

MODELLING OF THE REHYDRATION PROCESS OF DRIED BROCCOLI (*Brassica oleracea* L. var. *Italica*) STEMS

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ABSTRACT

Broccoli (*Brassica oleracea* L. var. *Italica*) is associated with numerous health benefits, due to its high content in various nutritional compounds. The production of dried broccoli stems can be a good strategy to add value to a by-product of broccoli's industry. This product can be used for direct consumption, or in salads and soups after rehydration.

This study aimed at assessing and modelling the rehydration kinetics of dried slices of broccoli stems with 1 mm thickness. Fresh broccoli stems were convective dried at 55°C and average air velocity of 1.22 m/s. Water rehydration of dried broccoli stems was carried out, until equilibrium moisture content, at six different temperatures (20-70°C).

Samples water uptake and the rate of moisture absorption increased, respectively, with time and temperature. The equilibrium moisture content was slightly affected by temperature. The *first order* and *Peleg* empirical models described well the kinetics at each temperature. The temperature dependence of the rehydration rate presented and *Arrhenius* behaviour, with activation energy of 5.74 ± 1.02 kJ/mol and rate at 55°C of 0.054 ± 0.003 min⁻¹. The *Peleg* rate and capacity constants presented a linear relationship with temperature. A *Peleg* distribution with linear temperature dependence was the best model to predict all experimental data.

INTRODUCTION

(*Brassica oleracea* L. var. *Italica*) is a brassica vegetable and classified in the *Italica* cultivar group of the species *Brassica oleracea*. This group is mainly related to cabbage, broccoli, kale, cauliflower, and Brussels sprouts. Broccoli, also known as the “Crown Jewel of Nutrition” (Vasanthi et al. 2009), is a vegetable with high nutritional value, having antioxidant properties (Perini et al. 2017), being rich in vitamins and minerals (Wu et al. 1992), and presenting health benefits.

It is a common belief that the edible part of broccoli is only the florets. Therefore, more than half of the plant is

discarded. This causes both food waste and environmental pollution. On the other hand, studies have shown that some vitamins and calcium contents in broccoli stems and leaves are 2 to 4 times higher than in broccoli florets (Wu et al. 1992).

Fresh broccoli has many metabolic reactions. Hence, its shelf life is shorter than other fruits and vegetables (Doymaz 2013). A variety of cooling, freezing and drying techniques have been used to prolong the life of broccoli after harvest and ensure that it can be used throughout the year (Mrkic et al. 2006). Drying is one of the oldest methods of food preservation and it plays a very important role in the food processing industry (Doymaz 2014). This process can be a good way to preserve foods with rich nutritional composition, contributing to a sustainable and safe food chain. Vegetable dehydration aim at reducing moisture content from 80-90 to 10-20%. Therefore, a reduction of microbial growth and other undesirable reactions is achieved.

Dried products are usually rehydrated before use. This process aims at restoring raw product properties. Food's chemical structure is affected by drying conditions and can influence rehydration behaviour (McMinn and Maere 1996). Rehydration of dried products usually consists of three stages: absorption of water into the dried material, swelling of rehydrated products, and leakage of solutes (Lee et al. 2006). Compared to the past, consumers are more aware of food products quality and nutritional content, therefore it is important to understand the rehydration process and to perform and optimize the steps correctly.

The modelling of rehydration kinetics allows the understanding of the influencing processing variables and predict the absorption of water and required soaking time (Hsu et al. 1983). The modelling principle should have a set of mathematical equations that can efficiently describe the system, and the solution of the equations will allow the estimation of process parameters. Therefore, the use of a simulation model is a precious and important tool for estimating the performance of rehydration systems (Górnicki et al. 2013). Different theoretical and empirical models have been used to model rehydration kinetics. Owing to Fick's Second Law, diffusion models have been used to define rehydration processes (García-Pascual et

al. 2005). Among the empirical models, the *Peleg* and *Weibull* models are often preferred.

The rehydration kinetics of broccoli stems was studied for slices of 4.6 mm thickness (Sanjuán et al. 1999), and a theoretical diffusional model described well the results at each temperature. Experiments were carried out in the range of 25 to 80°C, and it was observed that effective diffusivities increased and equilibrium moisture content decreased with temperature (Sanjuán et al. 1999). The Arrhenius model was not able to fit experiments at 80°C.

The objectives of this research work were to: (1) experimentally investigate the effects of water temperature (from 20 to 70°C) and time on the rehydration characteristics of 1 mm thickness slices of dried broccoli stems, and (2) to mathematically describe the process, to obtain predictive models that can be used to optimize the operating conditions.

MATERIAL AND METHODS

Raw Material

Broccoli (*Brassica oleracea* L. Var. *Italica*) was the raw material used in all the experiments. Broccoli heads were purchased from a local supermarket in Porto during the autumn and winter season. They were cleaned with tap water after delivery to the Food Processing Laboratory. Broccolis were cut off and all the florets were discarded. Main big stem (stalk) and other smaller stems were kept and kindly trimmed to clean small leaves. Then, they were sliced by 0.001 m thickness using a sharp planer.

Drying of Samples

Prepared slice samples were dehydrated in a tray dryer during approximately 4 h at 55 °C, until final equilibrium moisture content. A laboratory-type tray dryer (Armfield UOP8, Ringwood, England) was used. This dryer had four sample trays, and a digital balance (Sartorius, Goettingen, Germany) connected to a computer (Hewlett-Packard Vectra, Palo Alto, CA), running a program that enabled online detection of weight every 5 min. An average air velocity of 1.22 m/s was measured with a vane anemometer (Airflow LCA 6000, Buckinghamshire, England). The drying was carried out till moisture content of 7-9%. The raw samples presented initial moisture average content of 90% (w.b.). Dehydrated samples were stored in glass beakers at desiccator until they were used in the rehydration experiments.

Rehydration of Samples

Broccoli stems were rehydrated by immersion in a thermostatic water bath at a controlled temperature. Six rehydration temperatures were used: 20, 30, 40, 50, 60 and 70°C. The sample's weight was measured along rehydration time. In all experiments, 15 sampling times with approximately 1 g of dried slices of broccoli stems were used. Each isothermal experiment was performed in triplicate. After taking the rehydrated samples from the thermostatic bath, each sample was placed on absorbent paper for 2 minutes to eliminate the excess of water.

Then, they were placed into Petri dishes and analytically weighed (AE 2000, Mettler Toledo balance).

The initial sample's water content was determined by using a hot air oven (Ehret, Emmendingen, Germany) at 105°C for 24h, and weight loss was expressed as moisture content (AOAC 2002). For each sample, an average of three replicates was considered. The sample's moisture content along the rehydration process was calculated from initial water content and mass gain.

Rehydration Kinetics Modelling

The *Fick's Second Law* model, and the empirical models of *Weibull*, *first order* and *Peleg* are the most commonly used to mathematically describe the moisture uptake along with rehydration processes (Górnicki et al. 2013). These models were attempted to fit the experimental data of rehydration of dried broccoli stems, expressed on a dry basis (X , kg H₂O/kg db). Data was, however, better fitted by the *first order* and the *Peleg* models.

A *first order* kinetic model is described as:

$$-dX/dt = k_T(X - X_e) \quad (1)$$

where X_e is the equilibrium moisture content of the rehydrated material (kg H₂O/kg db), k_T the rehydration rate (min⁻¹), and t the rehydration time (min) (Krokida and Marinos-Kouris 2003).

The X as a function of time is obtained by integrating Equation (1) between initial time, where the moisture content is X_0 , and a given time:

$$X = X_e - (X_e - X_0) \cdot \exp(-k_T \cdot t) \quad (2)$$

The *Peleg* equation can be expressed as:

$$X = X_0 + \frac{t}{(k_1 + k_2 \cdot t)} \quad (3)$$

where k_1 is the *Peleg* rate constant (min kg db kg⁻¹ H₂O) and k_2 the *Peleg* capacity constant (kg db kg⁻¹ H₂O), that is a characteristic parameter for each different product and related with the equilibrium moisture content (Peleg 1988):

$$X_e = X_0 + \frac{1}{k_2} \quad (4)$$

The rehydration model parameters temperature dependence is normally well described by an *Arrhenius* type behaviour (García-Pascual et al. 2005):

$$k_T = k_{T_{ref}} \cdot \exp \left[-\frac{E_a}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right] \quad (5)$$

where $k_{T_{ref}}$ is the rehydration rate at a reference temperature (min⁻¹), E_a the activation energy (J mol⁻¹), T the absolute temperature (K), T_{ref} the reference temperature (K), and R is the universal gas constant (8.314 J K⁻¹ mol⁻¹).

Peleg's model parameters dependence on temperature can be described by linear relationships (Cunningham et al. 2007):

$$k_1 = k_{1a} + k_{1b} \cdot T \quad (6)$$

$$k_2 = k_{2a} + k_{2b} \cdot T \quad (7)$$

where k_{1a} and k_{2a} (min kg db kg^{-1} H₂O), and k_{1b} and k_{2b} (kg db kg^{-1} H₂O $^{\circ}C^{-1}$) are model parameters.

Replacing Equation (5) into Equation (2), and Equations (6) and (7) into Equation (3), the following models are obtained, respectively:

$$X = X_e - (X_e - X_0) \cdot \exp(-k_{Tref} \cdot \exp[-\frac{E_a}{R} (\frac{1}{T} - \frac{1}{T_{ref}})]) t \quad (8)$$

$$X = X_0 + \frac{t}{((k_{1a} + k_{1b} \cdot T) + (k_{2a} + k_{2b} \cdot T) \cdot t)} \quad (9)$$

Statistical Analysis

In order to compare the different experiments, the adimensional moisture content (X_{ad}) was calculated by dividing X by X_0 , for each independent experiment. Experimental data at each temperature was modelled using the *first order* and *Peleg* empirical models (Equations (2) and (3), respectively). For each model, the kinetic parameters were obtained by non-linear regression analysis. A one step non-linear regression to all data was carried out for the *first order* (Equation (8)), where the reference temperature was considered as 55 $^{\circ}C$, the average of the experimental temperatures (Arabshahi and Lund 1985), and *Peleg* (Equation (9)) models. The quality of the regressions was evaluated through the coefficient of determination, adjusted coefficient of determination, p -value, standard deviation and randomness and normality of residuals (Hill and Grieger-Block 1980). Statistical analysis was performed using the software STATA version 14.1 (Statacorp 2016).

RESULTS AND DISCUSSION

The dried slices with 1 mm thickness presented and appealing appearance, texture and flavour to be consumed as a snack. On the other hand, the rehydrated product presented and attractive colour and appearance to be added in soups or salads (Figure 1).



Figure 1: Example of a Dried and Rehydrated Sample

Figure 2 displays the moisture content results at each isothermal experiment. It can be observed that the rehydration rate increased with water temperature, and on the other hand the final equilibrium moisture content decreases with temperature. These observations have already been reported in rehydration studies on thicker slices of dried broccoli stems (Sanjuán et al. 1999). It is well known that rates of solute diffusion increase with temperature. Moreover, the equilibrium moisture content slight decrease, from 58 to 29 (adimensional value), maybe due to the cooking process and possible solid's losses.

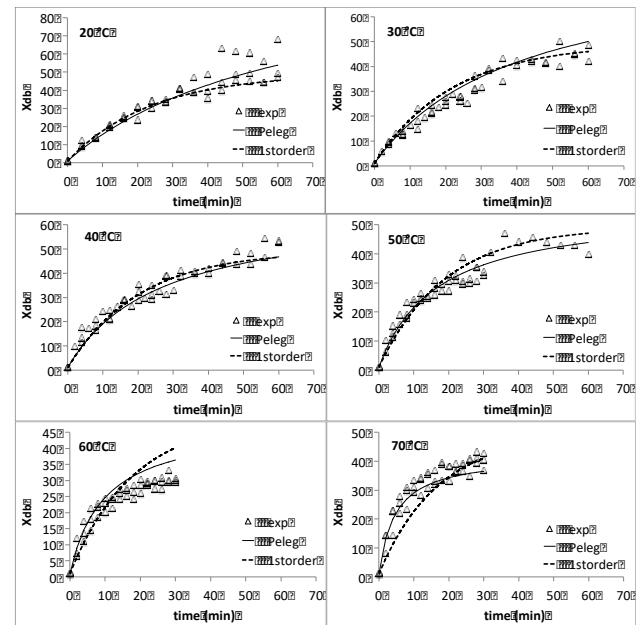


Figure 2: Experimental and Model Predicted Moisture Content at each Isothermal Experiment

Several theoretical and empirical models were attempted to mathematically describe the experimental results at each independent temperature. However, the *first order* (Equation (2)) and *Peleg* (Equation (3)) equations presented the best fit, with coefficients of determination larger than 0.99.

The *first order* kinetic parameters are presented in Figure 3 as a function of temperature. The model parameter X_e confirms that the equilibrium moisture value is slightly affected by the water temperature. The dependence of the rehydration rate, k , on temperature presents an *Arrhenius* behaviour.

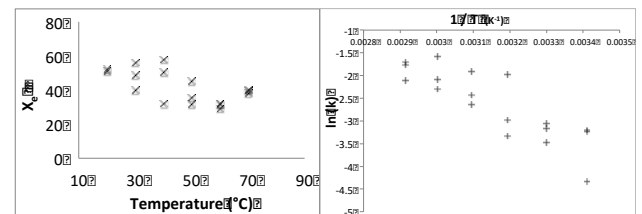


Figure 3: Rehydration Rate and Equilibrium Moisture Content, k and X_e , as a function of Temperature

It was observed that the *Peleg* rate constant, k_1 , and capacity constant, k_2 , presented linear relationships with temperature (Figure 4). This behaviour had already been observed for water absorption of pasta soaking (Cunningham et al 2007). k_2 increase with temperature is related to the decrease of equilibrium moisture content with temperature (Equation 4).

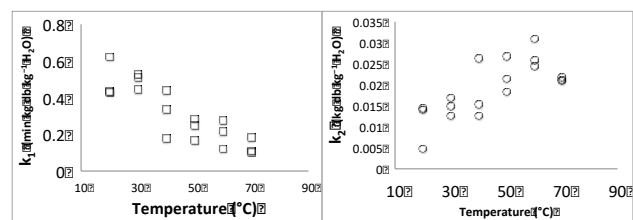


Figure 4: *Peleg* Model Parameters, k_1 and k_2 , as a Function of Temperature

In order to obtain a model able to predict water uptake as a function of time and temperature, a one-step non-linear regression to all data was carried out by fitting the *first order* model with *Arrhenius* behaviour (Equation 8), and *Peleg's* model with kinetic parameters linear behaviour with temperature (Equation 9). Tables 1 and 2 present regression results, respectively for *first order* and *Peleg* global models.

Table 1: Regression Results for *First Order* Global Model (Equation 8)

X_e	49.1±1.3	R^2	R^2_{adj}
$k_{55}^{\circ C}$ (min ⁻¹)	0.054±0.003	0.975	0.975
E_a (kJ mol ⁻¹)	5.77±1.02		

Table 2: Regression Results for *Peleg* Global Model (Equation 9)

k_{1a} (min kg db kg ⁻¹ H ₂ O)	0.785±0.038	R^2	R^2_{adj}
k_{1b} (min kg db kg ⁻¹ H ₂ O)	0.0094±0.0006	0.985	0.985
k_{2a} (kg db kg ⁻¹ H ₂ O)	0.0029±0.0010		
k_{2b} (kg db kg ⁻¹ H ₂ O)	0.00031±0.00002		

The predicted global model results for *first order* and *Peleg* models are presented together with experimental data in Figure 2. It can be observed that both models predict well moisture contents for low rehydration times and temperatures. The *Peleg* model can better predict equilibrium moisture contents and results at higher temperatures.

A diffusional model for infinite slab geometry was observed for dried broccoli stem slices with 4.6 mm thickness (Sanjuán et al. 1999), with an activation energy of 17.9 kJ/mol for relating mass diffusivity with temperature. In our work, Fick's law model did not describe well the experimental data, probably due to the different thickness of the samples. The rehydration rate, of the *first order* model, dependence on temperature presented and activation energy of 5.77 kJ/mol, that is

three times lower. However, these values can not be well compared due to the different models and parameters under evaluation.

CONCLUSIONS

Water rehydration of dried broccoli stems slices, with 1mm thickness, increases with time till an equilibrium value. The rehydration rate increases with temperature, and equilibrium water content is slightly affected by temperature. The *first order* and *Peleg* empirical models were able to predict experimental results at each isothermal conditions.

The rehydration dependence on temperature presented an *Arrhenius* behaviour for the *first order* model and linear relationships for *Peleg* rate and capacity constants.

The *Peleg* global model was the best to describe water absorption of 1 mm slices of dried broccoli stems.

These models have the potential to be used in analysis and engineering calculations for optimizing industrial rehydration processes.

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