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Scientific Research

# Effect of magnetized water on oat growth and drying kinetics of its sprouts for use in gluten-free product formulation

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**ABSTRACT**

One of the methods proposed in agriculture for optimal water use is to pass irrigation water through a magnetic field. The use of this magnetized water promotes seed germination and increases crop yields. Sprouted oat is a gluten-free product that contains various vitamins and nutrients, and its powder can be used to improve the quality of various foods. In this study, the effects of untreated water, magnetized water, and magnetic field on the oat growth and drying kinetics of its sprouts were investigated and modeled. A magnetic-alkaline water generator was used to magnetize water and generate magnetized water. The effect of different treatment on the effective moisture diffusivity coefficient of oat sprouts during drying was calculated and the rehydration of their dried sprouts was measured. The results of this study showed that oat seeds placed in the magnetized water and magnetic field increased their weight when soaked and also grew faster. Oat sprouts grown in the magnetic field lost moisture faster and dried faster due to their higher moisture content. The average effective moisture diffusivity coefficients calculated for oat sprouts grown by untreated water, magnetized water, and magnetic field mediums were $7.31\times10^{-11}$ $m^2s^{-1}$, $9.14\times10^{-11}$ $m^2s^{-1}$, and $15.22\times10^{-11}$ $m^2s^{-1}$, respectively. To study the drying kinetics of oat sprouts, various mathematical models were fitted to the experimental data, and overall, the Midilli model was chosen as the best model due to the highest fit and lowest error. The calculated rehydration of oat sprouts grown by untreated water, magnetized water, and magnetic field mediums was 182.93%, 184.40%, and 167.27%, respectively.

## 1-Introduction

Celiac disease is a lifelong intestinal disease caused by environmental and genetic factors, and as a result, the consumption of gluten protein in these individuals damages the mucous lining of the small intestine and reduces the absorption of essential nutrients such as proteins, carbohydrates, fat-soluble vitamins, iron and calcium. The only way to treat this disease is to use a gluten-free diet for life [1]; therefore, the production of gluten-free products is one of the priorities of the food industry to help these people. Dried and powdered oats can be used in the formulation of gluten-free products [2].

Oats, scientifically known as *Avena sativa*, are a small-flowered plant from the cereal family, so-called because of their slender, elongated shape and the same shape on both sides. Including oats in the diet has positive effects on human health. Oats contain gluten-free protein and a high amount of fiber (especially β-glucan content), which can help lower blood cholesterol, blood sugar, and insulin [3, 4]. Oats contain B vitamins, including biotin, niacin, pantothenic acid, and minerals, especially magnesium, which is an essential compound in enzyme function and energy production [5]. According to the results of Ekström et al. (2017), the glucans in oats are suitable for use in baking, and oats have interesting potential for use when adjusting the glycemic index of bread products [6].

Use of sprouted grains in the diet of people has increased due to their nutritional value and phytochemical content. These sprouted products contain valuable nutritional resources significantly during the germination period. These nutritional compounds include vitamins and secondary compounds that reduce the anti-nutritional factors of these products [7]. Zahir et al. (2021) confirmed that during the germination process, the amount of fibers, vitamins and minerals in soybeans increases and the activity of trypsin inhibitory enzymes and phytase decreases in it. Sprouted oats are also a valuable product for nourishing foods [8]. In a study, Cao et al. (2022) investigated the effect of replacing sprouted oat flour on the texture and digestibility of starch in wheat bread under laboratory conditions and stated that the polyphenols and butyric acid of the product increased and the germination process has the potential to produce nutritious bread with high digestibility [9].

Water plays an important role in health and treatment of many diseases and pain relief, such as reducing muscle spasms, increasing movement, joint mobility and increasing blood circulation. If water is exposed to a magnetic field that has a positive and negative pole, its molecules become magnetized [10]. This causes water molecules to come out of disorder and, while forming smaller water clusters, increases the number of clusters per unit volume and increases the solubility of water [11]. Magnetic water can have good effects on food due to its hexagonal structure. Among the effects of a magnetic field on some properties of water, we can mention the reduction of water surface tension, increase in pH, increase in viscosity and decrease in sediment formation [12]. Using this water increases the germination rate and increases crop production [13]. The effect of irrigation with magnetized water on the symbiosis between soybean and rhizobium was investigated by Aliverdi et al. (2021) and it was stated that this technology causes faster plant exit from the soil and can increase shoot and root dry weight, shoot and root nitrogen content, number and weight of bacterial nodules, number of pods, 100-seed weight, and plant yield [13]. Podleśny et al. (2004) reported that exposing bean seeds to a magnetic field before planting can have a significant effect on seed germination and yield [14]. In another study, the effect of magnetic water on four types of water including urban, deionized, rain and distilled was investigated. The effect of these magnetized waters on the germination rate of wheat and barley seeds




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showed that magnetic deionized water significantly increased the root fresh weight in wheat and the germination rate in barley. Magnetized urban water increased the shoot fresh weight and seedling root fresh weight in wheat but decreased the shoot dry weight and seedling vigor index in barley [15]. The importance of magnetic water in the treatment of diseases can be mentioned in its role in the treatment of diabetes. Since diabetic patients suffer from oxidative stress, magnetized water can reduce oxidative stress and be effective in the treatment of diabetes [16].

In this study, first, the effect of untreated water, magnetized water, and magnetic field on oat growth was investigated, and then the drying kinetics of germinated oats in a hot-air dryer are investigated. The effective moisture diffusivity coefficients is also calculated and reported. Then, different kinetic equations are investigated on moisture ratio data, and the best model for investigating the drying rate of sprouted oats with untreated water, magnetized water, and magnetic field is reported.

## 2- Materials and Methods

### 2-1- Preparation of sprouted oats

Initially, oat seeds (*Avena sativa* L.) were obtained from Pakan Bazr Isfahan Company (Isfahan, Iran). After cleaning and separating the waste, the seeds were washed and soaked in untreated water, magnetized water, and water in a magnetic field at a temperature of 25°C for 24 h (Figure 1). A magnetic-alkaline water production device (bipolar model with timer, Meghnatis Sazan Hayat Co., Iran) was used to magnetize the water and prepare the magnetized water (Figure 2). To prepare the magnetized water, 2 liters of tap water was poured into a polyethylene container and the water container was placed inside the device for 2 h. The magnetic field of the device and the magnetized water were measured by a Gauss meter (TES-3196, Taiwan) (Figure 3). The magnetic field intensity generated by the device was 2.8 Gauss, the magnetic field intensity of the water inside the device was 1.4 Gauss, and the magnetic field value of the magnetized water (outside the device) was 0.6 Gauss. In the next step, the excess water of the peeled seeds was removed and they were poured into a flat container and covered with a thin damp towel. In the germination stage, untreated water was used for the first group and magnetized water was used for the second group to germinate the seeds, and for the third group, the seeds were completely placed in the magnetic field along with the container and towel during the germination period. In total, the seeds were placed at a temperature of 25°C for 48 h for germination.

**Figure 1- Soaking, peeling, and sprouting steps**



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**Figure 2- Device for producing magnetized water**


**Figure 3- Gauss meter (digital magnetic field detector)**

### 2-2- Mass changes measurement of seeds

After 24 h of soaking and peeling, the weight of peeled grains and their skins was recorded with a digital scale (GM-300p, Lutron, Taiwan) with an accuracy of ±0.01 g. After germination, the weight of the grains was also measured. A moisture analyzer (DBS 60-3, Kern, Germany) was used to measure the moisture content of fresh and sprouted oats.

### 2-3- Drying sprouted oats

To dry the sprouted oat grains with untreated water, magnetized water, and magnetic field, a fan oven (Shimaz, Iran) at 70°C was used. The weight of the samples was measured every 5 min using a digital scale with an accuracy of ±0.01 g until a constant weight was reached.

### 2-4- Calculation of mosture ratio parameter

The moisture content reduction of sprouted oats, on a dry basis, was plotted against drying time and the effect of different germination conditions on them was investigated. The moisture ratio (MR) parameter was calculated using Equation 1 [17].

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

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), $M_0$ is the initial moisture content on a dry basis, and $M_e$ is the equilibrium moisture content (g water/g dry matter). For long drying times, the values of $M_e$ are very small compared to the values of $M_0$ and $M_t$; therefore, the equation for the moisture ratio during drying can be simplified to Equation 2, and equilibrium moisture measurements are not required to calculate the moisture ratio.





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

**2-5- Calculation of effective moisture diffusivity coefficients**

The theoretical model used to determine the effective moisture diffusivity coefficients of oat sprouts was based on Fick's second law of diffusion and using spherical coordinate. To solve Fick's equation, it was first assumed that 1) moisture removal was only by diffusion, 2) volumetric shrinkage was negligible, 3) temperature was constant during the process, and 4) diffusion coefficients remained constant during the process; then, Equation 3 was used to calculate the effective moisture diffusivity coefficients [18].

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

In these equations, r is the radius of the germinated oat (m), $D_{eff}$ is the effective moisture diffusivity coefficients ($m^2s^{-1}$), 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 drying time.

**2-6- Kinetic modeling**

In order to investigate the kinetics and predict the drying process of oat sprouts, kinetic modeling was performed with the help of experimental data and using different experimental drying models. Wang and Singh, Henderson and Pabis, Approximation of diffusion, Page, Newton, Midilli, Logarithmic, and Quadratic equations were selected and examined to model the drying process of oat sprouts and select the best kinetic model [19]. Matlab software version R2012a was also used to model the experimental drying data and obtain the model constants.

**2.7- Rehydration of dried oat sprouts**

To calculate the rehydration parameter, 5 g of dried oat sprouts were weighed and immersed in water at 50°C. The samples were removed from the water after 30 min and weighed. The rehydration ratio was calculated and reported using equation 4.

(4) $$RR = \frac{M}{M_0} \times 100$$

In this equation, M is the weight of oat sprouts after rehydration and $M_0$ is the weight of dried oats sprout.

**2-8- Statistical analysis**

The results of this study were analyzed using SPSS software V. 21. Drying tests were performed in three repetitions and to compare the average observed responses, Duncan's multiple range test was used at 95% confidence.

## 3- Results and discussions

**3-1- Weight and moisture changes of oats grain during soaking and sprouting processes**

The weight of the dry oats used at this stage was 10 g for each repetition. The average moisture content of the oat seeds was 3.7 % and the soaked oat seeds in the water was 36.4 %. During soaking process of oat seeds with untreated water, magnetic water, and in the magnetic field, the seeds were absorbed water about 58.80, 80.30, and 85.10 % of their initial weight, respectively.

After germination process, the weight of the oat seed sprouts was measured. The weight gains of sprouts in the presence of untreated water, magnetic water, and in the magnetic field (compared to the initial seed weight), were 76.60, 93.33 and 114.83 %, respectively. Putting oat seeds into magnetic water increased their growth rate. Of course, the growth rate of the seeds inside the magnetic field was higher, and there was a significant difference between the treatment and the other two treatments. Overall, the magnetized water, which was continuously in the magnetic field, increased the weight of the soaked seeds and increased the growth rate of oat seeds.

**3-2- Moisture loss of oat grains during drying**





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Drying rate is an important parameter that affects the drying process, and the drying characteristics of wet materials are also characterized by drying rate curves. By definition, drying rate is the amount of water removed per unit time [20]. Figure 4 shows the moisture loss of oat sprouts grown in different environments (untreated water, magnetized water, and magnetic field) during drying in the hot air dryer. According to this figure, oat sprouts grown in a magnetic field lose their moisture faster. The magnetic field increased the moisture content of the product during the soaking stage; in addition, it also increased the grain growth rate. As a result, sprouts grown in these conditions had more moisture and lost their moisture faster.

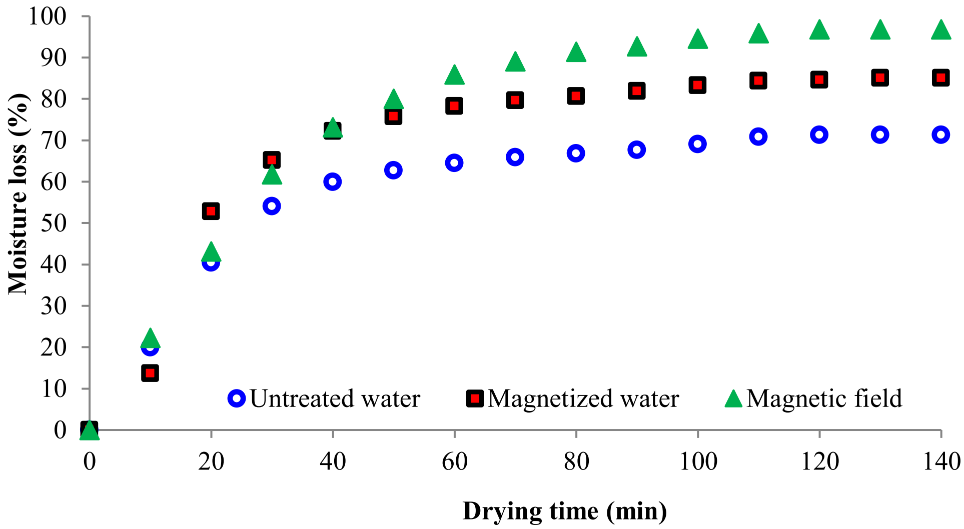


**Figure 4- Effect of experimental treatments on the moisture loss rate of sprouted oats during drying in the hot-air dryer**

**3-3- Effective moisture diffusivity coefficient**

Depending on the heat transfer method used, dryers have different methods and designs 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 the interior [20]. Figure 5 shows the effective moisture diffusivity coefficient of oat sprouts grown in untreated water, magnetized water, and a magnetic field during drying in the hot air dryer. According to this figure, oat sprouts grown in a magnetic field lose moisture more quickly and the effective moisture diffusivity coefficient values for these sprouts are higher. Sprouts grown in the presence of a magnetic field have more moisture and lose moisture more quickly.

The average effective moisture diffusivity coefficient calculated for oat sprouts grown in untreated water, magnetized water, and magnetic field were $7.31\times10^{-11}$ $m^2s^{-1}$, $9.14\times10^{-11}$ $m^2s^{-1}$, and $15.22\times10^{-11}$ $m^2s^{-1}$, respectively. There was no statistically significant difference between the effective moisture diffusivity coefficient values of sprouts grown in untreated water and magnetized water ($p>0.05$). Amin Ekhlas et al. (2023) reported the average effective moisture diffusivity coefficient of germinated wheat when dried at 70°C to be $1.65\times10^{-10}$ $m^2s^{-1}$, indicating that the effective moisture diffusivity coefficient of germinated wheat is slightly higher than that of germinated oats [18]. In another study, Salehi et al. (2024) investigated the effect of ultrasound pretreatment on the drying rate of lentil sprouts in hot air and infrared dryers. The average effective moisture diffusivity coefficient calculated for lentil sprouts placed in a hot air dryer was $3.76\times10^{-10}$ $m^2s^{-1}$ and for the infrared dryer was $1.6\times10^{-9}$ $m^2s^{-1}$ [21].





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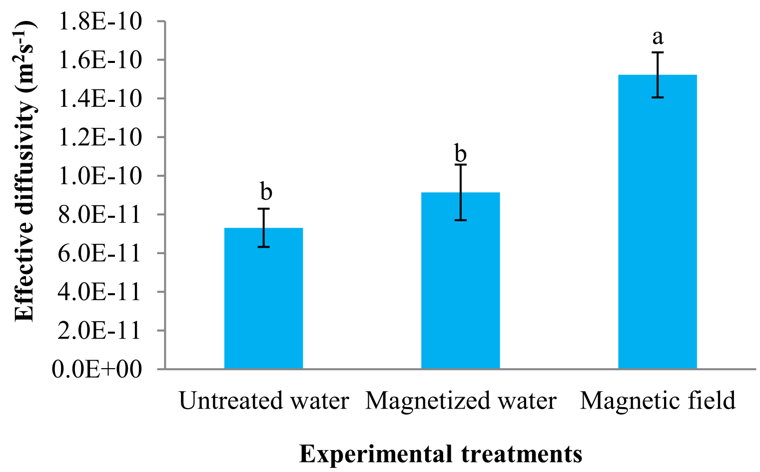


**Figure 5- Effect of experimental treatments on the effective moisture diffusivity coefficient of oat sprouts**
Different letters above the columns indicate significant difference (p<0.05).

## 3-4- Choosing the best kinetic model

One of the methods of drying agricultural products is the use of hot air and ovens, which reduce the moisture and water activity of the product and prevent the growth of microorganisms [20, 22]. By calculating the moisture ratio for all the studied treatments during the drying process of oat sprouts and fitting the points obtained from drawing moisture ratio-time diagrams, using the Wang and Singh, Henderson and Pabis, Approximation of diffusion, Page, Newton, Midilli, Logarithmic, and Quadratic models, the results for each model were examined.

The results obtained from these 8 models are reported in Table 1. In this table, the coefficients of the models and the calculated error for each model are also reported. The best model should have the highest coefficient of determination (r) and the minimum error values. The results showed that the best model with the highest fit for the drying process of oat sprouts is the Midilli model. Table 2 presents the sum of squares due to error (SSE), coefficient of determination and root mean square error (RMSE) as well as the constant coefficients of the Midilli model. Therefore, the use of the Midilli model is recommended to investigate the drying process of oat sprouts grown with untreated water, magnetized water and magnetic field. In a study, the kinetics of drying of germinated wheat in two hot air dryers (at a temperature of 70°C) and infrared (power of 250 W) were investigated by Amin Ekhlas et al. (2023). These researchers have recommended the Page model to investigate changes in the moisture content of germinated wheat during drying [18].

**Table 1- Calculated statistical parameters to verify the agreement of each mathematical model with the moisture ratio (MR) data**

| Model name | Wang and Singh | Henderson and Pabis | Approximation of diffusion | Page |
|---|---|---|---|---|
| Model equation | $MR=1+at+bt^2$ | $MR= a\exp(-kt)$ | $MR=a\exp(-kt)+(1-a)\exp(-kbt)$ | $MR=\exp(-kt^n)$ |
| Model constants | a=-0.0199<br>b=0.000097 | a=1.022<br>k=0.0314 | a= 1<br>k=0.0309<br>b=-1.477 | k=0.0242<br>n=1.065 |
| SSE[1] | 0.0548 | 0.0041 | 0.0043 | 0.0037 |
| r | 0.9573 | 0.9968 | 0.9966 | 0.9971 |
| RMSE[2] | 0.0649 | 0.0178 | 0.0189 | 0.0169 |

1- SSE: Sum of squares due to error; 2- RMSE: Root mean square error




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**Table 1- Continued from previous table**

| Model name | Newton | Midilli | Logarithmic | Quadratic |
|---|---|---|---|---|
| Model equation | MR=exp(-kt) | MR=aexp(-kt$^n$)+bt | MR=aexp(-kt)+c | MR=a+bx+cx$^2$ |
| Model constants | k=0.0307 | a=1.005<br>k=0.0198<br>n=1.135<br>b=0.0002 | a=1.016<br>k=0.0323<br>c=0.0097 | a=0.9165<br>b=-0.0176<br>c=0.00008 |
| SSE[1] | 0.0048 | 0.0013 | 0.0038 | 0.0398 |
| r | 0.9963 | 0.9990 | 0.9970 | 0.9690 |
| RMSE[2] | 0.0185 | 0.0109 | 0.0178 | 0.0576 |

1- SSE: Sum of squares due to error; 2- RMSE: Root mean square error

**Table 2- The constants and coefficients of the Midilli model**

| Experimental treatments | a | k | n | b | SSE[1] | r | RMSE[2] |
|---|---|---|---|---|---|---|---|
| Untreated water | 1.0117 | 0.0363 | 0.9533 | 0.0014 | 0.0068 | 0.9955 | 0.0245 |
| Magnetized water | 1.0283 | 0.0260 | 1.1029 | 0.0012 | 0.0258 | 0.9870 | 0.0482 |
| Magnetic field | 1.0067 | 0.0257 | 1.0747 | 0.0004 | 0.0019 | 0.9992 | 0.0128 |

1- SSE: Sum of squares due to error; 2- RMSE: Root mean square error

To examine the ability of the Midilli model, the moisture content values predicted by this model and the experimental moisture content values obtained are plotted together in Figure 6. As can be seen in this figure, there is a good agreement between the experimental moisture content and that predicted by the Midilli model; therefore, this model is suitable for predicting changes in the moisture content of oat sprouts.

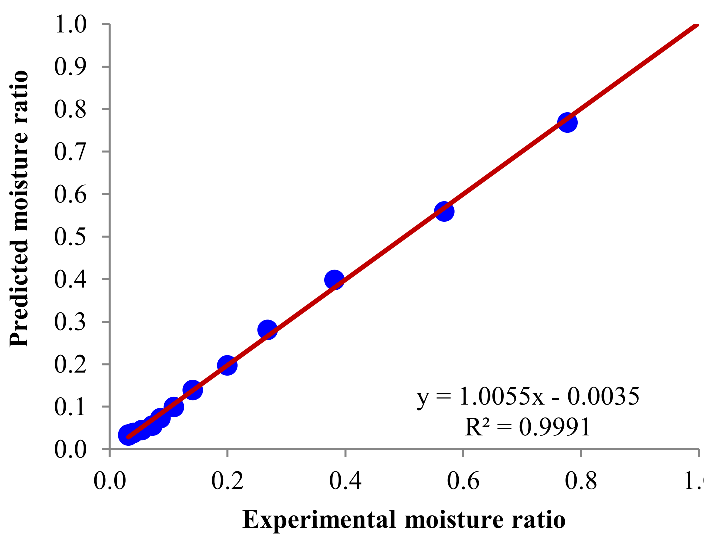


**Figure 6- Comparison of fitted data by Midilli model with experimental results of moisture ratio.**

### 3-5- Rehydration

Figure 7 shows the rehydration of dried oat sprouts grown in different conditions (untreated water, magnetized water, and magnetic field). According to this figure, dried oat sprouts grown in a magnetic field have significantly lower rehydration than the other two samples ($p<0.05$).





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This could be due to the faster moisture loss from these sprouts during drying, as a result of which some of the internal capillary tubes and surface pores of the grains are damaged and collapsed, reducing the rehydration capacity of the dried grain. The average rehydration calculated for oat sprouts grown in untreated water, magnetized water, and magnetic field was 182.93%, 184.40%, and 167.27%, respectively.

There was no statistically significant difference between the rehydration values of sprouts grown with untreated water and magnetized water (p>0.05). Amin Ekhlas et al. (2023) reported rehydration of germinated wheat dried at 70°C in the range of 214.46% to 218.21%, indicating that the rehydration of dried germinated wheat was higher than that of dried germinated oats [18]. In a study, Salehi et al. (2024) investigated the rehydration of dried lentil sprouts in hot air and infrared dryers. Their results showed that the rehydration of dried lentil sprouts in hot air dryer was higher than that in infrared dryer, and the average rehydration of dried lentil sprouts in hot air and infrared dryers was 304.52% and 226.27%, respectively [21].

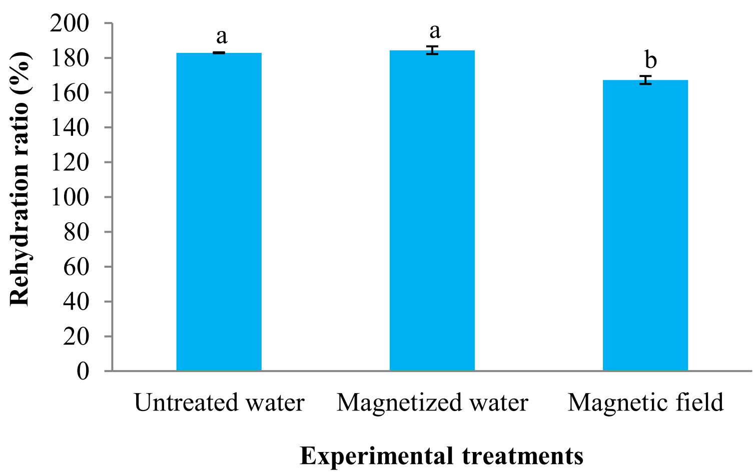


**Figure 7- Effect of experimental treatments on the rehydration ratio (%) of dried sprouted oats.**
Different letters above the columns indicate significant difference (p<0.05).

## 4- Conclusion

In this study, the effect of magnetized water and magnetic field on oat growth and drying kinetics of its sprouts was studied. A magnetic-alkaline water generator was used to magnetize water and prepare magnetized water. The growth rate of grains that were in the magnetic field was higher, and magnetized water combined with a magnetic field increased the growth rate and weight of soaked grains and sprouts. Sprouts grown in the presence of a magnetic field had more moisture and lost their moisture faster. Oat sprouts grown in a magnetic field lost moisture more rapidly and had higher effective moisture diffusivity coefficients for these sprouts. The best-fitting model for the drying process of oat sprouts was the Midilli model, and it is recommended to use this model to investigate the drying process of oat sprouts grown in untreated water, magnetized water, and a magnetic field. The highest rehydration of the dry product was for sprouts grown in untreated water and magnetized water; however, there was no statistically significant difference between the rehydration of sprouts grown in these two types of water (p>0.05).

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مقاله علمی_پژوهشی

# تأثیر آب مغناطیسی شده بر رشد جودوسر و سینتیک خشک شدن جوانه‌های آن برای استفاده در فرمولاسیون محصولات فاقد گلوتن

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**چکیده**

یکی از روش‌های پیشنهادشده در کشاورزی برای مصرف بهینه آب، عبور دادن آب آبیاری از یک میدان مغناطیسی است. استفاده از این آب مغناطیسی‌شده باعث افزایش سرعت جوانه‌زنی دانه‌ها و افزایش تولید محصول می‌شود. جودوسر جوانه‌زده محصولی فاقد گلوتن و حاوی انواع ویتامین‌ها و مواد مغذی است و از پودر آن می‌توان برای افزایش کیفیت مواد غذایی مختلف استفاده کرد. در این پژوهش اثرات آب تیمارنشده، آب مغناطیسی‌شده و میدان مغناطیسی بر رشد جودوسر و سینتیک خشک شدن جوانه‌های آن بررسی و مدل‌سازی شد. جهت مغناطیسی کردن آب و تهیه آب مغناطیسی شده از دستگاه تولیدکننده آب مغناطیسی-قلیایی استفاده شد. اثر تیمارهای مختلف بر ضریب نفوذ مؤثر رطوبت جوانه‌های جودوسر هنگام خشک شدن محاسبه و آبگیری مجدد جوانه‌های خشک‌شده آنها اندازه‌گیری شد. نتایج این پژوهش نشان داد که قرارگیری دانه‌های جودوسر درون آب مغناطیسی‌شده و میدان مغناطیسی باعث افزایش وزن آنها هنگام خیساندن و همچنین افزایش سرعت رشد آنها می‌شود. جوانه‌های جودوسر رشد کرده در میدان مغناطیسی به دلیل رطوبت بالاتر، با سرعت بیشتری رطوبت خود را از دست دادند و سریعتر خشک شدند. متوسط ضریب نفوذ مؤثر رطوبت محاسبه‌شده برای جوانه‌های جودوسر رشد کرده با آب تیمارنشده، آب مغناطیسی‌شده و میدان مغناطیسی به ترتیب برابر $۷/۳۱\times۱۰^{-۱۱}$ $m^2s^{-1}$، $۹/۱۴\times۱۰^{-۱۱}$ $m^2s^{-1}$ و $۱۵/۲۲\times۱۰^{-۱۱}$ $m^2s^{-1}$ بود. جهت مطالعه سینتیک خشک شدن جوانه‌های جودوسر، مدل‌های ریاضی مختلفی بر داده‌های آزمایشگاهی برازش و در مجموع مدل میدیلی بر اساس بالاترین برازش و کمترین خطا به‌عنوان بهترین مدل انتخاب شد. آبگیری مجدد محاسبه‌شده برای جوانه‌های جودوسر رشد کرده با آب تیمارنشده، آب مغناطیسی‌شده و میدان مغناطیسی به ترتیب برابر ۱۸۲/۹۳ درصد، ۱۸۴/۴۰ درصد و ۱۶۷/۲۷ درصد بود.