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Guragain, Mukesh ***Hot Air Drying of Horseradish: Empirical Drying Kinetic Modeling and Physical Quality Characteristics of Dried Horseradish***

Abstract

The main objectives of this study were to dry horseradish at 50, 70 & 85˚C using hot air convective dryer for characterizing the drying kinetics and to observe the effects of blanching and drying temperatures by comparing the physical properties (moisture content, color, water activity, piece density and rehydration capacity) of dried horseradish. The drying kinetic data were fitted in 8 empirical models to characterize the drying rate of horseradish. Blanching and drying temperature significantly affected ($P<0.05$) the quality of the dried horseradish. Brightness value of the dehydrated horseradish was inversely proportional to the drying temperature and unblanched samples exhibited higher brightness as compared to blanched samples. Minimum color difference was found in the unblanched samples dried at 70˚C. There was no significant difference in the piece density for controlled samples dried at different temperatures. Blanched sample dried at 50˚C exhibited significantly higher rehydration capacity. Water activity decreased with increased drying temperature. Page model and Diffusion approach model were the best fitted models to characterize the dehydration of horseradish at different drying conditions. The findings of this research are expected to be significantly important for the scientists and engineers who are interested to design the drying process of horseradish.

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I would like to dedicate this thesis to my loving parents who have always guided me and believed in me.

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Chapter I: Introduction

Drying is one of the most widely and commonly used technique for food preservation (Mitra, Meda, & Green, 2013). It involves the application of heat on material which results in transfer of moisture within the material to its surface and then removal from the surface to the atmosphere. The preservation of the fruits and vegetables through drying dates back for many centuries and was based on solar drying techniques. Many drying techniques have been developed over the years and except the freeze-drying technique, applying heat during drying through conduction, convection and radiation are the basic techniques used to force the water to vaporize, while forced air is applied to remove the vapor from the surface.

Fruits and vegetables are important sources of essential dietary nutrients such as vitamins, minerals and fibers. Since fruits and vegetables have high moisture content, they are classified as highly perishable commodities (Orsat, Changrue, & Vijaya Raghavan, 2006). Drying decreases the water activity of the material, reduces the microbiological activity and minimizes physical and chemical changes in the food (Ekechukwu, 1999). Since the early 20th century, the market of dehydrated vegetables has risen. Over 20% of the world perishable crops are dried to increase shelf-life which helps to fight the food insecurity of the growing population (Sagar & Kumar, 2010). The benefit of drying the fruits and vegetables is not only for the longer preservations but also for easy packaging and low-cost transportation. The challenge of drying fruits and vegetables is to reduce the moisture to certain level where microbiological growth will not occur while retaining the product quality and nutritional values.

One third of the global food production is lost on the harvesting field annually due to lack of proper processing in time. The loss is even more in developing countries where 30-40% of fruits and vegetables are wasted every year (Kumar, Karim, & Joardder, 2014). The market for dehydrated food is important for most of the agricultural countries worldwide. The demand for the dehydrated fruits and vegetables is increasing every year since the 90's. Japan consumes $7.6 billion worth of dehydrated vegetables, instant dried soup and seaweed excluding the usage in restaurants and institutions. In Europe, the market for dehydrated vegetables was estimated to be worth about $800 million which included dehydrated red pepper worth of $260 million in early 1990's. The growth in popularity of convenience foods such as dehydrated food mix, snacks, instant noodles in many Asian countries has triggered the demand for high-quality dehydrated fruits and vegetables (Duan, Zhang, Mujumdar, & Wang, 2010). In the United States, there is a large market for dehydrated grapes, garlic, onions and tomatoes.

Horseradish has been an important crop in parts of Europe and significant production also exists in the U.S and Canada. Historic areas of U.S production include Illinois, Wisconsin, California (northern), Oregon and New Jersey, where 3,500 to 4,000 acres are harvested annually (Bratsch, 2005). The primary market for horseradish is commercial processing where condiment makers usually work on contractual basis with large scale growers. The need of cold environment and large storage area can be a limiting factor for longer period of horseradish storage. Hence, horseradish could be stored and preserved alternatively for a long time by dehydrating them to low moisture content which is also desirable for production of many instant and convenient foods formulations.

Dehydrated products have gained huge popularity because of their storage life, ease of handling and increased usage in preparation of instant and continental foods. For small scale and new growers of horseradish, different value-added products from horseradish can be an area of interest. During the period of 2000-2008, the import share for dehydrated onions, potatoes and other vegetables increased by 65% than fresh vegetables in the USA. Hence, to increase the production of value added dehydrated horseradish, the drying effects of different industrially feasible drying techniques in relation to quality parameters should be studied. With increasing consumption of convenient and instant food formulations, finding out the effective and efficient drying process for horseradish and their process optimization is necessary considering quality concerns of consumers.

Statement of the Problem

Horseradish is produced in a good amount in Wisconsin and its neighboring states. Even though many researches on drying of different fruits and vegetables to study the feasibility and effect of different drying techniques have been reported, there is not much literature on dehydration of horseradish. Quality of the dehydrated product is significantly influenced by temperature and other parameters involved in drying. A very limited supply of data currently exists on the drying of fresh horseradish and study of their quality parameters.

Purpose of the Study

The aims of this study were to investigate the hot air drying kinetics by fitting commonly used empirical models to establish right hot air drying conditions for horseradish and to observe the effects of drying temperature and blanching pre-treatment on different physical properties such as water activity, color difference, piece density and rehydration capacity of dried horseradish.

Chapter II: Literature Review

Review of horseradish, fruits and vegetables drying, dehydration benefits, blanching, different thin layer drying models will be done in this chapter. Different quality parameters like color, piece density, water activity and rehydration capacity related to dehydrated food products will be discussed below.

Horseradish

Horseradish *(Armoracia rusticana)* is a hardy perennial crop belonging to the Brassicaceae family which is grown for its thickened white pungent roots (Rubatzky & Yamaguchi, 2012). Horseradish roots are used as condiments and spices for food stuffs and formerly used medicinally, particularly as an antiscorbutic. When the horseradish tissues are damaged by cutting, isothiocyanates are produced by breaking down of sinigrin (a glucosinate) in presence of enzyme from the damaged horseradish plant cells. The characteristics odor and taste of horseradish is due to the isothiocyanates formed by the action of myrosinase on glucosinates during the disruption of plant tissues. Isothiocyanates extracted from horseradish are also found to be antibacterial in nature (Kim & Shin, 2015). Furthermore, the horseradish peroxidase enzyme is widely used as a reagent for the detection and amplification of antibody, clinical diagnosis, and other microanalytical immunoassays (Mano & Michio, 1995).

Horseradish has been an important crop in parts of Europe and significant production exists in the U.S and Canada. Historic areas of U.S production include Illinois, Wisconsin, California (northern), Oregon and New Jersey, where 3,500 to 4,000 acres are harvested annually. North-temperate regions of the United States is found to be more suitable for production of horseradish and can often grow wild in areas with high soil moisture. Illinois being the highest producer of horseradish in U.S supplies over 50% of American demand, with majority of them being processed for the commercial condiment industry (Walters & Wahle, 2010). Horseradish roots and leaves have been used for condiments and different medicinal purposes in the past but today only horseradish roots are grounded and used as condiments for meats, seafoods and other products (Kumar, 2003; Swaider, Ware & McCollum, 1992). The primary market for horseradish is commercial processing.

In United States alone, around 244 million pounds of horseradish roots are grounded and processed every year to produce approximately 6 million gallons of prepared horseradish (what is horseradish, n.a). Horseradish are harvested once the tops are frozen which usually starts in November and continuing through winter when the soils are dry enough to support the harvesting machinery. They are usually stored in cold storage and pulled out as needed (Bratsch, 2005). Horseradish is also often dried and grounded to a powder for longer shelf life but some flavor and pungency are lost in the processing as compared to fresh product.

Horseradish can be stored satisfactorily for up to 10 to 12 months at 30 – 32˚F and relative humidity of 90 – 95 percentage as described in USDA Ag. Handbook #66. A high relative humidity is necessary for keeping up the quality during longer storage. Perforated lining bags or bin liners helps for maintaining high humidity. Horseradish roots are kept in dark to avoid green coloration when exposed to light. Roots which are harvested during their active growth period do not keep well as compared to roots conditioned by cold weather before harvesting. Horseradish can also be stored over winter in cool cellars or in deep outdoor pits or trenches (Hardenburg, Watada & Wang, 1986).

Dehydration

Drying is one of the most widely used postharvest technologies for food preservations. Drying process involves the reduction of the water content in the food to stop or slow the growth of spoilage microorganism and different deteriorative unwanted chemical reactions (Vega-Mercado, Góngora-Nieto & Barbosa-Cánovas, 2001). Food products are dried for increasing shelf life, reducing packaging costs, lowering transportation weight, easy handling, maintaining nutrition, improving appearance and preserving the originality (Chou & Chau, 2001).

During the drying of the fresh produce, significant changes takes place in the structural, physical and chemical structure of the product. Changes in these quality affects the final product quality and consumer acceptability. Studying different physical properties like color, texture, density, moisture and rehydration capacity are very important to determine the overall acceptability and quality of dehydrated food product (Amjad, Crichton, Munir, Hensel & Sturm, 2018; Meda, Mitra, Lee & Chang, 2016; Mitra & Meda, 2009).

Heat transfer for the water evaporation and mass transfer of water vapor are the two-simultaneous process involved in drying. Interaction occurs between the heat and mass transfer processes within the food itself and between the food and the drying surrounding. Products to be dried may have different shapes, water content, texture and temperature sensitivity and hence drying time, drying temperature and amount of heat supplied can be adjusted to obtain the desired moisture content in the final product (Berk, 2009; Margaris & Ghiaus, 2008).

Heat transfer and mass transfer can be different for different produce and drying conditions. Drying conditions have effect on the quality characteristics like color, texture, flavor, taste, appearance and nutritional values. Therefore, deciding suitable drying conditions is necessary for the food products to maintain the quality of dehydrated products. For a particular drying system and condition, the feed type, initial moisture content of the feed, physical structure (shape and size), drying kinetics, feed quantity and heat sensitivity of the material should be considered (Jangam, 2011). In terms of mode of operation, drying methods can be grouped into continuous or batch wise and based on the heat supply method it can be convective, conductive, radiative and dielectric (Geankoplis, 2003).

Different types of dryers and drying methods are used to remove moisture from wide variety of food products. Conventional drying process ranges from the natural sun drying to industrial drying process. Some of the most common types of drying processes and dryers are sun drying, hot air oven drying or conventional drying, fluidized bed drying, microwave drying, spray drying, freeze drying, infrared drying and osmotic dehydration (Leon, Kumar & Bhattacharya, 2002).

Convectional drying (hot air drying). Hot air is used to generate heat for the evaporation of water in case of convective drying and hence it is also called hot air drying. Convectional drying is one of the widely used drying process for industrial scale drying of food products. Cabinet dryer also known as tray or compartment dryer is the most common convective drying process. A typical convective dryer consists of removal trays set in the cabinet where the food is put, and hot air is circulated by a fan to come in contact with the food (Jayaram & Das Gupta, 1995). Transfer of heat takes place by convection method where removal of water takes place in two stages. The water is transferred to the surface of the product on first stage and the surface water is removed in the form of water vapor to the surrounding in second stage (Karam, Petit, Zimmer, Djantou & Scher, 2016).

During the conventional drying process, drying of the food materials generally takes place in three different periods. The first period is constant rate period with a constant drying rate. In this stage, moisture is removed from the saturated surface and water diffuses from a thin stagnant film of air close to the upper most surface of food materials. During the constant rate period, the surface of the solid is initially very wet and a continuous film of water exists on the surface. The rate of water removal is independent of the solid and essentially the same as the rate from a free liquid surface (Smith, 2011). During the constant rate period, removal of water is directly proportional to the heat transfer rate into the material (Toledo, 2007).

In some foods where the movement of water is controlled by capillary and gravity forces, a measurable constant rate period is found to be existed but in well-structured foods where the liquid movement is by the diffusion, water is removed from the surface which is not immediately replenished by diffusion movement of water and exhibits very short or no constant rate period. (Kaya, Aydın & Demirtaş, 2007). Towards the end of the constant rate period, there is drastic decrease in drying rate which is known as falling rate period. Insufficient water on the surface is unable to maintain the continuous film of water. During this period, the rate of liquid movement to the surface is less than the rate of evaporation from the surface and the surface becomes continually depleted in liquid water. Almost all the free water in the material are removed in this period. After the sharp decrease in drying rate, the removal of remaining bound water is very slow and complex process. The vapor pressure of the solid becomes equal to the partial vapor pressure of the drying air and no longer drying takes place. This limiting amount of moisture content to which the material can be dried under the given drying condition is known as equilibrium moisture content (Rizvi, 1986).

Fruits and vegetables are highly sensitive to the heat treatment and their drying requires more effective and fast thermal process. Researchers like Maskan (2001), Baysal, Icier, Ersus & Yıldız (2003) and Mujumdar & Law (2010) have suggested that conventional drying process tends to cause undesirable changes in the final dehydrated product as compared to other modern effective drying techniques like microwave and infrared with similar setting.

Blanching

Blanching is one of the most widely used pre-treatments carried out before the processing of fruits and vegetables. It is a heat treatment process which is commonly completed prior to the freezing, canning and drying for different purpose as indicated in Table 1.

Table 1

Purpose of Blanching for Various Processes

Purpose	Freezing	Drying	Canning
Deactivation of enzyme	+	+	+
Vegetative cell destruction	+	+	
Removal of gas from plant tissue	+	+	+
Product shrinkage	+	+	+
Cleaning foreign materials	+	+	+
Stabilization of color	+	+	+
Aid in vacuum packaging			+

(Akyol, 2006)

Note. The + sign for each unit operation indicates the purpose of blanching.

The objectives of blanching are to inactivate or slow down the enzymatic activities and to reduce the microbial load, preserve quality attributes, removal of gas from vegetative tissues and cleaning (Pan et al., 2005). Conventional blanching is carried out with hot water or steam or the combination of both. These methods are widely used in the food industries on a very big scale although there are different other new modern methods for blanching such as ultrasound blanching, infrared blanching and gas blanching.

High temperature blanching has adverse effects on the product’s texture, color, appearance and nutritional values. Hot water blanching can be carried out by low temperature long time (LTLT) or high temperature short time (HTST) methods. Regardless of both methods in water blanching, the chance of leaching out of the nutrients are more than any other methods as the product comes in direct contact with water. Textural and ultrastructural changes in carrot tissue were affected by blanching and it was found that pectin polysaccharides found abundantly in the primary wall and middle lamella between the vegetative cells are primarily responsible for most of the texture in fruits and vegetables. Texture is significantly affected by the time and temperature of exposure during the blanching. High temperature and longer blanching time have shown softening of texture and loss of nutrients. Short time blanching at higher temperature (90 – 100˚C) resulted in firmer product retention (Roy, Taylor & Kramer, 2001).

Therefore, blanching process should be monitored so that enzyme inactivation is ensured without compromising the quality. This can be achieved by studying the kinetics of enzyme deactivation and negative effects on quality parameters in different drying conditions. Blanching with hot water at 95˚C is the most effective process when carried out for (2-3) minutes (Arroqui, López, Esnoz & Vírseda, 2003; Jeremiah, 1996).

Quality Characteristics of Dehydrated Product

Different physical and chemical changes take place during drying which affect the quality of the dehydrated product. Properties such as color, texture, density, porosity and sorption characteristics of dehydrated material are affected by the drying methods. These properties characterize product quality and thus the effect of drying methods and conditions on these quality parameters is important, so that high-quality and convenient products are produced effectively at competitive cost (Krokida & Philippopoulos, 2005).

The changes in quality that can occur in any product during the drying are those in its optical properties (color, appearance), sensory properties (odor, taste, flavor), and structural properties (density, porosity, specific volume, textural properties, etc). The correlation between the color change and loss of active ingredients has been confirmed on many aromatic and medicinal crops. The rehydration properties, rehydration rate and rehydration capacity are important characteristics of many products related to their later preparation for consumption (Krokida & Maroulis, 2001).

Thin Layer Drying Models

Mathematical modelling of the drying process and conditions is very important part of fruits and vegetables drying (Castro, Mayorga & Moreno, 2018). The thin layer drying model has been considered suitable and widely used for characterizing the drying parameters. Many research studies based on mathematical modelling and experimental studies has been conducted on the thin layer drying process of fruits and vegetables (Dhanushkodi, Wilson & Sudhakar, 2017).

Page model was found to the best for describing the thin layer drying characteristics of potato slices in a continuous band dryer (Aghbashla, Kianmehr & Arabhisseini, 2009). Madamba, Driscoll and Buckle (1996) also found out that Page model gave better prediction of drying characteristics for thin-layer drying characteristics of garlic slices of 2-4 mm thickness dehydrated at a temperature range of 50-90˚C.

Akpinar and Bicer (2008) also investigated the modelling of thin layer solar drying of green pepper and found that logarithmic model was found to be most suitable for describing the drying characteristics. Henderson and Pabis model was found to be most suitable in describing the thin layer solar drying characteristics of banana, mango and cassava (Koua, Fassinou, Gbaha & Toure, 2009).

Zomorodian and Moradi (2009) studied different mathematical models for the thin layer forced convection solar drying of *Cuminum cyminum* using a solar cabinet dryer and the best thin layer drying models was selected among elven different models by comparing the coefficient of approximation (R^2) and root mean square error (RMSE). Diffusion model was found to be best fitted with R^2 value of 0.994 and RMSE of 0.0225.

Single layer drying of stone apple slices with thickness of 8 mm using the forced hot-air convection dryer at a drying temperature range from 40 to 70˚C was conducted by Rataguru and Routray (2012). The semi-empirical logarithmic model best explained the thin layer drying characteristics of the stone apple slices among six different thin layer drying models purposed. In another research studied by Nag and Dash (2015) where they studied the drying kinetics of the elephant apple *(Dillenia indica)* for drying temperature range of 50 – 80˚C, the drying rate was found to be gradually increasing with increasing drying temperature and most of the drying took place during the falling rate period. It was found that the two-term exponential model was the suitable thin layer drying model to describe the drying kinetics of the elephant apple slices.

Chapter III: Methodology

This chapter provides the description of the different drying conditions carried out in this study. This chapter explains the methods for preparation of samples, drying as well as measurement of moisture content, color, piece density, rehydration capacity and water activity.

Materials and Drying Sample Preparation

Horseradish roots were obtained from the Huntisinger Farms, Eau Claire. Fresh roots harvested at optimum maturity were used for the study. Roots in good shape with no any physical damage were selected and stored at 4˚C at a refrigerator before sample preparation for drying. Horseradish roots were sorted and cleaned under the running water to remove the adhering foreign materials. The cleaned and sorted horseradish roots were sliced to the thickness of 3mm to prepare samples for the hot air oven drying. Samples prepared were divided into two equal parts and one part of it was blanched and the other was controlled (unblanched). Both the blanched and unblanched samples were divided into 3 equal parts for drying at 3 different temperatures (50, 70 and 85˚C).

Blanching

Samples were subjected to short blanching treatment before drying. Prepared samples were submerged in the saucepan with hot water at (95±2)˚C for 2 minutes for a quick blanching treatment. The temperature of the blanched sample was brought down to room temperature of 21˚C. Blanching pretreatment was done to compare the effect of blanching on the final dehydrated product quality. Short blanching is preferred to avoid the nutrient loss and excessive moisture gain during blanching.

Dehydration of Horseradish

Samples were spread uniformly in aluminum trays (single layer). Each sample were dried at their respective temperatures of 50, 70 and 85˚C using a conventional mechanical hot air oven (Linder Bleu, model – M01450A/SA). Samples were weighed at every 10 minutes for the first hour and every 30 minutes afterwards until the sample reached to the constant weight to complete the drying. The weights were measured using ACCULAB-1200 (Sycamore, IL) model weighing balance with a readability of 0.01 gram. The final dried samples had less than 15% moisture content.

Determination of moisture content of the horseradish samples. Initial moisture content of the sample was determined by using ASABE standard procedure – (ASAE S410.2, 2010). Horseradish was cut into small-pieces of about 1cm3 in size and 5 grams of each sample was dried in a conventional hot air oven at 105˚C for 24 hours. The experiment was done in triplicate and moisture content was reported as mean. Moisture content was determined for dry basis and wet basis by using the following formulas and was expressed in percentage.

$$Dry\ basis\ (MC_{db}) = \frac{Initial\ weight\ (W_w) - Final\ weight\ (W_d)}{Initial\ weight\ (W_w)}$$

$$Wet\ basis\ (MC_{wb}) = \frac{Initial\ weight\ (W_w) - Final\ weight\ (W_d)}{Final\ weight\ (W_d)}$$

Quality Characterization of Dried Horseradish Samples

L-value, total color difference, piece density, water activity and rehydration capacity were measured for the dehydrated horseradish sample dried at different drying conditions. Following are the different methods used for the quality characterization of the dehydrated horseradish samples.

Determination of color of the dehydrated horseradish. The color of fresh and dehydrated sample was measured using the Hunter Lab Color-flex EZ- 1056 v firm ware 1.76 version colorimeter (Reston, Virginia). This system uses three parameters (L, a & b values) to describe the color inside the three-dimensional color space. The colorimeter was calibrated against the standard white and green plate before each color measurement. For each sample, 3 measurements were performed at different positions and the mean value was taken. The measurements were displayed in L, a and b values which represented the light-dark spectrum with a range from 0(black) to 100(white), the green-red from -60(green) to +60(red) and the blue-yellow spectrum with a range from -60(blue) to +60(yellow) dimensions respectively (Leon, Mery, Pedreschi and Leon, 2006).

Total color difference was calculated for each drying condition using the following equation, where subscript “0” refers to the color reading of fresh horseradish. Fresh horseradish was used for the reference and the larger ΔE represents greater color difference between the dehydrated and fresh horseradish samples.

$$\Delta \mathrm{E} = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2}$$

Where,

ΔE = Total color difference

Determination of water activity of dehydrated horseradish. Water activity of the dehydrated samples dried at different drying conditions was measured using the AQUA-LAB Dew point 4TE DUO (Corona, CA) water activity meter. Measurements were taken in triplicate for their water activity and the mean values were reported.

Determination of piece density of dehydrated horseradish. Piece density was calculated by dividing the mass of the dehydrated sample by volume. Mass was measured using analytical balance and volume was measured using the Rapeseed Displacement method standardized by AACC (1988). 5 grams of the sample was put in the 50-ml graduated cylinder and rapeseed was poured into the graduated cylinder to the 50-ml line. The dehydrated sample was separated from the rapeseed and the volume of rapeseed was measured. Each time before recording the volume, the cylinder was tapped vertically and horizontally until there was no change in volume. The volume of sample was calculated by subtracting the volume of rapeseed from the volume of the graduated cylinder.

The piece density was calculated with the equation below.

$$Piece\ Density\left(\frac{g}{mL}\right) = \frac{Mass\ of\ sample(g)}{Volume\ of\ sample\ (mL)}$$

Determination of rehydration capacity of dehydrated horseradish. 5 grams of samples were submerged in 250ml of distilled water at room temperature (20˚C) for 12 hours. After rehydration, excess water was drained and the surface water of the rehydrated sample was removed with blotting paper. Rehydration capacity of the dehydrated product was determined by using the following equation.

$$Rehydration\ capacity\ \left(\frac{g\ water}{g\ product}\right) = \frac{M_2 - M_1}{M_1}$$

Where, M_1 is the initial weight of the dehydrated sample and M_2 is the weight of the sample after rehydration.

Drying Kinetics and Empirical Mathematical Modeling of Horseradish Drying

The experimental drying curves for each drying condition were made by plotting the graph for experimental results of dimensionless moisture ratio versus drying time. The dimensionless moisture content was obtained using the following formula.

$$MR = \frac{(M - M_e)}{(M_0 - M_e)}$$

Where, MR = Moisture ratio (dimensionless)

M = Moisture content at certain time

Me = Equilibrium moisture content

M_0 = Initial moisture content

The complexity of the phenomenon occurring during the product drying has allowed the use of several empirical and semi-empirical models to describe the drying kinetics and predict the moisture ratio (MR) according to the drying time.

The drying curve were fitted with different thin-layer drying models used by various researchers in order to select the suitable model that predicts the thin-layer drying nature of the horseradish samples. The selected mathematical models tested are listed in Table 2. Non-linear regression techniques were used to obtain the specific constants in each of the selected models. During the analysis of the mathematical models, it was assumed that the samples used contained the same initial moisture content and no loss of heat to the insulations of dryer. The internal temperature gradient in samples, drying air humidity, and heat transfer between the material and volume contraction rate during the drying were very small.

Table 2

Different Thin Layer Drying Curve Models Used in this Study

Model name	Model	References
Newton	$MR = \exp(-kt)$	Bruce (1985)
Page	$MR = \exp(-kt^n)$	Page (1949)
Modified page	$MR = \exp[-(kt)^n]$	White et al. (1981)
Logarithmic	$MR = a \exp(-kt) + C$	Togrul & Pehlivan (2002)
Diffusion approach	$MR = a \exp(-kt) + (1-a) \exp(-kbt)$	Yaldiz et al. (2001)
Henderson & Pabis	$MR = a \exp(-kt)$	Henderson & Pabis (1961)
Two term	$MR = a \exp(-k_0t) + b \exp(-k_1t)$	Henderson (1964)
Two-term exponential	$MR = a \exp(-kt) + (1-a) \exp(-kat)$	Sharaf-Elden et al. (1980)

Data Analysis

The Statistical Program for Social Sciences (SPSS) version 21.0 was used for the data analysis. Data for quality parameters were analyzed by two-way ANOVA test. Mean values of all different drying conditions were compared using Tukey's HSD post-hoc test. All the tests were evaluated at a statistical significance of $p<0.05$.

Regression analysis for empirical modelling was performed using Microsoft Excel, 2013 and it's add on XLSTAT to determine the constants and coefficients of empirical models tested and to compare the different models to find the best fitting thin layer drying model for each drying condition. The coefficient of determination (R^2) was the primary criteria for selecting the best model to account for the variation in the drying curves of dried samples. Root mean square error value (RMSE) was used to determine goodness of fit of the models tested. Thin layer drying model with higher Coefficient of determination (R^2) and lower root mean square error value (RMSE) was considered as the best fitted model (Midilli and Kucuk, 2003; Akpinar et al., 2006). The statistical parameters were calculated by using the following relationships (Dhanushkodi, Wilson & Sudhakar, 2017):

$$R^2 = \frac{[\sum_{i=1}^{N}(MR_{exp,i} - \overline{MR_{exp}})(MR_{pre,i} - \overline{MR_{pre}})]}{\sum_{i=1}^{N}(MR_{exp,i} - \overline{MR_{pre}})^2 \sum_{i=1}^{N}(MR_{pre,i} - \overline{MR_{pre}})^2}$$

$$RMSE = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]^2}$$

Where, MR_{exp} and MR_{pre} represents experimental moisture ratio and predicted moisture ratio respectively.

Chapter IV: Results

Horseradish drying was performed using a conventional hot air dryer. The experiment was conducted in two phases. In the first phase, the dried samples were analyzed for their color, water activity, rehydration capacity and piece density to characterize the quality of the dehydrated horseradish. In the second phase, 8 different thin layer drying models were tested to characterize the horseradish drying kinetics and drying rates. The findings of the study are described below.

Quality Characterization of Dehydrated Horseradish

Quality changes of the dried horseradish occurred due to the different drying temperatures and blanching. The effect of the blanching and drying temperature on color, rehydration capacity, water activity and piece density of the dehydrated horseradish are presented in Table 3.

Table 3

Effects of Blanching and Drying Temperatures on the Quality of Dehydrated Horseradish

Independent variables		L-value	Total color difference	Water activity	Rehydration capacity	Piece density
Temperature	50˚C	51.07^{a}	12.16^{a}	0.25^{a}	1.98^{a}	0.69^{a}
	70˚C	48.95^{b}	7.37^{b}	0.11^{b}	1.83^{b}	0.71^{b}
	85˚C	38.96^{c}	15.32^{c}	0.07^{b}	1.49^{c}	0.72^{b}
Pretreatment	Control(C)	51.39^{a}	10.1^{a}	0.07^{a}	1.68^{a}	0.51^{a}
	Blanched(B)	41.26^{b}	13.22^{b}	0.22^{b}	1.86^{b}	0.91^{b}

Note. Means with the same superscript in the same row within the independent variable are not statistically different from each other at $\alpha = 0.05$.

L-value of dehydrated horseradish. Color measurements were performed, and it was found that the brightness color parameter in the dehydrated horseradish decreased with increasing temperature and blanching pretreatment had a negative effect on the brightness of the dehydrated horseradish. Samples which were unblanched and dried at 50˚C exhibited the highest brightness and samples which were blanched and dried at 85˚C had the lowest brightness in appearance. The result was similar to the result found by Rayaguru and Routray (2012) where stone apple slices dried at lower temperature had better brightness (higher L* values) compared to those dried at higher temperatures.

Table 4

ANOVA Result for the Effects of Blanching and Drying Temperatures on L-value of Dehydrated Horseradish

Independent variables	df	Mean square	F	Sig
Blanching	1	461.573	399.331	0.000
Temperature	2	251.068	217.212	0.000
Interaction of temperature and blanching	2	166.583	144.120	0.000

Significant interaction effect ($p<0.05$) of the independent variables i.e. temperature and blanching was found on the lightness value of the dehydrated horseradish. The magnitude of F-Statistics values from Table 4 suggested that the pretreatment has higher influence than temperature in the brightness of the dehydrated horseradish. Lightness values were significantly ($p<0.05$) different among samples dehydrated at 3 different temperatures (Table 3). Also, the blanched samples with mean lightness value of 51.39 were significantly lighter than the unblanched samples with mean lightness value of 41.26 (Table 3).

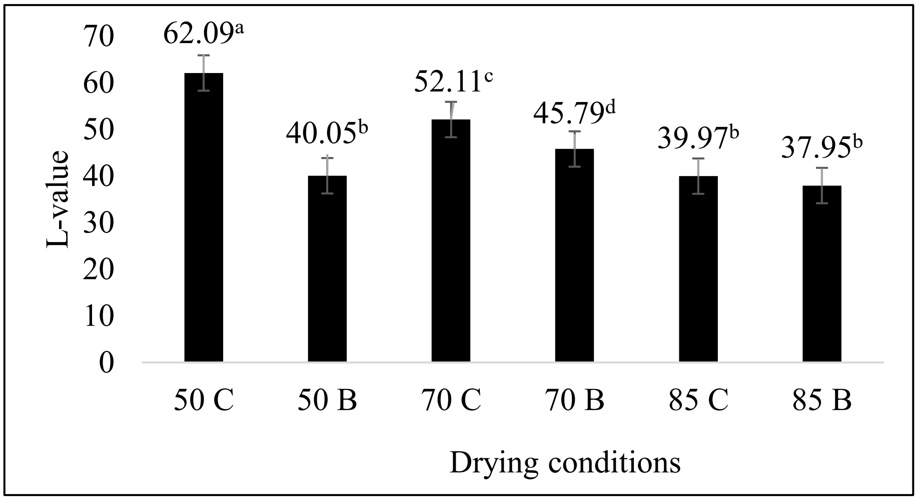

Figure 1. L-values for samples dried at 50, 70 and 85˚C. Letters C and B represent control and blanched samples respectively. Numbers on X-axis represent the drying temperatures and the bars indicated with different superscript letters are significant difference from each other at ($p<0.05$).

Conducting a Tukey Post-hoc test among the various drying conditions, it is clearly seen from Figure 1 that the unblanched samples dried at 50˚C with a mean lightness value of 62.09 was significantly brighter ($P<0.05$) than the other samples. At 50 and 70˚C, the lightness value for the unblanched samples were significantly higher ($p<0.05$) than the lightness value of the blanched sample, but at the higher temperature of 85˚C, there was no any significant difference ($p>0.05$) in the lightness value among the blanched and unblanched samples.

Total color difference of dehydrated horseradish. Total color difference measurements were done to study the difference in color between the dehydrated product and the original fresh horseradish color. Both temperature and pretreatment had a significant effect in color difference. Samples dried at 70˚C exhibited the minimum color difference when compared to the fresh horseradish. Also, the blanched samples exhibited significantly higher color difference as compared to the control (unblanched) sample. This may be due to the change in the pigment color from white to yellowish green due to the exposure to the surrounding water and heat during hot water blanching. Exposure to the sunlight and heat may result in the green coloration of horseradish (Hardenburg, Watada & Wang, 1986). Also, the browning reactions (both enzymatic and non-enzymatic) during the drying of the fruits and vegetables are related to the color change of the products. Color difference that occurs between the fresh and dried products during the drying process affects the apparent visual color of the dehydrated produce (Nagalakshmi, Mitra & Meda, 2014).

Table 5

ANOVA Result for the Effects of Blanching and Drying Temperatures on Total Color Difference of Dehydrated Horseradish

Independent variables	df	Mean square	F	Sig
Blanching	1	46.709	50.600	0.000
Temperature	2	96.082	104.085	0.000
Interaction of temperature and blanching	2	2.128	2.305	0.142

There was no any significant interaction effect (P>0.05) of the temperature and pretreatment variable on the color difference among the dehydrated samples. Considering the F-Statistics magnitude in Table 5, it can be observed that the temperature impacted more on the color difference as compared to the impact of blanching pretreatment.

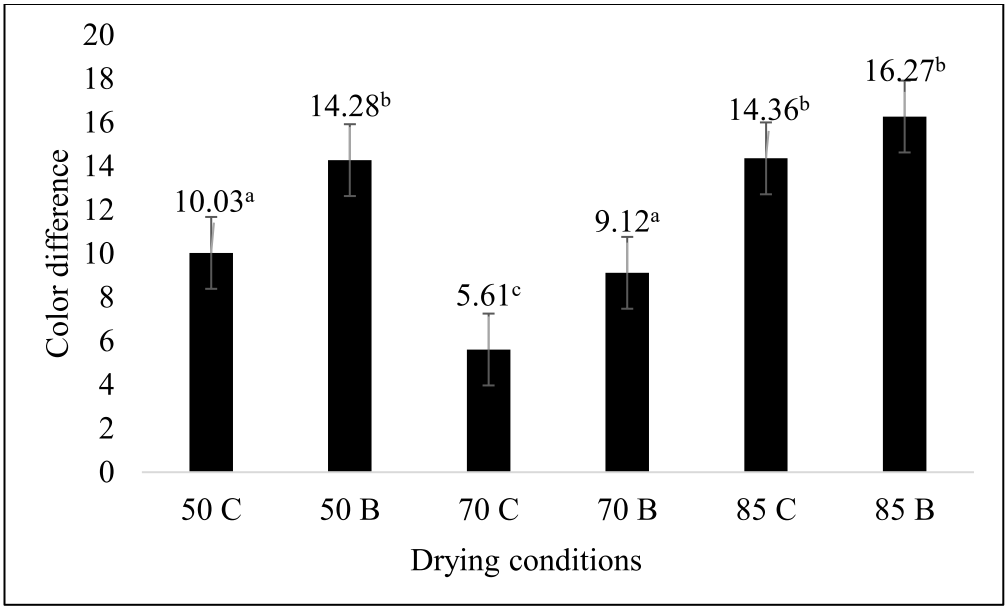

Figure 2. Total color differences for samples dried at 50, 70 and 85˚C. Letters C and B represent control and blanched samples respectively. Numbers on X-axis represent the drying temperatures and the bars indicated with different superscript letters are significant difference from each other at ($p<0.05$).

Tukey's post-hos test revealed that the sample dried at 70˚C showed significantly lower color difference ($P<0.05$) with mean value of 5.61 than all the other samples dried at different drying conditions. There was no significant difference between the blanched and unblanched samples dried at 85˚C but there was significant difference between the blanched and unblanched samples dried at 50 and 70˚C. Blanched sample dried at 50˚C and both blanched and unblanched samples dried at 85˚C showed significantly higher color difference from the rest of the samples dried in differen conditions with mean values of 14.28, 14.36 and 16.27 respectively.

Piece density of dehydrated horseradish. The result showed that the piece density was significantly affected by the blanching pretreatment and drying temperature. It was observed that the piece density for the blanched samples was higher than the control samples. Difference in drying temperature didn't affect the piece density for unblanched samples. Blanched samples dried at higher temperature exhibited higher piece density.

Table 6

ANOVA Result for the Effects of Blanching and Drying Temperatures on Piece Density of Dehydrated Horseradish

Independent variables	df	Mean square	F	Sig
Blanching	1	0.001	14.115	0.001
Temperature	2	0.696	6885.495	0.000
Interaction of temperature and blanching	2	0.000	1.347	0.297

Studying the Table 6, the F-statistics magnitude reveals that the impact of the temperature was much higher than the impact of the pretreatment in the piece density of the dehydrated samples. Horseradish dried at 50˚C had signifiacntly lower (P<0.05) density with mean value of 0.69 than the horseradish dried at 70 and 85˚C. Also, the blanched samples showed signifianctly higher density with mean value of 0.51 than the unblanched samples with mean value of 0.91. It was observed that the blanched samples had more shrinkage than the unblanched samples. The difference in the density of blanched and unblanched samples should have occoured due to the change in the texture and tissue structure due to heat during the blanching process.

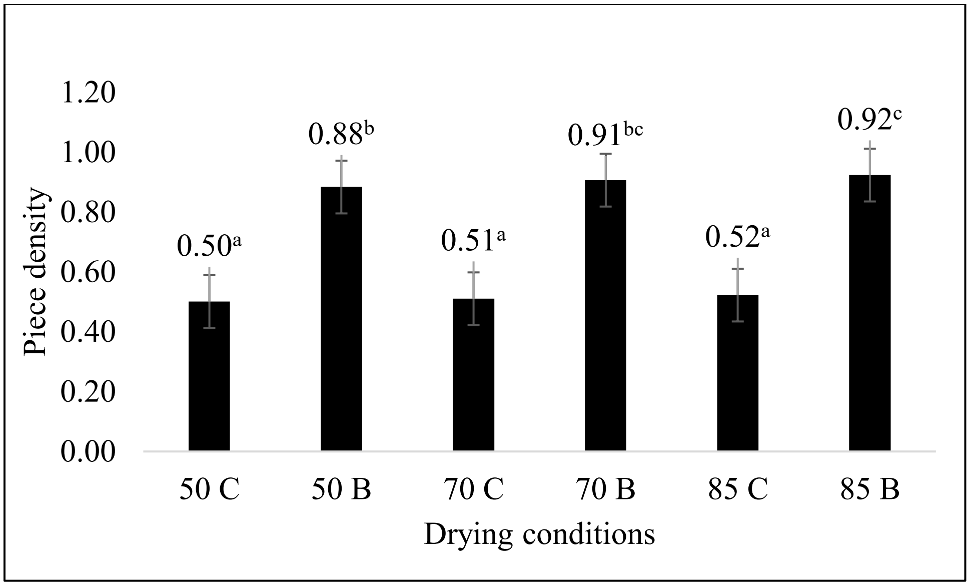

Figure 3. Piece density for samples dried at 50, 70 and 85°C. Letters C and B represent control and blanched samples respectively. Numbers on X-axis represent the drying temperatures and the bars indicated with different superscript letters are significant difference from each other at ($p<0.05$).

Studying the Figure 3, from Tukey's Post-hoc test conducted among piece density for different drying conditions, it can be clearly seen that there was no any significant difference among the unblanched samples dried at different temperatures. Also, among the blanched samples, samples dried at 50 and 70˚C were not significantly different and the samples dried at 70 and 85˚C were not significantly different in terms of density. As mentioned earlier, Figure 3 also suggests that the desnity of the blanched samples were signifianctly higher than the unblanched samples irrespective of their drying temperatures.

Rehydration capacity of dehydrated horseradish. Rehydration capacity was accessed as a part of quality assessment for the dehydrated horseradish. Rehydration capacity was found to be decreased with the increase in drying temperature. Drying in higher temperature destroys the tissue structure and textural structure of the dehydrated samples. This higher temperature may have decreased the porosity of the material which results in the decrease in the rehydration capacity of the dehydrated samples (Jangam, Chiang & Mujumdar, 2013). Also, the rehydration capacity was found to be higher in the blanched samples as compared to the control (unblanched) samples. Blanched horseradish sample dried at lower temperature of 50˚C exhibited highest rehydration capacity.

Table 7

ANOVA Result for the Effects of Blanching and Drying Temperatures on Rehydration Capacity of Dehydrated Horseradish

Independent variables	df	Mean square	F	Sig
Blanching	1	0.149	122.354	0.001
Temperature	2	0.369	303.698	0.000
Interaction of temperature and blanching	2	0.006	5.153	0.024

Significant interaction ($P<0.05$) effect of the temperature and blanching pretreatment variables on the rehydration capacity was observed as shown in Table 7 above. F-statistics magnitude suggests that temperature impacted more than blanching on the rehydration capacity of the dehydrated horseradish. The rehydration capacity decreased significantly with increasing temperature with the highest value of 1.98 for 50˚C and 1.49 for 85˚C. Also, the rehydration ratio was significantly higher ($p<0.05$) for the unblanched (control) sample in comparison to the blanched samples. Water absorption and adsorption characteristics are lowered due to the disruption of the plant tissues and textural change caused by increased drying temperature. The lowering of water adsorption and absorption capacities lowers the rehydration ability of the produce (Potter & Hotchkiss, 1995).

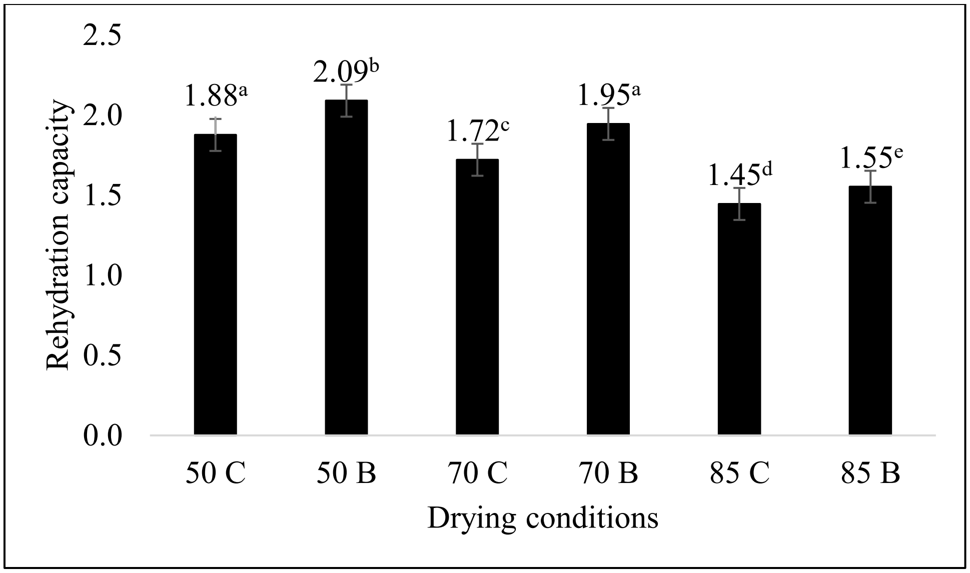

Figure 4. Rehydration capacity for samples dried at 50, 70 and 85°C. Letters C and B represent control and blanched samples respectively. Numbers on X-axis represent the drying temperatures and the bars indicated with different superscript letters are significant difference from each other at ($p<0.05$).

Blanched samples dried at 50°C showed significantly higher ($P<0.05$) rehydration capacity as compared to all other samples dried at different drying conditions. Both blanched and unblanched samples dried at 85°C tend to show the significantly low rehydration capacity with mean values of 1.55 and 1.45 respectively. Blanched sample dried at 50°C and unblanched sample dried at 70°C were not significantly different to each other in terms of their rehydration properties. Since higher rehydration capacity is desired among the dehydrated product, drying of blanched samples at 50°C seems to be suitable for getting higher rehydration capacity.

Water activity of dehydrated horseradish. Water activity of dehydrated horseradish was measured to study the effect of different drying conditions. Water activity was found to be higher in the blanched sample as compared to the unblanched dehydrated samples. Also, the water activity decreased on increasing the drying temperature for both blanched and control sample. Ratti (2001) also mentioned that higher drying temperature decreases the water activity of the dehydrated foods by removing the liquid water and bound water present in the food matrix. Horseradish samples which were unblanched (control) and dehydrated at 85˚C exhibited the lowest water activity.

Table 8

ANOVA Result for the Effects of Blanching and Drying Temperatures on Water Activity of Dehydrated Horseradish

Independent variables	df	Mean square	F	Sig
Blanching	1	0.100	119.598	0.000
Temperature	2	0.054	65.086	0.000
Interaction of temperature and blanching	2	0.015	18.128	0.000

Table 8 shows that the interaction effect of drying temperature and blanching pretreatment on the water activity of the dehydrated horseradish was found to be significant ($P<0.05$). The F-statistics magnitude in the above table shows that the impact of the blanching on the density of the product was higher in comparison to the impact on the piece density caused by the temperature and their interaction. Both the drying temperature and blanching significantly ($P<0.05$) affected the water activity of the dehydrated horseradish. From Table 3, it was found that the dehydrated sample with blanching pretreatment had significantly higher ($P<0.05$) water activity with mean value of 0.22 in comparison to the unblanched dehydrated sample with mean value of 0.7.

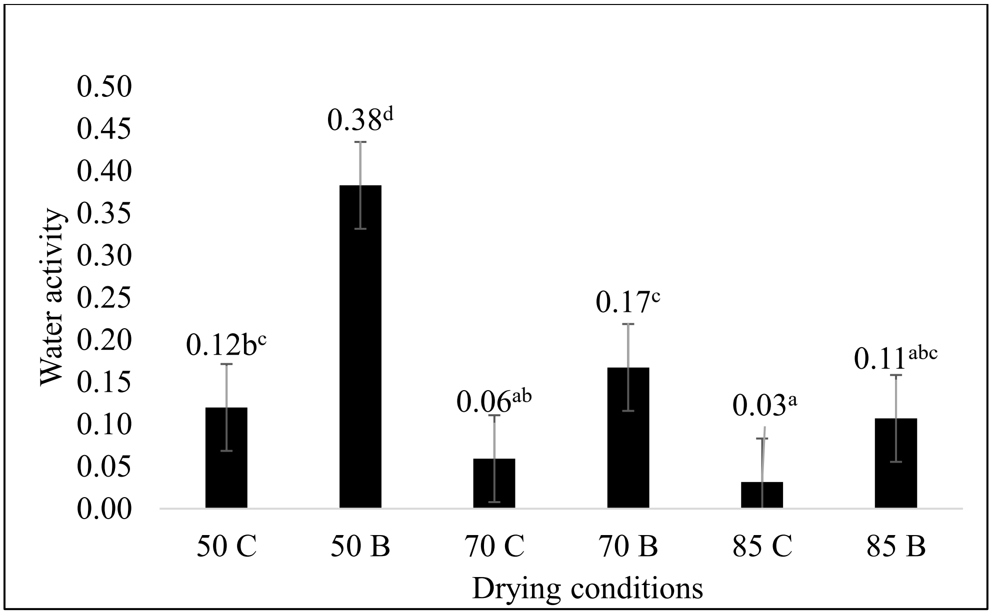

Figure 5. Water activity values for samples dried at 50, 70 and 85˚C (Letters C and B represent control and blanched samples respectively). Numbers on X-axis represent the drying temperatures and the bars indicated with different superscript letters are significant difference from each other at ($p<0.05$).

Tukey's post-hoc test revealed that blanched samples dried at 50˚C had significantly higher water activity value with mean of 0.38 as compared to all other samples dried at different drying conditions. Unblanched samples dried at 85˚C had the lowest water activity with mean value of 0.03 but was not significantly different from the blanched samples dried at 85˚C and unblanched samples dried at 70˚C.

As stated earlier, water activity seems to be decreasing from higher drying temperature to lower drying temperature for both the blanched and controlled (unblanched) samples.

Empirical Modeling and Drying Characteristics of Horseradish

Moisture content (dry basis) data for different drying conditions were converted into the most useful dimensionless moisture ratio expressions. Moisture ratios versus drying time for each drying condition time are graphically represented in Figure 6.

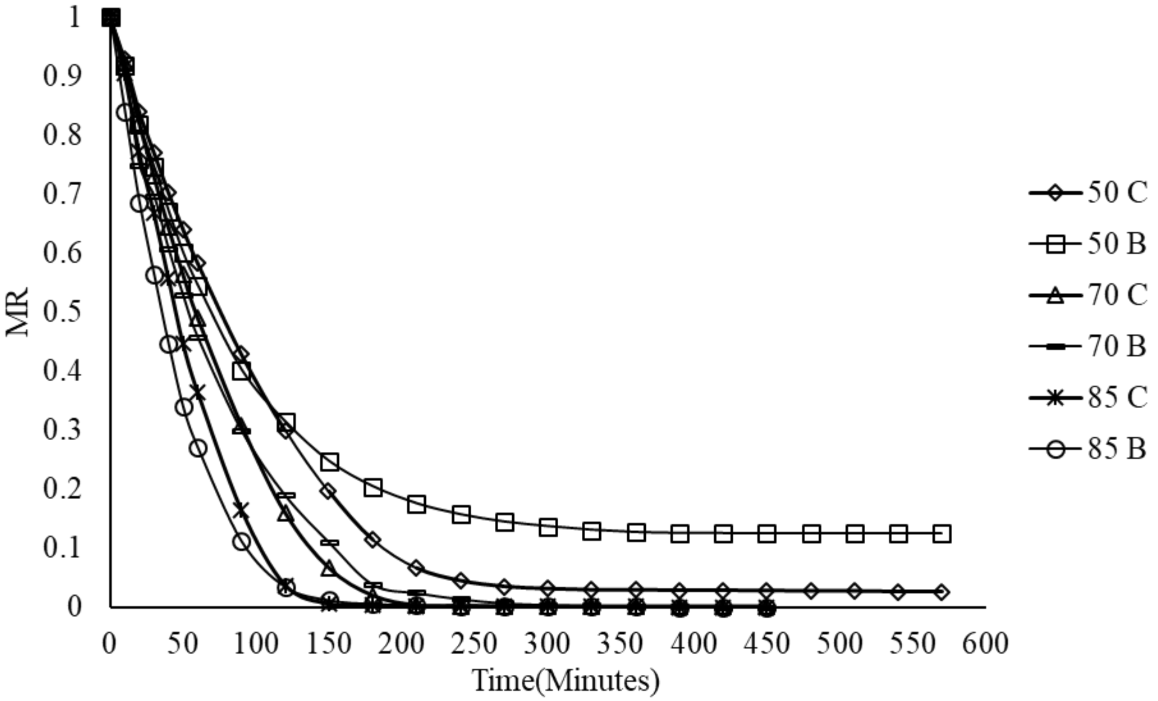

Figure 6. Relationship between moisture ratio (MR) and air-drying time at 50, 70 and 85˚C for control (C) and blanched (B) dried samples.

Eight different thin layer drying models listed in Table 2 were studied for each drying condition of the horseradish. The statistical results for R^2 and RMSE for all 8 different models that were fitted for each drying condition are listed in Table 9 and Table 10 below. Models with higher R^2 and lower RMSE was chosen as the best thin layer models to describe the drying rate for each drying condition. The solved values for drying constant and drying coefficient for the 5 best fitted models at each drying condition are listed in Table 11 below.

Table 9

Developed Model Statistical Justification of Fitting of Tested 8 Empirical Drying Models for Different Drying Temperatures for Controlled Samples (C)

	Drying temperature of control samples					
	50°(C)		70°(C)		85°(C)	
Tested models	R^2	RMSE	R^2	RMSE	R^2	RMSE
Diffusion approach	0.99813	0.01764	0.9986	0.01551	0.99847	0.01514
Modified page	0.99442	0.02886	0.99268	0.04357	0.99025	0.04397
Logarithmic	0.99492	0.02577	0.99268	0.0328	0.99046	0.03607
Page	0.99777	0.01813	0.9987	0.01293	0.9988	0.01147
Henderson & Pabis	0.99491	0.02524	0.99187	0.03365	0.99008	0.03764
Newtons	0.99442	0.02823	0.99261	0.04241	0.99024	0.0428
Two term exponentials	0.99441	0.0289	0.99266	0.04412	0.99022	0.04402
Two term	0.99491	0.02648	0.99187	0.0388	0.99008	0.03993

Table 10

Developed Model Statistical Justification of Fitting of Tested 8 Empirical Drying Models for Different Drying Temperatures for Blanched Samples (B)

	Drying temperature of blanched samples					
	50˚(B)		70˚(B)		85˚(B)	
Tested models	R^2	RMSE	R^2	RMSE	R^2	RMSE
Diffusion approach	0.99965	0.00649	0.99865	0.01391	0.99975	0.00539
Modified page	0.97941	0.07137	0.99771	0.02197	0.99716	0.02101
Logarithmic	0.99953	0.00658	0.99773	0.0174	0.99721	0.01791
Page	0.96769	0.05008	0.9981	0.01428	0.99951	0.00633
Henderson & Pabis	0.96752	0.06777	0.9974	0.0199	0.99713	0.01855
Newtons	0.97942	0.0698	0.9977	0.02139	0.99716	0.02456
Two term exponentials	0.97906	0.05496	0.99771	0.02201	0.99715	0.02104
Two term	0.99974	0.00509	0.9974	0.02111	0.99713	0.01968

Table 11

Fitted Model Parameters of Control (C) and Blanched (B) Horseradish Dried at 50, 70 and 85˚C.

Models		50˚(C)	50˚(B)	70˚(C)	70˚(B)	85˚(C)	85˚(B)
Diffusion approach	a	-0.5315	-0.0662	-1.0778	-0.5960	-1.2028	-6.0112
	b	0.5300	0.9171	0.6026	0.6242	0.6008	0.9140
	k	0.0249	0.0115	0.0336	0.0277	0.0455	0.0380
Page	k	0.0047	0.0300	0.0034	0.0082	0.0036	0.0106
	n	1.1655	0.7310	1.3146	1.1155	1.3820	1.1800
Henderson and Pabis	a	1.0402	0.9350	1.0668	1.0402	1.0698	1.0327
	k	0.0106	0.0076	0.0142	0.0105	0.0183	0.0219
Two term	a	0.7421	0.0911	0.2939	0.7422	0.1942	0.2536
	b	0.2979	0.9223	0.7729	0.2979	0.8756	0.7790
	k_0	0.0106	-0.0006	0.0141	0.0106	0.0183	0.0219
	k_1	0.0106	0.0119	0.0141	0.0106	0.0183	0.0219
Two term expo	a	0.0002	0.2949	0.0002	0.0002	0.0002	0.0002
	k	51.5329	0.0206	60.378	51.533	69.3381	109.338

Note. a, b and n are empirical constants for and k, k_0 and k_1 are empirical coefficients for drying models.

Figure 7 to 12 shows the graphical representation of the experimental moisture ratio curves and three best fitted thin layers models for each different drying condition. The best fitted thin layer drying predicted moisture ratio curve overlaps closely with the experimental MR curve in the moisture ratio vs time graph.

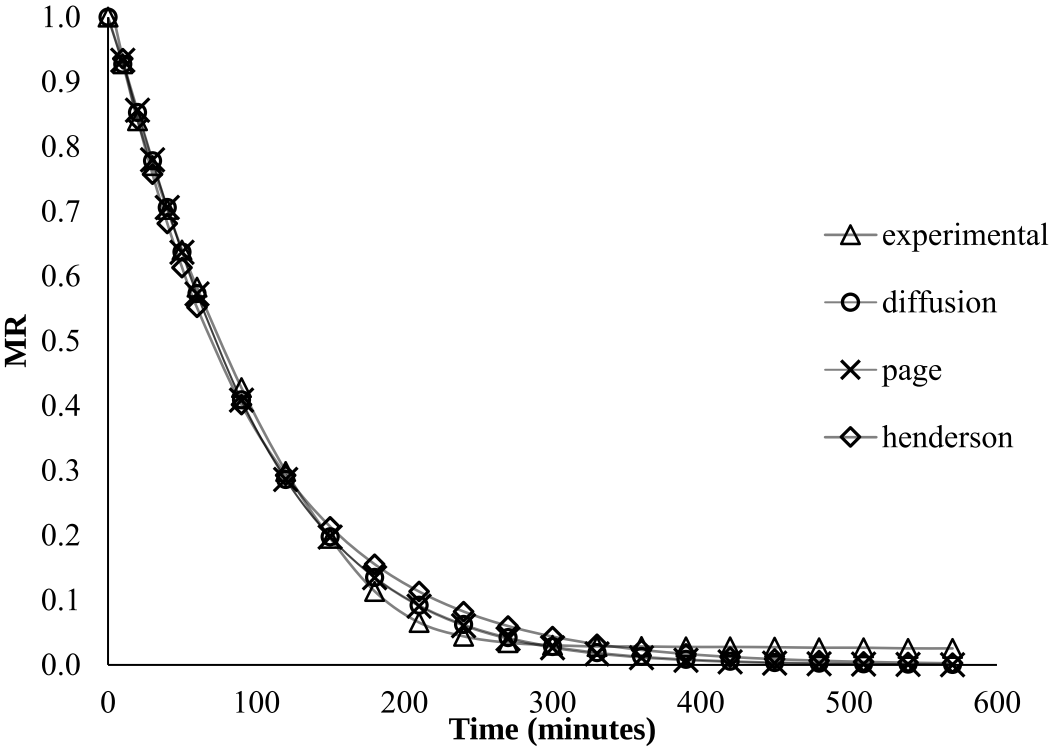

Figure 7. Experimental moisture ratio and predicted moisture ratios from 3 best fitted models for unblanched horseradish samples dried at 50˚C.

Diffusion approach model was found to be the best fitting thin layer drying model for describing the drying process of the unblanched horseradish dried at 50˚C with R^2 value of 0.99813 and RMSE value of 0.01746. Diffusion approach model was followed by Page model with R^2 value of 0.99777 and RMSE value of 0.01813.

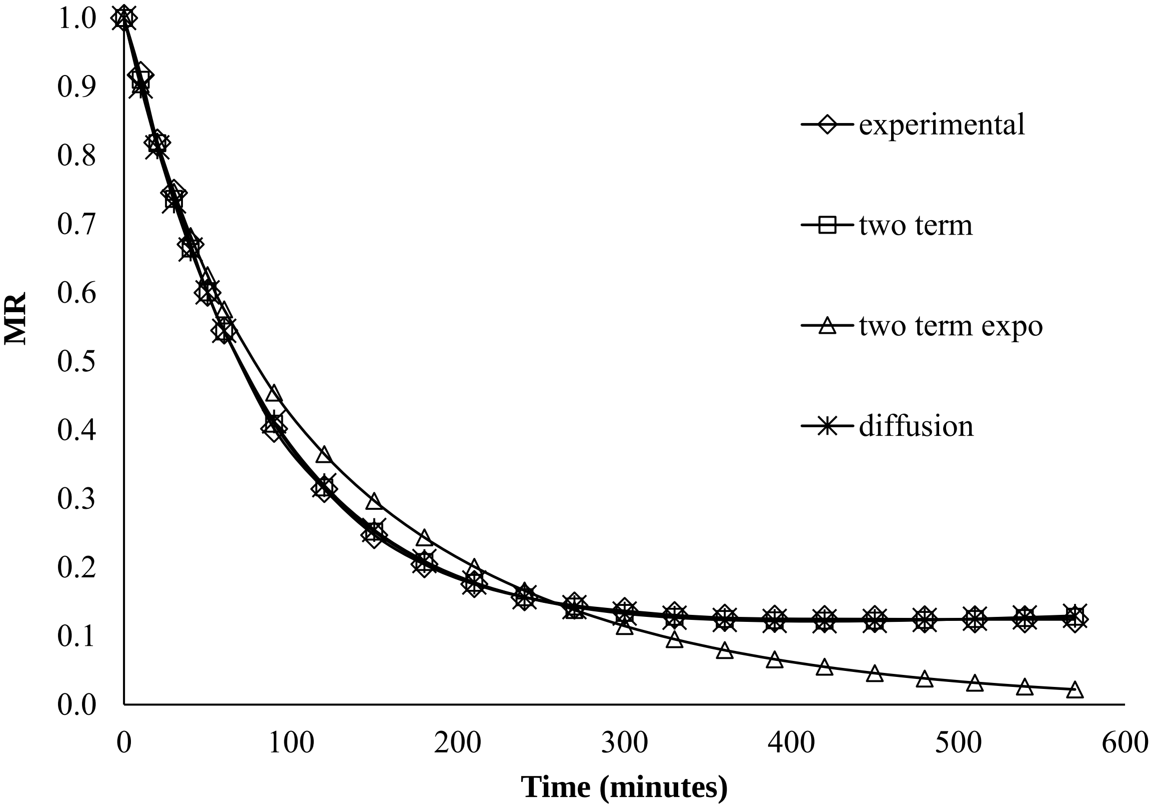

Figure 8. Experimental moisture ratio and predicted moisture ratios from 3 best fitted models for blanched horseradish samples dried at 50˚C.

For the blanched sample dried at 50˚C, diffusion approach model has the highest R^2 value of 0.9997 and was the best fitting thin layer drying model. The RMSE value for diffusion approach model was 0.00649. In the above figure, we can see diffusion approach predicted value curve closely overlapping with the experimental value curve. Other models like Two term and Page were also good fit for this drying condition.

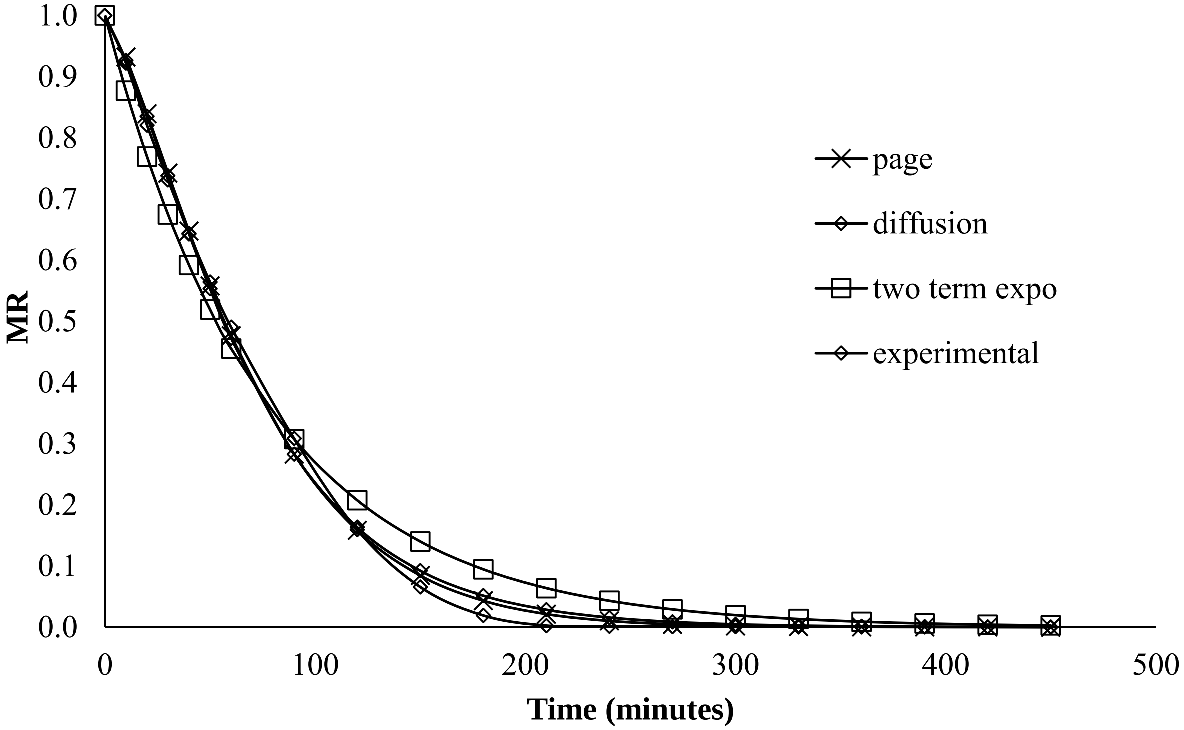

Figure 9. Experimental moisture ratio and predicted moisture ratios from 3 best fitted models for unblanched horseradish samples dried at 70˚C.

Page, diffusion approach and two term exponential model showed good fit of the predicted drying curve with experimental curve for the unblanched samples dried at 70˚C. Among them Page model was the best fitting thin layer drying model with the R^2 value of 0.9987 and RMSE value of 0.01293.

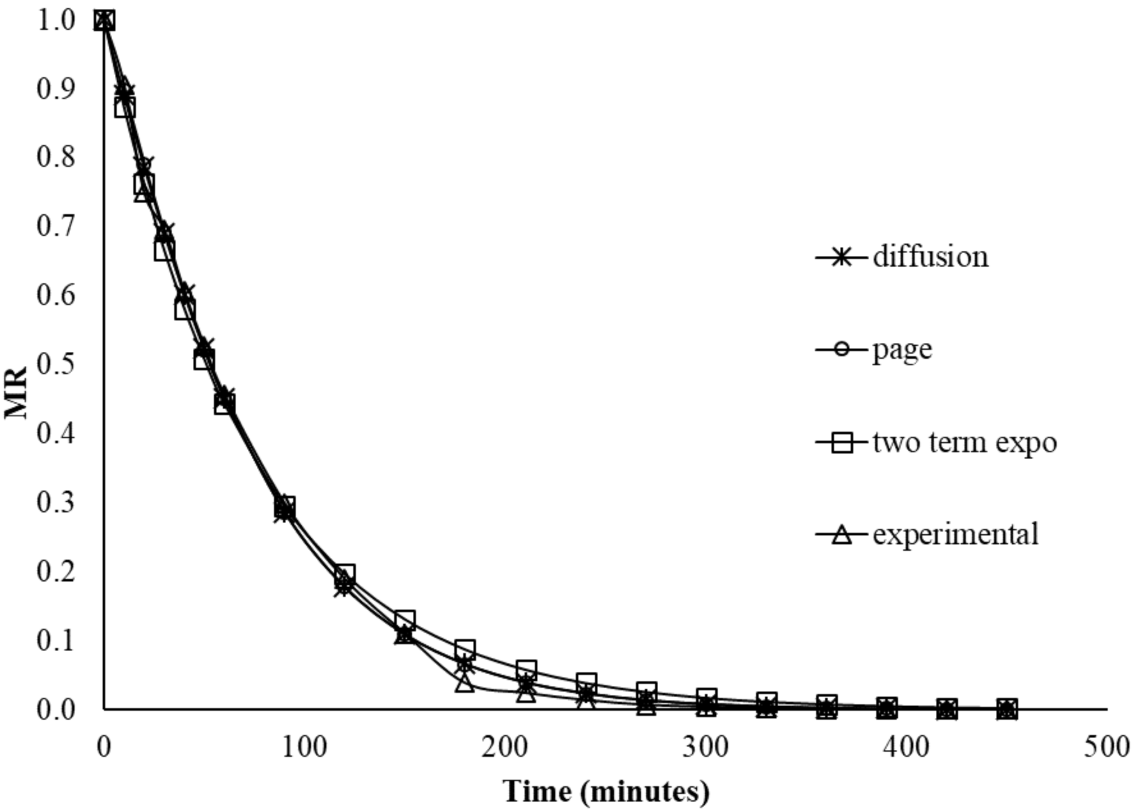

Figure 10. Experimental moisture ratio and predicted moisture ratios from 3 best fitted models for blanched horseradish samples dried at 70˚C.

For the samples which were blanched and dried at 70˚C, the diffusion approach was found to be best fit for predicting the thin layer drying nature. The R^2 and RMSE value for diffusion approach was found to be 0.99865 and 0.01391. Page model was the second best fitting thin layer drying model for this drying condition with R^2 value of 0.9981 and RMSE value of 0.01428.

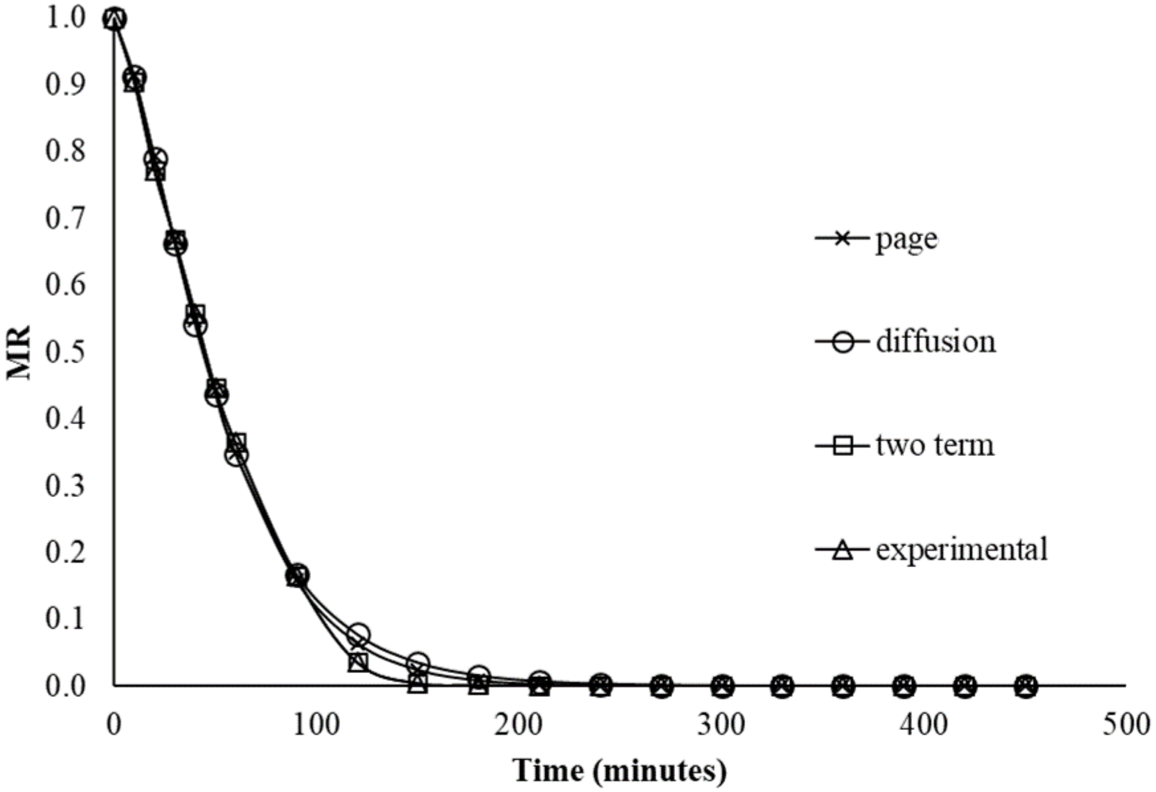

Figure 11. Experimental moisture ratio and predicted moisture ratios from 3 best fitted models for unblanched horseradish samples dried at 85˚C.

Page model was found to be best fitted thin layer drying model for the unblanched samples dried at 85˚C. The R^2 and RMSE value was found to be 0.9988 and 0.01147 respectively for Page model. Diffusion model with R^2 value of 0.99847 and RMSE value of 0.01514 was the second-best model for predicting the thin layer drying characteristics for this drying condition.

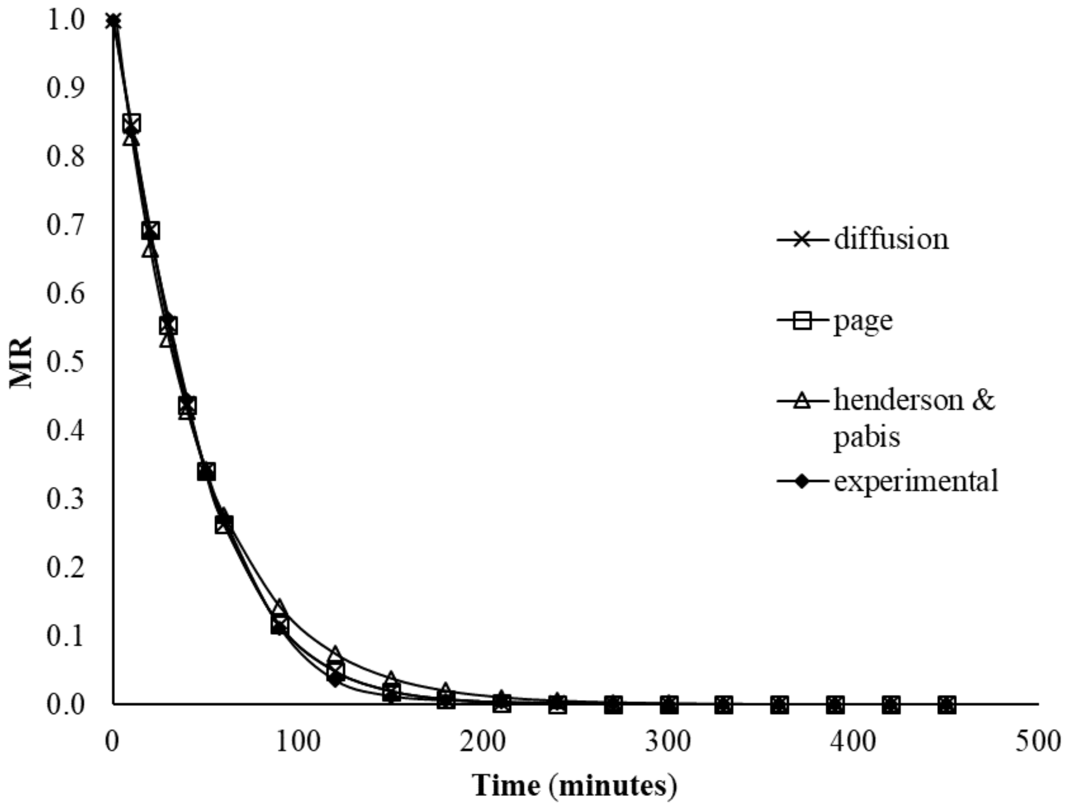

Figure 12. Experimental moisture ratio and predicted moisture ratios from 3 best fitted models for unblanched samples dried at 85˚C.

Like other drying conditions above, diffusion model was the best fitted thin layer drying model for prediction of drying of blanched samples at 85˚C. The R^2 and RMSE value for the diffusion model was 0.99975 and 0.00539 respectively. Page model was the second-best model for predicting the thin layer drying moisture ratio value for this drying condition with R^2 value of and RMSE value of 0.99951 and 0.00539 respectively.

Hence, Page model and Diffusion Approach model was found to be best fitted models for predicting the dehydration characteristics of horseradish at different drying condition. This result was similar to the results of many other studies done by different researchers. Sadi and Meziane (2015) found that Diffusion Approach model was most suitable to describe the microwave drying kinetics of the olive pomace. Zomorodian and Moradi (2009) also found out that Diffusion Approach was the best model to describe the thin layer drying kinetics of the *Cuminnum cyminum*. Many research studies have also found that Page model can be used successfully in describing the drying kinetics of the various fruits and vegetables like garlic, banana, mango, cassava and potato (Aghbashla, Kianmehr & Arabhisseini, 2009; Driscoll & Buckle, 1996; Koua, Fassinou, Gbaha & Toure, 2009).

Chapter V: Conclusion

This result indicated that both drying process variables (drying temperature and blanching pretreatment) had significant ($p<0.05$) effects on the color (L value and total color difference), water activity, piece density and rehydration capacity of the dehydrated horseradish. Unblanched samples exhibited higher brightness as compared to the blanched samples and the lightness value decreased with increasing drying temperature. Unblanched sample dried at 70˚C exhibited minimum color difference among all other drying condition. Blanching of horseradish before dehydration showed significantly higher density for dehydrated sample as compared to the unblanched samples irrespective of their drying temperature. Also, the drying temperatures did not have any significant effect on the density of the unblanched sample. Hence, for industrial drying process, dehydration of unblanched horseradish sample is preferred because of their low density. Rehydration capacity was found to be decreasing with increasing drying temperatures. Also, the blanched dehydrated samples exhibited higher rehydration capacity as compared to unblanched dehydrated samples. Samples which were blanched and dehydrated at 50˚C exhibited the highest rehydration capacities among all different drying conditions. Water activity was found to be significantly low (0.03) for the unblanched samples as compared to the blanched samples. The unblanched samples dried at higher temperature exhibited the lowest water activity among all the samples.

The experimental moisture ratio data from different drying conditions were fitted to 8 different thin layer drying models which were used by different researchers and it was found that diffusion approach and page model were the two best fitted thin layer drying models. Diffusion model was best for the samples dried at 50˚C with R^2 and RMSE values of 0.9996 and 0.0065 respectively for blanched samples and 0.9981 and 0.0175 respectively for unblanched samples.

Diffusion model was also the best fitted model for the blanched samples dried at 70˚C and 85˚C. The R^2 and RMSE values from the diffusion model for blanched samples dried at 70˚C were found to be 0.9987 and 0.0139 respectively and for the blanched samples dried at 85˚C, the R^2 and RMSE values were 0.9985 and 0.0151 respectively. Page model of thin layer drying was suitable for predicting the drying characteristics with R^2 and RMSE values of 0.9987 and 0.0129 respectively for unblanched samples dried at 70˚C and R^2 and RMSE values of 0.9988 and 0.0114 respectively for unblanched samples dried at 85˚C.

Recommendations

Based on the research conducted, following are the recommendations for the future research on the horseradish drying.

- Since drying was only preformed at the conventional oven drier, the effect of different driers such as microwave, vacuum, infrared and/or their combination studies would be recommended.
- The study of the effect of different drying conditions on the nutritional value of dehydrated horseradish can be studied.

References

Aghbashlo, M., Kianmehr, M. H., & Arabhosseini, A. (2009). Modeling of thin-layer drying of potato slices in length of continuous band dryer. *Energy Conversion and Management*, *50*(5), 1348-1355.

Akpinar, E. K. (2006). Determination of suitable thin layer drying curve model for some vegetables and fruits. *Journal of Food Engineering*, *73*(1), 75-84.

Akpinar, E. K., & Bicer, Y. (2008). Mathematical modelling of thin layer drying process of long green pepper in solar dryer and under open sun. *Energy Conversion and Management*, *49*(6), 1367-1375.

Amjad, W., Crichton, S. O. J., Munir, A., Hensel, O., & Sturm, B. (2018). Hyperspectral imaging for the determination of potato slice moisture content and chromaticity during the convective hot air drying process. *Biosystems Engineering*, *166*, 170-183.

Arroqui, C., López, A., Esnoz, A., & Vírseda, P. (2003). Mathematic model of an integrated blancher/cooler. *Journal of Food Engineering*, *59*(2), 297-307.

ASAE Standards. (2002). *Moisture measurement: Peanuts* (S410.1). St. Joseph, MI. ASAE.

Baysal, T., Icier, F., Ersus, S., & Yıldız, H. (2003). Effects of microwave and infrared drying on the quality of carrot and garlic. *European Food Research and Technology*, *218*(1), 68-73.

Berk, Z. (2009). Dehydration. *Food process engineering and technology*. 1st ed. New York, 459-510.

Bratsch, A. (2005). *Speciality crop profile: Horseradish.* Virginia State University. Virginia Cooperative Extension. Retrieved from https://pubs.ext.vt.edu

Bruce, D. M. (1985). Exposed-layer barley drying: Three models fitted to new data up to 150 C. *Journal of Agricultural Engineering Research*, *32*(4), 337-348.

Castro, A. M., Mayorga, E. Y., & Moreno, F. L. (2018). Mathematical modelling of convective drying of fruits: A review. *Journal of Food Engineering*, *223*, 152-167.

Chou, S. K., & Chua, K. J. (2001). New hybrid drying technologies for heat sensitive foodstuffs. *Trends in Food Science & Technology*, *12*(10), 359-369.

Dhanushkodi, S., Wilson, V. H., & Sudhakar, K. (2017). Mathematical modeling of drying behavior of cashew in a solar biomass hybrid dryer. *Resource-Efficient Technologies*.

Earle, H. R., & Yi, W. C. (1986). *The commercial storage of fruits, vegetables, and florist and nursery stocks (Agriculture Handbook Number 66).* Washington, D.C.: U.S.

Ekechukwu, O. V. (1999). Review of solar-energy drying systems I: An overview of drying principles and theory. *Energy Conversion and Management*, *40*(6), 593-613.

Geankoplis, C. J. (2003). *Transport processes and separation process principles.* (4th ed.). Upper Saddle River, NJ: Prentice Hall

Henderson, S. M. (1974). Progress in developing the thin layer drying equation. *Transactions of the ASAE*, *17*(6), 1167-1168.

Jangam, S. V. (2011). An overview of recent developments and some R&D challenges related to drying of foods. *Drying Technology*, *29*(12), 1343-1357.

Jayaraman, K. S., & Das Gupta, D. K. (1995). Drying of fruits and vegetables. *Handbook of Industrial Drying*, *1*, 643-690.

Jeremiah, L. E. (1996). *Freezing effects on food quality*. Boca Raton, FL: CRC Press.

Karam, M. C., Petit, J., Zimmer, D., Djantou, E. B., & Scher, J. (2016). Effects of drying and grinding in production of fruit and vegetable powders: A review. *Journal of Food Engineering*, *188*, 32-49.

Kaya, A., Aydın, O., & Demirtaş, C. (2007). Drying kinetics of red delicious apple. *Biosystems Engineering*, *96*(4), 517-524.

Koua, K. B., Fassinou, W. F., Gbaha, P., & Toure, S. (2009). Mathematical modelling of the thin layer solar drying of banana, mango and cassava. *Energy*, *34*(10), 1594-1602.

Krokida, M. K., & Maroulis, Z. B. (2001). Structural properties of dehydrated products during rehydration. *International Journal of Food Science & Technology*, *36*(5), 529-538.

Krokida, M. K., & Philippopoulos, C. (2005). Rehydration of dehydrated foods. *Drying Technology*, *23*(4), 799-830.

Kumar, C., Karim, M., & Joardder, M. (2014). Intermittent drying of food products: A critical review. *Journal of Food Engineering*, *121*, 48–57.

Leon, K., Mery, D., Pedreschi, F., & Leon, J. (2006). Color measurement in L∗ a∗ b∗ units from RGB digital images. *Food Research International*, *39*(10), 1084-1091.

Leon, M. A., Kumar, S., & Bhattacharya, S. C. (2002). A comprehensive procedure for performance evaluation of solar food dryers. *Renewable and Sustainable Energy Reviews*, *6*(4), 367-393.

Madamba, P. S., Driscoll, R. H., & Buckle, K. A. (1996). The thin-layer drying characteristics of garlic slices. *Journal of Food Engineering*, *29*(1), 75-97.

Magaris, D. P., & Ghiaus, A. (2007). Fruits and vegetables dehydration in tray dryers. *New Food Engineering Research Trends*, 45-102.

Maskan, M. (2001). Kinetics of color change of kiwifruits during hot air and microwave drying. *Journal of Food Engineering*, *48*(2), 169-175.

Meda, V., Mitra, P., Lee, J. H., & Chang, K. S. (2016). Optimization of microwave-vacuum drying processing parameters on the physical properties of dried Saskatoon berries. *Open Agriculture*, *1*, 7-17.

Midilli, A., & Kucuk, H. (2003). Mathematical modeling of thin layer drying of pistachio by using solar energy. *Energy Conversion and Management*, *44*(7), 1111-1122.

Mitra, P., & Meda, V. (2009). Optimization of Microwave-Vacuum Drying Parameters of Saskatoon Berries Using Response Surface Methodology. *Drying Technology: An International Journal*, *27* (10), 1089-1096.

Mitra, P., Meda, V., & Green, R. (2013). Effect of drying techniques on the retention of antioxidant activities of Saskatoon berries. *International Journal of Food Studies*, *2*, 224-237.

Moradi, M., & Zomorodian, A. (2009). Thin layer solar drying of cuminum cyminum grains by means of solar cabinet dryer. *American-Eurasian Journal of Agriculture and Environmental Sciences*, *5*(3), 409-413.

Mujumdar, A. S., & Law, C. L. (2010). Drying technology: Trends and applications in postharvest processing. *Food and Bioprocess Technology*, *3*(6), 843-852.

Nagalakshmi, S. A., Mitra, P., & Meda, V. (2014). Color, mechanical, and microstructural properties of vacuum assisted microwave dried saskatoon berries. *International Journal of Food Properties*, *17*(10), 2142-2156.

Orsat, V., Changrue, V., & Raghavan, G. V. (2006). Microwave drying of fruits and vegetables. *Stewart Post-Harvest Review*, *6*, 4-9.

Pabis, S., & Henderson, S. M. (1961). Grain drying theory. II. A critical analysis of the drying curve for shelled maize. *Journal of Agricultural Engineering Research*, *6*(4), 272-277.

Page, G. E. (1949). *Factors influencing the maximum rates of air drying shell corn in thin layers* (Master's thesis). Retrieved from https://docs.lib.purdue.edu/dissertations/AAI1300089/.

Pan, Z., Olson, D. A., Amaratunga, K. S. P., Olsen, C. W., Zhu, Y., & McHugh, T. H. (2005). Feasibility of using infrared heating for blanching and dehydration of fruits and vegetables. In *Annual Meeting of the American Society of Agricultural and Biological Engineers (ASAE).* Retrieved from http://www.catalyticdrying.com/pdf/feasibility-of-using-infrared-heating-for-blanching-and-dehydration-of-fruits-and-vegetables.pdf

Ratti, C. (2001). Hot air and freeze-drying of high-value foods: A review. *Journal of Food Engineering*, *49*(4), 311-319.

Rayaguru, K., & Routray, W. (2012). Mathematical modeling of thin layer drying kinetics of stone apple slices. *International Food Research Journal*, *19*(4), 1503.

Rizvi, S. S. (1986). Thermodynamic properties of foods in dehydration. *Engineering Properties of Foods*, *2*, 223-309.

Roy, S. S., Taylor, T. A., & Kramer, H. L. (2001). Textural and ultrastructural changes in carrot tissue as affected by blanching and freezing. *Journal of Food Science*, *66*(1), 176-180.

Rubatzky, V. E., & Yamaguchi, M. (2012). *World vegetables: Principles, production, and nutritive values*. Springer Science & Business Media.

Sadi, T., & Meziane, S. (2015). Mathematical modelling, moisture diffusion and specific energy consumption of thin layer microwave drying of olive pomace. *International Food Research Journal*, *22*(2).

Sagar, V. R., & Kumar, P. S. (2010). Recent advances in drying and dehydration of fruits and vegetables: a review. *Journal of Food Science and Technology*, *47*(1), 15-26.

Sharaf-Eldeen, Y. I., Blaisdell, J. L., & Hamdy, M. Y. (1980). A model for ear corn drying. *Transactions of the ASAE*, *23*(5), 1261-1265.

Smith, P. G. (2011). Minimal processing technology. In P. G. Smith (Ed.), *Introduction to food process engineering* (pp. 467-478). New York, NY: Springer US.

Toğrul, İ. T., & Pehlivan, D. (2002). Mathematical modelling of solar drying of apricots in thin layers. *Journal of Food Engineering*, *55*(3), 209-216.

Toledo, R. T. (2007). *Fundamentals of food process engineering* (3rd ed.). New York, NY: Springer US.

Vega-Mercado, H., Góngora-Nieto, M. M., & Barbosa-Cánovas, G. V. (2001). Advances in dehydration of foods. *Journal of Food Engineering*, *49*(4), 271-289.

Walters, S. A., & Wahle, E. A. (2010). Horseradish production in Illinois. *HortTechnology*, *20*(2), 267-276.

What is Horseradish? (n.d.). (Horseradish Information Council) Retrieved January 5, 2018, from Horseradish-the Secret Ingredient: http://horseradish.org/horseradish-facts/what-is-horseradish/

White, G. M., Ross, I. J., & Poneleit, C. G. (1981). Fully-Exposed drying of popcorn. *Transactions of the ASAE*, *24*(2), 466-0468.

Yaldiz, O., Ertekin, C., & Uzun, H. I. (2001). Mathematical modeling of thin layer solar drying of sultana grapes. *Energy*, *26*(5), 457-465.