International Food Research Journal 23(1): 34-39 (2016)
Journal homepage: *http://www.ifrj.upm.edu.my*

Modeling the solar drying kinetics of gamma irradiation-pretreated oyster mushrooms *(Pleurotus ostreatus)*

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Article history

Received: 29 November 2014
Received in revised form:
26 June 2015
Accepted: 2 July 2015

Keywords

Gamma irradiation
Mushrooms
Solar drying
Drying kinetics

Abstract

Oyster mushroom slices *(Pleurotus ostreatus)* were exposed to ɣ-radiation as a pretreatment and solar dried to investigate the influence of irradiation on drying kinetics. Processing conditions included exposure of mushrooms to 0 kGy (control), 0.5 kGy, 1.0 kGy, 1.5 kGy and 2.0 kGy of ɣ-radiation at a dose rate of 1.7 kGy/h and drying at a mean temperature of 53.2±6.4°C. Experimental drying data were fitted to 5 thin layer drying models by non-linear regression. Irradiation was observed to enhance the drying rate of mushroom slices, with higher doses causing faster moisture removal. Drying characteristics of slices exposed to lower dosages were best described by Page's model (R^2=0.9878, 0.9967, 0.9925 correspondingly for "control" (0.0 kGy), 0.5 and 1.0 kGy while the Diffusion model best fit the data for those exposed to higher doses of radiation (R^2=0.9938, 0.9890 for 1.5 and 2.0 kGy respectively). Deff ranged from 1.88 to 2.44 x 10^{-08} and increase from "control", 0.5 kGy, 1.0 kGy, 1.5 kGy to 2.0 kGy. Irradiation of mushrooms as a pretreatment for drying increases moisture diffusivity and drying rate with higher doses having the most effect.

Introduction

Mushrooms play a vital role in the biosphere and their production represents the most efficient bioconversion of a wide range of lingo-cellulosic waste materials including sawdust and corn cobs into expensive proteins. They are one of the highest protein producers per unit area and time (Kortei, 2011) and are nutritionally well endowed with essential amino acids, minerals and vitamins (Akindahunsi and Oyetayo, 2006; Kumari *et al*., 2011). Mushrooms are also known to possess medicinal properties because they contain bioactive compounds such as triterpenoids, lectins and steroids (Lindequist *et al*., 2005; Singh *et al*., 2012).

Fresh mushrooms have been reported to store from 1 to 3 days at ambient conditions because of their high moisture content and high transpiration rate (Mahajan *et al*., 2008). Therefore, it is necessary that they are marketed soon after harvest, or preserved with special care to maintain its wholesomeness. In this regard, several techniques, including solar drying, have been suggested to improve their shelf stability and enhance its economic potential. Solar drying is accomplished by exposing the produce to air in a chamber which is heated by concentrating the sun's energy with an insolation material. This reduces moisture content of the produce and stabilizes it by lowering the rate of chemical reactions and its susceptibility to microbial attack. Dehydrated mushrooms are used in several preparations, including soups and stews (Martinez-Soto *et al*., 2001).

Albeit one of the most widely employed drying techniques, solar drying may be slow and impart certain undesirable quality changes to the final product. As a result, pre-treatments have been applied to products before drying. These pretreatments, usually chemical, improve drying rates and or prevent undesirable changes associated with drying. Other pretreatments such as irradiation have been employed in food dehydration (Wang and Chao, 2002; Yu and Wang, 2005). Irradiation technology has proved effective in sterilizing and also extending the shelf life of food by delaying or eliminating biological processes. Its application in certain fruits and vegetables as a pre-treatment for drying have been shown to boost drying rates by altering the structure of tissues (Wang and Chao, 2002; Wang and Du, 2005). Application of irradiation prior to drying mushrooms may also result in changes that will affect

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its drying characteristics as well as quality of the final dried product.

Drying kinetics of different mushroom species, such as button and oyster mushrooms, have been reported in previous studies (Pal and Chakraverty, 1997; Giri and Prasad, 2007; Addo *et al*., 2009; Wakchaure *et al*., 2010; Tulek, 2011). However, the influence of irradiation as a pretreatment on the kinetics of solar-dried mushrooms has not yet been studied. This study therefore investigates the influence of gamma irradiation pre-treatment on drying kinetics of oyster mushrooms *(Pleurotus ostreatus)* dried in a tunnel solar dryer.

Materials and Methods

Mushroom species and growth parameters

Oyster mushrooms *(Pleurotus ostreatus)* originally from Mauritius, were cultivated on Triplochiton scleroxylon sawdust composted for 28 days and supplemented with 1% $CaCO_3$ and 10% rice bran as described by Obodai *et al*., (2003). This was carried out at the Mushroom Unit of the Council for Scientific and Industrial Research (CSIR)-Food Research Institute, Accra, Ghana. Growth and harvesting of mushrooms was from the period of September to December, 2013. Mature mushroom harvested 2 days after primodia emergence were used for the study.

Irradiation of mushroom materials

Forty (40) grams of mushroom slices (6.8±0.51 mm thick) were packed into polythene containers and irradiated at doses of 0.0 kGy (control), 0.5 kGy, 1 kGy, 1.5 kGy and 2 kGy at a dose rate of 1.7 kGy per hour in air at room temperature (28±1^{o}C) from a cobalt 60 source (SLL 515, Hungary). Doses were confirmed using the ethanol-chlorobenzene (ECB) dosimetry system at the Radiation Technology Centre of the Ghana Atomic Energy Commission, Accra, Ghana. For each dosage, a total of 520 g of mushrooms was irradiated.

Drying experiments

The oyster mushrooms slices (6.8±0.51 mm thick) were dried using a tunnel solar dryer designed and fabricated by the CSIR-Food Research Institute, Ghana. Prior to solar drying, the mushrooms were pretreated with gamma irradiation under the different dose treatments aforementioned. Mushrooms, weighing 150 g (in triplicates) were spread in a single layer on a wire mesh and loaded into the solar tunnel dryer. Drying was conducted between the hours of 0900 to 1700 hrs each day. Moisture loss during drying was determined by measuring the loss in weight of samples at 30 min interval, with an electronic balance (Kern 510, Kern and Sohn, GMbH, Germany). Sampling and weighing was done until a constant weight was attained (Akonor and Tortoe, 2014). Both experimental and control samples were dried simultaneously under the same weather condition. At the beginning and ending of each experimental run, moisture content of mushrooms was determined by standard methods (AOAC, 1990). Mean drying temperature and relative humidity over the drying period were 53.2±6.4°C and 30.7±5.8% respectively. Dried mushrooms were sealed air-tight and stored in rigid polypropylene containers.

Mathematical modeling

Moisture ratio (MR) of mushrooms for thin layer drying was calculated as follows:

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

Where M_t = Moisture content (%) after time t; M_e = Equilibrium moisture content and M_o = Initial moisture content. However, due to varying relative humidity and temperature during drying and the fact that M_e is very small, compared to M_o and M_t, it could be neglected, thus simplifying (1) according to Yaldyz and Ertekyn (2001) and Goyal *et al*., (2007) as:

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

Experimental data for moisture ratio vs. drying time were fitted to 5 drying models, commonly used to describe the thin layer drying kinetics of perishable fruits and vegetables, by Non-linear regression (Statgraphics Centurion 15.1). Models used were; Lewis [$MR = \exp(-kt)$], Page [$MR = \exp(-kt^n)$], Henderson and Pabis [$MR = a \exp(-kt)$], Diffusion model [$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$] and Wang and Singh [$MR = 1 + at + bt^2$]. In these models, a and b are dimensionless drying coefficients while k and n are drying constants (min^{-1}).

The main criterion for selecting the best model to describe the drying curves was the coefficient of determination (R^2). Also, the reduced chi square (χ^2) and the Root Mean Square Error (RMSE) were used to determine the goodness of fit between predicted and experimental data. High R^2 and low χ^2 and RMSE correspond to a better goodness of fit (Akpinar *et a*l., 2003). The χ^2 and RMSE were calculated from the following formulae:

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{expi} - MR_{prei})^2}{N - z} \quad (3)$$

$$RMSE = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}(MR_{expi} - MR_{prei})^2\right]} \quad (4)$$

Where N= Number of observations; z = Number of constants in the model; MR_{exp} and MR_{pre} are experimental and predicted moisture ratios respectively.

Effective moisture diffusivity

Generally, diffusion is assumed as the dominant transport mechanism during drying and the rate of moisture movement is therefore described by an effective diffusivity value, D_{eff} (m^2/s), which is related to MR by equation 5

$$lnMR = ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \quad (5)$$

Where *t*=drying time (min) and *L*= Half thickness of slices (m). The effective moisture diffusivity was obtained by plotting the experimental drying data in terms of lnMR against time, t (min). From equation 5, a plot of lnMR against drying time, t, gives a straight line with slope, K, where

$$K = \frac{\pi^2 D_{eff}}{4L^2} \quad (6)$$

Results and Discussion

Drying profiles

Drying curves from the drying experiment is displayed in Figure 1. As shown, exposure to radiation influenced rate of moisture loss in the mushrooms during drying, such that irradiated slices dried faster than the “control” (0.0 kGy). Among the mushrooms exposed to ɣ-radiation, the rate of moisture loss directly corresponded to radiation dosage, with those exposed to high levels of gamma rays drying faster.

High rate of moisture loss in irradiated mushroom may be attributed to the breakdown of tissue structures. Upon exposure to ɣ-irradiation, chitin, which is the main structural carbohydrate in mushrooms depolymerizes, resulting in loss of firmness (Akram *et al*., 2012). Consequently, resistance to moisture migration towards the surface of the product reduces. This observation affirms the suggestion that food structure is influential in determining moisture transport within food materials (Labuza and Altunakar, 2007). The drying curves showed no constant rate period, suggesting that diffusion is the dominant mode of moisture removal from the mushrooms (Srikiatden and Roberts, 2006). This observation corroborates earlier findings for other products such as white button mushrooms (Wakchaure *et al*., 2010), eggplant (Doymaz and Gol, 2011), leafy vegetables (Akonor and Amankwah, 2012).

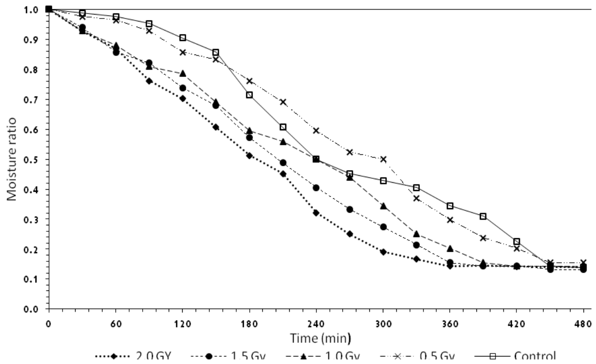

Figure 1. Influence of irradiation on drying rate oyster mushrooms

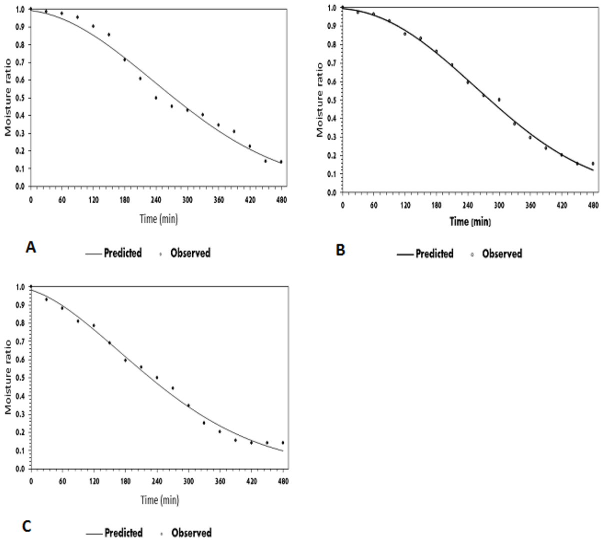

Figure 2. Model fit for control (A), 0.5 kGy (B) and 1.0 kGy (C) using Page’s model

Non-Linear regression modeling

Table 1 summarizes the outcome of the non-liner regression modeling using 5 thin layer drying models, and these were compared based on their R^2, χ^2 and RMSE. All 5 models showed very good fit (R^2>0.9) to the experimental data. Nevertheless, the Page and Diffusion models were the best to describe drying kinetics of mushrooms under the different experimental conditions. Drying kinetics of slices exposed to lower radiation dosages (0.5 – 1.0 kGy) was quite similar to the “control”. Under these experimental conditions, the Page’s model resulted in the highest R^2 and lowest χ^2 and RMSE and best suited its description.

The three indices were 0.9878, 0.0382, and 0.0014 for the control, 0.9967, 0.0184 and 0.004 for 0.5 kGy and 0.9925, 0.0274 and 0.0008 for 1.0 kGy. The Diffusion model best predicted drying behavior of mushrooms exposed to ɣ-radiation in excess of 1.0 kGy. Drying characteristics of mushrooms

Table 1. Drying models and selection criteria for best fit

Model	R^2	X^2	*RMSE*
0 kGy			
Lewis	0.9508	0.1287	0.0189
Page	***0.9878***	***0.0382***	***0.0014***
Henderson and Pabis	0.9304	0.0865	0.2755
Diffusion model	0.9862	0.0435	0.0020
Wang and Singh	0.9594	0.0693	0.0052
0.5 kGy			
Lewis	0.9446	0.1308	0.0195
Page	***0.9967***	***0.0184***	***0.0004***
Henderson and Pabis	0.9191	0.0932	0.0093
Diffusion model	0.9878	0.0389	0.0014
Wang and Singh	0.9771	0.0513	0.0028
1.0 kGy			
Lewis	0.9714	0.0982	0.0110
Page	***0.9925***	***0.0274***	***0.0008***
Henderson and Pabis	0.9191	0.0932	0.0093
Diffusion model	0.9891	0.0356	0.0012
Wang and Singh	0.9780	0.0518	0.0029
1.5 kGy			
Lewis	0.9781	0.0976	0.0109
Page	0.9938	0.0273	0.0007
Henderson and Pabis	0.9571	0.0669	0.0048
Diffusion model	***0.9938***	***0.0259***	***0.0007***
Wang and Singh	0.9731	0.0622	0.0041
2.0 kGy			
Lewis	0.9756	0.0935	0.0100
Page	0.9854	0.0403	0.0017
Henderson and Pabis	0.9667	0.0606	0.0039
Diffusion model	***0.9890***	***0.0367***	***0.0012***
Wang and Singh	0.9718	0.0709	0.0054

slices from this group were therefore dissimilar from the earlier group, which includes the “control”. Drying characteristics of mushroom slices in this study are quite different from observations made in some previous studies. In these earlier studies, drying characteristics were best described by Wang and Singh model (Arumuganathan *et al.*, 2009) Logarithmic model (Wakchaure *et al.*, 2010) and Midilli *et al* model (Tulek, 2011). Differences in variety and or processing conditions may account for the contrasting outcomes.

Figures 2 and 3 compare the experimental moisture ratios to those predicted by the Page’s (for control, 0.5 kGy and 1.0 kGy) and Diffusion models (for 1.5 kGy and 2.0 kGy). These models showed very good fit between the experimental and predicted moisture ratios, confirming the suitability of these models for describing solar drying of ɣ-irradiated mushrooms.

Effective moisture diffusivity

The effective moisture diffusivity (D_{eff}) describes the rate of moisture movement in food (Okos *et al.*, 2007). Deff varied between 1.88 and 2.44 x 10^{-08}m^2/s for the control and mushrooms treated with 2.0 kGy of ɣ-rays. The moisture diffusivity in the differently treated mushrooms increased with increasing dosage of ɣ-irradiation (Figure 4).

Differences in effective diffusivities may be attributed to the extent of tissue disruption that may have occurred in mushrooms as a result of irradiation. Gamma irradiation causes breakage of fibrous structure and enlarges the pores therein (Akram *et al.*, 2012) thus facilitating moisture removal. High diffusivity values as a result of increasing radiation exposure further emphasize the enhancement of moisture removal by this processing technology. Deff results obtained in this study were comparable to the generalized range of 10^{-9} – 10^{-12} for most foods (Labuza and Altunakar, 2007) higher than 1.55 – 4.02 x 10^{-09} m^2/s reported for milky mushrooms (Arumuganathan *et al.*, 2009) and 9.62 – 1.56 x 10^{-09} m^2/s reported for oyster mushroom (Tulek, 2011) but lower than 9.21 x 10^{-08}m^2/s to 1.49x10^{-07}m^2/s for white button mushrooms (Wakchaure *et al.*, 2010). These variations are likely to result from varietal and conditional differences adopted in these various studies.

Conclusion

The effect of irradiation as a pre-treatment prior to drying oyster mushroom slices was manifested in reduced drying time. Pre-treated slices dried faster

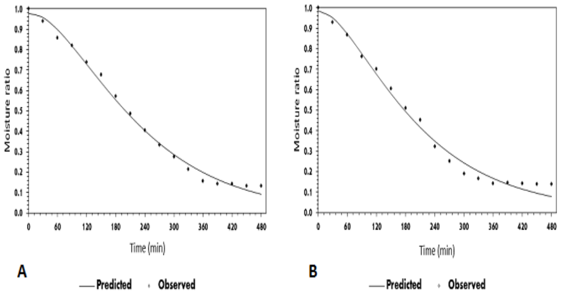

Figure 3. Model fit for 1.5 kGy (A) and 2.0 kGy (B) using diffusion model

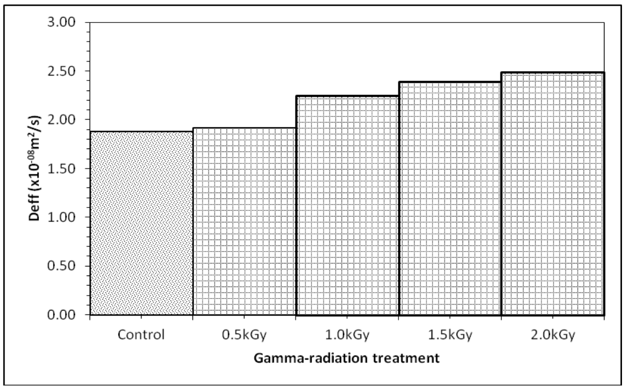

Figure 4. Effective moisture diffusivity of dried mushrooms

than the control, with increasing dosage resulting in shorter drying time. Among the 5 thin layer models, Page's model best predicted the drying characteristics of slices exposed to lower doses of ɣ-radiation, while Diffusion model gave the best results and adequately described the behavior of slices that received higher doses (1.5 and 2.0 kGy). Moisture diffusivity ranged between 1.88 and 2.44 x 10^{-08} m^2/s and was higher among the pretreated mushroom slices. Gamma irradiation appears to be a suitable pretreatment for drying mushrooms.

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