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Mathematical modelling and experimental analysis of broccoli (*Brassica oleracea* I.) In tray dryer

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Abstract
This present study aimed at investigating the thin layer hot air drying characteristics of broccoli. Fresh, un-blanched and blanched samples were dried at different temperature of 50 °C, 60 °C and 70 °C. Drying curves obtained from the experimental data were then fitted to the five semi theoretical and/or empirical thin layer drying models. The effects of drying air temperature on the models constants and coefficients were evaluated by a multiple regression technique. The results showed that, the moisture removal of blanched samples were fast compare to un-blanched. Comparing the correlation coefficients (r^2) and chi-square (χ^2) values of five models, it was concluded that the Exponential model was found to be the best model for describing the drying curves of broccoli.

Keywords: Broccoli, tray drying, pre-treatments, thin layer drying

Introduction
Broccoli scientific name is *Brassica oleracea var. italic*, it's belongs to family Brassicaceae. According to FAO, 2012 [1], China is the top world producer of broccoli (9,596,000 tons). Broccoli is an edible green plant that is classified in the Italica cultivar group of the species *Brassica oleracea*. They are rich in vitamin C, dietary fiber and also contain glucoraphin, sulforaphane, selenium and isothiocyanates. Broccoli is also a good source of indole-3-carbinol (Xiaofeng *et al.*, 2015) [2]. These constituents present in broccoli are known to be very popular since they possess several anti-cancer properties and benefits. Broccoli is known to be hearty and tasty vegetable which is rich in dozens of nutrients. It has many benefits such as: Cancer prevention, Cholesterol reduction, Reducing allergic reaction and inflammation, Antioxidant, Bone health, heart health, Diet aid. Carotene present in high quantities in broccoli improves eyesight and prevents cataracts. 100g of broccoli yields just about 34 calories, which is good for health and diet conscious (Ravi Kumar, 2015) [3].
Drying is an industrial preservation method in which water content and activity of the fruits and vegetables are decreased by heated air to minimize biochemical, chemical and microbiological deterioration (Doymaz and Pala, 2003) [4]. Mathematical modeling of drying process helps in understanding the physics of drying. A number of physical mechanisms have been proposed for describing migration of moisture in capillary porous products. Newman, 1931 [5] described the basic equation of diffusion theory for porous media with the assumption that the resistance to flow of moisture is uniform throughout the material. Drying makes foods more concentrated in form than foods preserved in other ways. They are less costly to produce, store and transport than canned or preserved foods. However, blanching of vegetables prior to drying is required to protect their colour, texture and nutrients and to inactivate harmful enzymes. Blanching has several advantages as it reduces drying time; inactivates the enzyme that brings undesirable changes in food product, expulses air from the tissue and better retains minerals and acids (Kumar *et al.*, 2015) [6].
Broccoli dehydration has not been investigated to a great extent and few data are available in the literature. Therefore, the objective of this study were to determine the effect of blanching on the drying kinetics of broccoli.

Material & Methods
Fresh, dark green broccoli (*Brassica oleracea var. italica*) was procured from the local market. So as to maintain the quality of raw material care was taken to select broccoli having nearly uniform shape, size and without any defect on visual inspection. In order to prepare the samples for the blanching process, the broccoli were washed in running water to remove debris and damaged portions and the flower along with stem parts were stripped from the plants.

Two different blanching processes were applied: conventional hot water blanching and potassium metabisulphite (KMS) (5 g/L in water) added hot water blanching.

Drying of Broccoli

Drying of broccoli were carried out in a convective tray dryer (Model No.MSW-216, MAC, New Delhi, India). It comprised of a centrifugal blower, an electrical resistance air heating section, the measurement sensors, and data recording systems. The blanched/unblanched leaves (100 g) were spread uniformly on the trays in single layer (Stainless steel mesh wire). The air velocity was continuously measured using an anemometer (Lutron, AM-4201, Taiwan). After attaining desired drying air temperature, samples were loaded onto the drying trays (80 × 60 cm^2) in single layer. All the experiments were carried out at fixed 1.1 ± 0.2 m/s air velocity. All drying experiments (50 °C, 60 °C and 70 °C) were conducted till the weights of the samples were stabilized up to 2 decimal points, which were assumed to be the stage of dynamic equilibrium. Each experimental run was conducted in triplicate and the average of the results was analyzed. The initial moisture content of fresh slices and the final moisture content of dried samples were determined by hot air oven drying method at 105 ºC for 24 h.

Drying analysis and evaluation of thin layer drying models

The drying characteristic curves were plotted after analyzing the experimental data. The moisture content was converted to moisture ratio (MR) using the following equation.

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \quad (1)$$

Where, M_0-Moisture content, kg water/kg dry matter at beginning of the drying,

M_e - Moisture content, kg water/kg dry matter when the equilibrium is reached,

M_t - Moisture content, kg water/kg dry matter at time t,

As the relative humidity of the drying air fluctuated continuously, M_e was assumed to be negligible and the expression was reduced to

$$MR = \frac{(M_t)}{(M_0)} \quad (2)$$

Mathematical modeling was carried out to describe the drying curve equation of broccoli and to determine the parameters of the thin layer drying models by fitting experimental data to the model equation. Five different commonly used models are given in Table 1 (Gupta *et al.*, 2002; Yaldiz *et al.*, 2001; Yagcioglu *et al.*, 1999; Sharaf-Elden *et al.*, 1980; Aghabashlo *et al.*, 2008) [7-11] and taken into account for specifying the most adequate model in thin layer drying of broccoli. The nonlinear regression analysis was performed using the software Origin Pro 8.0 (Origin Lab, USA). Although the coefficient of determination (R^2) was one of the primary criteria for selecting the best model to describe thin-layer drying of slices, the reduced chi- square (χ2) was also included to evaluate the goodness of fit of the models (equation 3 and 4). The lower chi- square (χ2) and the higher R^2 values, were chosen as the basis for goodness of fit (Gupta *et al.*, 2002) [7].

Table 1: Mathematical models used to describe thin layer drying

SN	Model Name	Model
1	Page [7]	$MR = \exp(-kt^n)$
2	Modified Page [8]	$MR = \exp[-(kt)]^n$
3	Henderson and Pabis [9]	$MR = a\exp(-kt) + (1-a)\exp(-kt)$
4	Two term exponential [10]	$MR = a\exp(-kt) + (1-a)\exp(-kt)$
5	Aghabashlo model [11]	$MR = \exp[-\frac{k_1 t}{(1+k_2 t)}]$

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,avg})2}{\sum_{i=1}^{N}(MR_{exp,i} - MR_{exp,avg})2} \quad (3)$$

$$x^2 = \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})2}{N-n} \quad (4)$$

Where, $MR_{exp,i}$ is the i^{th} experimentally observed moisture ratio, $MR_{pre,i}$ the i^{th} predicted moisture ratio, $MR_{exp,\ avg}$ is the average experimental moisture ratio, N the number of observations and n is the number of constants (Sarsavadia *et al.*, 1999) [12]. In this study the relationships of the constants of the best suitable model with the drying air temperature were also determined by multiple regression technique.

Results & Discussion

Drying experiments were carried out using tray drying and three different temperature of 50°, 60° and 70 ºC. The data on yield of dried broccoli using different methods indicated that there was a remarkable reduction in weight during drying due to moisture loss. Drying rate showed a fast increase at the beginning of the process and a subsequent decrease afterwards showing two differentiated periods i.e. the first, where drying rate decreases slowly to reach a plateau with a practically constant value; and the second with a rapidly decreasing drying rate. The capacity of air in removing of moisture depends on temperature and the moisture amount of air.

Figure 1 and 2 represents drying curve of fresh and broccoli at 50℃, 60℃ and 70℃, hot air temperature levels respectively under varied levels. It is clearly evident from the figures that moisture content of sample decreased with the increase in drying time until they reached a constant value, average initial moisture content of broccoli sample was (100%), which reduced faster during initial stage of drying, as evident by steeper slope of drying curves (Meher *et al.*, 2015) [13]. The moisture removal was at very fast rate in the sample of unblanched broccoli. The total time required for unblanched broccoli was 360 minutes at the temperature of 50 ℃ and blanched broccoli time required is more compare to unblanched broccoli sample. The results is in accordance with the Singh *et al.*, 2016 [6]. The drying rate of the sample of broccoli at the temperature 60 °C shown in Figure 2 was faster compared to broccoli blanched at 50 °C The total time required for blanched broccoli is 270 minutes and time required for unblanched broccoli is 410 minutes there was great difference between the time of blanched and unblanched broccoli but we observed the best result was seen at 60 ℃ for drying of broccoli there are minimum loss of minerals and nutrients (protein, fat, fiber, carbohydrate, sugar) and there are no burning of sample at this temperature and drying rate is very smoothly being.

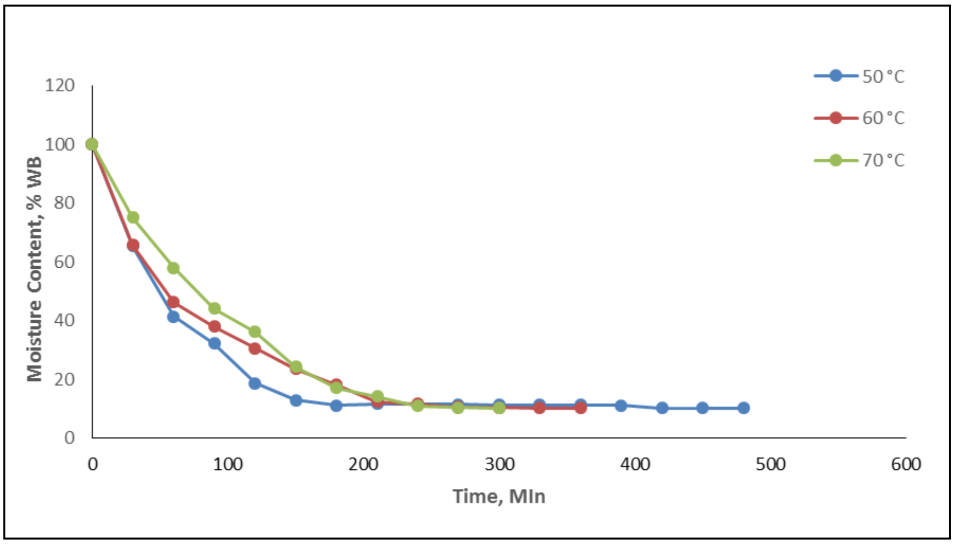

Fig 1: Time of drying vs moisture content for un-blanched samples

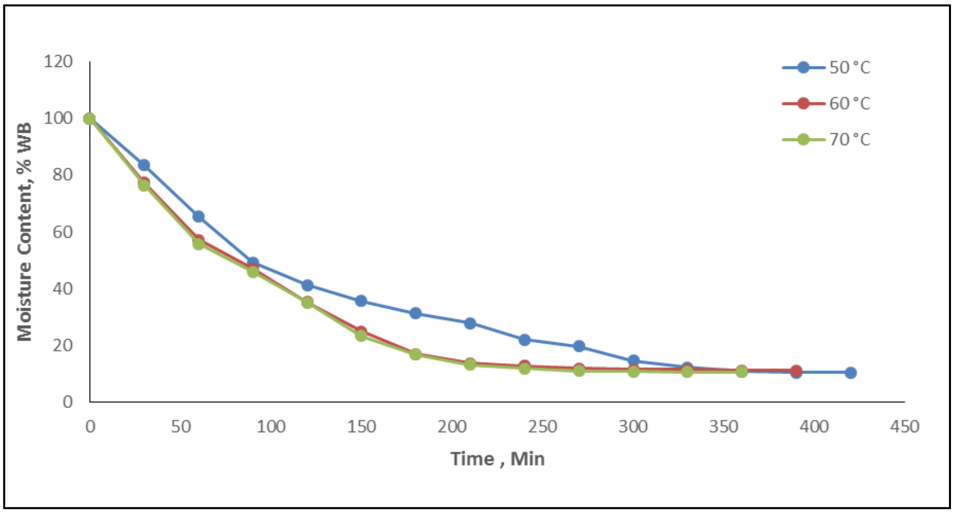

Fig 2: Time of drying vs moisture content for blanched samples

The drying data obtained in the experiments were converted to dimensionless moisture ratio (MR). In order to determine the experimental moisture ratio as a function of drying time, five semi-theoretical models were used. The estimated parameters and the results of statistical analysis of these models were presented in Table 2. For all drying condition the models showed coefficient of determination (R^2) values in the range of 0.9123 to 0.9989 (Sarsavadia *et al.*, 1980) [10]. Among the thin layer drying models tested (Table 2), the two term exponential model indicated the highest R^2 values with lowest χ^2 values.

Conclusion

Drying occurred mainly in the falling rate period. Hence, the drying process for broccoli is said to be dominantly driven by diffusion irrespective of the drying methods. The results of the drying kinetics showed that two term exponential model was best in describing tray drying process of broccoli. The values of constants were effectively correlated with temperature and the model is capable of providing reliable predictions of the moisture distributions of broccoli at any instant of time during the drying process.

Conflicts of Interest

The authors declares there are no conflicts of interest.

Table 2: Comparison of different drying models with drying coefficients (constants) at different drying temperatures

Model	Temp. (°C)	Model Constants	R^2	χ^2
Page	50	k=0.00413, n=1.28817	0.9743	0.00065
	60	k=0.00476, n=1.16551	0.9881	0.00050
	70	k=0.00611, n=1.11688	0.9779	0.00042
Modified Page	50	k=0.00666, n= 1.18962	0.9123	0.02891
	60	k=0.01404, n= 1.28353	0.9189	0.02830
	70	k=0.01266, n= 1.11016	0.9256	0.02925

Henderson and Pabis	50	k= 0.00434, a= 0.77143	0.9367	0.03652
	60	k= 0.01898, a= 1.01996	0.9382	0.03698
	70	k= 0.01266, a= 1.11016	0.9547	0.03922
Two-term exponential	50	a= 1.71397, k= 0.00983	0.9987	0.00041
	60	a= 1.89966, k= 0.02153	0.9989	0.00056
	70	a= 0.99861, k= 0.00911	0.9971	0.00039
Aghabashlo model	50	k_1= -0.06521, k_2=0.07825	0.9914	0.00061
	60	k_1= -0.00742, k_2=0.07825	0.9962	0.00042
	70	k_1= -0.00789, k_2=0.08698	0.9925	0.00056

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