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# Study on Mass Transfer and Physicochemical Properties of Avocado During Osmotic Dehydration

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**Abstract**

A previous study found that mass transfer occurring during the osmotic dehydration (OD) process. This phenomena is possible causing modification in physicochemical properties; therefore, understanding the OD effect on quality attributes is important. This research aimed to study the impact of sucrose concentration and immersion time on the kinetics of mass transfer and the physicochemical properties of avocado (*Persea americana* var. Miki) during the OD process. The samples were immersed in a sucrose solution (45, 55 and 65 ° Brix) for up to 300 min, then the mass transfer parameter and physicochemical properties were evaluated. The results showed that the highest rate of water removal (WR) was –0.037 $g.g^{-1}.h^{-1}$ using the 55 ° Brix solution, which also led to an increase in the soluble solid gain (SSG) value to 0.0126 $g.g^{-1}.h^{-1}$, while the highest WR/SSG ratio was obtained after 180 min of immersion using 65 ° Brix (2.451). A $2^{nd}$-order polynomial model accurately describes avocado mass transfer kinetics and their relationship to physicochemical properties. The model showed the best adjustment for WR, SSG, and weight loss (WL), as pointed out by $R^2$ = 0.9671, 0.8968 and 0.9573, respectively. WR has a negative effect on firmness ($R^2$ = 0.9278), vitamin C ($R^2$ = 0.9349), and total fat ($R^2$ = 0.8954). The uptake of sucrose correlated with decrease of vitamin C ($R^2$ = 0.9391), whereas WL also affected the loss of total fat ($R^2$ = 0.8288). The OD process modified the chroma of the avocado by reducing lightness, increasing greenness and yellowness, and yet protecting the flesh from the browning effect. Overall, this study provides insights into the relationship between mass transfer and physicochemical properties, and it is useful to predict the final condition of the osmo-avocado before subsequent processes.

**Keywords:** Mass transfer, Osmotic dehydration, Persea americana, Quality, Sucrose

**Introduction**

Over the last few years, there has been a significant increase in the demand for minimally processed fruits and vegetables, including avocado, as a substitute for a plant-based diet. Avocado (*Persea americana*) fruit pulp is a challenge to handle as it has a high content of unsaturated fatty acids and is sensitive to oxidative browning [1], off-flavour (oxidative rancidity), bitterness, and discoloration [2,3]. Several methods have been established for providing products capable of retaining the original commodity's freshness and quality for a long period of storage, including integrating the freezing process with OD [4]. OD has several advantages, such as enhancing the flavor [5], preventing color degradation and preventing enzyme browning [6]. OD is a method that allows the removal of partial water from the cell using a concentrated solution and the uptake of a solute into the immersed cell due to the exchange of material during the process. Two main counter-current flows occurred during OD: The first was the removal of water from the food and its subsequent addition to the solution, and the second was the movement of molecules from the solution into the food [7]. Additionally, there is a 3$^{rd}$ flow by which natural dissolved substances such as salts, sugar, minerals, and some organic acids are released from the food and dissolve into a solution [7,8]. **Figure 1** illustrates the mechanism of mass transfer during OD.

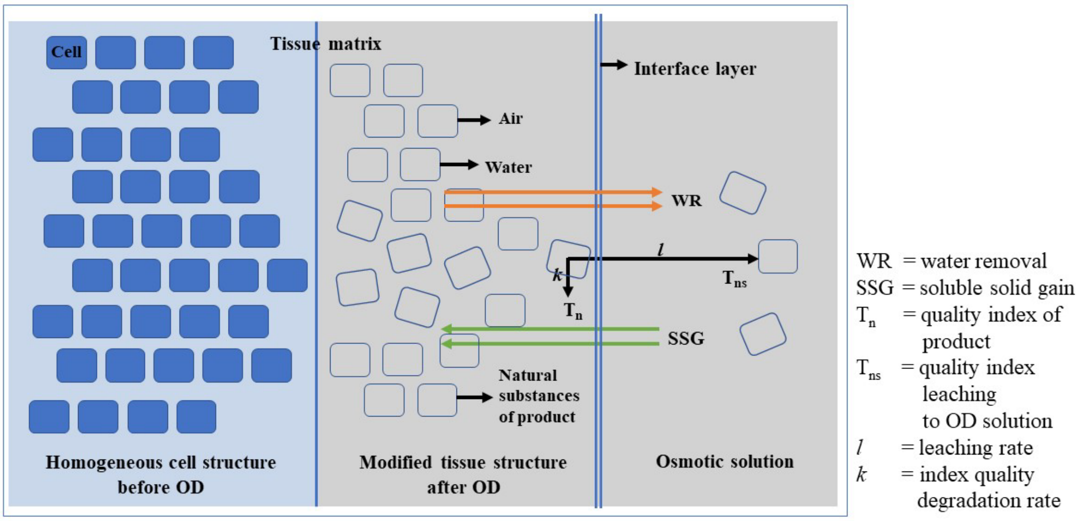


**Figure 1** Mechanism of mass transfer in cells during the OD process, adapted from [9].

There is a limit to the amount of water removed from the product, considering the effect on quality attributes following this movement. However, prolonged immersion time might be required to reach the precise amount of water in the final product. Previous studies showed a novel product obtained as OD alternated the physicochemical properties and bioactive compounds of foods [10,11]. Several studies have successfully modeled the mass transfer of OD (Peleg, Azuara, Weibull, and Fick's 2$^{nd}$ law model) and explained the OD impact on quality attributes in various fruits, such as mango [9], kiwifruit [12], cherries [13], sweet potatoes [14], peach [15], and mulberry [16]. However, there is still no clear explanation for how mass transfer parameters like water removal (WR), soluble solid gain (SSG), and weight loss (WL) affect the changes in physicochemical properties. Although Geethu *et al.* [17] has applied OD processes to avocado before freezing, there is still no preliminary study regarding mass transfer and its relationship with physicochemical properties. Therefore, the aim of this research is to examine the impact of OD processes on mass transfer parameters, the physicochemical properties of avocado during the OD process and the correlation between these factors.

## Materials and methods

### Materials

Avocado fruits (*Persea americana* var. Miki) were obtained from a local farmer (Ciomas, West Java, Indonesia) and stored at room temperature (27 - 29 °C) until they reached maturity level before being used. Ripe avocado was selected based on firmness and skin color (average firmness is 9.807 ± 2.16 N and chrome for skin color a* is –16.01 ± 0.94, b* is 30.90 ± 2.29). The avocado was peeled, and its pulp was cut into cubes of roughly 2×2×1.5 $cm^3$ manually. Commercial sucrose was utilized in order to set OD solutions.

### Osmotic dehydration set up

To make a sucrose solution of 45, 55 and 65 ° Brix, a specified quantity of sucrose was dissolved in a precisely determined volume of distilled water. The OD process was conducted at ambient temperature with constant stirring. The samples were set in a glass beaker and immersed in a sucrose solution, keeping a ratio of 1:5 (w/w) between the samples and the solution. This ratio was chosen to prevent significant dilution of the solution due to water removal, which could lead to a localized decrease in the osmotic impact during the process [18]. Subsequently, the samples were removed and wiped with tissue paper to eliminate any remaining surface water. Samples are then placed in the chiller (± 5 °C), not longer than 6 h before the subsequent analysis. Sampling was performed at 60 min intervals up to 300 min. Mass transfer parameters and physicochemical properties were analyzed shortly thereafter. Each treatment was performed in triplicate.

To evaluate the mass transfer, the weight of each sample was measured both before and following treatment using an analytical balance (accuracy 0.0001 g, OHAUS Model AX324, USA). The water content (WC) was measured by subjecting the sample to a drying process at a constant temperature of 105 °C for 24 h (ISUZU constant temperature oven, Model 2-2021, Japan) and calculated according to the gravimetric method. A refractometer (ATAGO Co., Ltd., model PAL-α) was used to assign the total soluble solids (TSS) values. The collected data was next utilized to ascertain the kinetics of water removal (WR), soluble solid gain (SSG), and weight loss (WL) in avocado samples employing the following equations [19]:

$$WR=\frac{(M_t)(x_t^w)-(M_0)(x_o^w)}{M_0} \tag{1}$$

$$SSG=\frac{(M_t)(x_t^s)-(M_0)(x_o^s)}{M_0} \tag{2}$$

$$WL=\frac{M_t-M_0}{M_0} \quad (3)$$

where $M_0$ = initial weight (g), $M_t$ = weight at a given time (g), $x_{w,o}$ = the initial mass fraction of water ($g.g^{-1}$), $x_{w,t}$ = the mass fraction of water at a given time ($g.g^{-1}$), $x_{s,0}$ = the initial mass fraction of soluble solids ($g.g^{-1}$), and $x_{s,t}$ = the mass fraction of soluble solids at a given time ($g.g^{-1}$).

The response of variables Y (WL, SSG, WR, and WC) can be described using a $2^{nd}$-order polynomial model (equation below), where the factors variables $x_i$ (OD concentration and time of immersion) are employed as predictors.

$$Y=a_0+\sum a_i x_i+\sum a_{ii} x_i^2 \quad (4)$$

where $a_0$ = intercept, $a_i$ = linier coefficient, and $a_{ii}$ = quadratic coefficient.

**Physical analysis**

A cylindrical avocado (height 2 cm, diameter 1 cm) was formed from treated samples before being subjected to a texture analyzer (Sun Scientific Co., Ltd., Model CR-500 DX, Japan). The test was conducted using a cylindrical probe (diameter = 2.5 cm), fitted with a 2 kg load and a maximum hold value of 60 mm. The data was documented as the firmness of the avocado mesocarp, measured in Newtons (N), which represents the maximal force required for penetration. The test was run before and after the osmotic, and each sample was performed in triplicate. The colors of the fresh and treated were assessed using a Konica Minolta colorimeter, Model CR-400, Japan. Each treatment was conducted 3 times. The data was displayed using the CIELa*b* coordinates. L denotes the attribute of lightness, with values between 0 (indicating black) and 100 (indicating white). The colors red-green and yellow-blue represented the coordinates of a* and b*, respectively. The difference between total chroma change (ΔC) and browning index (BI) was computed using the equation below [6,20]:

$$\Delta C=\sqrt{(\Delta a^2)+(\Delta b^2)} \quad (5)$$

$$BI=\frac{(x-0.31)\cdot 100}{0.172} \quad (6)$$

$$x=\frac{a+1.75L}{5.645L+a-3.012b} \quad (7)$$

**Chemical analysis**

The AOAC method [21] was used to determine the amount of vitamin C. Each duplicate involved blending 25 g of samples with a 3 % solution of metaphosphoric acid, followed by filtering the mixture using Whatman No. 42 filter paper. 2 mL of the filtered sample was placed in beaker glass and added with a 5 mL of metaphosphoric acid-acetic acid, then titrated using 2,6-dichlorophenolindophenol until a light but clearly visible rose-pink color remained for a duration of at least 5 s. Each sample underwent 2 separate extractions, and the results were expressed as mg of ascorbic acid per 100 mL of avocado samples. Total fat was determined by the Soxhlet method (Soxtec TM System, Model ST 243, FOSS). 2 g of sample was homogenized and hydrolyzed with 25 % hydrogen chloride for 15 min. The sample was then filtered using Whatman paper No. 40 and subsequently rinsed with hot water until the litmus paper indicated a blue color. The filtered material was then dried in an oven for 60 min at 105 °C. A dried filter was put in a thimble and 40 mL of hexane was used for the 3-step Soxhlet extraction procedure, which consists of boiling, rinsing, and recovery. Total fat was calculated based on the dry weight of the sample extracted in the Soxtec apparatus and denoted as % total fat. Each treatment was performed in duplicate.

### Statistical analysis

The influence of OD parameters (concentration and time of immersion) on mass transfer parameters and physicochemical properties was evaluated by ANOVA at a significance level ($p$ = 0.05), and later Tukey's post-hoc test was used to evaluate significant differences among the treatments. The experimental data was analyzed using multiple regressions to fit the model. All data was statistically performed by SPSS (IBM Statistic Version 25, Chicago, USA) and MS. Excel 2019.

## Results and discussion

### OD effect on mass transfer kinetics

The fresh avocado v. Miki was characterized by a WC of 90.81 ± 0.80 % and a TSS of 8.1 ± 0.1 ° Brix. **Table 1** statistically shows the observation of WC and TSS values throughout the OD process. Based on the results, OD concentration and time of immersion had a significant impact on WC and TSS ($p < 0.05$). The higher changes were observed on WC at 300 min of immersion using 65 ° Brix of OD concentration, which reduced by about 16.55 % (equal to 2.913 $g.g^{-1}$ d.m.), 65 ° Brix also resulted in higher sucrose uptake from solution into avocado mesocarp, about 28.37 °Brix at 300 min of immersion. [22] observed a reduction of WC of about 2.8 $g.g^{-1}$ d.m. using 50 °Brix sucrose after 60 min of immersion in apples, which have a higher WC reduction than the avocado. Most frequently, a higher concentration of the OD solution led to a faster rate of dehydration. Considering the chosen temperature in this research was lower, this resulted in a lower dehydration rate for the sample. However, it is worth noting that OD agents are crucial in aiding mass transfer throughout the OD process. The osmotic pressure is directly proportional to the molar mass of the solute. Therefore, when the molar mass decreases, the osmotic pressure increases for the same concentration. Although sucrose has a higher molecular weight than other typical carbohydrates, this research chose it as an OD agent due to its good performance as a water activity-lowering agent [23] and its sensory acceptance.

Overall, **Table 2** shows the impact of OD parameters (solute concentration and time of immersion) on WR, SSG, WL, and the WR/SSG ratio after the OD process. As the result shows, the OD parameters caused a significant effect on mass transfer kinetics ($p < 0.05$). The osmotic gradient promotes the rapid diffusion of water out of the tissue, whereas the diffusion of sucrose into the tissue is comparatively slower

(**Figure 2**) [24]. The rates of WR were found to be –0.034, –0.037 and –0.036 $g.g^{-1}.h^{-1}$ for 45, 55, and 65 ° Brix, respectively, while the values of the SSG were 0.0085, 0.0126 and 0.0084 $g.g^{-1}.h^{-1}$ for 44, 55, and 65 ° Brix, respectively. The concentration of 55 ° Brix indicated the greatest rate of WR and SSG if compared with 2 other concentrations. It is because moderate concentration promotes a stable driving force during the OD process. The result shows that using the 65 ° Brix solution did not show an increase in the rate of water removal or solid uptake. Although avocado samples experienced the highest WR/SSG ratios during 180 - 240 min, yet after this period, the ratio either marginally decreased or increased with time.

**Table 1** OD effect on WC and TSS.

| **OD Concentration (° Brix)** | **Time (min)** | **WC ($g.g^{-1}$)** | **TSS (° Brix)** |
|---|---|---|---|
| 45 | 60 | $0.8524 \pm 0.18^{Ad}$ | $11.13 \pm 0.25^{Aa}$ |
| | 120 | $0.8336 \pm 1.33^{Ac}$ | $11.57 \pm 0.32^{Aa}$ |
| | 180 | $0.8165 \pm 1.40^{Ab}$ | $12.93 \pm 0.81^{Aa}$ |
| | 240 | $0.7959 \pm 0.77^{Aa}$ | $12.97 \pm 0.74^{Aab}$ |
| | 300 | $0.7910 \pm 0.80^{Aa}$ | $15.70 \pm 0.24^{Ab}$ |
| 55 | 60 | $0.8404 \pm 1.30^{Bd}$ | $13.20 \pm 0.20^{ABa}$ |
| | 120 | $0.8165 \pm 2.46^{Bc}$ | $14.27 \pm 0.50^{ABa}$ |
| | 180 | $0.7916 \pm 0.96^{Bb}$ | $14.63 \pm 0.06^{ABa}$ |
| | 240 | $0.7759 \pm 0.82^{Ba}$ | $17.63 \pm 0.59^{ABab}$ |
| | 300 | $0.7564 \pm 0.85^{Ba}$ | $24.43 \pm 1.07^{ABb}$ |
| 65 | 60 | $0.8174 \pm 1.00^{Cd}$ | $13.17 \pm 0.60^{Ba}$ |
| | 120 | $0.7969 \pm 1.25^{Cc}$ | $15.27 \pm 0.35^{Ba}$ |
| | 180 | $0.7653 \pm 0.55^{Cb}$ | $19.23 \pm 0.31^{Ba}$ |
| | 240 | $0.7434 \pm 2.23^{Ca}$ | $22.83 \pm 2.70^{Bab}$ |
| | 300 | $0.7465 \pm 0.75^{Ca}$ | $28.37 \pm 0.67^{Bb}$ |

WC: Water content. TSS: Total soluble solids. Mean ± SD, n = 3. Different letters and lowercase in each column are significantly different ($p < 0.05$) according to Tukey's post-hoc test.

Khanom *et al.* [25] stated that using a 40 % sugar solution had significantly lower WR values for pineapples than 60 %, while Uddin *et al.* [26] observed that when the sugar concentration in carrots exceeded 60 %, further increases in sugar concentration did not cause any additional removal of water. A high concentration of sucrose created a crust that surrounded the surface like a barrier, thereby preventing mass transfer [27]. The study [22] examines the use of sucrose and other carbohydrates, such as erythritol, xylitol, maltitol, inulin, and oligofructose, as OD agents. According to their research, using 40 % erythritol and xylitol was more efficient at removing water than sucrose. This is because both of these types of carbohydrates have a molecular weight smaller than sucrose. Nevertheless, a decrease in molecular weight leads to an increase in SSG. Their findings also indicated that erythritol and xylitol exhibit a greater effect on SSG compared to sucrose. Additionally, the OD process, which lasted over 3 h in 30 and 40 % inulin solutions, also achieved a comparable amount of SSG as sucrose.

The 2$^{nd}$-order polynomial model fitted the experimental data. **Table 3** displays the coefficients derived from the 2$^{nd}$-order regression. In general, the time of immersion ($x_2$) significantly affected all mass transfer parameters ($p < 0.05$), whereas the concentration of OD ($x_1$) is not significantly different for both the linear and quadratic effects. This confirms that the time of immersion plays a critical role in determining the outcome of the OD process. On the linear effect, concentration has a positive impact on WR, SSG and WL, indicating OD concentration is promoting reduction on WR, WL, and addition to SSG, whereas on WC, it has a negative effect, meaning increasing OD concentration has an effect on reducing WC. The increase in solid uptake from the OD solution by the sample over time explains the positive effect of immersion time on SSG. On the contrary, the time of immersion has a negative effect on WR, WL, and WC, demonstrating the reduction of these mass transfer parameters over time. All parameters related to mass transfer exhibit a coefficient of correlation ($R^2_{adj}$), and $R^2$ values (plots comparing experimental and estimated data) indicate a satisfactory level of agreement. Hence, the quadratic models accurately depicted the data and could be employed to characterize the variations in mass transfer parameters.

**Table 2** Effect of OD concentration and time on WR, SSG and WL.

| OD Concen-tration (° Brix) | Time (min) | WR (g.g$^{-1}$) | SSG (g.g$^{-1}$) | WL (g.g$^{-1}$) | WR/SSG Ratio |
|---|---|---|---|---|---|
| 45 | 60 | –0.118 ± 0,01$^{Cc}$ | 0.083 ± 0.00$^{Aa}$ | –0.095 ± 0.01$^{Bc}$ | 1.413 ± 0.14$^{Aa}$ |
| | 120 | –0.149 ± 0,01$^{Cb}$ | 0.098 ± 0.01$^{Aab}$ | –0.112 ± 0.01$^{Bb}$ | 1.518 ± 0.14$^{Aab}$ |
| | 180 | –0.215 ± 0.02$^{Ca}$ | 0.102 ± 0.01$^{Abc}$ | –0.174 ± 0.03$^{Bab}$ | 2.116 ± 0.47$^{Ab}$ |
| | 240 | –0.257 ± 0.01$^{Ca}$ | 0.112 ± 0.01$^{Acd}$ | –0.205 ± 0.01$^{Ba}$ | 2.286 ± 0.25$^{Ab}$ |
| | 300 | –0.254 ± 0.01$^{Ca}$ | 0.118 ± 0.01$^{Ad}$ | –0.197 ± 0.01$^{Ba}$ | 2.161 ± 0.09$^{Ab}$ |
| 55 | 60 | –0.146 ± 0.02$^{Bc}$ | 0.091 ± 0.03$^{Ba}$ | –0.116 ± 0.01$^{Bc}$ | 1.600 ± 0.29$^{Aa}$ |
| | 120 | –0.205 ± 0.02$^{Bb}$ | 0.104 ± 0.02$^{Bab}$ | –0.162 ± 0.01$^{Bb}$ | 1.975 ± 0.19$^{Aab}$ |
| | 180 | –0.242 ± 0.02$^{Ba}$ | 0.120 ± 0.01$^{Bbc}$ | –0.182 ± 0.01$^{Bab}$ | 2.011 ± 0.02$^{Ab}$ |
| | 240 | –0.273 ± 0.00$^{Ba}$ | 0.128 ± 0.01$^{Bcd}$ | –0.206 ± 0.01$^{Ba}$ | 2.136 ± 0.18$^{Ab}$ |
| | 300 | –0.294 ± 0.02$^{Ba}$ | 0.142 ± 0.01$^{Bd}$ | –0.213 ± 0.02$^{Ba}$ | 2.074 ± 0.25$^{Ab}$ |
| **65** | 60 | –0.178 ± 0.01$^{Ac}$ | 0.109 ± 0.01$^{Ba}$ | –0.131 ± 0.01$^{Ac}$ | 1.644 ± 0.12$^{Aa}$ |
| | 120 | –0.263 ± 0.01$^{Ab}$ | 0.109 ± 0.01$^{Bab}$ | –0.215 ± 0.00$^{Ab}$ | 2.408 ± 0.13$^{Aab}$ |
| | **180** | **–0.311 ± 0.01$^{Aa}$** | **0.127 ± 0.00$^{Bbc}$** | **–0.245 ± 0.01$^{Aab}$** | **2.451 ± 0.10$^{Ab*}$** |
| | 240 | –0.316 ± 0.01$^{Aa}$ | 0.148 ± 0.02$^{Bcd}$ | –0.229 ± 0.02$^{Aa}$ | 2.137 ± 0.24$^{Ab}$ |
| | 300 | –0.323 ± 0.00$^{Aa}$ | 0.142 ± 0.02$^{Bd}$ | –0.241 ± 0.01$^{Aa}$ | 2.267 ± 0.27$^{Ab}$ |

WR: Water removal. SSG: Soluble solid gain. WL: Weight loss. Mean ± SD, n = 3. Different letters and lowercase in each column are significantly different ($p < 0.05$) according to Tukey's post-hoc test. *Maximum WR/SSG ratio.

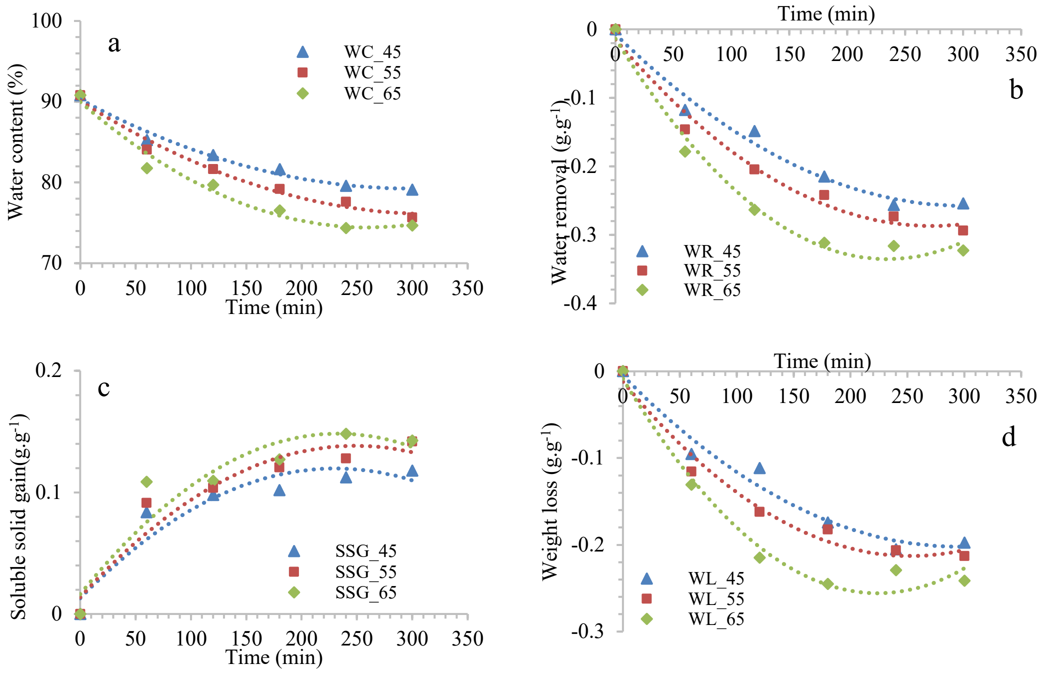


**Figure 2** Water content (a), water removal (b), soluble solid gain (c), and weight loss (d) of avocado cubes during treatment at different OD concentrations. Lines from the 2$^{nd}$-order polynomial model.

**Effect of mass transfer parameters on physicochemical properties**

The avocado mesocarp has a creamy texture, which makes it highly susceptible to textural damage during processing. The mesocarp samples of the fresh avocado had a hardness value of 5.073 N. **Table 4** shows a further statistical analysis of the OD parameters on physicochemical properties. **Figure 3(a)** exhibits the behavior of firmness in terms of water removal during the process. Following an immersion period of 180 min, samples of all concentrations demonstrated a substantial reduction in firmness, with the least amount of deformation occurring near the end of the process, when water removal almost plateaued. After 300 min of soaking, the samples show a softened appearance and are more elastic. Samples treated with a 45 ° Brix solution experienced the most minimal firmness reduction, close to the fresh one. Ferrari and Hubunger [28] reported contrasting findings regarding the effect of sucrose concentration on melon mesocarp firmness. Specifically, they observed an increase in firmness when treated with sucrose at 65 ° Brix. [29] examined the effect of erythritol alone and [30] a combination of glycerol and erythritol as an OD agent on peach chips and apricots respectively. The study revealed that the treatment resulted in improved cell wall strength and increased hardness of the chips. Prinzivalli *et al.* [31] and Chiralt *et al.* [32] noted a reduction in stress levels at the rupture point during the OD process of strawberries and kiwifruits, whereas Falade *et al.* [30] emphasized that prolonged OD causes changes in the size and shape of cells. After 180 min of immersion, their research revealed a significant increase in small intercellular spaces and a decrease in large intercellular spaces, likely due to the separation of some cells and the splitting of the central lamella [30].

**Table 3** Effect of OD concentration and time on WR, SSG, WL and WC.

| Coefficient | Mass transfer parameter | | | |
|---|---|---|---|---|
| | **WR (g.g$^{-1}$)** | **SSG (g.g$^{-1}$)** | **WL (g.g$^{-1}$)** | **WC (g.g$^{-1}$)** |
| Intercept ($a_0$) | 0.01323750 | –0.176426250 | –0.10932875 | 101.3813052 |
| Linier | | | | |
| $a_1$ | 0.00195200 | 0.006554000 | 0.00577960 | –0.265147054 |
| $a_2$ | –0.00168078* | 0.000696552* | –0.00140300* | –0.066833967* |
| Quadratic | | | | |
| $a_{11}$ | –0.00005510 | –0.000046150 | –0.00007853 | 0.000352592 |
| $a_{22}$ | 0.00000294* | –0.000001334* | 0.00000267* | 0.000095555* |
| $R^2$ | 0.9835 | 0.8877 | 0.957307639 | 0.9832 |
| $R^2_{adjusted}$ | 0.9775 | 0.8468 | 0.944171528 | 0.9772 |
| Stnd. Error | 0.0130 | 0.0134 | 0.019487122 | 0.6508 |
| n | 18 | 18 | 18 | 18 |
| SSRes | 0.001853 | 0.001983 | 0.004936723 | 4.6598 |

$x_1$ = OD concentration (°Brix), $x_2$ = time (min). *$p < 0.005$. Predicted $\hat{Y}$ (WR, SSG, WL, and WC) expressed by $\hat{Y} = a_0 + a_1.x_1 + a_2.x_2 + a_{11}.x_1^2 + a_{22}.x_2^2$.

**Table 4** Effect of OD concentration and time on firmness, color, vitamin C and total fat.

| **OD Concentration (° Brix)** | **Time (min)** | **Firmness (N)** | **Color (ΔC)** | **Vitamin C (mg. 100 mL$^{-1}$)** | **Total fat (%)** |
|---|---|---|---|---|---|
| 45 | 60 | $4.69 \pm 0.07^{Be}$ | $5.79 \pm 0.73^{Ba}$ | $8.48 \pm 0.71^{Bd}$ | $13.32 \pm 2.08^{Cc}$ |
| | 120 | $4.54 \pm 0.17^{Bd}$ | $7.13 \pm 2.39^{Bbc}$ | $8.31 \pm 0.36^{Bcd}$ | $13.49 \pm 1.22^{Cbc}$ |
| | 180 | $4.94 \pm 0.17^{Bc}$ | $6.35 \pm 0.51^{Bab}$ | $7.94 \pm 0.18^{Bbc}$ | $12.84 \pm 0.08^{Cab}$ |
| | 240 | $4.62 \pm 0.32^{Bb}$ | $6.82 \pm 1.47^{Babc}$ | $7.14 \pm 0.00^{Bab}$ | $11.32 \pm 0.81^{Ca}$ |
| | 300 | $4.08 \pm 0.65^{Ba}$ | $9.20 \pm 0.39^{Bc}$ | $6.51 \pm 0.06^{Ba}$ | $10.51 \pm 0.43^{Ca}$ |
| 55 | 60 | $4.55 \pm 0.18^{ABe}$ | $5.82 \pm 0.50^{Ba}$ | $8.22 \pm 0.72^{Ad}$ | $11.94 \pm 1.85^{Bc}$ |
| | 120 | $4.42 \pm 0.37^{ABd}$ | $7.26 \pm 2.45^{Bbc}$ | $6.97 \pm 0.24^{Acd}$ | $11.44 \pm 1.30^{Bbc}$ |
| | 180 | $4.36 \pm 0.32^{ABc}$ | $7.18 \pm 1.23^{Bab}$ | $6.38 \pm 0.11^{Abc}$ | $9.86 \pm 0.15^{Bab}$ |
| | 240 | $4.59 \pm 0.13^{ABb}$ | $7.62 \pm 2.71^{Babc}$ | $5.21 \pm 1.54^{Aab}$ | $9.23 \pm 0.14^{Ba}$ |
| | 300 | $4.38 \pm 0.40^{ABa}$ | $8.29 \pm 0.63^{Bc}$ | $4.91 \pm 1.48^{Aa}$ | $9.43 \pm 0.27^{Ba}$ |
| 65 | 60 | $4.47 \pm 0.10^{Ae}$ | $4.44 \pm 0.61^{Aa}$ | $8.17 \pm 0.35^{Ad}$ | $11.29 \pm 0.15^{Ac}$ |
| | 120 | $4.45 \pm 0.33^{Ad}$ | $6.94 \pm 0.35^{Abc}$ | $7.69 \pm 0.30^{Acd}$ | $10.35 \pm 0.44^{Abc}$ |
| | 180 | $4.13 \pm 0.16^{Ac}$ | $4.19 \pm 0.91^{Aab}$ | $6.68 \pm 1.25^{Abc}$ | $8.29 \pm 0.25^{Aab}$ |
| | 240 | $4.02 \pm 0.01^{Ab}$ | $6.24 \pm 0.81^{Aabc}$ | $6.15 \pm 0.64^{Aab}$ | $7.59 \pm 0.39^{Aa}$ |
| | 300 | $3.78 \pm 0.01^{Aa}$ | $7.11 \pm 1.01^{Ac}$ | $5.54 \pm 0.82^{Aa}$ | $7.57 \pm 0.11^{Aa}$ |

Means ± SD, n = 3 (for firmness and color), n = 2 (for vitamin C and total fat). Different letters and lowercase in each column are significantly different ($p < 0.05$) according to Tukey's post-hoc test.

The lightness (L) value of the fresh avocado mesocarp is 72.48 and the chrome (a* and b*) values are –1.41 and 65.64, respectively. The statistical analysis in **Table 4** shows the impact of OD parameters on ΔC. **Figures 3(b) - 3(c)** show that OD modified the chroma of the sample by reducing the L values, resulting in an increase in chroma change (ΔC) pointed by a slight increase in greenness (evidenced by higher a* values) and yellowness (shown by higher b* values). [33] reported that using trehalose resulted in the minimum total color change for pineapples after reconstitution. According to [34], WR causes the change in lightness and chrome, suggesting the possibility of both an enhancement of selective light absorption through an improvement in pigment concentration and an enhancement of surface reflection by raising the refractive index of the tissue liquid phase. Therefore, measuring the pigment content (xanthophyll and chlorophyll) in the sample is necessary for further evidence. It is also worth noting that the presence of a thin layer of sugar covering the surface gives it a glossy look (**Figure 4**). Nevertheless, during the OD process, the browning effect does not appear on avocado samples at all concentration levels (**Figure 3(d)**). This suggests that the OD can be used as a pre-treatment before subsequent processes because it effectively prevents enzymatic browning.

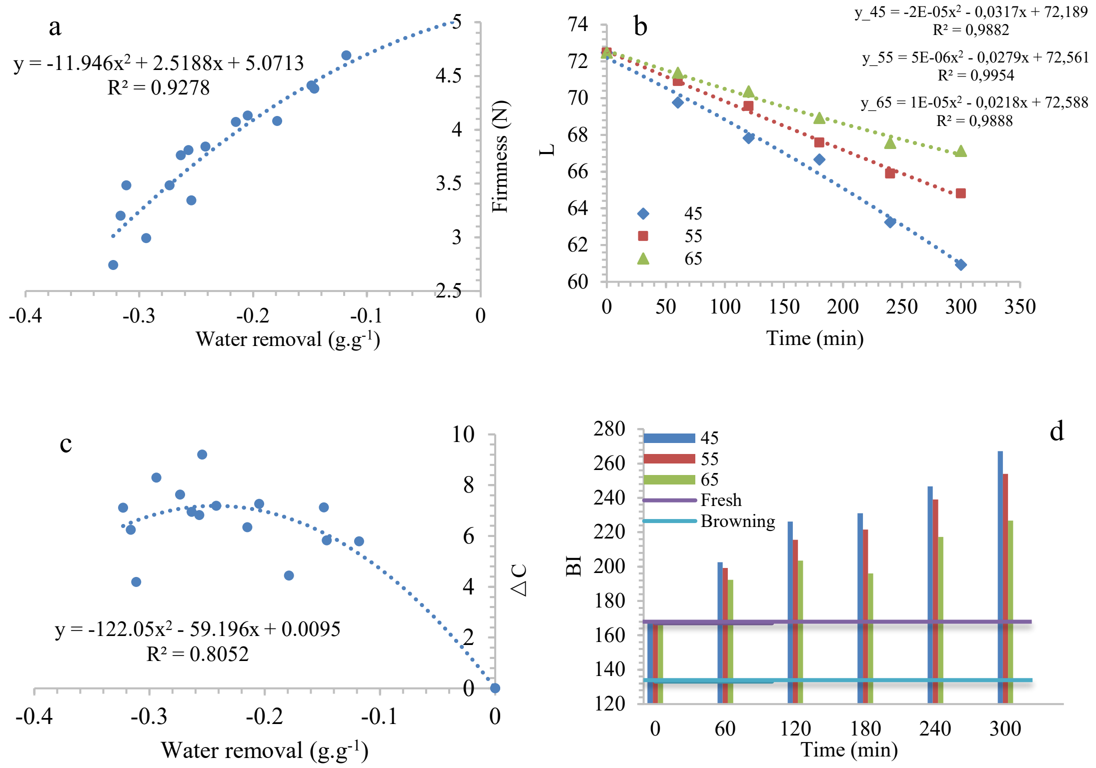


**Figure 3** WR vs. firmness (a), change in lightness (b), WR vs. chroma differance (c), and browning index (d) of avocado cubes during treatment at different OD concentrations.

Mass transfer mechanisms may explain vitamin C and total fat reduction during the OD process. When water is removed from the cell, a natural substance is also brought into the OD solution, causing the leaching phenomenon. **Figures 5(a) - 5(b)** show the degradation of vitamin C in relation to WR and TSS.

The 45 ° Brix concentration resulted in the minimum degradation of vitamin C loss (**Table 4** shows the significant difference, $p < 0.05$). The leaching of vitamin C into OD solution has the same profile as WR, where after 300 min of immersion, it shows an equilibrium condition. Mango *et al.* [9] and guava *et al.* [35] have also reported this phenomenon. However, the use of ultrasound-assisted OD leads to improvements in vitamin C content [36]. Their findings also revealed that using a natural hypertonic solution, namely grape and mulberry syrup, instead of a sugar solution increased the vitamin C values in kiwifruits. This is due to the fact that the natural solution contains less sugar, which in turn protects the behavior of vitamin C. The OD process also resulted in the degradation of total fat. **Figures 5(c)** - **5(d)** show the correlation between mass transfer and total fat. The reduction in fat content in avocado samples is in line with WR and WL. The statistical results show that all concentration levels have a significant difference in total fat values, and prolonged immersion created a huge loss of total fat (**Table 4**).

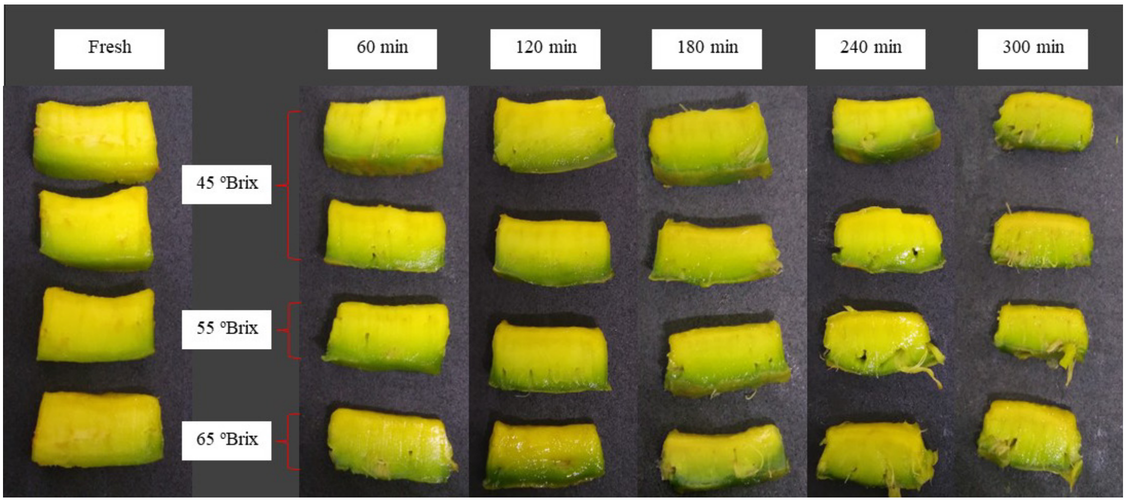


**Figure 4** A vertical slice (2 mm) of avocado cubes after OD processing.

**Physicochemical simulation**

Determining the chemical compounds at the final condition is crucial, as OD serves as a pre-treatment before subsequent processes. The result reveals that both vitamin C and total fat decrease as the time of immersion increases (**Figures 5(a)** - **5(d)**), thus making the time of immersion an important factor in maintaining the chemical compounds during the OD process. A simulation was done in order to determine the time of immersion. In this simulation, the change of WR as a function of time was determined by the regression values (**Table 3**), and the change of physicochemical properties as a function of WR was determined by the correlation regression for firmness and chroma change ($\Delta C$) shown in **Figures 3(a)** - **3(c)**, vitamin C, and total fat shown in **Figures 5(a)** - **5(d)**. Together, these values were used to develop scenarios of the physicochemical properties changing during the OD process. Vitamin C was chosen as the critical parameter and the target of the simulation. Based on practical needs (required minimum loss of vitamin C), 2 scenarios have been developed: Targeting 10 and 25 % of vitamin C loss from initial content. **Table 5** displays the simulation results; generally, a 10 % reduction in vitamin C corresponds to the least change in physicochemical properties. Thus, 30 - 75 min of immersion were suggested for the best time of immersion (using a 45 - 65 ° Brix sucrose solution).

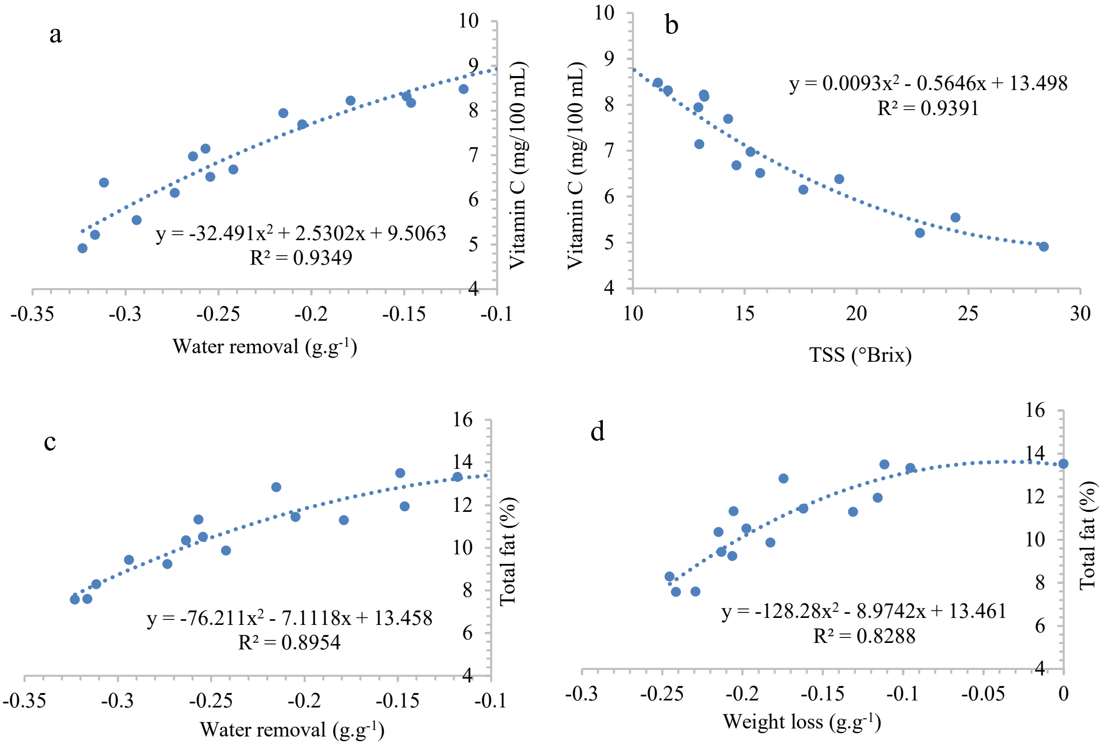


**Figure 5** Water removal vs. vitamin C (a), total soluble solids vs. vitamin C (b), water removal vs. total fat (c) and weight loss vs. total fat (d).

**Table 5** Simulation of physicochemical properties based on WR prediction and vitamin C loss. The initial amount of vitamin C is 9.570 mg/100 mL.

| **Scenario** | **OD Concentration (° Brix)** | **Vit.C (mg.100 mL$^{-1}$)** | **WR (g.g$^{-1}$)** | **Time (min)** | **Total Fat (%)** | **Firmness (N)** | **Chrome difference (ΔC)** |
|---|---|---|---|---|---|---|---|
| 10 % of Vit.C | 45 | 8.735 | –0.1200 | 75 | 13.214 | 4.597 | 5.355 |
| | 55 | 8.558 | –0.1363 | 60 | 13.011 | 4.506 | 5.811 |
| | 65 | 8.510 | –0.1404 | 30 | 12.953 | 4.482 | 5.916 |
| 25 % of Vit.C | 45 | 7.142 | –0.2336 | 210 | 10.960 | 3.831 | 7.178 |
| | 55 | 7.171 | –0.2319 | 150 | 11.007 | 3.844 | 7.174 |
| | 65 | 7.087 | –0.2367 | 105 | 10.872 | 3.806 | 7.183 |

## Conclusions

Using 55 ° Brix solution resulted the highest WR and SSG values. Increasing the solution concentration (65 ° Brix) did not promote WR and SSG rates. The 2nd-order polynomial model fits the mass transfer parameters. WR significantly affects the texture of avocado as well as the total amount of vitamin C and fat. WL contributed to a decrease in total fat, while sucrose uptake (TSS) reduced vitamin C. WR has a significant impact on the color change (ΔC). The sucrose layer protects the sample from the browning effect. Combining the WL and physicochemical property models is useful for designing OD processes and predicting the final fruit quality condition. For further research, it is necessary to investigate the use of other types of carbohydrates, such as stevia, honey, or other types of natural sugar, and their effect on mass transfer parameters (dehydration rate), physicochemicals (preventing the loss of nutrients) and good sensory acceptability.

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