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Impact of instant controlled pressure drop treatment on dehydration and rehydration kinetics of green moroccan pepper (*Capsicum annuum)*

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Abstract

A comparative study of various drying techniques were carried out on Green Moroccan Peppers GMPs, Traditional Hot Air Drying, Swell Drying SD, and freeze drying, in order to compare the dried product's behavior during drying and rehydration. Moreover, starting accessibility, and water effective diffusivity during drying and rehydration were studied. The water holding capacity of dried GMPs were investigated as well. The impacts of Instant Controlled Pressure Drop process (DIC) on dehydration and rehydration kinetics and functional properties (water holding capacity) were compared to Freeze Drying (FD) and Traditional Hot Air Drying processes (THD). DIC treatment was carried out on pre-dried peppers (classical hot air drying at 50 °C, 265 Pa initial partial pressure of vapor in the air flux, 1.2 m s^{-1}) to reach a moisture content of 20% dry basis varying the saturated steam pressure (ranged from 0.1 to 0.6 MPa) and heating time (ranged from 9 to 35 s) and keeping the initial water content constant at 20% db. Drying and rehydration kinetics of DIC-textured and untreated peppers were well interpreted by a specific model coupling a starting superficial interaction with Fickian diffusion. Response parameters (dependent variables) were the dehydration and rehydration starting accessibility δW_s (g H_2O/g dry matter), effective diffusivity D_{eff} (m^2 s^{-1}) and drying time $t_{d0,05\%}$ (min). Response Surface Methodology RSM was employed.

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Compared to THD, DIC treatment dramatically increased the starting accessibility and the effective water diffusivity during hot air drying; it allowed the drying time needed to get a final water content of 0.05% db, to decrease by 1.7 times. Regarding the rehydration ability, the time needed to reach 300% db, were reduced 3.7 times under optimum DIC conditions. Fickian diffusion model could not explain FD rehydration, which appeared as a pure water/surface interaction. Water Holding Capacity of DIC dried products was higher than FD and THD.

Keywords:Instant Controlled Pressure Drop; capsicum; drying kinetics; rehydration kinetics; water holding capacity

1. Introduction

Dehydration is one of the oldest and most widely used methods for fruit and vegetable preservation. Its main objective is to remove a main part of water to reach the level at which microbial spoilage and deterioration reactions are minimized or stopped [1-2]. Hot air drying is one of the most frequently used operations for food dehydration; nevertheless it damages structural, physical and chemical characteristics usually because of the overheating during the second stage of drying as a result of shrinkage phenomenon which is taken place in drying process. To overcome this phenomenon, a marriage of different drying process is used [3].

Many conventional methods are used in food drying including hot air drying, vacuum drying, drum drying, spray drying, freeze-drying, and so forth. Numerous emerging technologies have been developed recently as alternatives to more well-known methods (microwave drying, irradiation, ultrasounds etc.) nevertheless the high cost of some new technologies limits their application[4].

For this reasons new high-performance industrial drying technologies are needed. At this respect, new processes as the Instant Controlled Pressure Drop (DIC) could satisfy simultaneously such constraints. DIC is an innovative process, based on the thermo-mechanical effects induced by rapidly subjecting raw materials to saturated steam (from 0.1 up to 0.6 MPa), and followed by an abrupt pressure drop towards a vacuum (about 5 kPa) triggers simultaneously autovaporisation of volatile compounds and instantaneous cooling of the products which stops thermal degradation and induces swelling and possibly rupturing of the cell walls [5-6].

Peppers (genus Capsicum var.) belong to Solanaceae family; they are widely used because of their strong pungency, aroma, color and nutritional value [7-8]. Their importance gradually increased to become one of the most consumed spice crops worldwide [8]. In addition, the food industry employs them widely as coloring and flavoring agents in sauces, soups, processed meats, lunches, sweetmeats and alcoholic beverages [9]. They are commonly consumed in their dried form, nevertheless traditionally sun drying is carried out at the open air and exposed to the sunlight, which takes a lot of time (8-21 days) and decrease their quality [10-11]. Due to this extensive use, an increasing amount of research on the evaluation of dried pepper quality has concentrated on improving the preservation of this product [12-15].

This work aimed to determine the impact of DIC treatment on the dehydration and rehydration kinetics of Green Moroccan Peppers (Capsicum annum), in order to optimize the operation based on the final quality of the products. By modeling the process and evaluating its performances, we could compare the accuracy of DIC treatment to hot air traditional drying and freeze-drying. Moreover, the water holding capacity was also evaluated as an important physical property.

Nomenclature

ρ_w	apparent density of water in the material (kg m^{-3})
ρ_m	apparent density of water in the material (kg m^{-3})
v_w	absolute velocity of water flow within the porous medium (m s^{-1})
v_m	absolute velocity of solid medium (m s^{-1})
m_i	weight of the material before drying (kg)
m_d	weight of dry matter material (kg)
W	moisture content (kg water/kg dry matter)
W_0	value of moisture content calculated from diffusion model extrapolated to t=0 (% db)
W_∞	equilibrium water content at a very long time $t \rightarrow \infty$ (kg water/kg dry matter)
W_i	initial moisture content (kg water/kg dry matter)
D_{eff}	effective diffusivity of water within the solid medium (m^2 s^{-1}) for dehydration d or rehydration r
d_p	half thickness of peppers (m)
k	slope of y= Ln (Moisture Ratio) as a function of time (s^{-1})
δW_s	starting accessibility of water (kg water/ kg dry matter) for dehydration d or rehydration r
τ	Fick's number
A_i, q_i	Crank's coefficients according to the geometry of solid matrix
β_i	coefficient of linear effect
β_{ii}	coefficient of square effect
β_{ij}	coefficient of interaction effect
β_0	offset term
x_i	coded value of the ith variable
X_i	uncoded value of the ith test variable
X_0	uncoded value of the ith test variable at the center point
Y	predicted response
$t_{d5\%}$	drying time to reach moisture content of 5% db (min)
$t_{d300\%}$	rehydration time to reach moisture content of 300% db (min)
m_i, m_d	weights of the material before and after drying, respectively (kg)

2. Materials and Methods

2.1. Materials

Physiologically ripe Green Moroccan Peppers (GMPs), var. Capsicum annum were bought on March 2011, from a popular local market at La Rochelle, France. Products were transported to the laboratory and stored during 24 h at 5 °C.

2.2. Treatment methods

2.2.1. Sample Preparation

Before drying treatments, good quality peppers (absence of mold and insect contamination) were manually selected and washed. From whole washed fruit, peduncles, seeds, capsaicin glands, and placenta, were eliminated. The Pericarp was manually cut in rounds (to an average thickness of approximately 5.5±0.02 mm). Rounds peppers were divided in three lots, one for Traditional Hot Air Drying (THD), second for Freeze Drying (FD) and third for swell drying SD (Traditional Hot air Drying coupled to DIC process: SWELL-DRYING). Drying conditions are described in next section. Moisture content (dry basis db) of fresh peppers was measured as described in section 2.2.4.

2.2.2. Dehydration Methods

2.2.2.1. Freeze Drying

Traditional freeze drying (FD) was applied on GMPs, under these conditions of fundamental stages of treatment: external freezing (-20 °C for 2h), sublimation (-20 °C, 0.66 Pa for 12 h) and desorption (25 °C, 0.66 Pa for 12 h). Experiments were carried out in a RP2V standard freeze drier model (Serail, France).

2.2.2.2. Traditional Hot air Drying (THD)

Traditional hot air drying (THD) of GMPs was applied at 50 °C and 265 Pa as, respectively drying temperature and partial pressure of vapor in the 1.2 m s^{-1} air flux. Drying process ended when sample moisture content recorded no significant changes during the time (< 0.1% db). The product was cooled down at room temperature for 5 min and then packed in zip plastic bags. Experiments were carried out in a cabinet dryer D06064UNB 800 Model (Memmert, Germany).

2.2.2.3. Traditional Hot Air drying coupled to autovaporization DIC process (SWELL-DRYING):

- *Main stages of Swell-Drying SD*

The swell drying process consisted in three stages (Fig.1):

1. First stage (pre-drying): round fresh GMPs were dried under the same air conditions of THD, but in this case, drying process was stopped when samples reached 20% db as moisture content.
2. Second stage (DIC treatment), carried on a laboratory scale DIC reactor; it included four steps:
   2.1. First step: peppers were introduced in a processing reactor in which a vacuum of 30 mbar was established (Fig. 1a). The initial vacuum was carried out to facilitate and mediate the close exchange between the incoming steam and the product surface.
   2.2. Second step: saturated steam was injected into the reactor at a fixed pressure level (from 0.1 up to 0.6 MPa) (Fig. 1b). Once tested pressure was reached, this was maintained for a given time (from 5 up to 35 s) (Fig. 1c). Pressure and time operating parameters were selected as shown in experimental design section.

2.3. Third step: once treatment time finished, samples were subjected to an instant controlled pressure drop ($\Delta P / \Delta t > 0.5$ MPa.s^{-1}) towards vacuum (Fig. 1d).
2.4. Fourth step: after a vacuum stage, pressure was released toward the atmospheric pressure (Fig. 1e) and samples were removed from the reactor

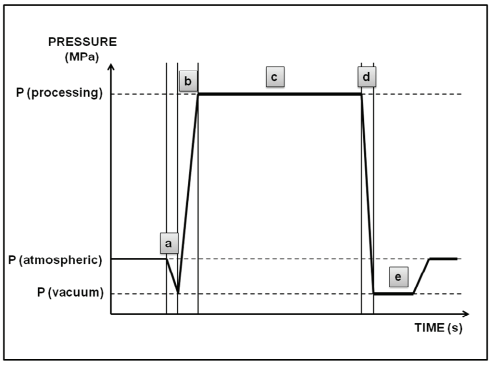

Fig.1. Schematic time-temperatures-pressures profiles of a DIC processing cycle. (a): establishment of the vacuum within the processing reactor; (b): injection of steam at the selected pressure; (c) maintain of treatment pressure during selected time; (d): instant controlled pressure drop towards vacuum and (e): establishment of the atmospheric pressure within the processing reactor

3. Third stage (post-drying), after DIC treatment samples were submitted to a second period of drying under the same conditions of THD. The follow-up of the operation allowed to establish drying kinetics versus time W=f(t). Dried products were allowed to cool down at room temperature for 5 min and then packed in polyethylene zip bags.

- *DIC treatment*

DIC equipment used to treat pre-dried peppers was a laboratory scale reactor MP model (manufactured at ABCAR-DIC Process; La Rochelle, France). Fig. 2shows a schematic diagram of DIC equipment.

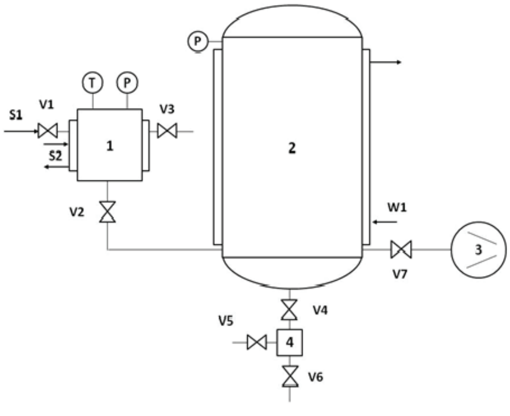

Fig. 2. Schematic diagram of DIC Equipment: (1) DIC Reactor, (2) Vacuum tank, (3) Vacuum pump, (4) Trap, V1-V7-valves, S1 and S2- saturated steam injection, W1- cooling water, P-Pressure gauge and T- thermocouples

The DIC equipment consists of three major components; first a double jacket processing vessel (1) where samples are set and treated, pressure is provided by steam and/or air injections, and a vacuum valve; second, the vacuum system, which consists mainly of a vacuum tank (2) and a water ring vacuum pump (3) and third the decompression system (V3). Processing vessel (18 L) is connected to the (2) vacuum tank (1600 L) by a 180-mm butterfly valve (V2), which is driven pneumatically. Saturated steam (S1) is supplied through the valve (V1) into the processing vessel. The double jacket is heated by saturated steam (S2). The reactor is equipped by a vent (V3). The vacuum tank is cooled by tap water (W1) circulating in a double jacket. Manometers and pressure transducers give the vessel and tank pressures. Condensates are removed from the reservoir through the trap (4) with a system of valves (V4, V5 and V6) [16].

For the DIC treatment of peppers, samples were enclosed in a perforated stainless steel container (175 mm of diameter) and set in the reactor (1) at atmospheric pressure and then this was closed. By opening the valve (V2) an initial vacuum was performed. After closing (V2), saturated steam was injected into the reactor by the valve (V1), injection was maintained manually during the given time of treatment, and it was afterward closed. The abrupt pressure drop towards a vacuum was carried out by an abrupt opening (<0.2 s) of the valve (V2). This abrupt adiabatic pressure drop triggered auto-vaporization of superheated liquid contained in the material, instantaneous cooling, structure swelling and even rupture of the cell walls as well. Finally, atmospheric pressure was restored in the autoclave by the vent (V3) and the material was recovered. The pressure in the vacuum tank (2) was almost constant and equal to 4 kPa. The processing parameters were heating time and pressure in the autoclave during the heating period maintaining the initial water content of pepper constant (20% db).

2.3. Assessment methods

2.3.1. Water Content Determination

Water content was determined according to Karathanos' method [17], which is accurate for agricultural crops with considerable amounts of sugar. Water content of fresh, pre-dried and complete dried peppers was gravimetrically measured in triplicate by drying2.5 ± 0.1 g of sample in a laboratory drying oven UFE 400 (Memmert, Germany), at 65 °C during 48 h. The water content dry basis db (W) of samples was calculated using the following equation:

$$W = \frac{m_t - m_d}{m_d} \tag{1}$$

2.3.2. Drying and rehydration kinetics

2.3.2.1. Dehydration Kinetics

Drying kinetics was only carried out for THD (as control sample) and SD samples (SD) using 3.05 ± 0.03 g samples. During oven drying, samples were weighted at regular intervals of time throughout the total drying period. The kinetics was followed up starting with approximately 20% db as initial water content. Sample's weight was recorded every 5 minutes (as interval time) during the first 30 minutes, then at 45, 60, 90, 120 minutes. Subsequently, the samples' weight was recorded (using an electronic balance EP2102, model Ohaus, United States) every hour until equilibrium water content (weight changes less than 0.01 g during 2 hours) was obtained. . Moreover, the evolution of sample's thickness was measured as well at the beginning and the end of the drying kinetics using a digital caliper. The change in sample's thickness was recorded as mean value of readings.

2.3.2.2. Rehydration Kinetics

Rehydration kinetics was studied for THD, SD, and FD samples. For this purpose dried peppers (0.51 ± 0.02 g) previously weighed with clip handle tea strainers, were submerged in distilled water at room temperature (19.5 ± 0.05 °C) during a given time interval times (0, 0.5, 2, 4, 6, 8, 10, 15, 30, 45, 60, 90, 120, 150 and 180 minutes). Dried peppers samples were withdrawn from the distilled water, blotted with tissue paper to remove superficial water, and reweighted (using a precision electronic balance AR2140, model OHAUS, China).[18]. The evolution in both weight and thickness of samples was followed up during the rehydration operation at every interval time.

2.3.2.3. Mathematical Modeling of drying and rehydration kinetics

For modeling the dehydration kinetics of peppers, the study of Mounir& Allaf (2009) [19] has been adopted. This study focus on the four physical mechanisms of transfer occurred during drying (Fig. 3.):

1. External heat transfer: from outside to the product surface, energy is generally brought by conduction or convection.
2. Internal heat transfer: within the product to conduct the necessary energy to transform water into vapor, energy is transmitted by conduction.
3. Internal water transfer: within the product, carried out either in liquid form or in vapor phase, by various process including capillarity for liquid form, and molecular diffusivity for both liquid and vapor phases. Mechanisms are regulated by the gradients of respectively water content and vapor partially pressure as driving forces.
4. External water transport: (in vapor form) from the product's surface towards outside is the principal driving force of dehydration. At the beginning of the operation, this transport is rapid and depends on the interface surface (enhanced by greatest gradient of humidity); afterward it is normally limited by the internal diffusion.

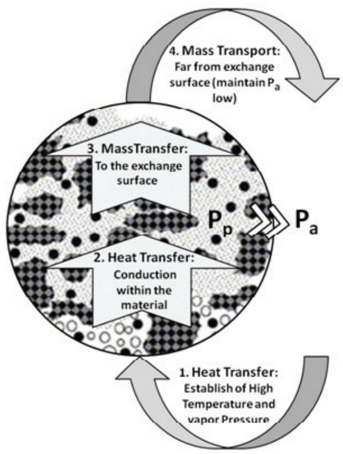

Fig. 3. Four physical transfer phenomena occurred during drying process. 1: External heat transfer by conduction or convection. 2: Internal heat transfer by conduction. 3: Internal mass transfer by diffusion. 4: External mass transport from product surface to surrounding air. Drying process can be intensified by increasing Pp (vapor partial pressure at the exchange surface of the product) being higher than the Pa (vapor partial pressure of external air)

By assuming that external heat and mass transfers do not limit the whole operation through adequate technical conditions of air flow (temperature, moisture content and velocity), only internal transfers may intervene as limiting processes [20]. In such conditions, as water transfer within the product seems to be the principal restrictive factor of the drying kinetics, the model proposed by Mounir and Allaf (2009) is adopted, with a Fick-type's relation [21]:

$$\frac{\rho_W}{\rho_m}(\vec{v_W} - \vec{v_m}) = -D_{eff}\vec{\nabla}\left(\frac{\rho_W}{\rho_m}\right) \tag{2}$$

At this stage of the operation, modification of structure through shrinkage as well as swelling phenomena may be assumed to be neglected and ρ_m=constant and v_m=0, Equation (2) becomes:

$$\rho_W\vec{v_W} = -D_{eff}\vec{\nabla}\rho_W \tag{3}$$

Using the balance mass, the second Fick law is obtained:

$$\frac{\partial\rho_W}{\partial t} = \vec{\nabla}\cdot D_{eff}\vec{\nabla}\rho_W \tag{4}$$

Although the effective diffusivity D_{eff} considerably varies versus the system temperature, it can be considered constant by assuming the hypothesis of both structural and thermal homogeneities:

$$\frac{\partial\rho_W}{\partial t} = D_{eff}\vec{\nabla}\cdot\vec{\nabla}\rho_W \tag{5}$$

And by assuming a one-dimensional flow, the whole process is controlled by the only mass transfer:

$$\frac{\partial\rho_W}{\partial t} = D_{eff}\frac{\partial^2\rho_W}{\partial x^2} \tag{6}$$

The provided solutions to this diffusion equation closely depend on the initial and boundary conditions. Using Fick's second law, a number of mathematical solutions have been proposed; in this study Crank's solution according to the geometry of the solid matrix was adopted [22]:

$$\frac{W_\infty - W}{W_\infty - W_1} = \sum_{i=1} A_i \exp\left(-q_i^2\tau\right) \tag{7}$$

where W, W_∞ and W_1 are the amounts of water content (db) in the solid matrix at time t (W), at equilibrium at very long time $t \rightarrow \infty$ (W_∞) and at the starting diffusion time (W_1), respectively. W_1 is the value of W at the time t_1 chosen as the beginning of the diffusion model gotten only for long time experiments. The difference between W_0 (theoretical value of W gotten by extrapolating the diffusion model) and the experimental one W_i, at t=0, corresponds to the amount of water available on the surface and extracted from it in a very short time. By modifying matrix structure, improving porosity, the values of W_∞ and W_0 vary depending on and characterizing DIC treatment.:

$$\frac{W_\infty - W}{W_\infty - W_1} = \sum_{1}^{\infty} A_i \exp\left(-q_i t\right) = \frac{8}{\pi^2} exp^{-\frac{\pi^2 D_{eff} t}{4d_p^2}} + \frac{8}{9\pi^2} exp^{-\frac{9\pi^2 D_{eff} t}{4d_p^2}} + \frac{8}{25\pi^2} exp^{-\frac{25\pi^2 D_{eff} t}{4d_p^2}} + \frac{8}{49\pi^2} exp^{\square} \tag{8}$$

Coefficients of Crank solutions A_i and q_i are given according to the matrix geometry Fick' s number (τ) is defined as:

$$\tau = D_{eff} * t/dp^2 \tag{9}$$

wheredp is the characteristic length (m). For this case an infinite plate is consider and dp is the half thickness of peppers. By limiting equation 8 to its first term, it could be expressed as:

$$\frac{W_\infty - W}{W_\infty - W_0} = Aexp(-kt) \tag{10}$$

The logarithmic representation of equation 10 as a straight line leads to determine D_{eff} from the slope *k:*

$$LN(Y) = LN\left(\frac{W_\infty - W}{W_\infty - W_0}\right) = kt \tag{11}$$

Where *k*corresponds to:

$$k = \frac{\pi^2 D_{eff}}{4{d_p}^2} \tag{12}$$

And the effective diffusivity is:

$$D_{eff} = \frac{4{d_p}^2}{\pi^2} k \tag{13}$$

The experimental data used for such empirical model exclude the ones concerning the points close to t=0; the extrapolation of the model thus obtained allowed the W_0 to be determined as, generally, different from the initial humidity content W_i. The difference δW_s between W_i and W_0 reveals the humidity quickly removed from the surface independently from diffusion processes; this quantity has been defined as "*starting accessibility of water*.

$$\delta W_s = W_i - W_0 \tag{14}$$

The values of drying time to get water content of 0.05% db ($t_{d0.05\%}$), the "starting accessibility" ($\delta W_{s,d}$)and the drying effective diffusivity ($D_{eff,d}$) have been considered as the main response parameters characterized on drying process.

For rehydration kinetics, similar argument has been applied, evaluated response parameters were the values of rehydration time to get water content of 300% db ($t_{r300\%}$), the "rehydration starting accessibility" ($\delta W_{s,r}$)and the rehydration effective diffusivity ($D_{eff,r}$)

2.3.3. Water Holding Capacity

Water holding capacities were evaluated on THD, SWELL-DRYING process and for FD. For this purpose dried peppers were ground in a Grindomix GM-100 (Retsch, Germany) at 6.5 x 1000 rpm for 3 min, and moisture content of powders was determined. On 30-mL centrifuge plastic tubes, 22.5 ml of distilled water were added to 2.5 g of powder peppers at room temperature (23 °C). Sample tubes were hand shaken vigorously for 1 min then incubated for 1 hour at room temperature. After standing,samples were centrifuged twice (3K15 SIGMA centrifuge model, Germany), first at 3500 rpm, 23 °C for 30 min and the second for 5 minutes. Between the first and second centrifugations supernatant water was eliminated. The final water content represented the calculatedWHC (% db) determined as mentioned in moisture content section). Applied method was based on [23] protocol, with slight modifications [22].

2.4. Experimental Design and Statistical Analysis

The different responses were considered as dependent variables and analysed through a correlation matrix and a RSM method; this last concerned:

- A central composite rotatable design with two-independent variables (n=2), DIC steam pressure “P” (MPa) and the thermal treatment time “t” (s), and five levels (- α , - ,-1, 0, +1 and + α) was used, to reduce experimental points [24-25]; the . The design included 11 total experiments:
  - Factorials points (2^n): 4 points (-1/- / -1; -;-1/+1; +1/-1 and +1/+1)
  - Star points (2*n): 4 points (- α /0; + α /0; 0/- α and 0/+ α)
- Three repetitions of the central points: (0,0)

The value of α (axial distance) depending on the number of parameters considered (n) is calculated as $\alpha = \sqrt[4]{2^n}$ $=(2^n)^{0.25}$. For this study, α =1.4142.

In order to select the range values of DIC selected variables “P” and “t”, some preliminary experiments were carried out. The operative DIC parameters applied were shown on Table 1.

Table 1. Coded levels for independent variables used in the developing experimental data

	Coded level				
	– α	-1	0	+1	+α
Steam pressure (MPa)	0.10	0.17	0.35	0.53	0.60
Processing time (s)	5	9	20	31	35

Run experimental values were shown in Table 2.

Table 2. Run experimental values

	DIC Treatment										
	1	2	3	4	5	6	7	8	9	10	11
Pressure (MPa)	0.6	0.35	0.35	0.53	0.53	0.35	0.17	0.17	0.1	0.35	0.35
Time (s)	20	35	20	31	9	20	9	31	20	5	20

The experiments were run in random in order to minimize the effects of unexpected variability in the observed responses due to extraneous factors.

According to the statistical method, a second order polynomial function was assumed to approximate the response under considerations. The general (equation 14) and specific (equation 15) models applied in this study were applied [26]:

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i \chi_i + \sum_{i=1}^{n} \beta_{ii} \chi_i^2 + \sum_{i=1}^{n-1} \sum_{j=2}^{n} \beta_{ij} \chi_i \chi_j + \varepsilon \qquad (15)$$

$$Y = \beta_0 + \beta_1 \chi_1 + \beta_2 \chi_2 + \beta_{11} \chi_1^2 + \beta_{22} \chi_1^2 + \beta_{12} \chi_1 \chi_2 \qquad (16)$$

Where Y is the response, β_i, β_{ii}, and β_{ij} are the regression coefficients, $X_{1,2}$ are the independent variables, ε is random error, i and j are the indices of the factors.

Design analysis of results data was done by the surface response methodology, performed on Statgraphics Plus for Windows, (4.1 version). This method is based on predicted model equation allows obtaining the surface response plots, to optimize the responses. other analysis subsequently were performed, as analysis of variance (ANOVA) to determine the significant differences between independent variables ($P \leqslant 0.05$):

- 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.

Dependent variables of the study of dehydration and rehydration kinetics used, the starting accessibility ($\delta W_{s,d}$and $\delta W_{s,r}$), the effective moisture diffusivity ($D_{eff,d}$ and $D_{eff,r}$) and the time to reach a specific moisture content ($t_{d0.05\%}$ and $t_{r300\%}$) were studied as responses The water holding capacity (WHC) was evaluated as a quality parameter of dried products. An initial statistical analysis of the correlations between the various response parameters was carried out in order to well understand the phenomena and to reduce the number of dependent variables to be studied.

3. Results

3.1. Experimental results

3.1.1. Drying Kinetics

The drying kinetics was studied on fresh Green Moroccan Peppers with 1094.74 kg H_2O/100 kg dry matter as initial water content, till 20 kg H_2O/100 kg dry matter (pre-dried products). The GMP drying kinetics study was performed on the second phase of drying (from around 20% db to 0.5% db) under THD and SWELL-DRYING conditions (Fig. 4. and Fig. 5.).

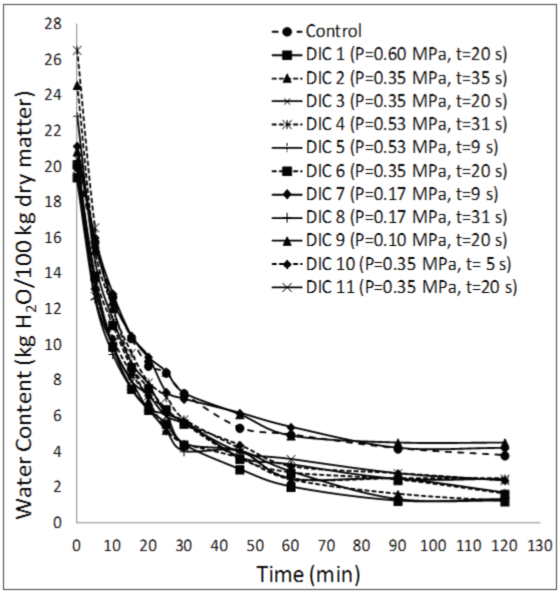

Fig. 4. Drying kinetics of Green Moroccan Peppers: Control (THD) and SD (DIC treated) Air flux conditions of drying (T: 50 °C; P: 265 Pa and velocity: 1.2 m s^{-1})

As observed in Fig. 4., the SD (DIC treated) samples had a quick drying kinetics compared to the control (THD), where the SD samples needed about 35 min to obtain 4% db as final water content against 90 min for the control sample (THD) (Fig. 5.). Fig. 8 shows these results perceived through RSM analysis. Even at very low severity air flux conditions of drying (50 °C as inlet air temperature; 265 Pa as air moisture partial pressure and 1.2 m s^{-1} as velocity), samples treated by DIC under P=0.35 MPa, t=35 s and P=0.6 MPa, t=20 s could reach a final water content of 1.21% and 1.23% db, respectively, while FD was found at much higher value (4.5± 0.4% db) (Table 3).

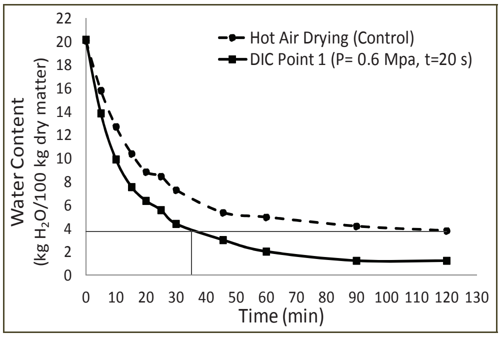

Fig. 5. Drying kinetics of Green Moroccan Peppers: Control (THD) and SD; DIC Point 1 (P=0.6 MPa, t= 20 s)

The modeling of drying was achieved leading to determine the effective water diffusion $D_{eff,d}$ and the starting accessibility $\delta W_{s,d}$, as well as the water content at 120 min ($W_{t=120\ min}$), the necessary drying time to attain 5% as final water content dry basis ($t_{d5\%}$). These response parameters were illustrated in Table 3.

As shown in Table 3, the starting accessibility and water effective diffusivity were increased by 2.5 times compared to the control sample (THD). SD samples treated by DIC under P=0.35 MPa, t=35 s had a starting accessibility and a water effective diffusivity of 12.66 % db and 24.19 x $10^{-10} m^2 s^{-1}$, respectively against 5.64 % db and 10.16 x $10^{-10} m^2 s^{-1}$ for the control sample (THD).

Table 3. Results of evaluated drying kinetics parameters: water content at 120 min ($W_{t=120\ min}$), drying time to reach a final water content of 0.05% db ($t_{d5\%}$), starting accessibility (δWs,d) and effective diffusivity (Deff,d). R^2 is the correlation coefficient between the experimental and predicted data values of the model

Trial no.	Pressure (MPa)	Time (s)	$W_{t=120\ min}$ (% db)	$t_{d5\%}$ (min)	$\delta W_{s,d}$ (% db)	$D_{eff,d}$ ($10^{-10} m^2 s^{-1}$)	R^2 (%)
DIC 1	0.6	20	1.23	140.53	8.09	25.00	97.85
DIC 2	0.35	35	1.21	119.97	12.66	24.19	99.50
DIC 3	0.35	20	1.31	168.53	8.90	23.53	97.76
DIC 4	0.53	31	2.49	152.66	11.83	23.42	97.58
DIC 5	0.53	9	2.45	159.48	10.12	21.91	98.08
DIC 6	0.35	20	1.62	168.53	7.39	20.63	98.95
DIC 7	0.17	9	4.20	179.99	7.14	13.15	98.17
DIC 8	0.17	31	1.68	139.94	8.76	22.11	99.54
DIC 9	0.1	20	4.51	210.98	6.54	11.50	97.88
DIC 10	0.35	5	2.39	182.25	8.18	19.19	98.10
DIC 11	0.35	20	2.39	186.20	8.39	19.92	97.08
Control	-	-	3.79	204.19	5.64	10.16	96.58

3.1.2. Rehydration kinetics

The inverse operation of drying is the rehydration; the capacity and rate of rehydration were investigated. Similar to drying modeling, the rehydration response parameters were studied as well; the water content dry basis at 180 min ($W_{t=180\ min}$), the rehydration time to attain a final water content of 300% db ($t_{r300\%}$), the starting accessibility ($\delta W_{s,r}$) and the effective diffusivity D_{eff} (As shown in Table 4, the rehydration starting accessibility and water effective diffusivity of dried GMPs were increased by 125% and 272% respectively compared to the control sample (THD). SD samples treated by DIC under P=0.35 MPa, t=20 s had starting accessibility and water effective diffusivity of 126.39% db and 13.59 $10^{-10} m^2 s^{-1}$, respectively against 100.92% db and 4.99 $10^{-10} m^2 s^{-1}$ for the control sample (THD).

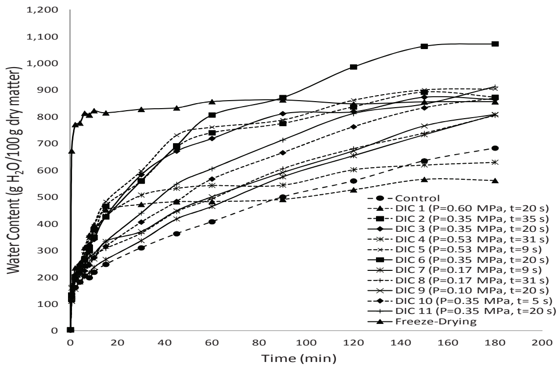

Fig. 6. Rehydration kinetics of Green Moroccan Peppers: Control (THD), Freeze-Dried g (FD) and SD Rehydration was evaluated using distilled water at room temperature of 19.5 ± 0.5 °C

Fig. 6.andFig. 7.show the rehydration kinetics (capacity and rate) of GMPs dried by various techniques (THD, FD, and SD); the SD samples showed high capacity with rapid rate of water uptake compared to control (THD). The rehydration is an important dried food characteristic normally affected by drying technique and drying conditions as well. Our results show that the behavior of dried product during rehydration is drying technique dependent. Most of SD samples showed high water uptake (up to 235% db) during the first two minutes of rehydration time (total time: 180 min) compared to the control (THD) (162% db), while the freeze dried (FD) sample was found with 771% db with rapid rate of water uptake (Fig. 7.).

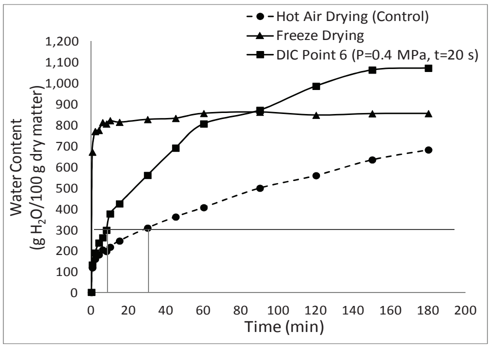

Fig. 7. Rehydration kinetics of Green Moroccan Peppers: Control (THD), Freeze Drying (FD) and Swell-Dried (SD) Point 6 (P=0.4 MPa, t=20 s)

As shown in Table 4, the rehydration starting accessibility and water effective diffusivity of dried GMPs were increased by 125% and 272% respectively compared to the control sample (THD). SD samples treated by DIC under P=0.35 MPa, t=20 s had starting accessibility and water effective diffusivity of 126.39% db and 13.59 $10^{-10}m^2\ s^{-1}$, respectively against 100.92% db and 4.99 $10^{-10}m^2\ s^{-1}$ for the control sample (THD).

Table 4. Water Holding Capacity (WHC) and results of evaluated rehydration kinetics parameters: water content at 180 min ($W_{t=180\ min}$), rehydration time to attain a final water content of 300% db ($W_{tr300\%}$), starting accessibility ($\delta W_{s,r}$) and effective diffusivity ($D_{eff,r}$). R^2 is the correlation coefficient between the experimental and predicted data values of the model

Trial no.	Pressure (MPa)	Time (s)	WHC (% db)	Wt=180 min (% db)	tr300% (min)	δ Ws,r (% db)	Deff,r (10-10 m2 s-1)	R2 (%)
DIC 1	0.6	20	213.79	561.57	6.23	103.79	46.52	98.47
DIC 2	0.35	35	278.14	872.85	7.26	121.55	17.42	97.58
DIC 3	0.35	20	217.96	865.14	8.21	109.04	17.64	98.01
DIC 4	0.53	31	246.94	630.06	7.62	89.91	33.38	97.86
DIC 5	0.53	9	310.72	904.31	6.30	137.78	21.80	98.90
DIC 6	0.35	20	251.40	1072.87	7.83	126.39	13.59	97.38
DIC 7	0.17	9	563.46	807.43	19.15	91.00	5.93	94.41
DIC 8	0.17	31	647.16	805.29	13.03	167.24	8.13	97.48
DIC 9	0.1	20	451.32	808.58	12.40	140.53	7.21	90.29
DIC 10	0.35	5	490.57	869.46	14.79	113.61	9.04	93.58
DIC 11	0.35	20	281.41	912.00	13.04	75.12	11.95	92.90
Control	-	-	618.99	682.82	23.86	100.92	4.99	90.68
FD	0.6	20	147.49	856.07	-15.79	590.59	20.59	63.08

3.2. Correlation terms

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

- water content at 120 min as total drying time ($W_{t=120\ min}$), to attain a final water content of 5% db ($t_{d5\%}$),
- starting accessibility ($\delta W_{s,d}$) and water effective diffusivity during drying ($D_{eff,d}$),
- water content at 180 min as total rehydration time ($W_{t=180\ min}$), to attain a final water content of 300% db ($t_{r300\%}$),
- starting accessibility ($\delta W_{s,r}$) and water effective diffusivity ($D_{eff,r}$) during rehydration.

Normal correlations could be identified; they mainly concerned effective diffusivity $D_{eff,d}$ and drying time and starting accessibility $\delta W_{s,d}$. Water Holding Capacity WHC was correlated with rehydration effective diffusivity $D_{eff,d}$; both revealing deep behavior. However, it was not correlated with starting accessibility $\delta W_{s,r}$, which is normally linked to exchange surface.

Table 5.Correlations between drying and rehydration response parameters, and the Water Holding Capacity (WHC)

Coefficients of correlation	Drying kinetics				Rehydration kinetics				WHC
	$W_{t=120\ min}$	$t_{d5\%}$	□$W_{s,d}$	$D_{eff,d}$	$W_{t=180\ min}$	$t_{r300\%}$	□$W_{s,r}$	$D_{eff,r}$	
$W_{t=120\ min}$	1,00	**0,78**	-0,55	**-0,92**	-0,14	**0,69**	-0,14	-0,52	0,58
$t_{d5\%}$	**0,78**	1,00	**-0,77**	**-0,84**	0,10	0,64	-0,23	-0,56	0,38
□$W_{s,d}$	-0,55	-0,77	1,00	**0,74**	-0,01	-0,66	0,02	0,45	-0,51
$D_{eff,d}$	**-0,92**	**-0,84**	**0,74**	1,00	0,02	**-0,83**	0,08	0,68	-0,68
$W_{t=180\ min}$	-0,14	0,10	-0,01	0,02	1,00	-0,14	0,26	-0,53	-0,11
$t_{r300\%}$	**0,69**	0,64	-0,66	-0,83	-0,14	1,00	-0,21	**-0,69**	**0,83**
□$W_{s,r}$	-0,14	-0,23	0,02	0,08	0,26	-0,21	1,00	-0,21	0,31
$D_{eff,r}$	-0,52	-0,56	0,45	**0,68**	-0,53	**-0,69**	-0,21	1,00	**-0,69**
WHC	0,58	0,38	-0,51	**-0,68**	-0,11	**0,83**	0,31	**-0,69**	1,00

3.3. RSM analysis

3.3.1. Drying kinetics

3.3.1.1. Dehydration Time

The estimated drying time to attain 5% db as final water content from 20% db for THD 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:0.35 MPa, t:35 s, with time decreasing (compared to control) from 204.19 to 119.97 min

Fig. 8.illustrated the impact of operating parameters (saturated steam pressure, thermal holding time, with constant initial water content) of DIC treatment on drying time for SD samples. The obtained results showed that the thermal holding time had a significant effect on decreasing drying time, while the saturated steam pressure had an effect on drying time as well, but not significant as a result of nearby treatment; the higher the saturated steam pressure, the shorter the drying time.

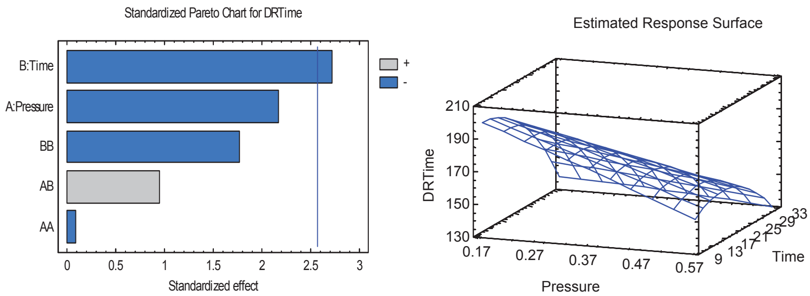

Fig. 8. Effects of Pressure (MPa) and time (s) of DIC treatment on the drying time ($t_{d0.05\%}$) of SD Green Moroccan Peppers: (left) Pareto Chart and (right) response surface

By expressing the steam pressure (P) in MPa and the treatment time (t) in s, the statistical analysis allowed us to obtain the following regression model for the drying time, with R^2 of 76.57%:

$$t_{d5\%}(min) = 214.97 - 143.686*P + 1.29843*t - 21.1798*P^2 + 4.19571*P*t - 0.107511*t^2 \tag{17}$$

In order to minimize the drying time, the optimum conditions of DIC treatment were 0.6 MPa and 36 s as saturated steam pressure and thermal holding time, respectively.

3.3.1.2. Starting Accessibility during dehydration

The starting accessibility ($\delta W_{s,d}$) is defined as the accessibility of water to be removed from the product's surface at the beginning of drying before water diffusion occurs. Fig. 9 shows the effect of operating parameters (saturated steam pressure, thermal processing time, with constant initial water content) of DIC treatment for SD samples on the drying starting accessibility of water.

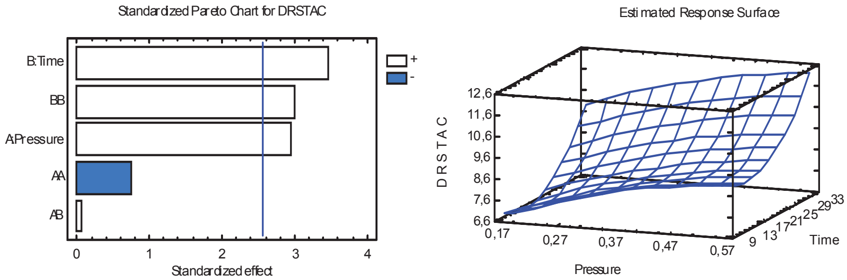

Fig. 9. Effects of DIC operating parameters; pressure (MPa) and time (s) on the starting accessibility (□Ws,d) of SD Green Moroccan Peppers: (left) Pareto Chart and (right) response surface

The obtained results demonstrated that the both operating parameters; saturated steam pressure and thermal processing time, had significant effects on starting accessibility during drying. The higher the DIC saturated steam pressure and processing time, the higher the starting accessibility.

The starting accessibility $\delta W_{s,d}$(% db) was increased from 5.64% to 12.66% for control sample (THD) and SD sample (treated at P: 0.35MPa, t: 35 s) representing an increase of 224%. We observed furthermore an increase by 116% in the starting accessibility even under soft conditions of DIC treatment (low pressure-short time; P: 0.1 MPa, t: 20 s).

Statistical analysis of the experimental design allowed obtaining the prediction model for starting accessibility:

$$\delta W_{s,d}(\%db)=7.06224+12.1309*P–0.305849*t–9.47789*P^2+0.0113636*P*t+0.0102927*t^2 \tag{18}$$

Steam pressure values (P) were expressed in MPa and treatment time (t) in seconds with R^2 of 86.67%.

In order to maximize the starting accessibility (13.31% db), the optimum conditions of DIC treatment were 0.60 MPa during 35.55 s as saturated steam pressure and thermal holding time respectively.

3.3.1.3. Effective Diffusivity during dehydration

Fig. 10 illustrated the effect of operating parameters (saturated steam pressure, thermal holding time, with constant initial water content) of DIC treatment for SD samples on the water effective diffusion during drying. The saturated steam pressure was fount the most influencing compared to the thermal holding time, the higher saturated steam pressure the higher rate of water effective diffusion. The effect of thermal holding time is significant but stable reflecting the good definition of time limits.

The rapid rate of water effective diffusivity (525 x $10^{-10}m^2s^{-1}$) was obtained for SD sample (treated at P: 0.60 MPa, t: 20 s) against 10.16 x $10^{-10}m^2s^{-1}$ for control sample (THD) with an increase of 246% (table 3). A slight increasing of water effective diffusivity (11.05 x $10^{-10}m^2s^{-1}$) was observed under soft conditions of DIC treatment (low pressure-short time; P: 0.1 MPa, t: 20 s), it was increased by 113% compared to control sample (THD).

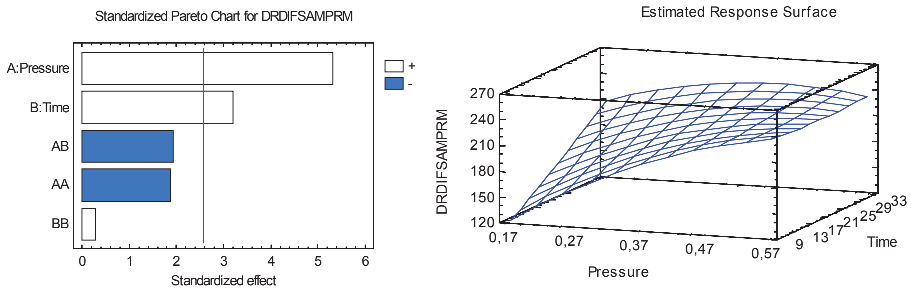

Fig. 10. Effects of DIC operating parameters; Pressure (MPa) and time (s) on the effective diffusivity (Deff,d) of SD Green Moroccan Peppers: (left) Pareto Chart and (right) response surface plot

Using a second-order empirical equation to express the effective diffusivity ($D_{eff,d}$) versus DIC operating parameters, the following regression model could be established:

$$D_{eff,d}\ (10^{-10}\ m^2s^{-1})=-12.9591+705.603*P+4.51591*t-458.816*P^2-9.2601*P*t+0.0171646*t^2 \quad (19)$$

Where, P: is the saturated steam pressure (MPa), t: the thermal holding time (s). With R^2 of 90.17%

In order to maximize the water effective diffusivity (25.04 $10^{-10}m^2s^{-1}$), the optimum conditions of DIC were 0.41 MPa and 35.55 s as saturated steam pressure and thermal holding time respectively.

3.3.2. Rehydration process

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 dried samples by different drying techniques (THD, SD, and, FD), the operating parameters of DIC treatment were evaluated as well but only for SD samples.

Fig. (11) showed the influence of 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 parameters influencing the time of rehydration; the higher saturated steam pressure the shorter time of rehydration. The short time-rehydration was observed for SD samples treated at P: 0.6 MPa, t: 20 s and P: 0.35 MPa, t: 35 s; the rehydration time was 6.23 min and 6.23 min respectively in order to attain the 300% db as final water content after rehydration.

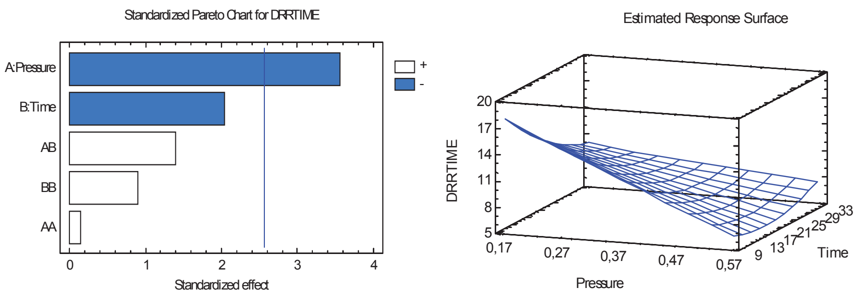

Fig. 11. Effects of DIC operating parameters; Pressure (MPa) and time (s) on the rehydration time ($t_{d300\%}$) of SD Green Moroccan Peppers: (left) Pareto Chart and (right) response surface

The statistical analysis of the experimental design, in the range of chosen variation of DIC parameters allowed us to obtain the regression model for the rehydration time:

$$t_{r300\%}(min)=30,2258-40,7597*P-0,83644*t+4,61673*P^2+0,939394*P*t+0,00830238*t^2 \quad (20)$$

Where, P: is the saturated steam pressure (MPa), t: the thermal holding time (s), with R^2 of 79.52%. In order to minimize the rehydration time (5.10 min), the optimum conditions of DIC treatment were 0.60 MPa and 16 s as saturated steam pressure and thermal holding time respectively.

3.3.2.2. Starting Accessibility at rehydration process

The starting accessibility ($\delta W_{s,r}$) was defined as the amount of water to be immediately absorbed by the product's surface before starting the subsequent diffusion within the product. The effect of DIC operating parameters (saturated steam pressure and thermal holding time) on the starting accessibility during rehydration is illustrated in Fig. 12. The results show that neither saturated steam pressure nor thermal holding time had a significant effect on the starting accessibility during hydration $\delta W_{s,r}$; their effect was slight and heterogeneous. Whereas, the highest starting accessibility (167.24% db) was obtained under P: 0.17 MPa, t: 31 s, compared to control (100.92% db).

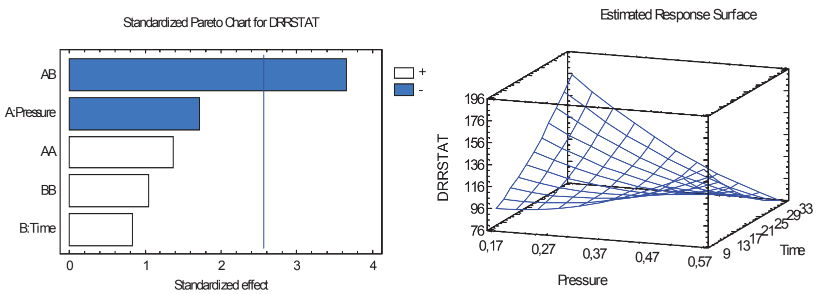

Fig. 12. Effects of DIC operating parameters; Pressure (MPa) and time (s) on the starting accessibility ($\delta W_{s,r}$) of SD Green Moroccan Peppers: (left) Pareto Chart and (right) response surface

Statistical analysis of the experimental design at the studied range of processing parameters allowed us to obtain the prediction model for the rehydration starting accessibility:

$$\delta W_{s,r}\ (\%\ db)= 66{,}2238 + 46{,}008*P + 3{,}47686*t + 300{,}148*P^2 - 15{,}6705*P*t + 0{,}0614448*t^2 \quad (21)$$

Where, P: is the saturated steam pressure (MPa), t: the thermal holding time (s), with R^2 of 79.21%.

In order to maximize the starting accessibility (221.47% db), the optimum conditions of DIC treatment were 0.09 MPa and 35.55 s as saturated steam pressure and thermal processing time, respectively.

3.3.2.3. Rehydration Effective Diffusivity

Effective diffusivity 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 water effective diffusivity was shown in Fig. 13. The water effective diffusivity was significantly increased by increasing the saturated steam pressure; whereas, the thermal processing time had a slight and stable effect. It is interested to mention that a similar behavior was observed for the water effective diffusivity during drying where the saturated steam pressure was the major affecting the water effective diffusivity while the effect of thermal holding time was slight and stable reflecting a god definition of time limits and nearby treatment.

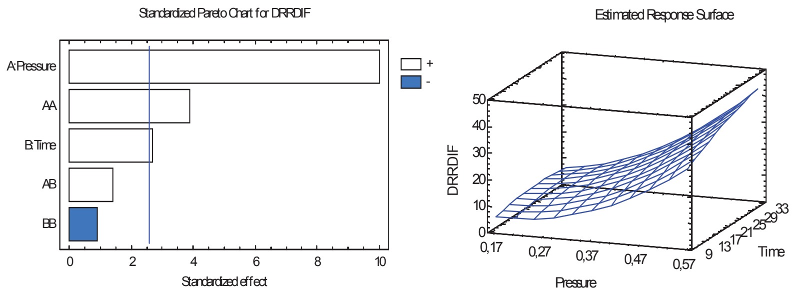

Fig. 13. Effects of DIC operating parameters; Pressure (MPa) and time (s) on water effective diffusivity (D_{eff_r}) of SD Green Moroccan Peppers: (left) Pareto Chart and (right) response surface plot

The rapid rate of water effective diffusivity $D_{eff,r}$(46.52 $10^{-10}m^2s^{-1}$)was obtained for SD sample treated at P: 0.60 MPa, t: 20 s against 4.99 x $10^{-10}m^2s^{-1}$ for control sample (THD) with an increase of 932% (As shown in Table 4, the rehydration starting accessibility and water effective diffusivity of dried GMPs were increased by 125% and 272% respectively compared to the control sample (THD). SD samples treated by DIC under P=0.35 MPa, t=20 s had starting accessibility and water effective diffusivity of 126.39% db and 13.59 $10^{-10}m^2\ s^{-1}$, respectively against 100.92% db and 4.99 $10^{-10}m^2\ s^{-1}$ for the control sample (THD).

Using a second-order empirical equation to express the effective diffusivity (D_{eff_rehy}) versus DIC operating parameters, the following regression model could be established:

$$D_{eff,r}\ (10^{-10}\ m^2s^{-1})=10{,}1566-76{,}4651*P+0{,}29557*t+171{,}329*P^2+1{,}18434*P*t-0{,}0104667*t^2 \quad (22)$$

Where, P: is the saturated steam pressure (MPa), t: the thermal holding time (s), with $R^2$of 96.22%.

3.3.3. Water Holding Capacity

The water holding capacity (WHC) was the main physical property capable to indicate an important functional property of dried foodstuffs, revealing the tissue structural damage caused by the different drying techniques.

A comparative study was carried out to compare the water holding capacity of GMPs dried by different techniques (THA, SD, and FD), the obtained results were illustrated in table (6), the SD samples showed the highest water holding capacity with 647% db followed by THD with 619% db, while the FD showed modest water holding capacity of (147% db).

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

THD	FD	SWELL-DRYING Treatments										
		1	2	3	4	5	6	7	8	9	10	11
619	147	214	278	218	247	311	251	565	647	451	491	281

The impact of DIC operating parameters (saturated steam pressure and thermal holding time with constant initial water content) on the water holding capacity of SD peppers was studied (Fig. 14), the water holding capacity significantly decreased with increasing the saturated steam pressure; the higher the saturated steam pressure, the lower the water holding capacity, while the thermal holding time had insignificant effect.

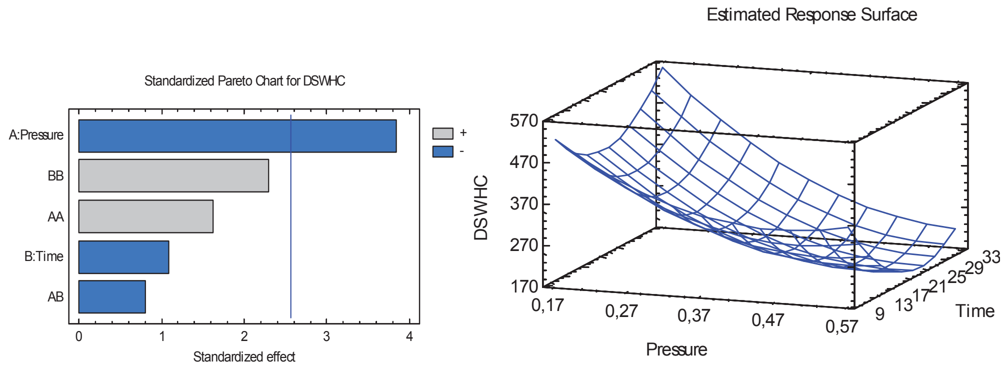

Fig. 14. Effects of DIC operating parameters; Pressure (MPa) and time (s) on the water holding capacity (% db) of SD Green Moroccan Peppers: (left) Pareto Chart and (right) response surface

Statistical analysis of the experimental design at the studied range of processing parameters allowed us to obtain the prediction model for the WHC:

$$WHC\ (\%\ db) = 949,396 - 1654,93*P - 25,747*t + 1915,11*P^2 - 18,6187*P*t + 0,726901*t^2 \qquad (23)$$

Where, P: is the saturated steam pressure (MPa), t: the thermal holding time (s), with R^2 of 82.05%.
In order to maximize the water holding capacity (749.22% db), the optimum DIC operating parameters were 0.09 MPa and 35.55s as saturated steam pressure and thermal holding time respectively.

4. Discussion

Drying is one of the most common methods to preserve peppers [12, 27-29]. By following the operation kinetics, one can design the operation, predict a model and optimize this process [30]. The traditional food hot air drying kinetics commonly included two periods: the first involves quick water removal (until the critical moisture point) which is characterized by a rapid period ; the second has limited water removal as a result of entrapment of this water which is characterized by slow period. The operation is often associated with product's shrinkage which dramatically reduces the diffusivity of water within the material [12, 43]. The long-time/high-temperature operation implies the deformation and the thermal degradation of the product [31] (loss of vitamins and bioactive molecules, degradation of pigments and color, poor nutrition value…).

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

In this study the Instant Controlled Pressure Drop DIC was coupled to THD; defined as Swell Drying SD, in order to intensify the THD.

As mentioned above (results), the THD was intensified by inserting the DIC process before starting the second period of THD. The resulted swell drying SD operation shows shorter time than THD (control) with possibly lower final water content. It results from the structural modifications occurred thanks to the texturing by DIC. Some of these modifications were the breakdown of the plant cell walls entrapping water inside. It leads to release the entrapped water thus becoming more available and accessible to be quickly removed by evaporation preventing the associated problems; product's shrinkage (texture compactness), super heating and hence product thermal degradation (loss of vitamins and bioactive molecules, degradation of pigments and colour, and poor nutrition value).

Texturing by DIC induces an autovaporization 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 implies mechanical constrains on the cell wall leading to its break down and formation of pores as well specially after pressure dropping towards vacuum crossing the glass transition border.

The internal gradient of water concentration is the driving force in both drying and rehydration, the open and spongy texture improved significantly the starting accessibility and water effective diffusivity during both operations. The high water effective diffusivity reflected the short time drying and/or rehydration. These results are in agreement with those reported by other authors; Pilatowski et al., (2010) and Cong et al., (2009) reported time decreasing from 205 min to 11.10 min for paddy rice [39][40]; Mounir et al., (2009) reported a significant decrease in drying time of apple from 6 h to 1 h [41]. Al Haddad et al. showed a significant decrease in drying time, the authors studied the swell drying SD and DIC coupled to the drying by microwave (700 W), this study was carried out on apple and mango cubes. They reported a drying time less than 5 min in case of DIC coupled to the drying by microwave, followed by 2 h for SD, while, it is more than 8 h for THD (5% db as final moisture content) [42].

In particular case of peppers many studies reported drying times varying from some hours to many days. Kaleemullah and Kailappan reported drying times of 32 h at 50 °C air temperature in a rotary dryer (from 330% to 10.5 % db as final water content), 8 h at 50 °C air temperature using a mechanical dryer (from 200.87% to 9.13% db as final water content) and 14-21 days for sun drying [11]. Other studies reported different levels of final moisture content. For example, the final water content of sun dried peppers was ranged from 12.7% to 26.8 % db[8], while it was ranged from 8 % to 10.5 % db for hot air dried [12][32][11], 4.0% to 5.9% db for freeze dried [33] and 3.5 % db for microwave dried [12]. It reaches 1% for the present Swell-Drying. The possibility to attain such a low final water content with SD samples is explained by the high value of diffusivity compared to THD samples.

Water holding capacity revealed the amount of water absorbed during rehydration (capacity and rate). The high capacity of water holding is due to some structural modifications and increasing in polar groups at the surface which react with water molecules.

The RSM analysis for all response parameters showed the saturated steam pressure was the major affecting on the studied response parameters. We can explain these results by the mechanical strains induced as a result of steam expansion within the product implying some textural modifications.

Another important response to evaluate the performance of drying process is the effective diffusivity of moisture content (D_{eff}). It has been accepted that in the falling rate period shrinkage dramatically reduces the diffusivity of water within the material [12, 43] and that the most relevant way to intensify the drying process is to improve such a diffusivity through higher temperature and/or more expanded structure. The first route is correlated with Arrhenius-type law with activation energy. However, greater thermochemical degradation occurs with increased temperature [43].

In this study the effective diffusivity was improved by expanding the structure of pepper applying the DIC treatment. The obtained value of DIC Point 1 (P= 0.6 MPa, t=20 s) increased the effective diffusivity by 2.5 times compared to the control's (25 $10^{-10}m^2s^{-1}$ instead of 10.16 $10^{-10}m^2\ s^{-1}$, respectively).

Reported estimated moisture effective diffusivity of peppers is within the general range of 10^{-9}-10^{-11}. Arslan and Özcan (2011) reported the effective diffusivity (D_{eff}) values of pepper slices for the sun, oven 50 °C, oven 70 °C, microwave 210 W and microwave 700 W drying process of 0.31×10^{-9}, 0.40×10^{-9}, 1.31×10^{-9}, 55.97×10^{-9} and $87.39\times10^{-9}m^2s^{-1}$, respectively [12]. Scala and Crapiste (2008) reported the diffusion coefficient of pepper in a thin layer cross-flow laboratory scale dryer of 5.01 $5.01\times10^{-10}m^2s^{-1}$ at 50 °C to 8.32 $10^{-10}m^2s^{-1}$ at 70 °C[44]. Kiranoudis et al., (1992) obtained the D_{eff} value of moisture for green pepper as 8.9 $10^{-9}m^2s^{-1}$ at a drying temperature of 70 °C[45]. Sanjuán et al., (2003) observed effective diffusion coefficients of 37.23 $10^{-11}m^2s^{-1}$ for shredded samples and 4.38 $10^{-11}m^2\ s^{-1}$ at 50 °C for whole peppers [37]. Doymaz and Pala, (2002) reported for red peppers dipped on cold aqueous alkali emulsions of ethyl oleate D_{eff} in the range of 22.5 10^{-9}–27.4 $10^{-9}m^2s^{-1}$[10]. Kaleemullah and Kailappan, (2006) reported an increase on the effective moisture diffusivity from 3.78 to 7.10 $10^{-9}m^2s^{-1}$ as drying temperature increase from 50 to 65 °C[46]. Faustino et al., (2007) studied the interval of temperature from 30 °C to 70 °C and obtained the effective diffusivity varied between 9.0 $10^{-10}m^2\ s^{-1}$ at 30 °C and 8.0 $10^{-9}m^2s^{-1}$ at 70 °C[47] and Vega et al., (2007) found for red bell pepper at 50 °C a D_{eff} of 3.2 $10^{-9}m^2s^{-1}$. The variety of calculated D_{eff} on the studies could be caused by the differences in capsicum varieties, drying equipment and other uncontrolled parameters. As observed the scale values obtained from D_{eff} presented in this study agrees with Scala and Crapiste, (2008) and Faustino et al., (2007) studies, both based on the activation energy and analyzed at the first phase of drying, improved the D_{eff} by increasing the temperature. Compared their results with the obtained of this study, it was found that whereas they improved D_{eff} at first phase, the DIC treatment improved the second phase, showing higher values than reported for the first phase.

Else, obtained results of this study compared to some previous studies of the impact of DIC on the effective diffusivity (D_{eff}) strengthen its positive effect: Setyopratomo et al., (2009) increase the D_{eff} of cassava flour from 1.37 to 3.26 $10^{-10}m^2s^{-1}$ (P=0.4 MPa and t=30 s) respect to the conventional drying [23]. Albitar et al., (2001) improved the D_{eff} of onion from 1.02 to 2.09 x $10^{-10}m^2s^{-1}$ (P=0.50 MPa, t=10 s) respect to untreated samples. Pilatowski et al., (2010) and Cong et al., (2009) increased the D_{eff} of paddy rice being the optimum 1.18 $10^{-13}m^2s^{-1}$ (P=0.54 MPa, t= 26 s). For the last two studies and for the present one the steam pressure has been the mainly parameter affected the D_{eff}.

Many other researchers have used DIC process coupled to hot air drying. Their various works agreed with these findings, where the treatment also triggers acceleration on the dehydration process of the products [31, 48-49, 51].

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 show 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 SD is a flexible process; the operating parameters (saturated steam pressure and thermal holding time) can be optimized to meet the product's quality attributes and the industrials needs as well.

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