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Scientific Research

Investigation of moisture diffusivity rate and drying kinetics of quinoa sprouts in an infrared dryer

Sepideh Vejdanivahid [1], Fakhreddin Salehi [2*]

[1] MSc Student, Department of Food Science and Technology, Faculty of Food Industry, Bu-Ali Sina University, Hamedan, Iran.

[2*] Associate Professor, Department of Food Science and Technology, Faculty of Food Industry, Bu-Ali Sina University, Hamedan, Iran.

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*Corresponding Author E-

F.Salehi@basu.ac.ir

ABSTRACT

By using modern drying technologies such as infrared and selecting the right conditions for this technology, dried quinoa sprouts can be produced with desirable quality and high nutritional value, and it is possible to use this dried product and its powder to fortify various food products such as breads, pastries, protein bars, cakes, pancakes, etc. In this study, the effect of infrared lamp irradiation power and sample distance from the heat source on the drying kinetics of quinoa sprouts was investigated and modeled. By increasing the infrared lamp power from 250 W to 375 W, moisture was removed from the quinoa sprouts faster and the product dried in a shorter time. However, when using 375 W, the sprouts quickly burned before completely drying. By reducing the infrared lamp distance from 10 cm to 5 cm, moisture was removed from the quinoa sprouts more quickly and the product dried in shorter time. The average drying times of quinoa sprouts when dried with the infrared lamp with power of 250 W at distances of 5, 7.5 and 10 cm were 10.7, 17.3 and 18.0 min, respectively. The calculated effective moisture diffusivity coefficient for quinoa sprouts dried under a 250 W infrared lamp at distances of 5, 7.5, and 10 cm were 6.60×10^{-10} m^2s^{-1}, 2.55×10^{-10} m^2s^{-1}, and 0.83×10^{-10} m^2s^{-1}, respectively. To investigate the drying kinetics of quinoa sprouts, various mathematical models were fitted to the experimental data, and the Page model, which had the best fit and the least error, was selected as the best model. In general, using the infrared heat source with a power of 250 W at a distance of 5 cm from surface of the quinoa sprouts is recommended for drying this product, as it has a short drying time and does not burn.

1-Introduction

Quinoa is a member of the *Chenopodiaceae* family and is known as a dicotyledonous pseudocereal. Quinoa is high in protein and contains a variety of vitamins (folate, niacin, and riboflavin), bioactive compounds (saponins, phenolic compounds, phytosterols, and peptides), minerals (iron, magnesium, phosphorus, potassium, and zinc), fiber, and essential amino acids. Quinoa seeds are known as a complete protein source because they contain all 9 essential amino acids required by the body [1-3]. These properties have made quinoa a valuable additive in the production of a variety of innovative food products, including gluten-free products, quinoa milk, baby food, and nutraceutical products [4, 5]. Quinoa seeds can be considered as a very useful food for children, the elderly, women at risk of osteoporosis, athletes, and people with anemia, diabetes, dyslipidemia, and celiac disease due to their high nutritional value, lack of gluten, low glycemic index, and therapeutic properties [6].

Sprouted grains and cereal-like grains have higher nutritional value and physiological benefits than conventional grains and cereal-like grains and their processed products [7]. During sprouting, some compounds are broken down for respiration and synthesis of new cellular components, which leads to significant changes in biochemical, nutritional and sensory properties. In general, sprouting improves the nutritional value of grains and legumes. During this process, anti-nutritional compounds such as phytic acid are reduced and the content of vitamins, fiber and beneficial plant compounds such as ferulic acid is increased [8]. Karimi and Saremnezhad (2020) investigated the effect of sprouting process on some functional properties of Iranian lentil cultivars. All tests were performed on lentil flour of Iranian cultivars Kimia and Gachsaran in unsprouted (control) and sprouted states for 24 and 48 hours. According to the results of this study, sprouting increased the concentration of gamma-aminobutyric acid in both cultivars studied, while it had a decreasing effect on iron concentration [9]. One of the methods of preserving agricultural products is drying them, which reduces the moisture and water activity of the product and prevents microorganisms growth [10, 11]. Based on the heat transfer method, different dryers have different methods for heating the product and removing moisture from it. In most drying methods, heat is first transferred to the outer surface of the wet material and then to its interior [5, 10]. Infrared radiation is a new and efficient technology that uses electromagnetic waves to directly transfer thermal energy to food. This method improves the mechanical and functional properties of grains by penetrating into the grains and creating structural changes in the starch. The advantages of infrared include reducing drying time, reducing energy consumption, and improving product quality. This radiation also reduces the mechanical resistance of grains, increases brittleness, and improves their milling process. It also changes the water absorption capacity and viscosity of starch, making it more suitable for use in products such as puddings, soups, and sauces. On the other hand, this technology increases the digestibility of starch and increases the efficiency of the process by reducing processing time and cost [12, 13].

The aim of this study was to investigate the effect of infrared lamp power and heat source distance on drying rate, moisture diffusivity coefficients, and drying kinetics of quinoa sprouts and to select the best drying conditions. Also, moisture removal kinetics from sprouts was modeled with the help of different experimental models.

2- Materials and Methods

2-1- Sprouting process of quinoa

In this study, white quinoa seeds, harvested from Peruvian farms and packaged in Iran (OAB Company, Iran). First, the seeds were washed and soaked in tap water for 1 hour at a temperature of about 25°C (Figure 1). Next, the seeds were poured into flat containers and covered with a thin, damp towel. The seeds were moistened every 6 h with a water sprayer bottle. In total, the seeds were placed at a temperature of about 25°C for sprouting for 72 h (Figure 2).

Figure 1- Soaking and sprouting steps of quinoa seeds

Figure 2- Sprouted quinoa seeds

2-2- Infrared drying

In this study, an infrared dryer with two irradiation powers of 250 W (Figure 3) and 375 W was used to dry quinoa sprouts. To investigate the effect of the distance of the irradiation source from the sample surface, the sprouts distance from the lamp surface was considered at three levels of 5, 7.5, and 10 cm. The weight changes of the samples during drying were recorded every minute by a digital balance (GM-300p, Lutron, Taiwan) with an accuracy of ± 0.01 g.

Figure 3- Infrared dryer

2-3- Mosture ratio parameter

The drying rate is the amount of water removed per unit time [10]. In this study, first, the reduction in moisture content of quinoa sprouts against the drying time, on a dry basis, was plotted and the effect of different germination conditions on them were investigated. Then, the moisture ratio

(MR) parameter was calculated using equation 1 [14].

(1)

$$MR = \frac{M_t}{M_o}$$

In this equation, MR is the moisture ratio (dimensionless), M_t is the moisture content on a dry basis at any time t (g water/g dry matter), and M_0 is the initial moisture content on a dry basis.

2-4- Effective moisture diffusivity coefficients

Throughout the drying process, diffusion is the dominant phenomenon of moisture transfer from the center of the sample to the surface. The theoretical model used to determine the effective moisture diffusivity coefficient (D_{eff}) of quinoa sprouts was based on Fick's second law of diffusion and using spherical coordinates. Equation 2 was used to calculate the effective moisture diffusion coefficient [15].

(2)

$$Slope = \frac{\pi^2 D_{eff}}{r^2}$$

In these equation, r is the quinoa radius (m), D_{eff} is the effective moisture diffusivity coefficient (m^2s^{-1}), n is a positive integer, t is the drying time (s), and Slope is the slope of the natural logarithm of the experimental data moisture ratio (lnMR) versus dehydration time.

2-5- Kinetic modeling

Mathematical modeling of the drying process is used to design, improve existing drying systems and even process control. In order to investigate the kinetics and predict the drying process of quinoa sprouts, kinetic modeling was performed with the help of experimental data and using different experimental drying models. Wang and Singh, Henderson and Pubis, Approximation of diffusion, Page, Newton, Midilli, logarithmic, and quadratic equations (Table 1) were selected and examined to model the drying process of quinoa sprouts by infrared and select the best kinetic model [16].

The best model should have the highest coefficient of determination (r) and the lowest sum of squares due to error (SSE), and root mean square error (RMSE). Matlab software, version R2012a, was used to model the experimental drying data and obtain the model constants.

Table 1- Mathematical models used to model the drying kinetics of quinoa sprouts

Model	Equation
Wang and Singh	$MR=1+at+bt^2$
Henderson and Pabis	$MR= a\exp(-kt)$
Approximation of diffusion	$MR=a\exp(-kt)+(1-a)\exp(-kbt)$
Page	$MR=\exp(-kt^n)$
Newton	$MR=\exp(-kt)$
Midilli	$MR=a\exp(-kt^n)+bt$
Logarithmic	$MR=a\exp(-kt)+c$
Quadratic	$MR=a+bx+cx^2$

2-6- Statistical analysis

Quinoa sprout drying tests were performed in triplicate. Duncan's multiple range test was used to compare the mean of the observed responses at a 95% confidence level. The results were analyzed using SPSS version 21 software.

3- Results and discussions

3-1- Drying kinetics of quinoa sprouts

Infrared radiation provides rapid and direct heat to the product, which is faster and more efficient than convection dryers, where some of the heat is lost to the exhaust air.

Most of the infrared radiation is absorbed by surface molecules. This phenomenon causes rapid heating of the product, reducing thermal stresses in the product and thus maintaining its quality. This can reduce drying time, reduce energy costs, and also evenly distribute the temperature throughout the product, resulting in a higher quality product [17]. Figure 4 shows the effect of infrared lamp power on the moisture loss rate of quinoa sprouts during drying in an infrared dryer. By increasing the infrared power from 250 W to 375 W, moisture was removed from the quinoa sprouts more quickly and the product was dried in a shorter time. Of course, using 375 W power reduced the drying time of the product, but the sprouts quickly burned and turned black before they were completely dry. Therefore, using 375 W power is not recommended for irradiating and drying sensitive sprouts such as quinoa. On the other hand, the drying speed of the product with a power of 250 W was suitable and the product did not burn. Therefore, using a power of 250 W is recommended for drying quinoa sprouts. The average drying time of quinoa sprouts when dried with an infrared lamp with a power of 250 watts at distances of 5, 7.5, and 10 cm was 10.7, 17.3, and 18.0 min, respectively.

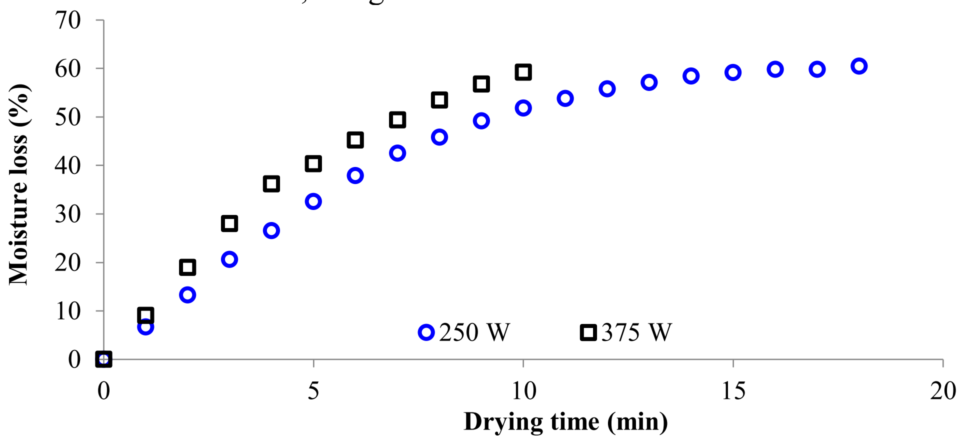

Figure 4- Effect of infrared radiation power on moisture loss rate of sprouted quinoa seeds during drying in the infrared dryer (10 cm distance)

By decreasing infrared lamp distance from the surface of the samples, the surface temperature of the samples increased faster, and this increase in temperature increased the vapor pressure inside the sample and, as a result, increased the rate of moisture removal from the product. Figure 5 shows the effect of the infrared lamp distance on the rate of moisture loss of quinoa sprouts during drying in an infrared dryer. By decreasing the distance of the infrared lamp from 10 cm to 5 cm, moisture was removed from the quinoa sprouts more quickly and the product was dried in less time. At a distance of 5 cm from the irradiation source to quinoa sprouts surface, infrared radiation was absorbed by the sprouts to a greater extent and the drying time was reduced. These results are consistent with the results of Amini et al. (2020) for drying basil seed gum with an infrared dryer [18]. These researchers reported that changing the distance of the infrared heating lamp from the surface of the wet samples had a significant effect on their drying time, and by decreasing the lamp distance, the drying time decreased.

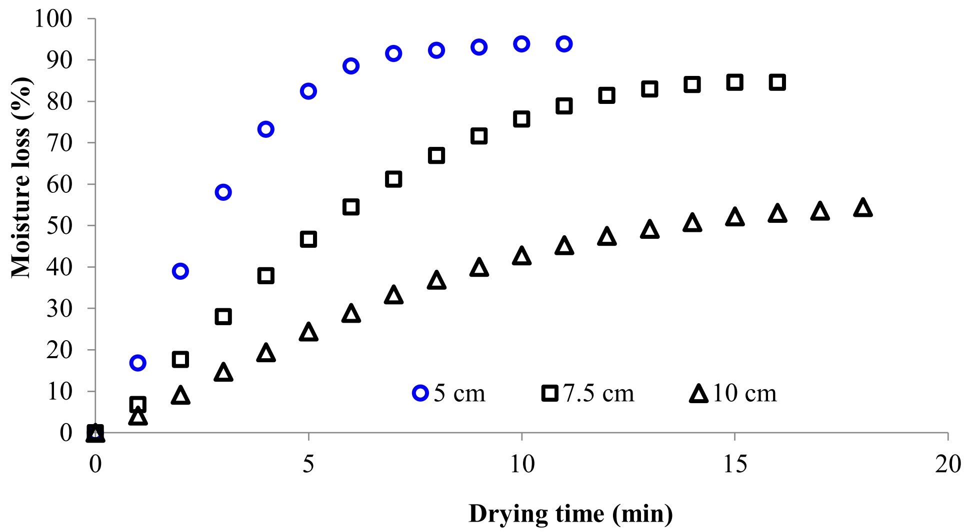

Figure 5- Effect of radiation lamp (250 W) distance from sprouted quinoa seeds on the moisture loss rate during infrared drying

3-2- Effective moisture diffusivity coefficient

Figure 6 shows the effect of infrared lamp distance from the surface of quinoa sprouts on the change in the effective moisture diffusivity coefficient during drying in an infrared dryer. The average calculated effective moisture diffusion coefficient for quinoa sprouts when dried with an infrared lamp with a power of 250 W at distances of 5, 7.5 and 10 cm were 6.60×10^{-10} m^2s^{-1}, 2.55×10^{-10} m^2s^{-1}, and 0.83×10^{-10} m^2s^{-1}, respectively. There was a statistically significant difference between the values of the effective moisture diffusivity coefficient of sprouts when drying at a distance of 5 cm, 7.5 and 10 cm ($p<0.05$), and this coefficient increased with decreasing the distance between the lamp and samples. In a study, Vejdanivahid and Salehi (2024) investigated the effect of microwave treatment time on the rate of moisture loss, effective moisture diffusivity coefficient and rehydration of quinoa sprouts during drying. The results showed that microwave pretreatment for 30 s increased the rate of moisture loss, increased the effective moisture diffusivity coefficient and reduced the drying time of fresh quinoa sprouts. By pre-treating quinoa sprouts with microwave for 30 s, it was observed that the effective moisture diffusivity coefficient increased significantly from 5.73×10^{-11} m^2s^{-1} to 10.49×10^{-11} m^2s^{-1} ($p<0.05$) [5].

In line with the results of this study, the effective moisture diffusivity coefficient of sprouted wheat when dried at 70°C was reported to be 1.65×10^{-10} m^2s^{-1} [15]. In another research paper, the average effective moisture diffusivity coefficient for lentil sprouts placed in hot air and infrared dryers was reported to be 3.76×10^{-10} m^2s^{-1} and 1.6×10^{-9} m^2s^{-1}, respectively [19]. In a study by Amini et al. in 2022, it was reported that by increasing the irradiation power in an infrared dryer, the effective moisture diffusivity coefficient increases and consequently the drying time of the product decreases. Also, according to the results of this study, by decreasing the distance of the samples from the irradiation lamp surface, the effective moisture diffusivity coefficient also increases [20].

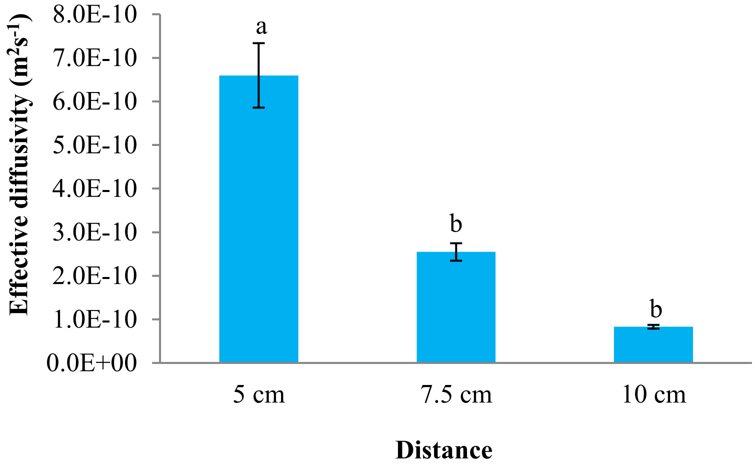

Figure 6- Effect of radiation lamp distance from sprouted quinoa seeds on the effective moisture diffusivity coefficient of quinoa sprouts

Different letters above the columns indicate significant difference ($p<0.05$).

3-3- Choosing the best kinetic model

Using kinetic models, a better understanding of the drying process as a function of various variables can be achieved with less cost and time. By calculating the moisture content for all the studied samples during the drying process of quinoa sprouts and fitting the points obtained from moisture ratio-time graphs, the results for each model were examined using the Wang and Singh, Henderson and Pubis, Approximation of diffusion, Page, Newton, Midilli, logarithmic, and quadratic equations. The results obtained from these 8 models are reported in Table 2. This table also reports the model coefficients and the calculated error for each model. The results showed that the Page and Midilli models fit the data very well; however, given that the Page model has two fixed coefficients and the Midilli model has four fixed coefficients, the Page model was chosen as the better model for investigating the drying kinetics of quinoa sprouts. Table 3 presents the SSE, r, and RMSE, as well as the fixed coefficients of the Page model. In a study, the drying kinetics of germinated wheat was investigated in two hot air and infrared dryers with a power of 250 W. The results of this study also show that the Page model is suitable for investigating the changes in the moisture content of wheat sprouts during drying [15]. Nosrati et al. (2018) modeled the drying of paddy in a laboratory hot-infrared air vibrating bed dryer. In this study, by examining the presented models and the relationship between their terms and coefficients, two Page and Verma models were presented to predict the drying process of paddy. The results showed that the constant coefficients of both models show a predictable trend under different experimental conditions [21].

Table 2- Statistical parameters to verify the agreement of each mathematical model with the moisture ratio (MR) data during quinoa sprouts drying

Model name	Model constants	Sum of squares due to error	r	Root mean square error
Wang and Singh	a=-0.2221 b=0.0122	0.0057	0.9957	0.0239
Henderson and Pabis	a=1.074 k=0.3338	0.0289	0.9785	0.0538
Approximation of diffusion	a= 6.541 k=0.1674 b=0.8929	0.0159	0.9882	0.0421

Page	k=0.1704 n=1.456	0.0003	0.9997	0.0060
Newton	k=0.3138	0.0369	0.9726	0.0579
Midilli	a=0.9948 k=0.1669 n=1.467 b=-7.28e-6	0.0003	0.9997	0.0064
Logarithmic	a=1.145 k=0.268 c=-0.0938	0.0153	0.9886	0.0413
Quadratic	a=1.016 b=-0.2276 c=0.0126	0.0053	0.9961	0.0242

Table 3- The constants and coefficients of the Page model during quinoa sprouts drying

Power	**Distance**	**k**	**n**	**Sum of squares due to error**	**r**	**Root mean square error**
250 W	5 cm	0.2102	1.3127	0.0032	0.9986	0.0156
	7.5 cm	0.0963	1.1733	0.0077	0.9976	0.0200
	10 cm	0.0755	0.8772	0.0082	0.9934	0.0214
375 W	5 cm	0.2305	0.7820	0.0050	0.9938	0.0266
	7.5 cm	0.1710	0.7680	0.0049	0.9935	0.0212
	10 cm	0.0956	0.9758	0.0020	0.9973	0.0149

To examine the ability of Page's model, the moisture content values predicted by this model and the experimental moisture content values obtained after applying different infrared powers and at distances of 5, 7.5, and 10 cm are plotted side by side in Figure 7. As can be seen in this figure, there is a good agreement between the experimental moisture content and that predicted by Page's model; therefore, this model is suitable for predicting the changes in moisture content of quinoa sprouts during drying by infrared radiation.

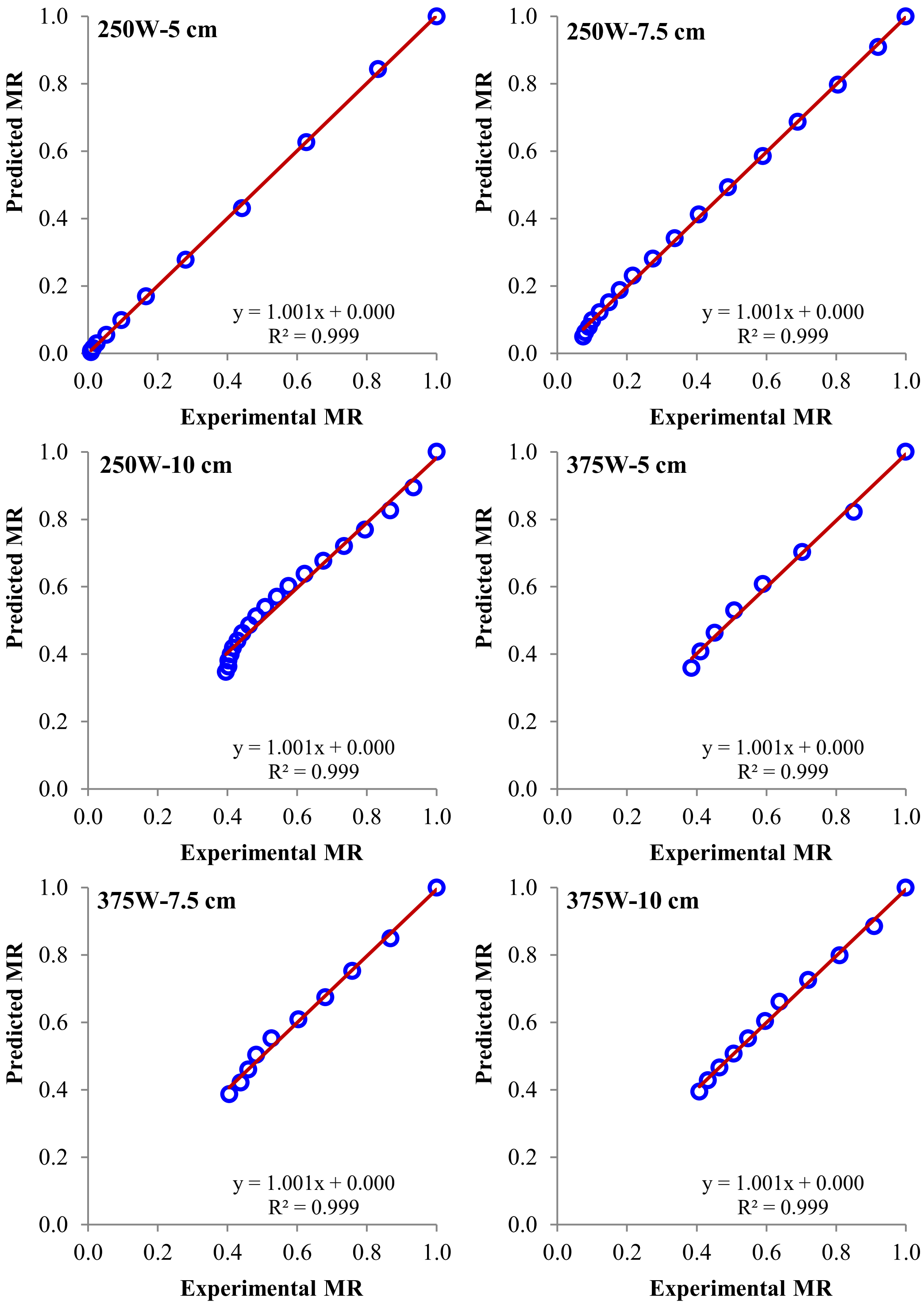

Figure 7- Comparison of fitted data by Page model with experimental results of moisture ratio (MR).

4- Conclusion

The drying process protects the food by reducing moisture and also prevents spoilage during storage by reducing microbial activity. In this study, an infrared dryer with two radiation powers of 250 W and 375 W at different distances from the surface of the sprouts was used to dry quinoa sprouts. By increasing the power of the infrared lamp from 250 W to 375 W, moisture was removed from the quinoa sprouts more quickly and the product was dried in less time. Using 375 W power for irradiating and drying sensitive sprouts such as quinoa is not recommended because the product burns quickly before it is completely dry. By reducing the distance of the infrared lamp from 10 cm to 5 cm, moisture was removed from the quinoa sprouts more quickly and the product was dried in less time. By reducing the distance between the infrared lamp and the quinoa sprouts, the effective moisture diffusivity coefficient increased. The best model with the highest fit for the drying process of quinoa sprouts was the Page model, and it is recommended to use this model to investigate the drying process of quinoa sprouts by infrared radiation. In general, it is recommended to use a 250 W infrared lamp at a distance of 5 cm from the surface of the quinoa sprouts to dry this product.

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بررسی سرعت انتشار رطوبت و سینتیک خشک شدن جوانه‌های کینوا در یک خشک‌کن فروسرخ

سپیده وجدانی وحید[۱]، فخرالدین صالحی[۲*]

۱-دانشجوی کارشناسی ارشد گروه علوم و صنایع غذایی، دانشکده صنایع غذایی، دانشگاه بوعلی سینا، همدان، ایران.

۲*- دانشیار گروه علوم و صنایع غذایی، دانشکده صنایع غذایی، دانشگاه بوعلی سینا، همدان، ایران.

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* مسئول مکاتبات:

F.Salehi@basu.ac.ir

با به‌کارگیری فناوری‌های نوین خشک‌کردن مانند فروسرخ و انتخاب شرایط مناسب این فناوری، می‌توان جوانه کینوا خشک‌شده با کیفیت مطلوب و ارزش غذایی بالایی تولید کرد که امکان استفاده از این محصول خشک و پودر آن برای غنی‌سازی مواد غذایی مختلف مانند انواع نان، شیرینی، پروتئین‌بار، کیک، پنکیک و غیره وجود دارد. در این پژوهش اثر توان پرتودهی لامپ فروسرخ و فاصله نمونه از منبع حرارتی بر سینتیک خشک شدن جوانه‌های کینوا بررسی و مدل‌سازی شد. با افزایش توان لامپ فروسرخ از ۲۵۰ وات به ۳۷۵ وات، رطوبت با سرعت بیشتری از جوانه‌های کینوا خارج و محصول در زمان کوتاه‌تری خشک شد. البته هنگام استفاده از توان ۳۷۵، جوانه‌ها قبل از خشک شدن کامل، سریع می‌سوختند. با کاهش فاصله لامپ فروسرخ از ۱۰ سانتی‌متر به ۵ سانتی‌متر، رطوبت با سرعت بیشتری از جوانه‌های کینوا خارج و محصول در زمان کوتاه‌تری خشک شد. متوسط زمان خشک‌کردن جوانه‌های کینوا هنگام خشک شدن با لامپ فروسرخ با توان ۲۵۰ وات در فواصل ۵، ۷/۵ و ۱۰ سانتی‌متر به ترتیب برابر ۱۰/۷، ۱۷/۳ و ۱۸/۰ دقیقه بود. ضریب نفوذ مؤثر رطوبت محاسبه‌شده برای جوانه‌های کینوا هنگام خشک شدن با لامپ فروسرخ با توان ۲۵۰ وات در فواصل ۵، ۷/۵ و ۱۰ سانتی‌متر به ترتیب برابر $۱۰^{-۱۰}$ m^2s^{-1} ×٦/٦۰، m^2s^{-1} $۲/۵۵×۱۰^{-۱۰}$ و m^2s^{-1} $۰/۸۳×۱۰^{-۱۰}$ بود. جهت بررسی سینتیک خشک شدن جوانه‌های کینوا، مدل‌های ریاضی مختلفی بر داده‌های آزمایشگاهی برازش و مدل پیج بر اساس بالاترین برازش و کمترین خطا به‌عنوان بهترین مدل انتخاب شد. در مجموع، استفاده از منبع حرارتی فروسرخ با توان ۲۵۰ وات در فاصله ۵ سانتی‌متری از سطح جوانه‌های کینوا، برای خشک‌کردن این محصول به دلیل زمان کوتاه خشک شدن و عدم سوختگی، توصیه می‌شود.