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Scientific Research

Effect of ultrasonic waves and drying method on the moisture loss kinetics and rehydration of sprouted wheat

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ABSTRACT

In this research, the effect of ultrasound time and dryer type (hot-air and infrared) on the drying time, effective moisture diffusivity coefficient and rehydration of wheat sprouts were investigated and drying kinetics were modeled. To apply ultrasound pre-treatment, the sprouts were placed inside the ultrasonic bath machine for 0, 5, 10, and 15 minutes, and after leaving the machine and removing extra moisture, the samples in thin layers were placed in the hot-air (with a temperature of 70°C) and infrared (power of 250 W) dryers. The results showed that sonication up to 5 minutes, causes an increase in moisture removal rate from the sprouts, an increase in the effective moisture diffusivity coefficient, and as a result, reduces the drying time. By increasing sonication time from zero to 5 min, the average drying time of sprouts in the hot-air and infrared dryers decreased from 126.7 min to 120.0 min, and from 25.7 min to 21.3 min, respectively. The average drying time of the samples in the hot-air dryer was 150.8 min and in the infrared dryer was 28.0 min. Also, the average effective moisture diffusivity coefficient calculated for the samples placed in the hot-air dryer was equal to 1.65×10^{-10} m^2s^{-1} and for the infrared dryer it was equal to 8.59×10^{-10} m^2s^{-1}. The time of ultrasound and drying treatment had significant effects on the rehydration of samples, and the value of this parameter was higher for samples dried in the hot-air dryer. In order to investigate the drying kinetics of wheat sprouts, mathematical models were fitted to the experimental data, and the Page model with two parameters (k and n) was chosen as the best model based on the highest accuracy. Generally, 5 minutes pre-treatment by ultrasound and then using an infrared dryer is the best condition for drying wheat sprouts.

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1. Introduction

Today, the use of sprouted grains in people's diet has increased due to the publication of scientific research results on their nutritional values and phytochemical contents [1]. Sprouted grains significantly contain valuable food resources during the germination period. These nutritious compounds include vitamins and secondary compounds that reduce the anti-nutritional factors of these products[2]. In addition, sprouting has a great and beneficial effect on the technological processes and the quality of the resulting products. During germination, the percentage of soluble substances and reviving sugars as well as the seed volume increases. Germinated wheat has high enzyme activity and several enzymes such as alpha-amylase, beta-amylase maltase are activated during germination and cause the breakdown of starch and the production of regenerating sugars. Germinated wheat powder has a high nutritional value and includes soluble sugars, essential amino acids, fatty acids (mainly linoleic acid and linolenic acid), salts and vitamins (B_1 (thiamine), B_2 (riboflavin), B_5 (pantothenic acid), B_6 (pyridoxine), B_7 (biotin) and E) [3, 4].

Dried wheat germ and its powder can be used to enrich various food products, including noodles, pasta, bread, cakes, breakfast cereals, meat products and kebabs [5, 6]. Examining and choosing the right method for drying sprouted products is essential. For example, Jaribi et al. (2022) investigated the effect of drying methods (freezing, hot air, and microwave-vacuum) on durum wheat germ characteristics and recommended the use of microwave-vacuum method for wheat germ drying [7]. In another study, Shingar et al. (2013) used a fluid bed dryer to dry germinated wheat. Germination caused a significant increase in protein content. The drying conditions had an effect on the color and color indices of the bud, and during drying, the brightness of the product increased, while the yellowness and redness decreased. Dried sprouted wheat showed excellent regeneration and maintained its quality. In this research, laboratory data were modeled using Fick's diffusion equation and effective moisture penetration coefficients were calculated and reported [5].

One of the methods of drying agricultural products is the use of infrared radiation, which increases the drying speed, maintains the quality of the final product, and reduces the cost.production process due to the reduction of energy consumptionto be The use of this method as a new technology has been developed in various parts of the food industry, such as drying fruits and vegetables [8]. In this regard, Hosni et al. They investigated the microwave and found that the amounts of organic acids and vitamin C in the product dried by the infrared method were higher compared to the microwave method, and compared to the traditional methods, the infrared dryer performs the drying operation in less time. In addition, by using the infrared method, the chemical properties of sumac fruit are preserved and the color changes are less [9]. Ultrasound consists of sound waves with a higher frequency than human hearing. By adjusting the ultrasonic frequency, this method can be used in many industries, including food processing industries. The use of ultrasonic waves as a pretreatment is a suitable non-thermal method to increase the efficiency of the drying process, and during the application of this process, the quality characteristics of the product are less damaged [10]. Using new methods such as ultrasound and infrared reduces drying time and increases the quality of dried products. The study of the published sources shows that so far no research has been done regarding the effect of ultrasound application time on the drying kinetics of wheat germ with infrared radiation and hot air. Therefore, in this research, the effect of ultrasonic waves and drying methods, including hot and infrared air, on the kinetics of moisture loss, drying time, effective moisture penetration coefficient, and rehydration of wheat germ were investigated and modeled.

2- Materials and methods

2-1- Preparation of wheat germ

To prepare sprouts, first wheat seeds (*Summer wheat* L.) Pishgam variety was obtained from Hamedan city and carefully cleaned and separated from their wastes. Then the seeds were washed and soaked in water at 25 degrees Celsius for 24 hours. Next, their excess water was completely removed and the seeds were germinated in a container covered with a thin towel for 48 hours at a temperature of 25 degrees Celsius (the water of the samples was changed every 6 hours).

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2-2- Application of ultrasound treatment

After completing the germination process of wheat seeds, the ultrasonic process was applied inside the ultrasonic bath (model vCLEAN1-L2, manufactured by Becker Iran Company). To apply the ultrasonic pretreatment, the sprouts were placed in the ultrasonic bath machine with a frequency of 40 for 0, 5, 10 and 15 minutes. kilohertz and power of 100 watts.

2-3- Hot air drying process

The sprouts treated with ultrasound were placed in a thin layer inside a fan oven (Fan Azma Gostar, Iran) with a temperature of 70 degrees Celsius. Changes in the weight of the samples during drying until reaching a constant weight, by a digital balance (E&D[1], Japan) was recorded with an accuracy of ± 0.01 g.

2-4- infrared drying process

At the beginning of this process, like the hot air process, the sprouts treated with ultrasound were placed inside the device in a thin layer to be dried with infrared (with a power of 250 watts). For irradiation, a 250 watt infrared lamp made by Noor (Iran) was used. The distance of the samples from the surface of the lamp was considered to be 5 cm. Weight changes of samples during drying by digital scale[2]It was recorded with the accuracy of ± 0.01 gram which was placed under the dryer until the weight stability was reached.

2-5- Calculation of humidity ratio parameter

The decrease in the moisture content of the sprouts, on a dry basis, was investigated against the drying time and the effect of different drying treatments on it. Humidity ratio parameter[3] (MR) was calculated through equation 1 [11].

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

In this equation, MR: moisture ratio (dimensionless), M_t Moisture content on a dry basis at any time t (grams of water per gram of dry matter), M_0 Initial moisture content on dry basis and $M_{It\ is}$ It is the equilibrium moisture content (grams of water per gram of dry matter). For long drying times, values of $M_{It\ is}$Compared to the values of M_{of}, M_t It is very small; Therefore, the equation of moisture ratio during drying can be simplified as equation 2, and to calculate the moisture ratio, it is necessary to measure the equilibrium humidity [12].

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

6-2- Calculation of the effective penetration coefficient of moisture

In this research, the theoretical model used to determine the effective diffusion coefficient of moisture[4]Wheat germs based on Fick's second law of penetration[5]and using spherical coordinates[6]Was. To solve Fick's equation, it is first assumed that 1) the moisture exit is only by permeation, 2) volume shrinkage is negligible, 3) the temperature is constant during the process, and 4) the permeation coefficients remain constant during the process; Then equation 3 is used [13].

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-\frac{\pi^2 n^2 D_{eff}}{r^2}t\right] \quad (3)$$

For long drying periods, equation 3 can be simplified by using only the first term in the set without greatly affecting the accuracy of the prediction. By taking the natural logarithm of the sides of equation 3, equation 4 is obtained:

$$\ln MR = \ln\left(\frac{M_t - M_e}{M_0 - M_e}\right) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{r^2}\right) \quad (4)$$

Finally, the effective diffusion coefficient of humidity through the slope of the natural logarithm of the humidity ratio of the experimental data (*ln*MR) was calculated against the drying time and using equation 5.

$$Slope = \frac{\pi^2 D_{eff}}{r^2} \quad (5)$$

In these equations, r is the average radius of germinated wheat (m), D_{eff} Effective moisture

1. AND, EK-410i, Japan
2. Digital balance, LutronGM-300p (Taiwan)
3. Moisture ratio (MR)
4. Effective moisture diffusivity coefficient (D_{eff})
5. Fick's second law of diffusion
6. Spherical coordinate

penetration coefficient (m^2s^{-1}), n is a positive integer, t is the drying time (s) and Slope is the slope of the line.

2-7- Kinetic modeling

In this study, in order to investigate the kinetics and predict the drying process of sprouts, kinetic modeling was done with the help of experimental data and using different experimental models of drying. Wang and Singh, Henderson and Pabis, diffusion approximation, Page, Newton, Midilli and logarithmic equations were selected and analyzed to model the drying process of sprouts and choose the best kinetic model[14]. In order to model the experimental data of drying and obtain the constants of the models, MATLAB software version R2012a was also used.

8-2- Dehydration of dried sprouts

To calculate the rehydration parameter, the dried sprouts were weighed and immersed in water with a temperature of 50 degrees Celsius.They got mad. After 30 minutes, the samples were removed from the water and weighed. The ratio of water absorption was calculated and reported by equation 6.

$$RR = \frac{M}{M_0} \times 100$$

(6)

In this equation, M is the weight of the sample after reabsorption of water and M_0 The weight of the sample is dry.

9-2- Statistical analysis

This research was analyzed in a factorial format based on a completely random design and using SPSS version 21 software. Drying tests were performed in three repetitions and Duncan's multi-range test was used to compare the observed average responses at the 95% probability level.

3. Results and Discussion

3-1- Checking the drying time

The results of the analysis of the variance of the application time of ultrasound and the type of dryer (hot air and infrared) on the drying time of wheat sprouts are reported in Table 1. As can be seen in this table, the effect of the independent variables of ultrasound application time and dryer type is significant at the 5% level ($p<0.05$). Also, their mutual effects are also significant at the 5% level ($p<0.05$).

Table 1 Results of analysis of variance for drying time parameter of wheat sprouts.

Sources of changes	Degrees of freedom	Sum of squares	Mean square	P
Dryer	1	90528	90528	0.000
Time	3	6254	2085	0.000
Dryer × Time	3	3280	1093	0.000
Error	16	160	10	
Total	23	100222		

Figure 1 shows the effect of ultrasound application time and the type of dryer (hot air and infrared) on the drying time of wheat sprouts. As can be seen in this figure, by increasing the time of applying ultrasound up to 5 minutes, the drying time of the samples has decreased; However, by increasing the ultrasound treatment time to 10 and 15 minutes, due to the damage to the surface cavities and capillary tubes in the buds, the moisture was hardly removed from the samples and the drying time became longer. By increasing the ultrasound treatment time from 0 to 5 minutes, the average drying time of sprouts in hot air and infrared dryers decreased from 126.7 minutes to 120.0 minutes and 25.7 minutes to 21.3 minutes, respectively. The average drying time of the samples was 150.8 minutes in the hot air dryer and 28.0 minutes in the infrared dryer. In a research, Salehi et al. (2022) investigated the effect of ultrasound power and time on the efficiency of the osmotic dehydration process of banana slices. According to the results of this research, the application of ultrasound treatment increased the amount of moisture removed from banana slices and as a result reduced the time of the dehydration process [15].

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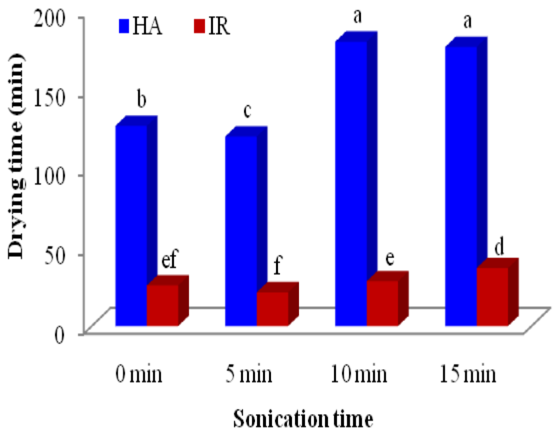

Fig 1 Effect of different ultrasound pretreatment on the drying time of wheat sprouts (HA=Hot-air dryer; IR=Infrared dryer).
Different letters above the columns indicate significant difference ($p<0.05$)

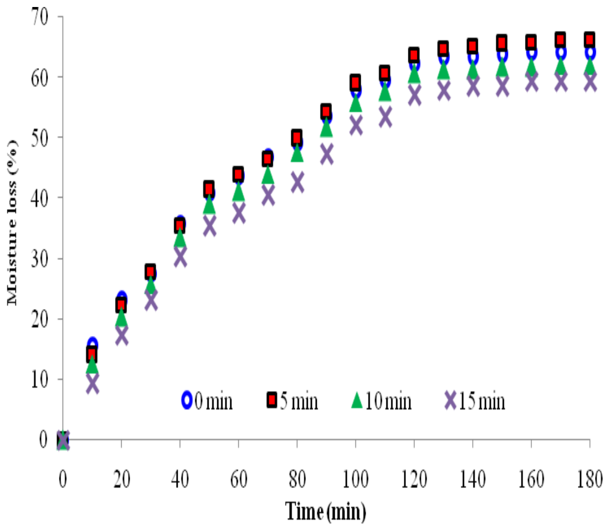

Fig2 Moisture loss of wheat sprouts during drying in the hot-air dryer

Figures 2 and 3 show the moisture loss of wheat sprouts treated with ultrasound during drying in hot air and infrared dryers, respectively. According to these two forms, treating wheat sprouts for 5 minutes by ultrasonic waves accelerates the removal of moisture; However, with the increase of treatment time, the result is reversed and the rate of moisture removal from the samples has decreased. Hassan et al. (2020) investigated the phytochemical characteristics of sorghum sprouts processed with ultrasound for use in practical foods.
Check out. Among the different treatment levels, ultrasound at 40% range for 5 minutes showed significant results. After germination, sorghum sprouts treated with ultrasound showed a superior profile of phytochemicals, which can be used as valuable raw materials for the production of functional foods. be used with high protein and low cost [16].

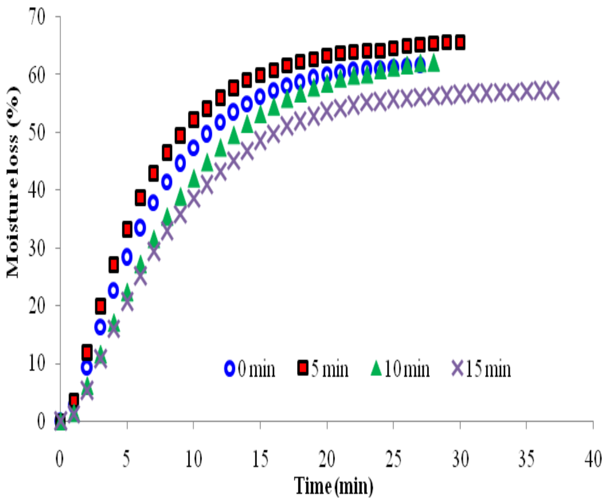

Fig 3 Moisture loss of wheat sprouts during drying in the infrared dryer

2-3- Effective moisture penetration coefficient

As can be seen in Figure 4, by increasing the time of applying ultrasound to 5 minutes, the effective penetration coefficient of moisture has increased. By increasing the time of ultrasound treatment from zero to 5 minutes, it was observed that**Effective moisture penetration coefficient** For wheat sprouts placed in the infrared dryer from $m^2s^{-1}$$^{10-}$$10\times5/9$ has $m^2s^{-1}$$^{10-}$

10 x 5.10 increased**(05/0<p)**. medium**The effective moisture penetration coefficient calculated for the samples placed in**Hot air dryer is equal to $m^2s^{-1}10^{-10}$1.65 x 10 and for the infrared dryer it is equal to $m^2s^{-1}10^{-10}$It was 8.59 x 10. Statistically significant difference between values**Effective moisture penetration coefficient of samples dried in hot air dryer was not observed (p<0.05).**Rafiei et al. (2008) investigated wheat drying in a hot air dryer with inlet air temperatures of 35, 45, 50, 60 and 70 degrees Celsius. The effective penetration coefficient of moisture for wheat in this research is in the range of $m^2s^{-1}10^{-10}$0.23 x 10 (for 35 degrees Celsius) to m^2s^{-1} 10^{-10}1.14×10 (for 70 degrees Celsius) has been reported [13].

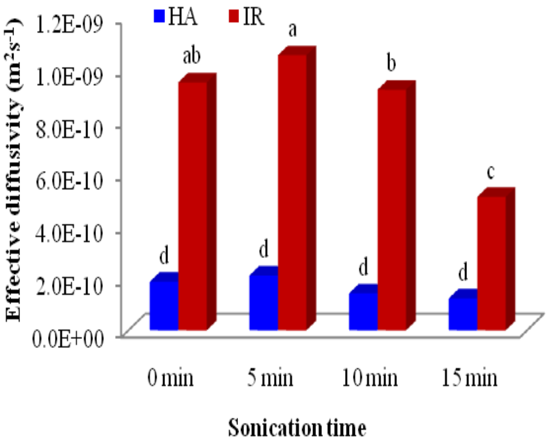

Fig 4 Effect of different ultrasound pretreatment on the effective moisture diffusivity coefficient of wheat sprouts
(HA=Hot-air dryer; IR=Infrared dryer).
Different letters above the columns indicate significant difference (p<0.05)

3-3- Choosing the best kinetic model

By calculating the value of the moisture ratio for all the studied treatments during the process of drying the sprouts (using equation number 2) and fitting the points obtained by drawing the moisture-time ratio diagrams, by means of Wang and Singh, Henderson and Pabis models, diffusion approximation, Page , Newton, Midilli and logarithmic, the results were analyzed for each model. The best model should have the highest coefficient of explanation (r) and minimum error values. The results showed that the best model with the highest fit, regarding the sprout drying process, is Page's model. In Table 2, the sum of squared errors[7] (SSE), coefficient of explanation and root mean square error[8] (RMSE) as well as constant coefficients of the Page model (n and k) are presented. Therefore, it is recommended to use the page model to investigate the drying process of wheat germs treated with ultrasound. In line with the results of this research, Rafiei et al. (2008) also recommended the use of the Page model to investigate the kinetics of wheat drying in a hot air dryer [13].

To check the ability of the proposed Page model, the values of the moisture ratio changes predicted by the Page model and the experimental moisture ratio values obtained (ultrasonic pretreatment time equal to 5 minutes and in the infrared dryer) are shown in Figure 5. As can be seen in this figure, there is a good agreement between the experimental and model-predicted moisture ratios; Therefore, the proposed Page model is suitable for predicting changes in the humidity ratio of wheat germ samples treated with ultrasound.

Table 2 The constants and coefficients of the approved model (Page)

Dryer type	Sonication time (min)	k	n	SSE	r	RMSE
Hot-air dryer	0	0.018	1.015	0.016	0.995	0.030
	5	0.016	1.049	0.016	0.995	0.030
	10	0.017	0.997	0.010	0.996	0.024
	15	0.016	0.985	0.008	0.997	0.022
Infrared dryer	0	0.106	1.088	0.011	0.997	0.019
	5	0.098	1.150	0.017	0.997	0.024

7. Sum of squares due to error (SSE)

8. Root mean square error (RMSE)

10	0.058	1.232	0.011	0.998	0.020
15	0.111	0.901	0.050	0.990	0.037

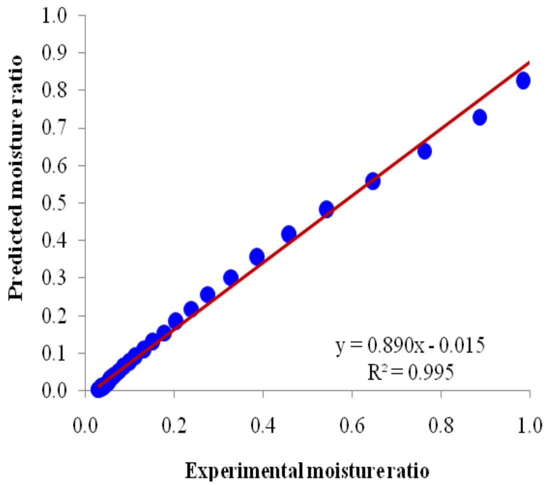

Fig 5 Comparison of fitted data by Pagemodel with experimental results of moisture ratio (sonication time=5 min and at infrared dryer).

In recent years, the use of ultrasound to increase the nutritional value of processed food products, by preserving or modulating their components, has been considered. Figure 6 shows the effect of ultrasound application time and the type of dryer (hot air and infrared) on the rehydration of wheat sprouts. As it can be seen in this figure, by increasing the time of ultrasound application up to 5 minutes, the rehydration of the samples has increased; However, by increasing the ultrasound treatment time to 10 and 15 minutes, due to damage to the surface cavities and capillary tubes in the buds, water hardly entered the dried samples and rehydration of these samples decreased.

3-4- rewatering

The results of the variance analysis of the application of ultrasound and the type of dryer (hot air and infrared) on the rehydration of dried wheat sprouts are reported in Table 3. In this table, it can be seen that the effect of the independent variables of ultrasound application time and the type of dryer at the 5% level on the change of rehydration is significant ($p<0.05$); But their mutual effects are not significant at the 5% level ($p<0.05$).

Table 3 Results of analysis of variance for rehydration of dried wheat sprouts in hot-air and infrared dryers.

Sources of changes	Degrees of freedom	Sum of squares	Mean square	P
Dryer	1	2373.46	2373.46	0.000
Time	3	2816.49	938.83	0.001
Dryer × Time	3	102.51	34.17	0.773
Error	16	1460.17	91.26	
Total	23	6752.63		

By increasing the ultrasonic treatment time from zero to 5 minutes, the average rehydration of sprouts in hot air and infrared dryers increased from 214.46 to 218.21% and 195.57 to 204.64%, respectively. The average moisture content of re-dried wheat sprouts in hot air and infrared dryers was 207.57% and 187.69%, respectively. In terms of the rehydration parameter, no significant difference was observed between the samples treated with ultrasound for 5 minutes and dried in hot air and infrared dryers ($p<0.05$).

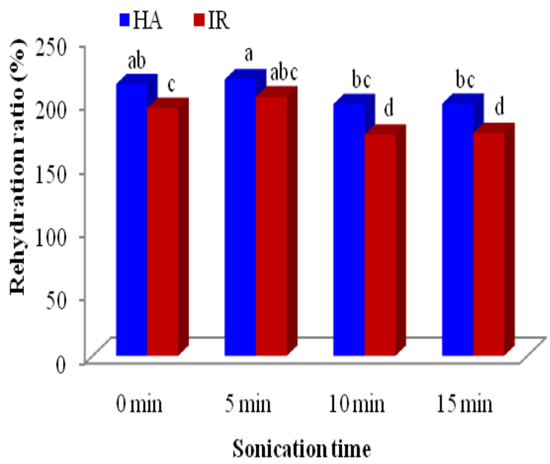

Fig 6 Effect of different ultrasound pretreatment on the rehydration of dried wheat sprouts (HA=Hot-air dryer; IR=Infrared dryer).

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

4 - Conclusion

In this research, the effect of ultrasonic pretreatment on the drying kinetics of wheat sprouts in hot air and infrared dryers was studied. The average drying time of the samples was 150.8 minutes in the hot air dryer and 28.0 minutes in the infrared dryer. By increasing the ultrasound treatment time from zero to 5 minutes, it was observed that**Effective moisture penetration coefficient** It increased for wheat sprouts placed in hot air and infrared dryers. By increasing the ultrasound treatment time from zero to 5 minutes, it was observed that**Effective moisture penetration coefficient** For the buds placed in the infrared dryer from $m^2s^{-110-}10\times5/9$ has m^2s^{-1} $^{10-}10$ x 5.10 increased. By increasing the ultrasound application time to 10 and 15 minutes,**Effective moisture penetration coefficient** decreased and consequently the drying time was longer. The time of application of ultrasonic waves and the drying method had a significant effect on the rehydration of the samples. Rehydration of wheat germ dried in hot air dryer was more than infrared dryer.

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6- Resources

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مقاله علمی_پژوهشی

اثر امواج فراصوت و روش خشک‌کردن بر سینتیک افت رطوبت و آبگیری مجدد گندم جوانه زده

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چکیده

در این پژوهش اثر زمان فراصوت و نوع خشک‌کن (هوای داغ و فروسرخ) بر زمان خشک‌شدن، ضریب نفوذ مؤثر رطوبت و آبگیری مجدد جوانه‌های گندم بررسی و سینتیک خشک شدن مدل‌سازی شد. برای اعمال پیش‌تیمار فراصوت، جوانه‌ها به مدت ۰، ۵، ۱۰ و ۱۵ دقیقه داخل دستگاه حمام فراصوت قرار گرفتند و بعد از خروج از دستگاه و حذف رطوبت اضافی، نمونه‌ها به‌صورت لایه نازک داخل خشک‌کن‌های هوای داغ (با دمای ۷۰ درجه سلسیوس) و فروسرخ (توان ۲۵۰ وات) قرار گرفتند. نتایج این پژوهش نشان داد که تیمار فراصوت تا ۵ دقیقه، سبب افزایش سرعت خروج رطوبت از جوانه‌ها، افزایش ضریب نفوذ مؤثر رطوبت و در نتیجه باعث کاهش زمان خشک‌کردن می‌گردد. با افزایش زمان تیمار فراصوت از صفر به ۵ دقیقه، میانگین زمان خشک شدن جوانه‌ها در خشک‌کن‌های هوای داغ و فروسرخ به ترتیب از ۱۲۶/۷ دقیقه به ۱۲۰/۰ دقیقه و ۲۵/۷ دقیقه به ۲۱/۳ دقیقه کاهش یافت. متوسط زمان خشک شدن نمونه‌ها در خشک‌کن هوای داغ ۱۵۰/۸ دقیقه و در خشک‌کن فروسرخ ۲۸/۰ دقیقه بود. همچنین متوسط ضریب نفوذ مؤثر رطوبت محاسبه شده برای نمونه‌های قرار گرفته در خشک‌کن هوای داغ برابر $1/65\times10^{-10}\,m^2s^{-1}$ و برای خشک‌کن فروسرخ برابر $8/59\times10^{-10}\,m^2s^{-1}$ بود. زمان اعمال امواج فراصوت و روش خشک‌کردن تأثیر معنی‌داری بر آبگیری مجدد نمونه‌ها داشتند و مقدار این پارامتر برای نمونه‌های خشک‌شده در خشک‌کن هوای داغ بیشتر بود. جهت بررسی سینتیک خشک شدن جوانه‌های گندم، مدل‌های ریاضی بر داده‌های آزمایشگاهی برازش و در مجموع مدل پیج با دو پارامتر (**k** و **n**) بر اساس بالاترین صحت به‌عنوان بهترین مدل انتخاب شد. به‌طورکلی، بهترین شرایط برای خشک‌کردن جوانه‌های گندم، ۵ دقیقه پیش‌تیمار با فراصوت و سپس استفاده از خشک‌کن فروسرخ بود.

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