazhooh and Ramaswamy (2009) recommended Peleg model was the best fit for WL in osmotic dehydration, but our findings showed higher RMSE and χ^2 values for Peleg model (Supporting Information Table S3), which could be related to process parameters and experimental conditions used in the study.

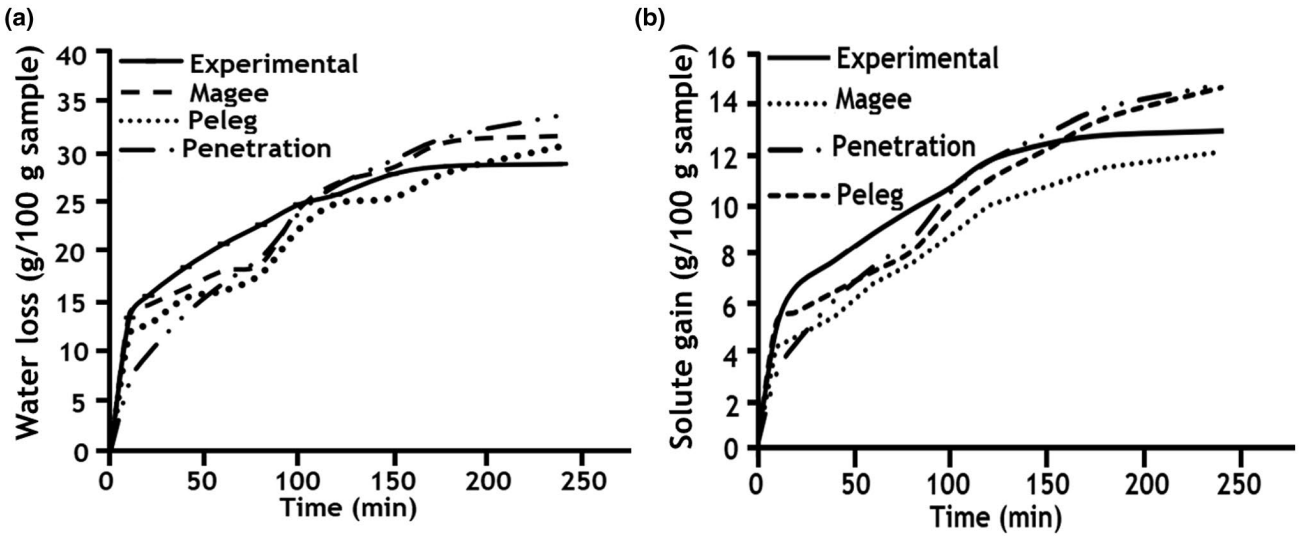

FIGURE 3 Comparison of experimental and predicted values using the best fitting models at 60° Brix and 50°C. (a) water loss and (b) solute gain

3.2.2 | Solute gain

The SG during osmosis at different concentrations and temperatures over time were determined experimentally and predicted (Figure 3b). The Penetration model reported the lowest goodness of fit between predicted and observed data with higher R^2 of 0.96 and lower RMSE (0.548) and χ^2 (0.334) as shown in Supporting Information Table S2. These higher values of R^2 and lower values of the goodness of fit of Penetration model might be ascribed to the less proportion of the variance in the experimental and predicted data. Likewise, Page (R^2 => 0.98, $\chi^2 = 0.001$) and Power law (R^2 => 0.99, $\chi^2 = 0.001$) models were the best fitted for moisture ratio and SG ratio, respectively (Supporting Information Tables S4 and S5). It may be concluded from the kinetic study of osmotic dehydration that the rate of WL and SG increased with an increase in osmotic parameters.

3.3 | Optimization of osmotic dehydration process

3.3.1 | Water loss

The model *F*, R^2, adjusted R^2, and adequate precision values were 67.82, 0.9840, and 0.9690, respectively, indicating the significance of the model ($p < .05$) as shown in Supporting Information Table S6. The fitted model for WL of process variables after eliminating the insignificant terms was shown in Equation 5,

$$\begin{aligned}\text{Water loss} = {} & 23.53 + 3.63X_1 + 3.37\times X_2 + 1.90\times X_3 + 0.49\times X_4 + 0.75\times X_1\times X_2 \\ & + 0.38\times X_1\times X_3 - 0.038\times X_1\times X_4 - 0.19\times X_2\times X_3 + 0.076\times X_2\times X_4 + 0.13\times X_3\times X_4 - 0.25\times X_1^2 \\ & - 0.33\times X_2^3 - 0.22\times X_3^2 - 0.063\times X_4^2. \end{aligned} \quad (5)$$

The magnitude of B coefficients is presented in Supporting Information Table S6, which revealed that the linear term of blanching time had a maximum effect (3.63), followed by osmotic solution concentration (3.37), process duration (1.90), and process temperature (0.49) on WL during osmotic dehydration samples in sucrose solution. This indicated that the increased osmotic solution concentration and blanching time resulted in an increase in WL (Figure 4a), which could be related to the blanching process that denatures the cellular membrane, thus allowing quicker WL. Rittirut and Siripatana (2009) observed similar findings in Bilimbi fruit during osmotic dehydration. The increased WL related to high temperature, which reduced the viscosity of the solution and improved the interaction between sample and solution. Also, less viscosity of the solution increased the water in/out flow that increased the extraction ability of the solution. The increased temperature further influenced the cell wall activities, such as plasticizing effect to increase the moisture permeability and easy movement across the cell wall (Phisut, 2012). Moreover, high temperature further promotes moisture diffusion within the sample and thus water molecules can easily reach the sample surface and can be removed into the osmotic solution. Another possible explanation could be related to increased surface heat transfer coefficient, which influences the heat and mass transfer rate (Sharma et al., 2003). The variation in WL with process duration and temperature is shown in Figure 4a. The surface plots showed that the WL increased with the increase in temperature and concentration. In addition, with the increase of duration and blanching time, the WL also increased at all conditions.

3.3.2 | Solute gain

The ANOVA results ($F = 60.56$; $R^2 = 0.9826$; adjusted $R^2 = 0.9660$; $p < .05$) showed the significance difference for quadratic regression model that used to produce the second order model (Supporting Information Table S7). The fitted model for SG after eliminating insignificant terms was shown in Equation 6,

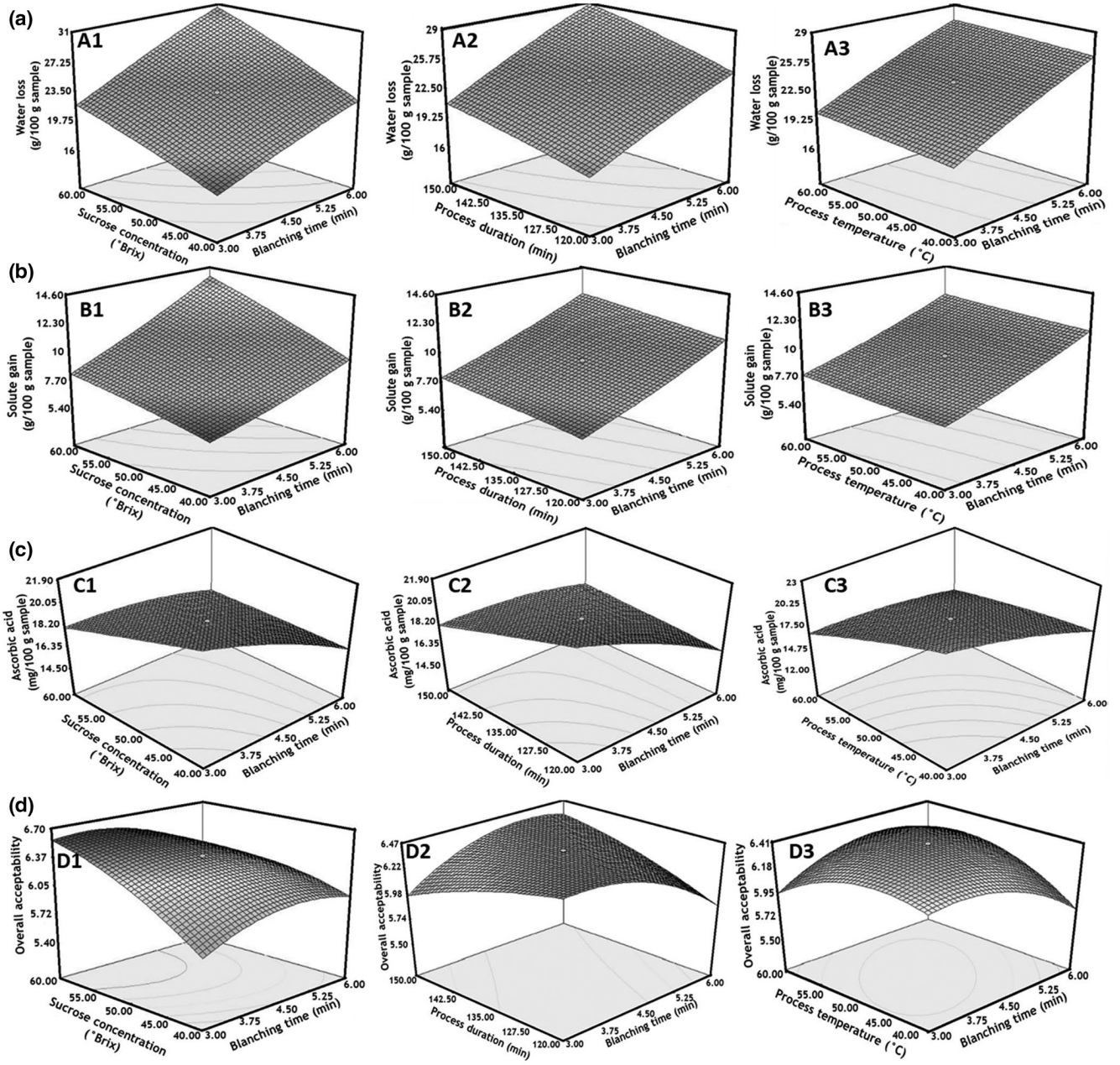

FIGURE 4 Effect of process parameters on Kinnow peel. (a) water loss, (b) solute gain, (c) ascorbic acid content, and (d) overall acceptability

$$\begin{aligned}\text{Solute gain} = {} & +9.48+2.13\times X_1+1.55\times X_2+0.63\times X_3+0.31\times X_4+0.66\times X_1\times X_2 \\ & +0.04\times X_1\times X_3+0.02\times X_1\times X_4+0.14\times X_2\times X_3+0.05\times X_2\times X_4 \\ & +6.250E-004\times X_3\times X_4+0.20\times X_1^2-0.13\times X_2^2-0.03\times X_3^2+0.06\times X_4^3.\end{aligned} \quad (6)$$

The findings showed that the blanching time (2.13), sucrose concentration (1.55), process duration (0.63), and process temperature (0.31) had the maximum effect on the SG. Figure 4b shows the effect of changing concentration and time on SG. Increased SG was observed with an increase in blanching time, due to damage in the tissues of the peel and thus the solute penetrated into the product. Similarly, increased SG with increase in osmotic solution concentration may be due to increase in the concentration gradient. The amount of SG increased with the time and increase in the process temperature were the consequences of damage in the tissues of the food product, which allowed the solute into the product and the Penetration rate of the solute increased over time (Kumar et al., 2012).

3.3.3 | Ascorbic acid content

The statistical analysis ($F = 9.17$; $R^2 = 0.8954$; adjusted $R^2 = 0.7977$; $p < .05$) revealed a significance for second order model (Supporting Information Table S8). The equation of the model fitted for ascorbic acid content after eliminating the non-significant terms was shown in Equation 7,

$$\text{Ascorbic acid} = +18.78 - 1.71\times X_1 - 0.95\times X_2 - 0.74\times X_3 - 2.10\times X_4 + 0.94\times X_1\times X_2 + 1.16\times X_1\times X_3 + 0.93\times X_1\times X_4 + 0.47\times X_2\times X_3 + 0.28\times X_2\times X_4 - 0.18\times X_3\times X_4 - 0.49\times X_1^2 - 0.038\times X_2^2 - 0.038\times X_3^2 - 0.24\times X_4^2. \quad (7)$$

The effect of sucrose concentration, process duration, and temperature on ascorbic acid content is shown in Figure 4c. The ascorbic acid content was extremely influenced by blanching time (−1.71), osmotic solution concentration (−0.95), process duration (−0.74), and process temperature (−2.10). The ascorbic acid content decreased with increase in blanching time. This was expected due to the degradation effect of blanching on thermosensitive compounds, such as ascorbic acid.

The decreased ascorbic acid content was observed with increased temperature, indicating that the higher temperature may enhance the release of ascorbic acid into osmotic solution and therefore induce the damage of ascorbic acid (Nadia et al., 2013). Also, increased osmotic solution concentration resulted a decrease in ascorbic acid content. Similarly, Nadia et al. (2013) observed the effect of osmotic solution concentration on the ascorbic acid content, where authors reported decreased ascorbic acid content with increased solute concentration. It seems possible that these results were due to outgoing moisture flux along with water-soluble ascorbic acid.

3.3.4 | Overall acceptability

The statistical analysis ($R^2 = 0.8760$; adjusted $R^2 = 0.7610$; $p < .05$) clearly explained the suitability of quadratic regression to produce a second order model (Supporting Information Table S9). The model fit for overall acceptability is shown in Equation 8,

$$\text{Overall acceptability} = +6.40 - 0.05\times X_1 + 0.26\times X_2 - 4.167E-003\times X_3 + 0.021\times X_4 - 0.16\times X_1\times X_2 + 0.23\times X_1\times X_3 + 0.17\times X_1\times X_4\times + 0.17\times X_2\times X_3 - 0.04\times X_2\times X_4 + 0.02\times X_3\times X_4 - 0.18\times X_1^2 - 0.12\times X_2^2 - 0.05\times X_3^2 - 0.18\times X_4^2. \quad (8)$$

The linear terms of all the variables had a positive effect on overall acceptability (Supporting Information Table S9). Blanching time (−0.05) and osmotic solution concentration (0.26) had a maximum positive effect on overall acceptability, followed by process time (-4.16×10^{-3}) and process temperature (0.021). However, the firmness and appearance of samples were higher compared to control (samples without osmotic dehydration). Blanching time had a significant effect on the quality of the final product as shown in Figure 4d. Phisut (2012) reported the influence of blanching for the inactivation of undesirable enzymatic reactions and quality attributes of fruit tissue, particularly to maintain the texture of fruit tissues. The concentration showed a relatively much effect on the overall acceptability of samples, which may be due to the inactivation of undesirable enzymatic reactions and improved quality characteristics, including, appearance, texture, and color (Figure 4d). Accordingly, these findings corroborate with a previous study documented for dehydrated ripe mango slices (Kumar et al., 2012).

4 | CONCLUSIONS

This study aimed to understand the mass transfer kinetics during osmotic dehydration of Kinnow peel in osmotic solution and the osmotic dehydration process was optimized to achieve the best quality product. It was found that the rate of WL and SG of the sample increased with increase in osmotic dehydration parameters. The Penetration model was the best fitted for WL and SG compared to other models. Page and Power law models were the best fitted for moisture ratio and SG ratio, respectively. The optimum conditions for osmotic dehydration were 60° Brix at 48°C for 150 min with a blanching time of 3.60 min. We concluded that osmotic dehydration may depend on blanching time, the concentration of osmotic solution, temperature, and time. All processing parameters had a significant impact on the WL, SG, ascorbic acid content, and overall acceptability during osmotic dehydration. The optimized mass transfer kinetics of Kinnow peel osmotic dehydration process serves as the basis for the sustainable valorization of Kinnow peel through the development of novel food products.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Balpreet Kaur : Data curation; Formal analysis; Investigation; Writing – original draft. **Priya Rana:** Software; Validation; Writing – review & editing. **Kandi Sridhar:** Software; Validation; Writing – original draft; Writing – review & editing.

ETHICAL STATEMENT

Ethics approval was not required for this research.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available within the article and/or its supplementary material.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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