Mathematical Modeling of Drying Kinetics of Mint Leaves in Forced Convective Portable Vegetable Dryer

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Abstract— **In this paper, a mathematical model is developed for thin layer drying of mint leaves in portable convective dryer considering drying kinetics. Experimental data for the drying of mint leaves was obtained at its optimum drying temperature of 50^{0}C and air flow rate of 0.01275 m^3/sec. Four mathematical models namely Page model, Modified Page Model, Logarithmic model and Handerson & Pabis model were tested to fit the experimental data. The Logarithmic model was found to satisfactorily describe kinetics of forced convection drying of mint leaves. The Logarithmic model is used to predict instantaneous moisture ratios and drying time which facilitates design of dryer and simulation of drying process. Also the empirical relation for dimensionless drying rate was developed from the characteristic drying curve obtained from experimental data which is of sigmoid type which can be used to predict the instantaneous drying rate.**

Keywords— ***Convective drying; Mathematical model; Mint leaves; Dimensionless drying rate***

I. INTRODUCTION

Variety of leafy vegetables cultivated in India provide rich sources of vital nutrients like vitamins (beta-carotene, ascorbic acid, riboflavin, folic acid), micronutrients (Vitamin A, iron) and minerals (calcium, potassium, sodium and phosphorous)[1]. Most commonly used leafy vegetables in India are Coriander, Fenugreek, Dill leaves, Spinach, Curry leaves, Mint and Drumstick leaves. Drying of vegetables is one of the oldest methods of food preservation which enhances shelf life, transportability along with retention of concentration of nutrients, flavour and aroma [2]. To enable storage at ambient temperature, the water activity (a_w) of various perishable foods must be decreased to value<0.5 by drying [4].

Drying is a complex heat and mass transfer process in which water is transferred by diffusion from inside the food material to the air-food interface and by convection from the interface to the air stream [3].

Factors affecting drying can be classified as:

i. External factors like temperature, pressure, humidity, velocity of the surrounding air and area of the exposed surface

ii. Internal factors related to the properties of the food material such as moisture diffusivity, moisture transfer coefficient, water activity, structure and composition [5]. In the literature several methods, theoretical, semi-empirical and empirical methods are used to analyze drying of hygroscopic products [8]. Semi empirical models are based on Newton's Law of cooling applied to mass transfer assuming isothermal conditions and confining resistance to moisture transfer to product surface [7]. Quality of dried food products is judged by its color, brightness, aroma, texture, nutritional content, stability over time. Modeling tools mentioned above are often used to optimize the quality of final dried product [4].

Objectives of present study are:

1. To experimentally investigate the drying of mint leaves in the portable convective Vegetable dryer designed for experimentation.

2. To develop mathematical model to best describe convective drying kinetics of mint leaves.

3. To develop empirical model from experimental data for convective drying of mint leaves.

II. MATERIALS AND METHODS:

Material: Mint leaves were procured from the local market and used for experimentation.

Drying Equipment: A portable Vegetable Dryer was designed and fabricated as shown in figure 1 and figure 2, with the following specifications. The drying compartment was constructed from plywood (10 mm thickness) coated with aluminium foil (13 micron thickness) having the overall dimension of 16''×16''×12''. Three trays with stainless steel mesh (diameter 11'') were provided inside the drying chamber for loading the leaves of vegetables to be dried. The dryer is equipped with heating element (500 W), an axial flow fan (85 CFM), thermostat (range: 35^{0}C-75^{0}C) and mechanical timer (range: 0 to 30 min). A digital electronic balance SCALETEC, CWS-610l with the range of 0–600 gram and an accuracy of 0.01 gram was used for measurement of the moisture loss of samples.

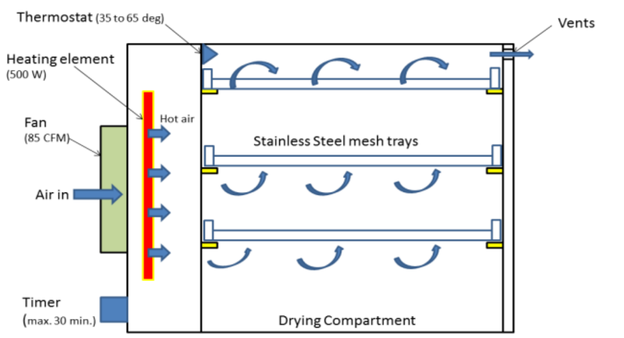

Figure 1. Schematic representation of Forced Convective Portable Vegetable Dryer

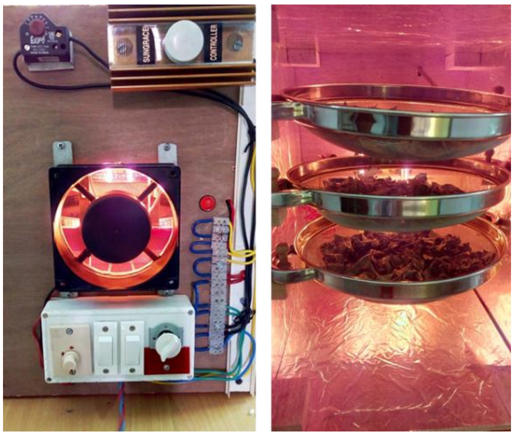

Figure 2. Drying of mint leaves in Forced Convective Portable Vegetable Dryer

III. EXPERIMENTAL METHOD

The drying of the mint leaves was carried out at its optimum drying temperature of 50°C [6] and an air flow rate of 0.01275 m^3/s. The mass of the mint leaves used in drying experiments was 100.0 ± 0.01 gram and they were uniformly distributed in three trays of the drying compartment. The measurements of weight loss of mint leaves were recorded at equal time intervals (5 minutes) during the experimentation using the Digital Electronic Balance. For each drying experiment, the weight of mint leaves was measured by removing trays from the drying compartment for approximately 15-20 seconds. The drying experiment was carried out until final moisture content of mint leaves reduced to 10 %, so that its water activity reduces below 0.5, which enables its storage at ambient temperature [4].

IV. MATHEMATICAL MODELING OF DRYING CURVES FOR MINT LEAVES IN A FORCED CONVECTIVE PORTABLE VEGETABLE DRYER

The drying curve was fitted with four semi-empirical models. The correlation coefficient and the statistical parameter of reduced chi-square were the criteria to determine the model to best describe drying of mint leaves. These parameters can be calculated as:

$$r = \frac{\sum XY}{\sqrt{(\sum X^2)(\sum Y^2)}} \tag{1}$$

Where r = Coefficient of Correlation

$X = MR_{pre,i} - \overline{MR_{pre}}$ = deviation of i^{th} predicted moisture ratio from mean predicted moisture ratio

$Y = MR_{exp,i} - \overline{MR_{exp}}$ = deviation of i^{th} experimental moisture ratio from mean experimental moisture ratio

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{2}$$

Where $MR_{exp,i} = i^{th}$ experimental moisture ratio

$MR_{pre,i} = i^{th}$ predicted moisture ratio

χ^2 = reduced chi-square

N = number of observations

n = number of constants in the drying equation

Fitting the experimental data for drying curves, semi-empirical models namely Page Model, Logarithmic model, Handerson & Pabis model, and Modified Page model were considered [1]. The drying model coefficients were determined (as shown in Table 1) for these semi-empirical models.

The model with the highest value of correlation coefficient and lowest value of reduced chi-square is selected to best describe drying kinetics. The Logarithmic model showed best fit with experimental data (r = 0.9980, χ^2 = 0.000319) and hence this model was used to describe the drying kinetics of Mint leaves.

Table 1: Results of coefficients of semi-empirical models and statistical analysis on modeling of moisture ratio (MR) versus drying time (t) for mint leaves at its optimum drying temperature of 50^0C

Model	Coefficients	r	χ^2
Page $MR = \exp(-kt^n)$	k = 0.002355, n = 1.580669	0.9976	0.00063
Modified Page $MR = \exp(-(kt)^n)$	k = 0.021747, n = 1.580669	0.9976	0.000632
Handerson and Pabis $MR = a\exp(-kt)$	a = 1.123965, k = 0.02394	0.9896	0.001863
Logarithmic $MR = a\exp(-kt) + c$	a = 2.083355, k = 0.007999, c=-1.04689	0.9980	0.000319

From the experimental data for the weight of mint leaves measured during the drying process, the instantaneous moisture content was determined. Moisture contents of mint leaves during the convective drying were expressed in a dimensionless form as moisture ratio given as:

$$MR = \frac{X_t - X_e}{X_0 - X_e} \tag{3}$$

X_t = instantaneous moisture content of mint leaves

X_e = equilibrium moisture content of mint leaves

X_o = initial moisture content of mint leaves

The successive instantaneous moisture contents of mint leaves were used to calculate instantaneous drying rate as:

$$DR = \frac{X_{t+\Delta t} - X_t}{\Delta t} \tag{4}$$

The drying rate was normalized by taking ratio of instantaneous drying rate to the initial drying rate for obtaining the Dimensionless Drying rate as follows:

$$f = \left(-\frac{dX}{dt}\right)_t \Big/ \left(\frac{dX}{dt}\right)_0 \quad (5)$$

where f is dimensionless drying rate

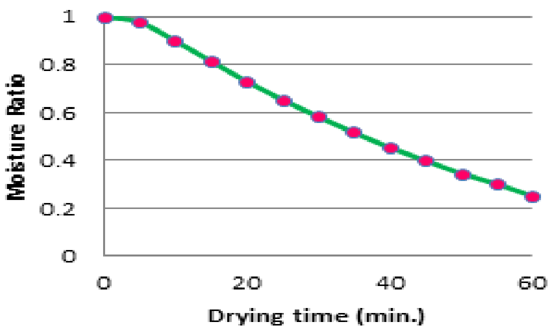

Figure 3: Graph of Variation of moisture ratio as a function of time for mint leaves at 50^0C

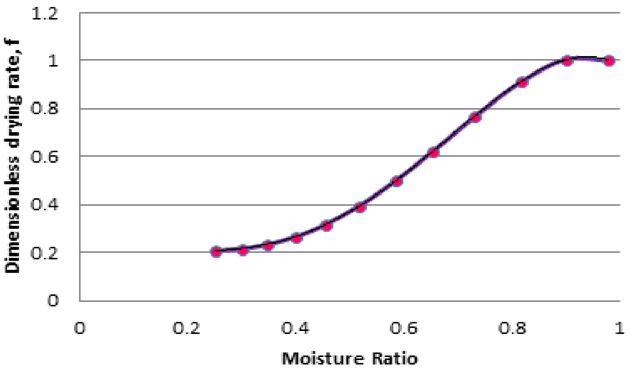

Figure 4: Graph of Variation of Dimensionless drying rate as a function of moisture ratio for mint leaves at 50^0C

Characteristic Drying Curve:

From the experimental data, graph of Moisture Ratio (MR) versus drying time (t) was plotted as shown in figure 3.

From the experimental data, graph of dimensionless drying rate (f) versus moisture ratio (MR) was plotted as shown in figure 4 and the polynomial found to best fit the characteristic drying curve is given as:

$$f = -7.5973MR^4 + 13.255MR^3 - 5.7942MR^2 + 0.9933MR + 0.1502 \quad (6)$$

V. RESULTS AND DISCUSSIONS

The drying of mint leaves in portable vegetable dryer was conducted at 50^0C & air flow rate of 0.01275 m^3/s. [6] The drying rate decreased continuously with decreasing moisture content and no any constant drying rate period was observed.

The rate of water removal was higher during initial stage of drying. As the drying proceeded, the free water present decreased rapidly and at the final stage, free water was hardly available which made drying very slow.

Four models selected from the literature were referred to illustrate the characteristics of drying process & establish mathematical model for drying of mint leaves. Among these models, the Logarithmic model was the best for describing convective drying of mint leaves (correlation coefficient r=0.9980 and reduced chi-square χ^2 = 0.000319) as it showed good agreement with the data obtained from the experimentation of present study. This model can be used to predict the instantaneous moisture content of mint leaves during the drying process at a temperature of 50^0C.

The statistical methods of regression and correlation analysis are often required for modeling of drying kinetics of leafy vegetables. When no mathematical relationship exists, linear and nonlinear regression models are important tools to establish the relationship between different variables. From the experimental data of dimensionless drying rate and moisture ratio, the empirical model in the form of polynomial was determined to best fit the characteristic drying curve which can be used for determining instantaneous drying rate.

VI. CONCLUSIONS

1. The semi-empirical Logarithmic model which satisfactorily describes the drying kinetics of mint leaves can be used to determine the instantaneous moisture ratios and the drying time for mint leaves.

2. The experimental results shows that the dimensionless drying rate characteristic curve takes a form of sigmoid type. The drying operation was seen to occur at falling rate and no any constant drying rate period observed.

3. We found that developed empirical model could be used to predict dimensionless drying rate of mint leaves during drying process particularly at its optimum drying temperature of 50^0C.

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