Comparative study of various drying processes at physical and chemical properties of strawberries (Fragaria var. camarosa)

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Abstract

The objective of this work was to study and compare different drying processes of strawberry. The impact of DIC as texturing process within a swell drying operation was quantified when inserted before the second stage of hot air drying (swell drying SD). The obtained results showed that DIC treatment has a great impact on drying kinetics and performances compared to those of classical hot air drying. The drying of DIC-textured strawberry was accelerated even under low temperature (soft conditions). That can be explained by the direct impact of swelling on diffusivity and starting accessibility. Indeed, the mechanical effect of pressure drop leads to a great expansion of the structure, while the short thermal treatment time can preserve the quality. Thus, the new modified texture makes the trapped water accessible for improving the diffusion especially in the second stage of drying after the shrinkage of product, as well as in the rehydration process; the water holding capacity can be much higher. So the necessary time to reach the optimum final water content for the storage is shorter in case of DIC-swell dried strawberry compared to the classical hot air dried products.

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Keywords: Instant controlled pressure drop; capsicum; drying kinetics; rehydration kinetics; water holding capacity

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1. Introduction

Strawberry is one of the most delicate and highly perishable fruits, due to respiration, weight loss and susceptibility to fungal contamination. At the same time, they are sensitive to chemical and microbial deterioration during post-harvest storage and handling, therefore, they have a rather limited shelf life in a fresh form [1]. Hence, large range of unit operations have been proposed and used to preserve it. New operations such as swell drying and freezing of partially dried products were defined combined to Instant Controlled Pressure Drop (DIC).

DIC is a high temperature short time (HTST) treatment followed by an abrupt pressure drop towards a vacuum implying an auto-vaporization of small amount of water from the products. It hence induces an instant cooling of treated products preventing their thermal degradation. Such a cooling gotten by abruptly dropping the pressure from high saturated steam level (from 0.1 up to 0.6 MPa to about 5 kPa with a rate of $\Delta P/\Delta t>0.5 \text{ MPa s}^{-1})$ [2, 3] allows the product to cross the glass transition border. Thus the new swelled/expanded texture obtained after DIC treatment can be maintained. Thus, DIC treatment has two effects: the thermal effect as a result of the short-time/high-temperature induced by saturated steam; and the mechanical effect, which is induced by the difference between the high pressure inside the product and the surrounding vacuum. DIC enhances many unit operations such as drying; freezing and even extraction may not only maintain valuable compounds found in fresh products but can also improve both of their availability and activity. Likewise, DIC process has been used to swell-dry, decontaminate, and texture various fruits and vegetables; it ensures a high quality by improving the kinetics and the capacity of both dehydration and rehydration processes as well as the possibility of preserving and even increasing the organoleptic content and the availability of bioactive compounds such as antioxidant activity [4-6]. Moreover, dried products could be directly consumed as snacking or in many other powder forms to produce high quality puree, jam, ice-cream, baby foods, breakfast cereals, possibly rehydrated with yoghurt and bakery products [7].

The aim of this study was to compare various drying techniques; Hot Air Drying (HAD), Freeze Drying (FD), and Swell drying (SD); coupling the traditional hot air drying to DIC treatment. A comparative study was conducted to evaluate the different drying techniques in terms of drying kinetics (drying time starting accessibility, effective water diffusivity), rehydration kinetics (rehydration time, starting accessibility, effective water diffusivity), and water holding capacity of dried strawberries (Fragaria Var. Camarosa).

2. Materials and Methods

2.1. Materials

The strawberries (Fragaria Var. Camarosa) were purchased from a popular local market of La Rochelle city, France. They were transported to the laboratory and stored at 5°C for 24 h.

2.2. Methods

2.2.1. Sample Preparation

Strawberries were selected, cleaned and washed with potable water; they were subsequently cut with a hand knife into 4-5 slices. For the treatment, they were divided in three lots for being processed by hot air HAD, freeze-drying FD and swell drying SD.
2.2.2. Dehydration Methods

2.2.2.1. Hot air drying HAD

Strawberries slices were dried in the hot air dryer (Memmert: Universal Oven UNB Model 800) at 50 °C; the initial partial pressure of vapor in the air was 265 Pa with an air flux of 1.2 ms⁻¹. They were dried until attaining water content of 3% db (dry basis). These samples were recorded as HAD.

2.2.2.2. Freeze Drying FD

A freeze-drying equipment (model: RP2V, Serail, France) was used for drying the strawberry slices. The conditions were divided in three steps: external freezing (at -20 °C for 2h), sublimation (-20 °C, 0.66 Pa for 12 h) and desorption (25 °C, 0.66 Pa for 12 h). Afterword, the slices were packed in hermetically sealed bags and stored until their characterization. These samples were recorded as FD.

2.2.2.3. Swell Drying SD

The strawberries slices were firstly dried at 50 °C in the same conditions as HAD for 8h until attaining18% of water content. After drying, the slices were packed in zip plastic bags and stored in a cold room at 5 °Cfor24 h. The partially hot air-dried slices were DIC treated according to the experimental design (Table 2); to be completely dried by traditional convective hot air drying at 60 °C to reach about 3% db for approximately 1 h. These samples were recorded as SD.

Fig. 1. Schematic diagram of the DIC reactor: (1) Processing vessel; (2) Vacuum tank, (3) Quick motion valve; (4) Steam generator; (5) Condensers; (6) Vacuum pump; (7) Air compressor.

The experimental set-up has been largely described [8]; [2]; [9]; it is composed of three main elements (Fig.):

1. The processing vessel (1), where the samples are placed and treated.
2. The vacuum system, which consists mainly of a vacuum tank (2) with a volume 130 times greater than the processing vessel, and an adequate vacuum pump. The initial vacuum level was maintained at 5 kPa in all the experiments.
3. A pneumatic valve (3) that ensures the connection/separation between the vacuum tank and the processing vessel. It is capable of producing the abrupt pressure drop within the reactor in less than 0.2 s (ΔP/Δt > 0.5 MPa s⁻¹).
2.2.3. Assessment methods

2.2.3.1. Water Content

The water content of different samples (fresh, pre-dried and completely dried strawberries) was determined according to Karathanos’s method[10]. Approximately, 2.5 ± 0.1 g of each sample was dried in the oven UFE 400 (Memmert, Germany) at 65ºC for 48 h. The measurements were triplicated. The water content dry basis (% db) was calculated according to the equation (1):

$$W = \frac{m_i - m_d}{m_d}$$  \hspace{1cm} (1)

Where, W is the water content of samples (% db or kg of H_2O/100 kg of dry basis), m_i is the initial weight of the material before drying (kg) and m_d is the final weight of the material after drying (kg).

2.2.3.2. Drying Kinetics

Drying kinetics were performed for HAD and SD samples. Approximately, 3.00 ± 0.05 g of each sample was used. They were placed in the hot air oven (Memmert: Universal Oven UNB Model 800) at 65ºC and weight loss was recorded using an electronic balance (model EP2102, Ohaus, US). The weight loss was recorded every 5 minutes as interval time during the first 30 minutes, subsequently after 45, 60, 90, 120 minutes, after 120 minutes the weight loss was recorded every hour until equilibrium water content (change on weigh less than 0.01 g) was recorded.

2.2.3.3. Rehydration Kinetics

The capacity and rate of rehydration of HAD, SD and FD samples were evaluated as following: strawberry sample (about 0.51 ± 0.02 g) was placed in the clip handle tea strainers, and submerged in distilled water (at 20 ± 0.05ºC). At specific time intervals (0, 0.5, 2, 4, 6, 8, 10, 15, 30, 45, 60, 90, 120, 150 and 180 min), samples were taken off from the water, blotted with tissue paper to remove superficial water, and re weighted. Weight was recorded using an electronic balance AR2140 (OHAUS, China).

2.2.3.4. Drying and Rehydration kinetics

As reported by Allaf and Coll, drying kinetic model adopted consists in three stages: initial surface interaction, diffusion phase and paradoxical phase. The experimental results used for the mass diffusion model excluded the ones close to t=0 as well as the ones implying the paradoxical phase (long time stage); they allowed to determine the effective diffusivity (D_{eff,d}) of water within the porous medium. By extrapolating this diffusion model towards t=0, W_o was calculated as, usually, different from the initial humidity content W_i. The difference between W_i and W_o defined as the “starting accessibility” (δW_{s,d}=W_i-W_o) reflects the water quickly removed from the surface, independently from diffusion processes. Adding to this phenomenon, the drying time to get water content of 3.0% db was (t_{3.0%}).

Concerning the rehydration kinetics, a similar model has been applied. Evaluated response parameters were the values of rehydration time to get water content of 300% db (t_{300%}), the “starting accessibility” (δW_{s,r}) revealing the water immediately retained (hold) at the surface and the effective diffusivity of rehydration (D_{eff,r}).

2.2.3.5. Water Holding Capacity

The water holding capacity (WHC) for the different dried samples (HAD, SD, FD) was determined using the centrifuge technique. Two grams of the sample in powder were mixed with 20 mL distilled water, placed in 30 mL plastic centrifuge tubes, and allowed to set at room temperature (20±2 ºC) for
about 45 min prior to the test run. The tubes were centrifuged (Centrifuge Model Sigma 3K15) at 3000 rpm for 35 min. After centrifugation, the extra supernatant from the centrifuged sample was drained and the sample was reweighted. The samples were then dried in hot air oven at 65 °C for 48 h for water content determination. WHC was calculated as the amount of water (g) absorbed by 100g of dry basis.

2.2.4. Experimental Design

In order to study the effect of DIC operating parameters (saturated steam pressure “MPa” and thermal holding time “s”) on the different response parameters (effective water diffusivity, starting accessibility, the needed time to attain reach a specific water content for both drying and rehydration, and water holding capacity); a 2-parameter, 5-level central composite rotatable design (Table 2) was used with 4 factorial points and 4 axial points while the central point was triplicated. The ranges of operating parameters were defined after preliminary trials (Table 1). The 11 runs were achieved in random to minimize the effects of unexpected variability due to external factors. The analysis was carried out with the statistical program (Statgraphics, Centurion XV, USA). The mathematical empirical model applied in this study is:

\[ Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \beta_{ij} X_i X_j + \epsilon \]  

(2)

\[ Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 \]  

(3)

Where Y is the response, \( \beta_i, \beta_{ii}, \beta_{ij} \) are the regression coefficients, \( X_i \) are the independent variables, \( \epsilon \) is random error, \( i \) and \( j \) are the indices of the factors. Results were expressed by:

- surface response methodology plots to optimize the responses,
- the analysis of variance (ANOVA) to determine significant differences between independent variables (\( P \leq 0.05 \)),
- Pareto charts to identify the impact of variables on responses,
- general trends to analyze responses behavior in front of variable changes,
- empirical model coefficients to determine the models of each response, and \( R^2 \) to accurate fitting models to real data.

<table>
<thead>
<tr>
<th>Run</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<th>10</th>
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<tbody>
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<td>0.35</td>
<td>0.53</td>
<td>0.53</td>
<td>0.35</td>
<td>0.35</td>
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<td>0.17</td>
<td>0.10</td>
<td>0.35</td>
</tr>
<tr>
<td>Time t (s)</td>
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<td>20</td>
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<td>13</td>
<td>27</td>
<td>20</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

\[ \alpha (\text{axial distance}) = \frac{2}{N} \]  

\( N \) is the number of experiments of orthogonal design, i.e. of the factorial design. In this case \( \alpha = 1.4142 \).
3. Results

3.1. Experimental results

3.1.1. Drying Kinetics

The drying kinetics (drying time, starting accessibility, effective water diffusivity) was studied for control (HAD) and DIC treated (SD) strawberries (Fig. 2 and 3), the obtained results showed that the SD (DIC treated) samples had a quick drying kinetics compared to control (THD). As shown in the Fig. 2, the drying time of all SD samples was shorter than control (HAD). The necessary time to reach 4% dry basis for SD strawberry at 0.60 MPa; 20 s (DIC 1) was about 45 min, while HAD strawberry needed unidentified time to attain the same level of water content dry basis (Fig. 3).

Table 3. Results of evaluated drying kinetics parameters: water content at 120 min ($W_{t=120\text{ min}}$), drying time to reach a final water content of 0.05% db ($t_{d3\%}$), starting accessibility ($\delta W_{s,d}$) and effective water diffusivity ($D_{eff,d}$). $R^2$ is the correlation coefficient between the experimental and predicted data values of the model.

<table>
<thead>
<tr>
<th>Trial no.</th>
<th>Pressure (MPa)</th>
<th>Time  (s)</th>
<th>$W_{t=120\text{ min}}$ (% db)</th>
<th>$t_{d3%}$ (min)</th>
<th>$\delta W_{s,d}$ (% db)</th>
<th>$D_{eff,d}$ ($10^{-10}m^2 s^{-1}$)</th>
<th>$R^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIC 1</td>
<td>0.6</td>
<td>20</td>
<td>1.54</td>
<td>49.63</td>
<td>2.68</td>
<td>5.00</td>
<td>98.12</td>
</tr>
<tr>
<td>DIC 2</td>
<td>0.35</td>
<td>30</td>
<td>2.58</td>
<td>80.78</td>
<td>1.78</td>
<td>3.13</td>
<td>96.75</td>
</tr>
<tr>
<td>DIC 3</td>
<td>0.35</td>
<td>20</td>
<td>1.62</td>
<td>56.50</td>
<td>1.97</td>
<td>5.10</td>
<td>99.59</td>
</tr>
<tr>
<td>DIC 4</td>
<td>0.53</td>
<td>27</td>
<td>2.80</td>
<td>88.49</td>
<td>1.64</td>
<td>4.89</td>
<td>95.89</td>
</tr>
<tr>
<td>DIC 5</td>
<td>0.53</td>
<td>13</td>
<td>2.28</td>
<td>84.27</td>
<td>1.24</td>
<td>3.16</td>
<td>98.23</td>
</tr>
<tr>
<td>DIC 6</td>
<td>0.35</td>
<td>20</td>
<td>2.94</td>
<td>92.52</td>
<td>1.68</td>
<td>3.17</td>
<td>99.25</td>
</tr>
<tr>
<td>DIC 7</td>
<td>0.17</td>
<td>13</td>
<td>4.18</td>
<td>125.25</td>
<td>2.19</td>
<td>0.52</td>
<td>99.63</td>
</tr>
<tr>
<td>DIC 8</td>
<td>0.17</td>
<td>27</td>
<td>3.99</td>
<td>122.32</td>
<td>1.02</td>
<td>1.62</td>
<td>96.95</td>
</tr>
<tr>
<td>DIC 9</td>
<td>0.10</td>
<td>20</td>
<td>6.18</td>
<td>186.85</td>
<td>0.69</td>
<td>0.39</td>
<td>97.35</td>
</tr>
<tr>
<td>DIC 10</td>
<td>0.35</td>
<td>10</td>
<td>2.21</td>
<td>83.18</td>
<td>2.57</td>
<td>1.56</td>
<td>97.55</td>
</tr>
<tr>
<td>DIC 11</td>
<td>0.35</td>
<td>20</td>
<td>2.36</td>
<td>82.70</td>
<td>2.46</td>
<td>4.50</td>
<td>99.62</td>
</tr>
<tr>
<td>Control</td>
<td>-</td>
<td>-</td>
<td>7.45</td>
<td>448.84</td>
<td>0.30</td>
<td>0.11</td>
<td>92.24</td>
</tr>
</tbody>
</table>

Fig. 2. Drying kinetics of dried strawberries: Control (HAD) and SD, the drying was performed (at initial air temperature of 65°C, initial vapor pressure of 265 Pa, flux velocity of 1.2 m s$^{-1}$).
The drying kinetics in our study was identified through the starting accessibility $\delta W_{s,d}$ and the effective water diffusivity $D_{\text{eff},d}$, so these characteristics were studied as well. As shown in Table, $\delta W_{s,d}$ and $D_{\text{eff},d}$ of SD were increased by about 9 and 46 times respectively compared to control sample (HAD). For SD samples treated by DIC under $P=0.60$ MPa, $t=20$ s, they were 2.68% (db) and $5.00 \times 10^{-10} \text{m}^2 \text{s}^{-1}$ respectively against 0.30% (db) and $0.11 \times 10^{-10} \text{m}^2 \text{s}^{-1}$ for control sample (HAD).

![Fig. 3. Kinetics of Strawberry Drying performed at 65°C: Control HAD, and SD (DIC treated at P: 0.60 MPa, t: 20 s).](image)

3.1.2. Rehydration Kinetics

The reconstitution of dried material through the rehydration is investigated; the capacity and rate of rehydration were measured (Fig. 4 and Fig. 5). Similar to drying modeling, the rehydration response parameters were studied as well; water content dry basis at 180 min ($W_{t=180 \text{min}}$), rehydration time to attain a final water content of 300% db ($W_{r300\%}$), starting accessibility ($\delta W_{s,t}$) and effective water diffusivity.

![Fig. 4. Kinetics of dried strawberry rehydration performed at room temperature (20 ± 0.05°C): Control HAD, and SD (DIC treatments 1-11).](image)

Fig. 4 showed the rehydration kinetics (capacity and rate of water absorption) of HAD, FD, and SD samples. The obtained results illustrated an improvement in the capacity and the rate of rehydration for all SD samples compared to control (HAD). The rehydration is an important characteristic of dried food, normally affected by drying technique and drying conditions as well. Our results showed that the behavior of dried product during rehydration is drying technique dependent. The SD samples showed high capacity
with rapid rate of water uptake compared to control (HAD), however the FD samples had the highest
capacity and rate of water absorption compared to both SD and HAD samples.

During the first five minutes of rehydration time (total time: 180 min), SD samples had high water
uptake (200% db) compared to HAD as control (100% db), while FD samples were found with 550% db
with rapid rate of water uptake (Fig. 5). DIC1-SD strawberries treated under saturated steam pressure of
P: 0.60 MPa for t: 20s were found to get the highest rehydration kinetics.

![Rehydration kinetics of dried strawberries: Control (HAD) and SD (DIC point 1; P: 0.60 MPa, t: 20 s) the rehydration was performed at room temperature (20 ± 0.05°C).](image)

Fig. 5. Rehydration kinetics of dried strawberries: Control (HAD) and SD (DIC point 1; P: 0.60 MPa, t: 20 s) the rehydration was performed at room temperature (20 ± 0.05°C).
Table 4. Water Holding Capacity (WHC) and computed rehydration kinetic parameters: Wt=180 min (water content at 180 min), τ300% (rehydration time to attain a final water content of 300% db), δWs (starting accessibility), and Deff,r (effective water diffusivity). R^2 is the correlation coefficient between the experimental and predicted data values of the model.

<table>
<thead>
<tr>
<th>Trial no.</th>
<th>Pressure (MPa)</th>
<th>Time (s)</th>
<th>WHC (% db)</th>
<th>Wt=180min (% db)</th>
<th>τ300% (min)</th>
<th>δWs (% db)</th>
<th>Deff,r (10^{-10} m^2 s^{-1})</th>
<th>R^2(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIC 1</td>
<td>0.6</td>
<td>20</td>
<td>108,16%</td>
<td>299.81</td>
<td>193.57</td>
<td>39.89%</td>
<td>2.77</td>
<td>97.96</td>
</tr>
<tr>
<td>DIC 2</td>
<td>0.35</td>
<td>30</td>
<td>228,51%</td>
<td>407.67</td>
<td>66.53</td>
<td>59.95%</td>
<td>2.84</td>
<td>98.37</td>
</tr>
<tr>
<td>DIC 3</td>
<td>0.35</td>
<td>20</td>
<td>162.94%</td>
<td>392.06</td>
<td>58.40</td>
<td>41.97%</td>
<td>4.03</td>
<td>98.43</td>
</tr>
<tr>
<td>DIC 4</td>
<td>0.53</td>
<td>27</td>
<td>84.55%</td>
<td>370.60</td>
<td>85.66</td>
<td>39.37%</td>
<td>4.74</td>
<td>97.62</td>
</tr>
<tr>
<td>DIC 5</td>
<td>0.53</td>
<td>13</td>
<td>230.03%</td>
<td>390.75</td>
<td>65.01</td>
<td>48.60%</td>
<td>3.37</td>
<td>98.23</td>
</tr>
<tr>
<td>DIC 6</td>
<td>0.35</td>
<td>20</td>
<td>204.29%</td>
<td>365.00</td>
<td>61.63</td>
<td>74.85%</td>
<td>4.65</td>
<td>99.25</td>
</tr>
<tr>
<td>DIC 7</td>
<td>0.17</td>
<td>13</td>
<td>134.78%</td>
<td>444.32</td>
<td>34.41</td>
<td>23.00%</td>
<td>1.19</td>
<td>94.90</td>
</tr>
<tr>
<td>DIC 8</td>
<td>0.17</td>
<td>27</td>
<td>133.33%</td>
<td>403.18</td>
<td>60.16</td>
<td>29.50%</td>
<td>2.52</td>
<td>95.89</td>
</tr>
<tr>
<td>DIC 9</td>
<td>0.1</td>
<td>20</td>
<td>222.63%</td>
<td>467.73</td>
<td>40.24</td>
<td>45.28%</td>
<td>1.02</td>
<td>98.26</td>
</tr>
<tr>
<td>DIC 10</td>
<td>0.35</td>
<td>10</td>
<td>235.97%</td>
<td>411.12</td>
<td>44.89</td>
<td>69.59%</td>
<td>2.13</td>
<td>99.36</td>
</tr>
<tr>
<td>DIC 11</td>
<td>0.35</td>
<td>20</td>
<td>157.56%</td>
<td>394.79</td>
<td>65.96</td>
<td>71.67%</td>
<td>4.53</td>
<td>98.95</td>
</tr>
<tr>
<td>Control</td>
<td>-</td>
<td>-</td>
<td>288.97</td>
<td>613.5</td>
<td>55.48</td>
<td>10.81%</td>
<td>0.67</td>
<td>98.48</td>
</tr>
<tr>
<td>FD</td>
<td>0.6</td>
<td>20</td>
<td>190.44</td>
<td>403.97</td>
<td>37.59</td>
<td>592.94%</td>
<td>2.42</td>
<td>91.19</td>
</tr>
</tbody>
</table>

The starting accessibility δWs and the effective water diffusivity Deff,r revealing the kinetics of rehydration of dried strawberry were increased by 662% and 676%, respectively compared to the control sample HAD. SD samples treated by DIC at P=0.35 MPa for t=20 s had δWs and Deff,r of 71.67% db, and 4.5310^{-10} m^2 s^{-1}, respectively against 10.81% db, and 0.6710^{-10} m^2 s^{-1} for HAD as control. It worth to mention here that, although the rehydration of freeze dried FD samples were found with δWs higher than SD samples, one cannot assume FD rehydration as a diffusion phenomenon; it should be only based on a superficial exchange phenomenon and Deff,r of FD was incomparable in our study.

3.2. Correlation terms

The different response parameters concerning both of drying and rehydration kinetics were:

- Wt=120 min: the water content at 120 min
- τ300%: the drying time to attain water content of 3% db
- δWs,d: the drying starting accessibility,
- Deff,d: the effective water diffusivity during drying,
- Wt=180 min: the water content at 180 min as total rehydration time
- τ300%: the time to attain a final water content of 300% db,
- δWs,r: the rehydration starting accessibility
- Deff,r: the effective water diffusivity during rehydration.
Table 5. Correlations between drying and rehydration response parameters, and the Water Holding Capacity (WHC).

<table>
<thead>
<tr>
<th></th>
<th>δW&lt;sub&gt;s,d&lt;/sub&gt;</th>
<th>D&lt;sub&gt;eff,d&lt;/sub&gt;</th>
<th>t&lt;sub&gt;d3%&lt;/sub&gt;</th>
<th>δW&lt;sub&gt;s,r&lt;/sub&gt;</th>
<th>D&lt;sub&gt;eff,r&lt;/sub&gt;</th>
<th>t&lt;sub&gt;300%&lt;/sub&gt;</th>
<th>WHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>δW&lt;sub&gt;s,d&lt;/sub&gt;</td>
<td>1.00</td>
<td>0.50</td>
<td>-0.74</td>
<td>0.42</td>
<td>0.32</td>
<td>0.42</td>
<td>-0.46</td>
</tr>
<tr>
<td>D&lt;sub&gt;eff&lt;/sub&gt;</td>
<td>0.50</td>
<td>1.00</td>
<td>-0.66</td>
<td>0.32</td>
<td>0.84</td>
<td>0.62</td>
<td>-0.54</td>
</tr>
<tr>
<td>t&lt;sub&gt;d3%&lt;/sub&gt;</td>
<td>-0.74</td>
<td>-0.66</td>
<td>1.00</td>
<td>-0.60</td>
<td>-0.64</td>
<td>-0.28</td>
<td>0.56</td>
</tr>
<tr>
<td>δW&lt;sub&gt;s,r&lt;/sub&gt;</td>
<td>0.42</td>
<td>0.32</td>
<td>-0.60</td>
<td>1.00</td>
<td>-0.01</td>
<td>-0.22</td>
<td>0.04</td>
</tr>
<tr>
<td>D&lt;sub&gt;eff&lt;/sub&gt;</td>
<td>0.32</td>
<td>0.84</td>
<td>-0.64</td>
<td>-0.01</td>
<td>1.00</td>
<td>0.26</td>
<td>-0.43</td>
</tr>
<tr>
<td>t&lt;sub&gt;300%&lt;/sub&gt;</td>
<td>0.42</td>
<td>0.62</td>
<td>-0.28</td>
<td>-0.22</td>
<td>0.26</td>
<td>1.00</td>
<td>-0.46</td>
</tr>
<tr>
<td>WHC</td>
<td>-0.46</td>
<td>-0.54</td>
<td>0.56</td>
<td>0.04</td>
<td>-0.43</td>
<td>-0.46</td>
<td>1.00</td>
</tr>
</tbody>
</table>

δW<sub>s,d</sub>: Drying Stating accessibility; % db  
D<sub>eff,d</sub>: Drying diffusivity; m<sup>2</sup>s<sup>-1</sup>  
t<sub>d3%</sub>: Dehydratation time (from 10% db to 3% db); min  
δW<sub>s,r</sub>: Stating accessibility; % db  
D<sub>eff,r</sub>: Rehydration diffusivity; m<sup>2</sup>s<sup>-1</sup>  
t<sub>300%</sub>: Rehydration time from 100% db to 300% db and WHC; % db  

Normal correlations could be identified; they mainly concerned effective water diffusivity D<sub>eff,d</sub> and drying time and starting accessibility δW<sub>s,d</sub>. Water Holding Capacity WHC was correlated with effective water diffusivity during rehydration D<sub>eff,d</sub>; both revealing deep behavior. However, it was not correlated with starting accessibility δW<sub>s,r</sub>, which normally is linked to the only exchange surface.

3.3. RSM analysis

3.3.1. Drying operation

3.3.1.1. Drying time

The estimated drying time to attain 3% db as final water content from 10% db for HAD and SD samples was calculated from the Fick’s diffusional model. As observed in Table 3, the rapid drying operation was achieved for SD sample (treated by DIC) under P: 0.60 MPa, t: 20s), with time decreasing (compared to control) from 448.84 to 49.63 min.

Fig. 6 illustrates the impact of operating parameters (saturated steam pressure, thermal holding time, with constant initial water content) of DIC treatment on the necessary time of drying to obtain final water content of 3% dry basis for SD samples. We observed that the most influencing parameters was the saturated steam pressure, the higher the saturated steam pressure, the shorter the drying time, while the impact of thermal holding time was insignificant and stable as a result of nearby treatment.
Fig. 6. Effects of DIC operating parameters; Pressure (MPa) and time (s) on the drying time (td0.03%) of SD Strawberries: (left) Pareto Chart and (right) response surface.

3.3.1.2. Starting accessibility

Concerning the starting accessibility, there was no significant effect of either saturated steam pressure or thermal treatment time (results none shown). However, the mean starting accessibility value for the DIC treated sample was much higher than those of freeze dried samples (1.81% against 0.30% respectively).

3.3.1.3. Effective water diffusivity

As the drying is a water removal process, so the diffusion of water and starting accessibility during the drying were studied as well. Fig. 7 illustrated the impact of DIC operating parameters (saturated steam pressure and thermal holding time with constant initial water content) on effective water diffusivity during drying. The obtained results showed that both saturated steam pressure and thermal processing time had significant impacts on effective water diffusivity; the higher the saturated steam pressure, the higher the effective water diffusivity within the product under intensified drying conditions.

Fig. 7. Effects of DIC operating parameters; Pressure (MPa) and time (s) on the starting effective water diffusivity (Deff,d) of SD Strawberries: (left) Pareto Chart and (right) response surface.
3.3.2. Rehydration operation

3.3.2.1. Rehydration time

A comparative study of rehydration kinetics (the capacity and the rate of water uptake during a given time) was performed to compare the behavior of different dried samples (HAD, SD, and FD); the operating parameters of DIC treatment were evaluated as well but only for SD samples.

Fig. 8 showed the influence of the operating parameters (saturated steam pressure and thermal holding time with constant initial water content) of DIC treatment on the rehydration time of SD samples. The saturated steam pressure was the major parameter influencing the rehydration time; the lower the saturated steam pressure, the shorter the rehydration time. The shortest rehydration time was observed for SD samples treated at P: 0.17 MPa for t: 9s; and at P: 0.1 MPa for t: 20s; the rehydration time was then 34.41 min and 40.24 min, respectively in order to attain the 300% db as final water content.

3.3.2.2. Starting accessibility

The starting accessibility ($\delta W_{s,r}$) was defined as the amount of water available or accessible on the product’s surface after water uptake, to be subsequently diffused within the product. The effect of DIC operating parameters (saturated steam pressure P and thermal holding time t with a constant initial water content) on the starting accessibility during rehydration is illustrated in Fig. 8.

Fig. 9. Effects of DIC operating parameters; Pressure (MPa) and time (s) on the starting accessibility ($D_{e,f,r}$) during the rehydration of SD Strawberries: (left) Pareto Chart and (right) response surface.
The results showed that neither P nor t had a significant effect on $\delta W_{s,r}$. Whereas, the highest starting accessibility (74.85% db) was obtained with P: 0.35 MPa for t: 20 s compared to control (10.81% db). We observed that the starting accessibility decreased by increasing the saturated steam pressure after 0.35 MPa.

3.3.2.3. Effective water diffusivity

Effective water diffusivity during rehydration of dried products is the transfer phenomenon enables the adsorbed water on the product’s surface to be effectively diffused within the product during its rehydration. The impact of DIC operating parameters (saturated steam pressure and thermal holding time with constant initial water content) on the effective water diffusivity was shown in Fig.. The effective water diffusivity was significantly increased by increasing the saturated steam pressure; the higher saturated steam pressures the higher rate of water diffusivity during the rehydration of SD samples, whereas, the thermal holding time had a slight effect. It is interested to mention here that a similar behavior was observed for the effective water diffusivity during drying where the saturated steam pressure was the major affecting the effective water diffusivity while the effect of thermal holding time was slight reflecting a good definition of time limits and nearby treatment.

The rapid rate of effective water diffusivity $D_{eff,r}$ ($4.65 \times 10^{-10} \text{m}^2 \text{s}^{-1}$) was obtained for SD sample (treated at P: 0.35 MPa, t: 20 s) against $0.67 \times 10^{-10} \text{m}^2 \text{s}^{-1}$ for control sample (HAD) with an increase of 694% (table 4). As mentioned before that the rehydration of freeze dried products is not diffusion phenomenon but it based on superficial exchange phenomenon; thus the effective water diffusivity of FD was incomparable in our study.

![Standardized Pareto Chart for Deff](image1)

**Fig. 10.** Effects of DIC operating parameters; Pressure (MPa) and time (s) on the effective water diffusivity ($D_{eff,r}$) during the rehydration of SD Strawberries: (left) Pareto Chart and (right) response surface

3.3.3. Water holding capacity

The capacity of water holding of strawberry samples dried by different techniques of drying was studied, was studied (Fig. 12), the water holding capacity was significantly decreased with increasing the saturated steam pressure; the higher saturated steam pressure the lower water holding capacity, while the thermal holding time had insignificant effect. The HAD strawberry samples was found with the highest values of water holding capacity compared to FD and SD samples. The high capacity (235.97%) to hold water was found for SD treated at P: 0.35 and t: 10 s (Table 6). The study of DIC operating parameters (saturated steam pressure and thermal holding time at constant initial water content) showed that neither the saturated steam pressure nor thermal holding time had a notable effect on this response parameter.
Fig. 11. Effects of DIC operating parameters; Pressure (MPa) and time (s) on the water holding capacity (% db) of SD Strawberries: (left) Pareto Chart and (right) response surface

Table 6: Water Holding Capacity (% db) of dried Strawberries: Freeze drying FD, Traditional Hot Air Drying; THD (control), and Swell Drying SD.

<table>
<thead>
<tr>
<th>THD</th>
<th>FD</th>
<th>SWELL DRYING SD samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHC (%db)</td>
<td>289</td>
<td>190</td>
</tr>
</tbody>
</table>

4. Discussion

Drying is one of the most common methods to preserve strawberries[7, 11, 12] and following up its kinetics is the best way to design, predict a model and optimize this process [1, 13, 14]. The traditional food hot air drying commonly includes two periods. The first involves quick water removal (until the critical moisture point) often associated with product’s shrinkage, which finally dramatically reduces the diffusivity of water within the material with almost great deformation of the product [15-17]. The second has limited water removal as a result of the low diffusivity value, implying long-time period, high heating temperature and hence thermal degradation [18] revealed by a loss of vitamins and bioactive molecules, degradation of pigments and color, and poor nutrition value with a high energy consummation.

So new trends in food processing are focused on the marriage between new and innovative techniques to the Traditional Hot Air Drying (HAD) with the objective of drying resulting in costs reduction (short drying-time with low energy consumption), and product’s quality preservation.

In this study, Instant Controlled Pressure Drop DIC was coupled to HAD; defined as Swell Drying SD, in order to intensify the HAD. The operation can be considered as an intensification of HAD. The obtained results showed the shorter time of SD compared to HAD (control) with lower final water content. This can be explained by the structural modifications occurred as a result of texturing by DIC. Some of these modifications were the breakdown of the plant cell walls entrapping water inside. SD is a relevant solution to dried product’s shrinkage (texture compactness), product deformation, super heating, and hence thermal degradation (loss of vitamins and bioactive molecules, degradation of pigments and color, and poor nutrition value).

Texturing by DIC induced an auto vaporization of a small amount of product’s water resulting in open texture as a result of gas (saturated steam) expansion within the product. The later produced some mechanical constrains on the cell wall leading to its expansion and to get pores specially since pressure dropping towards a vacuum allows crossing the glass transition border.
The internal water transfer (water diffusion) is the driven force in both drying and rehydration, the open and spongy texture improved significantly the starting accessibility and effective water diffusivity during both drying and rehydration operations. The higher the effective water diffusivity, the shorter the drying and/or rehydration times. These results are in agreement of those reported by other authors reporting time decreasing from 205 min to 11.10 min for paddy rice [19][20]. It was also reported a significant decrease in drying time of apple from 6 h to 1 h [21] and Al Haddad et al. showed a significant decrease in drying time, when they studied the DIC swell drying SD coupled to a final drying by microwaves (700W). This study was carried out on apple and mango cubes. They reported needed time was less than 5 min in the case of DIC coupled to the drying by microwaves, followed by 2 hours for the usual SD. While, they found that HAD needed 8 hours to attain a higher water content (5% db as final moisture content) [22].

The low final water content of SD samples was explained by the rapid removal of water as the diffusivity was improved compared to HAD samples. Others studies reported different levels of final moisture content confirming that the drying kinetics and the final water content are drying techniques and conditions dependent.

Water holding capacity revealed the amount of water absorbed during rehydration (capacity and rate), the low capacity of water holding of SD compared to HAD is due to the structural modification, the texture was become open and spongy which makes it difficult to catch and hold the absorbed water, this can explain the low capacity of water holding for FD samples, in addition to the texture collapse of FD products. The low water holding capacity for SD strawberries may be due to some breaking cell walls.

The RSM analysis for all response parameters showed that DIC saturated steam pressure was the major affecting on the studied response parameters. This can be explained by the mechanical strains induced as a result of steam expansion within the product implying some chemical and textural modifications.

5. Conclusions

Different drying techniques were studied in terms of drying kinetics, starting accessibility and water effective diffusivity during drying. Some of physical and functional properties of dried peppers were studied as well, such as rehydration kinetics (capacity and rate), starting accessibility and water effective diffusivity during rehydration and the water holding capacity.

The obtained results shows that the swell drying SD can be used as an alternative technique to dry the foodstuffs with high quality during short time decreasing the costs of the operation. The product quality attributes are drying technique dependent. The SD is a flexible process; the operating parameters (saturated steam pressure and thermal processing time) can be optimized to meet the product’s quality and attributes depending on industrial and consumer needs as well.

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References


