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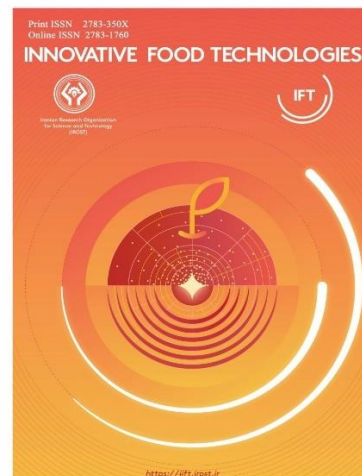
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Impact of drying techniques on the physicochemical and quality properties of sprouted quinoa powder

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Abstract

This study investigated the effects of various drying methods including convective, infrared, and microwave drying on the moisture content, pH, acidity, color indices, total phenolic content (TPC), and antioxidant capacity (AC) of sprouted quinoa powder. Initially, the quinoa seeds were soaked in magnetized water for 1 h. Then the quinoa seeds were incubated in a magnetic field at 25°C for 72 h for sprouting. To increase the phenolic compounds of the powders, the sprouts were treated by ultrasound for 5 min. The sprouts were dried in three ways and the powder prepared from them was analyzed. The infrared radiation facilitated removal of moisture from the quinoa sprouts, increased the effective moisture diffusivity coefficient, and shortened the dehydration duration. The moisture content and pH of the sprouted quinoa powders were in the range of 2.61 % to 7.03 %, and 5.95 to 6.08, respectively. The acidity of convective, infrared, and microwave dried sprouted quinoa powders was 1.24 %, 1.19 %, and 0.81 %, respectively. Among the sprouted quinoa powders, the sample dried using microwave treatment exhibited the lowest lightness value (67.78) and the highest redness (9.89) and yellowness (21.09) indices. The infrared-dried powders had the maximum TPC and AC. The TPC of convective, infrared, and microwave dried powders were 916.98, 1268.48, and 1262.46 µg gallic acid/g dry, respectively. In summary, using infrared was chosen as the best way to dry quinoa sprouts because it dries them faster, keeps the right color parameters, and results in the highest levels of beneficial compounds.

Keywords: Antioxidant capacity; Color indices; Infrared; Microwave; Sprouted quinoa.

1. Introduction

Quinoa (*Chenopodium quinoa* Willd.) is a type of grain that grows in the Andes Mountains. It has become more popular in recent years because it is good for the environment and its seeds are very nutritious. Quinoa plant was originally cultivated in South America, but is now used worldwide [1-4]. Out of the original countries that produce this Andean grain, only Peru, Bolivia, and Ecuador are among the top ten biggest exporters. Quinoa's recent popularity has made it one of the world's most popular crops, and it is now used in many cuisines around the world as a substitute for rice or couscous [5].

Due to the growing trend of functional food products, sprouted cereals and legumes are of particular interest, and these sprouted products can be used as potential sources of nutritional compounds in functional food formulations [6-8]. Enzymes are activated throughout the germination procedure, which helps to improve the digestibility of compounds contained in the grains. The germination process increases vitamins, phenolic compounds, and dietary fibers, and enhances antioxidant activity through the accessibility of reducing sugars and free amino acids (FAAs), especially lysine [9].

Magnetized water is water passed through a magnetic field. Magnetic water has a hexagonal structure, which can have a positive effect on food products [10-13]. Irrigation with magnetized

water can significantly improve plant growth and development, both quantitatively and qualitatively [10, 14].

As a non-thermal method, ultrasound has a wide range of applications in the food industry. This technique uses more frequent sound waves than the human audible area (over 20 kHz). Ultrasound uses support in processes such as extracting phenolic compounds and dietary fiber, inactivation of enzymes such as peroxidase and lipoxygenase, and assistance in processes such as freezing, thawing, drying, and inactivating microorganisms and enzymes [15, 16]. Yang et al. [17] investigated the impact of sonication on the structural and functional characteristics of quinoa protein. They reported that applying sonication at an optimal intensity induced favorable alterations in the protein's spatial structure, primarily through mechanical vibrations and cavitation effects, ultimately enhancing its functional and digestibility characteristics.

Drying is a preservation method that removes or decreases the moisture content of an agricultural crop. This process can influence the nutritional value of food products [18, 19]. Infrared radiation is a new and efficient technology that uses electromagnetic waves to transfer heat energy directly 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 benefits 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 [8, 20, 21].

Microwaves are part of the electromagnetic spectrum and lie between the dielectric and infrared waves. Due to their low frequency, they can't break chemical bonds or harm food molecules like X-rays and gamma rays can. Microwaves generate heat in the product by causing molecular friction between water molecules. The heat generated by the microwave system in the product depends on the amount of water in the food [4, 7].

This study aimed to evaluate the effects of convective, infrared, and microwave drying methods on the moisture content, pH, acidity, color indices, total phenolic content (TPC), and antioxidant capacity (AC) of sprouted quinoa powder.

2. Materials and Methods

2.1. Quinoa sprouts

We purchased white quinoa seeds harvested from Iran (packaged by OAB Company, Iran). First, the quinoa seeds were cleaned and soaked in magnetized water in a magnetic field for 1 h at 25°C. Then, the seeds were poured into a flat container and covered with a thin towel. During the sprouting stage, the seeds were placed entirely inside the magnetic field along with the container and towel. The seeds were moistened with a water sprayer bottle every 6 hours. In total, the seeds were kept at a temperature of about 25°C for 72 hours until they sprouted [4].

A magnetic-alkaline ionized water production device (bipolar model with timer, Meghnatis Sazan Hayat Co., Iran) was used to magnetize the water and prepare the magnetized water. The strength of the magnetic field created by the device was checked with a Gauss meter (Model TES-3196, Taiwan). The device created a magnetic field strength 2.8 Gauss and the magnetic field strength of the magnetized water inside the device was 1.4 Gauss.

2.2. Ultrasonic pretreatment

Ultrasonic pretreatment was used on the sprouted quinoa seeds with an ultrasonic water bath (Backer, vCLEAN1-L6, Iran). This device holds 6 liters of water and works at a frequency of 40 kHz with a power of 150 watts. The sprouted quinoa seeds were put in the ultrasonic water bath at 25°C for 5 minutes.

2.3. Drying of sprouted quinoa

To dry the ultrasonic-pretreated sprouted quinoa seeds, approximately 10 g of fresh sprouts were subjected to three different drying systems: convective, infrared, and microwave drying (Figure 1). In the convective drying method, the samples were placed in a conventional oven (K.M 55, Pars Azma Co., Iran) operating at 70 °C. For infrared drying, the sprouts were positioned 5 cm below a near-infrared lamp (250 W, Iran). Microwave drying was performed using a microwave oven (Gplus, GMW-M425S.MIS00, Goldiran Industries Co., Iran) at a power level of 440 W. During each drying process, the sample weight was recorded at 5 min intervals using a digital balance (GM-300p, Lutron, Taiwan) with a precision of ± 0.01 g, until a constant weight was achieved [22].

Figure 1

2.4. Drying rate and moisture diffusivity of quinoa sprouts

The quinoa sprouts were spread out evenly in a single layer on a tray in the dryers. The moisture loss rate was carefully measured every minute using a digital balance (± 0.01 g, GM-300p, Lutron, Taiwan).

Drying thin layers of agricultural products can be explained using one-way diffusion of moisture, based on Fick's second law. The D_{eff} of quinoa sprouts during dehydration was measured using the method explained by Salehi [8]. By graphing the laboratory results of $\ln(MR)$ on one side and process time (t) on the other. Subsequently, we computed D_{eff} by applying the equation 1:

$$D_{\text{eff}} = -\frac{r^2 \times S}{\pi^2} \quad (1)$$

Where D_{eff} is the effective moisture diffusivity coefficient (m^2/s), S is the slope, and r is the average radius of the quinoa sprouts, which is equal to 0.001025 meter in this research.

2.5. Powdering the dried sprouts

Dried quinoa sprouts were ground using an industrial grinder (Best, China). The prepared powder was packed into polyethylene bags to prevent moisture absorption during storage. The bags were then stored in a refrigerator at 6°C until the experiment.

2.6. Moisture content

A moisture analyzer (DBS 60-3, Kern, Germany) was used to measure the moisture content of fresh and sprouted quinoa seeds.

2.7. pH of powders

According to Iranian National Standard No. 37 (2018), to measure the pH of the sprouted quinoa powder, ten g of the powder was mixed thoroughly with 100 milliliters of distilled water and left for 20 min. After calibrating the pH meter electrode (Metrohm, 827pH lab, Switzerland) with buffer solutions 4 and 7, the pH of the aqueous phase was estimated with the pH meter.

2.8. Acidity of powders

According to Iranian National Standard No. 103 (2018), to measure the acidity of the sprouted quinoa powder, ten g of the powder was poured into a 125 milliliter Erlenmeyer flask, and then 50 milliliters of 67 % ethanol (Kimia Alcohol Zanjan Co., Iran) was added. After stirring with a stirrer for 5 min and after settling, the upper layer of the solution was passed through filter paper. In the next step, 25 milliliters of the filtered solution was poured into an Erlenmeyer flask. After adding three drops of 3 % phenolphthalein reagent, titration was carried out with 0.1 N NaOH (sodium hydroxide) solutions. The titration was completed when a pink color appeared. In the final step, the amount of NaOH used was recorded and the acidity was calculated using the method and equation described by Samary et al. [14].

2.9. Color parameters of powders

Image processing methods were used to measure the color parameters of sprouted quinoa powder. The surface images of powders were captured with a scanner (HP Scanjet-300). The color space of the photos was converted from RGB to L* (lightness), a* (green/red), and b* (blue/yellow) using ImageJ software (V.1.42e, USA) and the corresponding plugin [23].

2.10. Total phenolic content (TPC)

The TPC of sprouted quinoa powder was measured using the method explained by Samary et al. [14]. The TPC of sprouted quinoa powder was expressed as microgram gallic acid equivalent per g ($\mu\text{g GAE/g}$).

2.11. Antioxidant capacity (AC)

To estimate the AC of the sprouted quinoa powder, in the first step, a 2,2-diphenyl-1-picrylhydrazyl solution (DPPH, Sigma-Aldrich, USA) was prepared at a concentration of 0.1 mM. Subsequently, the AC of sprouted quinoa powder was calculated according to the procedure of Salehi et al. [24]. To prepare sprouted quinoa powder extract, 2 g of powder was added to 20 milliliters of 80 % methanol and mixed for 30 min with a magnetic stirrer (Shimaz, Iran). After transferring the mixture to a Falcon tube, the Falcon tube was centrifuged for 5 min at 4000 rpm in a centrifuge (Universal 320R, Hettich, Germany). After the separation step, the supernatant of the prepared mixture was considered as the extract. To measure the free radical scavenging activity of sprouted quinoa powder, 2 milliliters of the extract was placed in a test tube along with 2 milliliters of DPPH solution. The mixture was incubated at 25°C for 30 min and then placed in a dark environment. The absorbance of the samples was read at 517 nm using a spectrophotometer (XD-7500, Lovibond, Germany).

2.12. Statistical analysis

The findings of this work were analyzed using SPSS software (version 21). The tests were run three times, and Duncan's multiple range test was used with a confidence level of 95 % to compare the average of the observed results. Excel 2013 was used to create the graphs.

3. Results and Discussion

3.1. Drying characteristics and moisture diffusivity

The influence of drying method on the water loss rate of quinoa sprouts is shown in Figure 2. The maximum moisture loss rates during drying of the quinoa sprouts were obtained for the infrared dryer while the minimum moisture loss rates belonged to the convective dryer. Heirani et al. [25] aimed to investigate the drying behavior of stale bread using 3 various drying

methods: convective, microwave, and combined convective–microwave drying. Their findings indicated that the shortest drying time was achieved with the combined convective–microwave dryer. Nachaisin et al. [26] used a dryer that combines infrared heat and convective to dry instant sprouted brown rice. The study found that using infrared radiation made sprouts dry faster and shortened the drying time.

Figure 2

Influence of drying method on the D_{eff} of quinoa sprouts is shown in Figure 3. The infrared radiation facilitated the removal of moisture from the quinoa sprouts, increased the D_{eff} , and shortened the drying time. The D_{eff} values of quinoa sprouts during drying by convective, infrared, and microwave were $0.46 \times 10^{-10} \text{ m}^2/\text{s}$, $1.15 \times 10^{-10} \text{ m}^2/\text{s}$, and $0.91 \times 10^{-10} \text{ m}^2/\text{s}$, respectively.

Figure 3

3.2. Moisture content

Figure 4 illustrates the effect of different dehydration methods on the moisture content of quinoa sprout powders. The results showed that the moisture content varied between $2.61 \pm 0.17 \%$ and $7.03 \pm 1.37 \%$, depending on the drying technique employed. Among the treatments, the quinoa sprouts dried using infrared radiation retained the highest moisture content, suggesting a milder dehydration effect or shorter drying duration. In contrast, the convectively dried samples exhibited the lowest moisture content, indicating a more intense or prolonged drying process. These findings highlight the significant influence of the drying method on the final moisture level of sprouted quinoa powders, which in turn can affect their shelf life, texture, and suitability for various food applications.

Figure 4

3.3. pH and acidity of powders

Figure 5 shows the impact of drying method on the pH of the powder prepared from quinoa sprouts. The lowest pH value was found for the convective dried quinoa sprouts (5.9 ± 0.01), which showed a considerable difference from the other powders ($p < 0.05$).

Figure 5

In this work, the acidity of the quinoa seed powder used was $0.67 \pm 0.02 \%$. During sprouting, the acid content of the quinoa increases due to increased enzymatic and microbial activity. Figure 6 shows the impact of drying method on the acidity of the quinoa powder prepared from sprouts. The lowest acidity ($0.81 \pm 0.07 \%$) was found for the microwave dried quinoa sprouts, which showed a significant difference from the other powders ($p < 0.05$).

Figure 6

3.4. Color parameters of powders

When analyzing color indices, the lightness index or L^* ranges from 0 to 100. The closer this number is to 100, the lighter the sample is. The redness index or a^* ranges from -120 to +120, and a negative value of this index indicates that the sample is green, while a positive value indicates that the surface color is closer to red. The yellowness index or b^* has a range between -120 and +120, and a negative value means that the color is closer to blue, while a positive value means that the color is closer to yellow [23]. In this study, the L^* , a^* , and b^* values of the quinoa seed powder (unsprouted) used in this study were 89.21, 2.03, and 12.41, respectively. Due to increased enzymatic activity and non-enzymatic browning, sprouting of quinoa seeds significantly increased the redness index of the powders. According to a report by Ozturk et al. [27], powder becomes darker than wheat seed powder upon germination, the lightness decreases, and the yellowness and redness increase upon sprouting.

The effect of drying method on the color parameters of sprouted quinoa powder is shown in Figure 7. The lightness, redness, and yellowness indices of the sprouted quinoa powders were in the range of 67.78 to 85.79, 3.46 to 9.89, and 16.61 to 21.09, respectively.

Figure 7

Samples dried using infrared and microwaves were a bit darker and less lightness index compared to those dried with convective. In line with the results of this study, Irakli et al. [28] found that using infrared heat on rice bran made it darker. This happened because the infrared heat caused a chemical reaction (Maillard) that created brown compounds.

The microwave energy can easily go into the quinoa sprouts and heat them up, causing them to brown more. Among the sprouted quinoa powders, the dried sample with microwave had the lowest lightness index (67.78), and the highest redness (9.89) and yellowness (21.09) indices. Goharpour et al. [7] conducted a study to evaluate the effects of different drying techniques on the color characteristics of ground sprouted chickpeas. The findings revealed that the samples subjected to infrared drying demonstrated the most pronounced changes in color indices, including the lowest lightness value and the highest values of redness and yellowness among all drying methods tested. These results suggest that infrared drying significantly influences the visual appearance of sprouted chickpea powders, likely due to intensified Maillard reactions or pigment transformations occurring during the drying process.

3.5. Total phenolic content (TPC)

Sprouting is a beneficial bioprocess that enhances the palatability, nutritional profile, digestibility, and overall quality of edible seeds, making it a valuable technique in the development of functional food products [8, 29]. Sprouted quinoa is a gluten-free powder (proper for people with celiac disease) and contains fiber, as well as various vitamins, phenolic compounds, antioxidants, and nutrients, and its powder can be used to improve the quality of various foods [4]. The TPC of the quinoa seeds powder used in this study was 758.80 ± 49.85 μg gallic acid/g. During sprouting, the TPC of the quinoa sprouts increases due to increased enzymatic activity. In line with the findings of the present work, Gan et al. [30] reported that the phenolic compounds in edible seeds increased significantly during sprouting.

Figure 8 shows the impact of drying method on the TPC of the quinoa powder prepared from sprouts. The lowest TPC was found for the convective dried quinoa sprouts, which showed a significant difference from the other powders ($p < 0.05$). The infrared-dried quinoa sprouts powders had the maximum TPC. The infrared and microwave drying time was short, so most of the phenolic compounds were retained. The TPC of convective, infrared, and microwave dried powders were 916.98 ± 8.31 , 1268.48 ± 35.50 , and 1262.46 ± 4.15 μg gallic acid/g dry, respectively. Goharpour et al. [7] examined the effects of different drying methods on the TPC and AC of ground sprouted chickpeas. Their findings demonstrated that infrared drying required less time compared to hot-air and microwave methods, thereby better preserving bioactive compounds and resulting in higher TPC and AC levels in the final product. Aboud et al. [31] confirmed that orange peels dried with infrared radiation have more TPC than those dried in a convective because infrared helps to reactive some small antioxidants.

Figure 8

3.6. Antioxidant capacity (AC)

AC is one of the bioactive substances that have been studied in germinated grains and edible seeds, and germination has been shown to increase the AC of many edible seeds. Gan et al. [30] and Sharma et al. [32] results also show that the sprouting process increases the AC of extracts

from sprouted seeds. Some researchers have reported that the vitamin content, phenolic compounds, and AC of raw quinoa seeds increased significantly 72 h after sprouting [33, 34]. The AC of the quinoa powder used in this study was 83.18 ± 0.51 %. During sprouting, the AC of the quinoa sprouts increases due to increased TPC.

Figure 9 illustrates the effect of different drying methods on the AC of quinoa powder derived from sprouts. The results indicate that prolonged drying durations are associated with a reduction in phenolic compounds, which in turn leads to a decline in the antioxidant potential of the final product. Among the evaluated drying techniques, the convective drying method resulted in the lowest AC values, exhibiting a statistically significant difference compared to the infrared and microwave-dried samples ($p < 0.05$). These findings highlight the importance of selecting appropriate drying methods to preserve the functional and bioactive properties of sprouted quinoa powder. The infrared-dried quinoa sprouts powders had the maximum AC. The AC of convective, infrared, and microwave dried powders were 73.66 ± 0.90 %, 95.07 ± 0.49 %, and 79.59 ± 3.01 %, respectively.

Figure 9

4. Conclusion

This study examined the impact of different drying methods on the moisture content, pH, acidity, color indices, TPC, and AC of sprouted quinoa powder. The maximum moisture loss rate and D_{eff} value during drying of the quinoa sprouts were obtained for the infrared dryer. The quinoa sprouts dried using infrared had the highest moisture content. Among the sprouted quinoa powders, the dried sample with microwave had the lowest lightness, and the highest redness, and yellowness parameters. By employing infrared drying methods, we were able to expedite the drying process while retaining more phenolic compounds, ultimately improving the AC of the sprouted quinoa powder. In this study, the infrared-dried quinoa sprouts powders had the maximum TPC and AC. Generally, using an infrared dryer to dry sprouted quinoa makes the product better, which can enhance the nutrition of foods that include this product powder.

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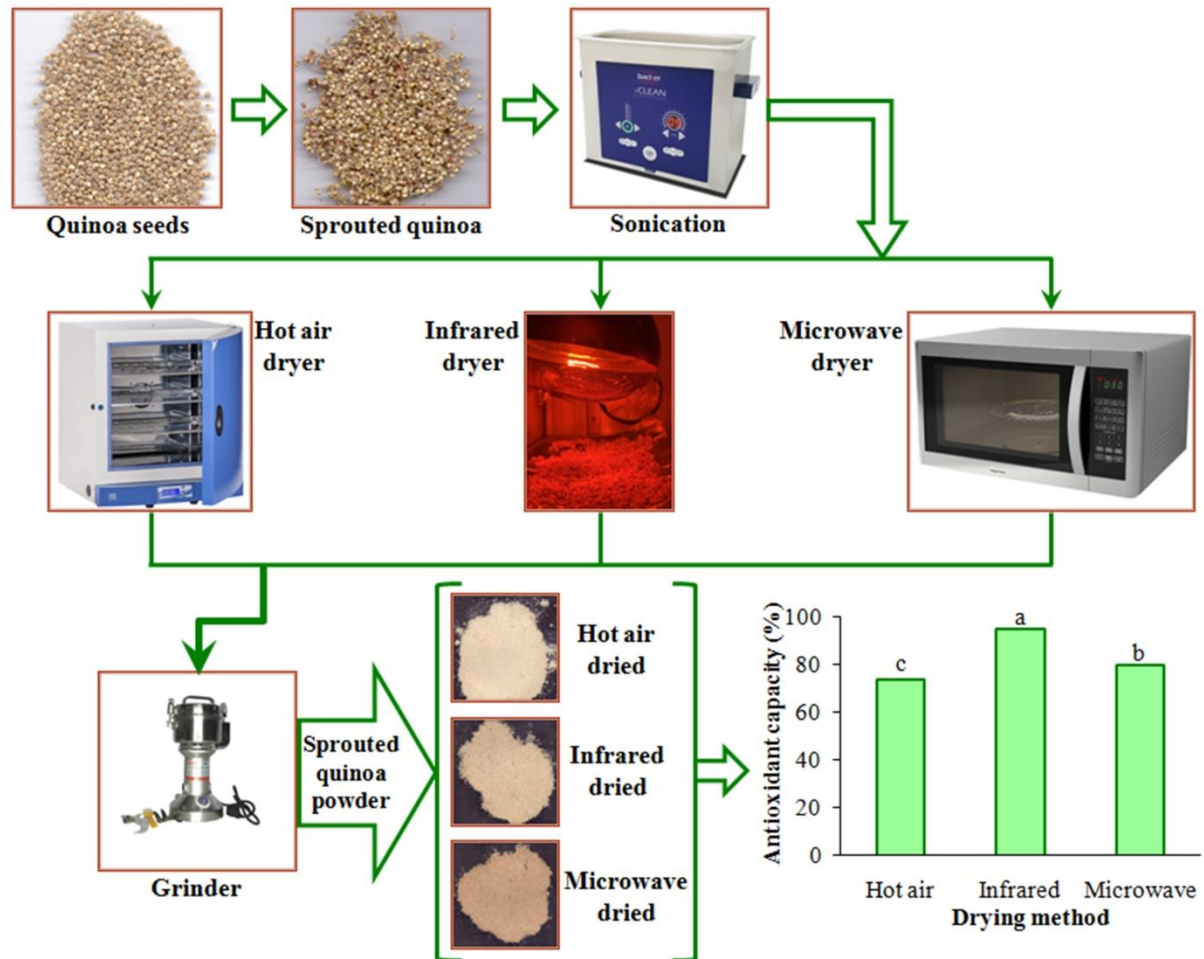


Figure 1- Steps for drying quinoa sprouts by convective, infrared, and microwave techniques for powder production

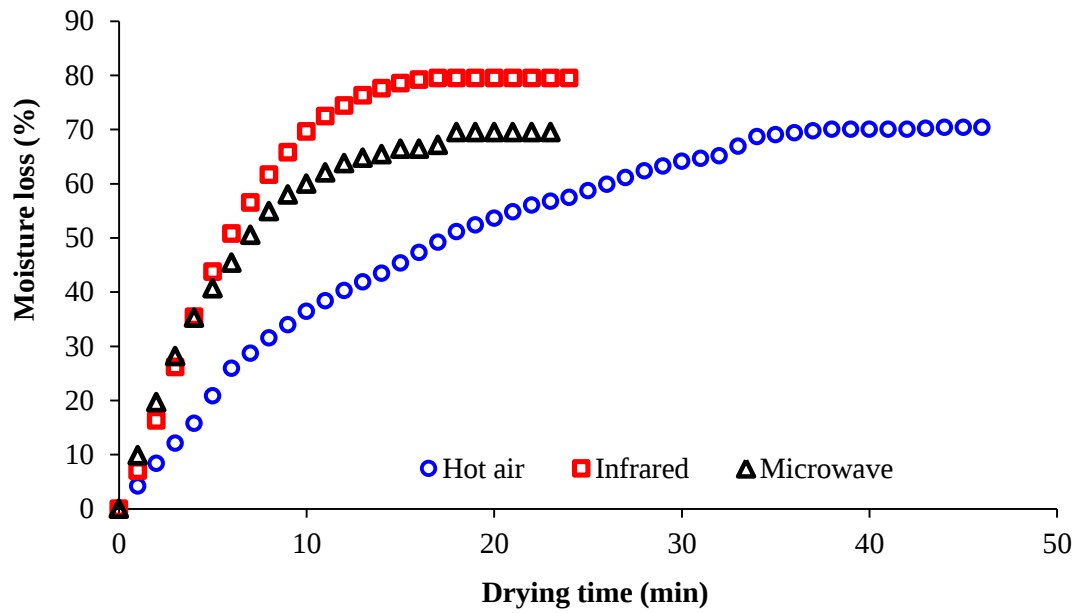


Figure 2- Influence of drying method on the moisture loss rate of quinoa sprouts

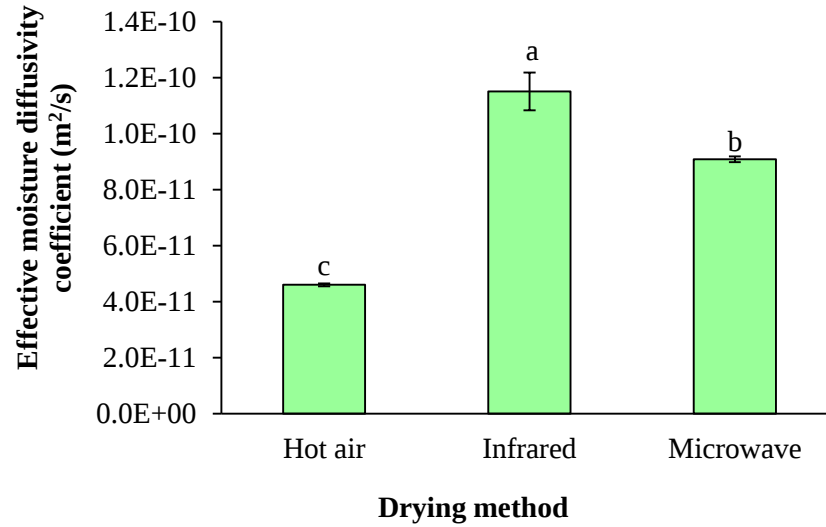


Figure 3- Influence of drying method on the effective moisture diffusivity coefficient of quinoa sprouts

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

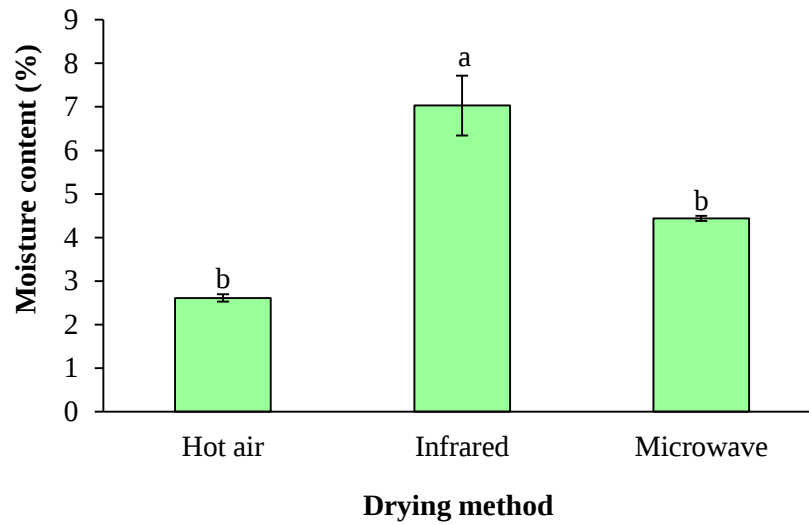


Figure 4- Influence of drying method on the moisture content of sprouted quinoa powder
Different letters above the columns indicate significant differences ($p < 0.05$).

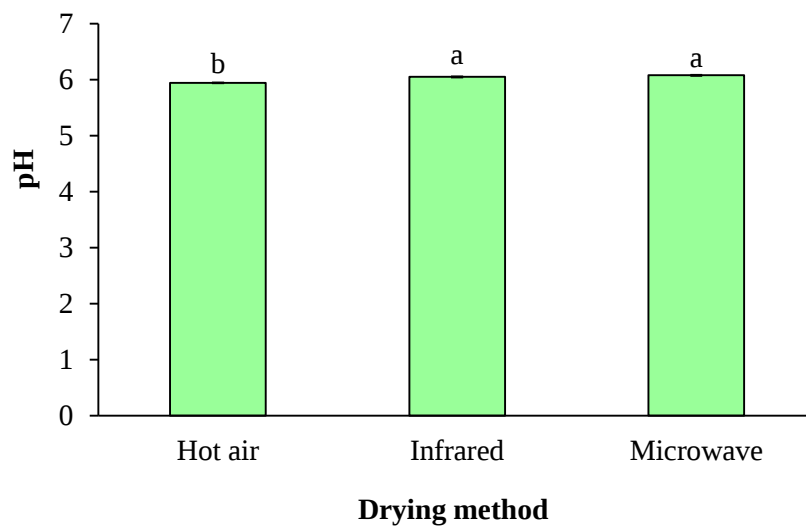


Figure 5- Influence of drying method on the pH of sprouted quinoa powder
Different letters above the columns indicate significant differences ($p < 0.05$).

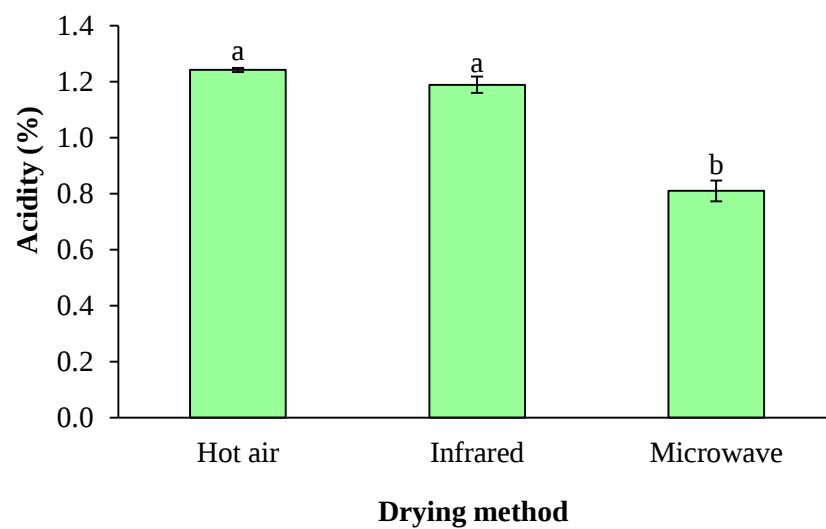


Figure 6- Influence of drying method on the acidity of sprouted quinoa powder
Different letters above the columns indicate significant differences ($p < 0.05$).

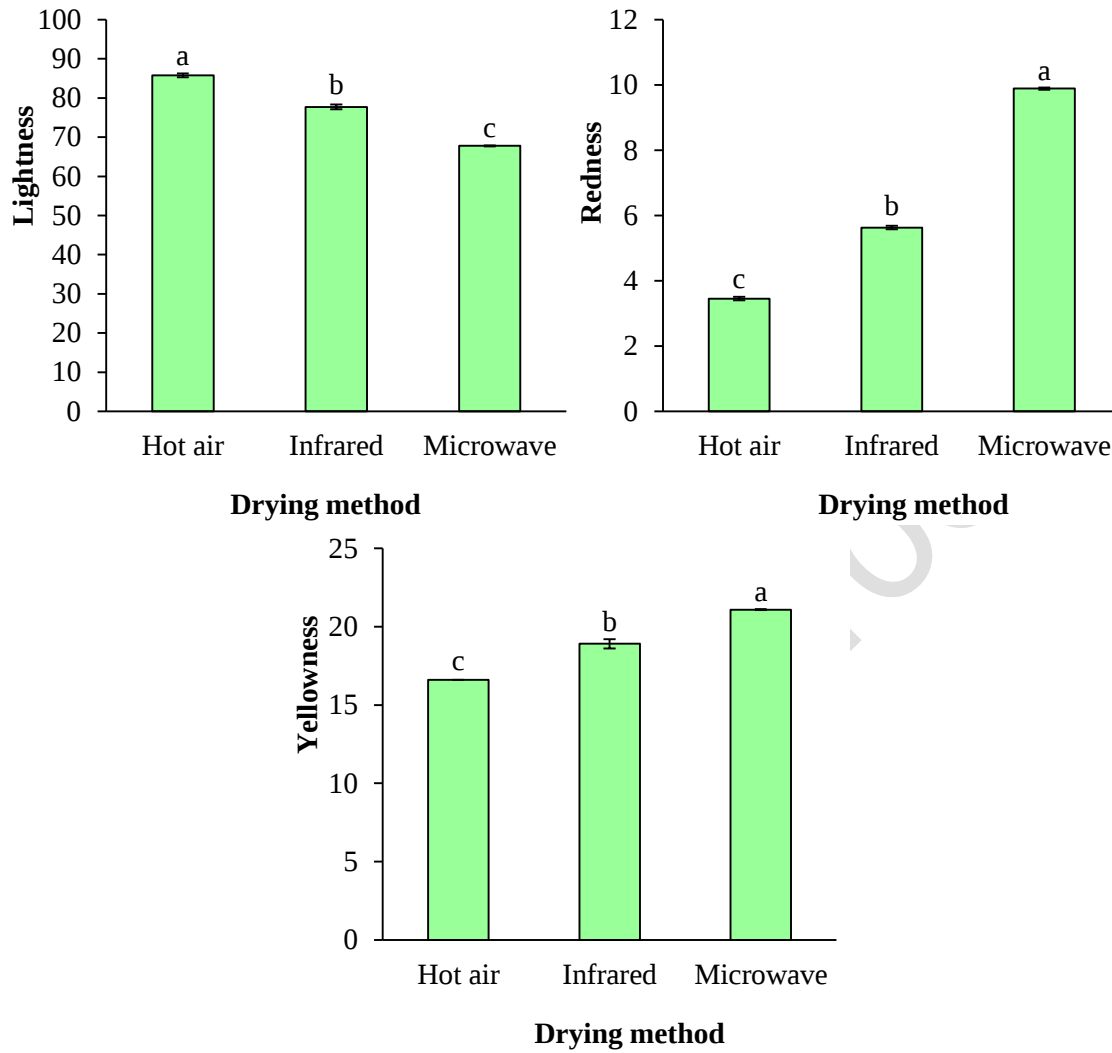


Figure 7- Influence of drying method on the color indices (lightness, redness, and yellowness) of sprouted quinoa powder

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

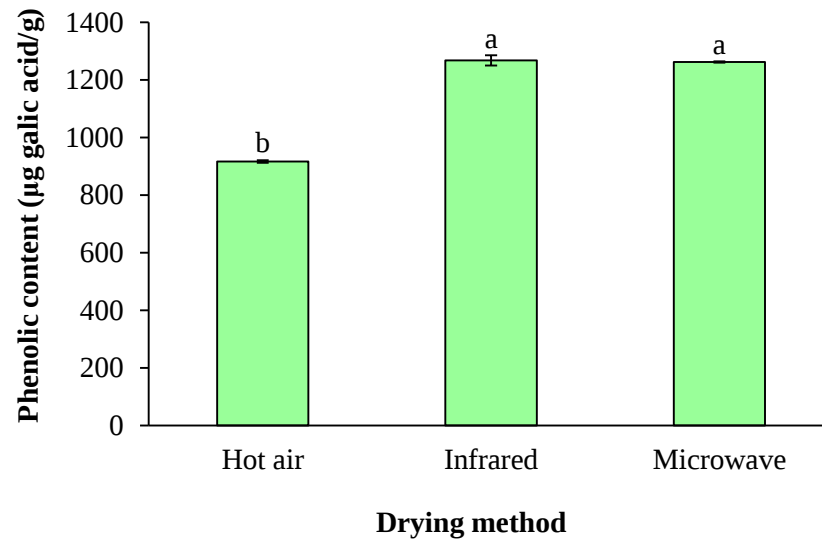


Figure 8- Influence of drying method on the total phenolic content of sprouted quinoa powder

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

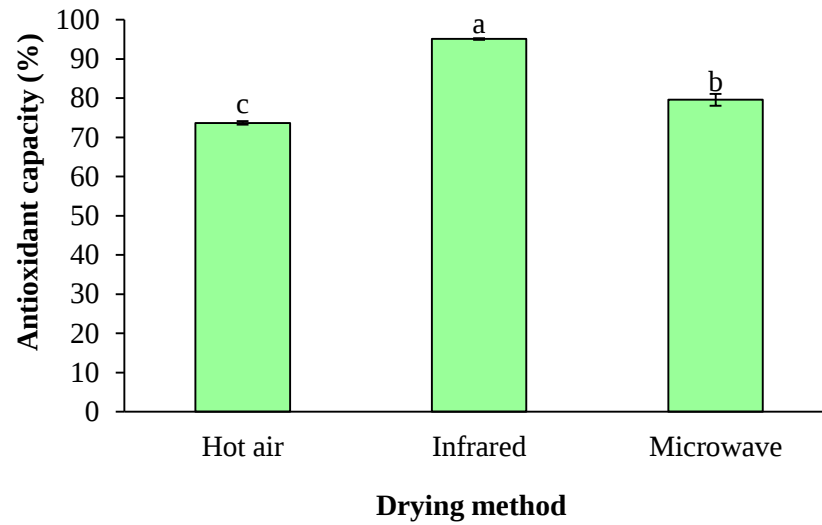


Figure 9- Influence of drying method on the antioxidant capacity of sprouted quinoa powder

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

تأثیر روش‌های خشک‌کردن بر ویژگی‌های فیزیکوشیمیایی و کیفیت پودر کینوا جوانه‌زده

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چکیده

این پژوهش به بررسی تأثیر روش‌های مختلف خشک‌کردن شامل خشک‌کردن همرفتی، فروسرخ و مایکروویو بر مقدار رطوبت، pH، اسیدیته، شاخص‌های رنگ، مقدار فنلی کل و ظرفیت آنتی‌اکسیدانی پودر کینوا جوانه‌زده پرداخت. در ابتدا، بذره‌های کینوا به مدت یک ساعت در آب مغناطیسی خیسانده شدند. سپس به‌منظور جوانه‌زنی، بذرها به مدت ۷۲ ساعت در دمای ۲۵ درجه سلسیوس در میدان مغناطیسی نگهداری شدند. برای افزایش ترکیبات فنلی، جوانه‌ها به مدت ۵ دقیقه تحت تیمار فراصوت قرار گرفتند. جوانه‌ها به سه روش مختلف خشک شدند و پودر حاصل از آن‌ها مورد تجزیه و تحلیل قرار گرفت. تابش فروسرخ باعث تسهیل در حذف رطوبت از جوانه‌های کینوا، افزایش ضریب نفوذ مؤثر رطوبت و کاهش زمان خشک‌کردن شد. میزان رطوبت و pH پودرهای کینوای جوانه‌زده به ترتیب در محدوده ۲/۶۱ تا ۷/۰۳ درصد و ۵/۹۵ تا ۶/۰۸ بود. اسیدیته پودرهای خشک‌شده به روش‌های همرفتی، فروسرخ و مایکروویو به ترتیب ۱/۲۴٪، ۱/۱۹٪ و ۰/۸۱٪ اندازه‌گیری بود. در میان نمونه‌ها، پودر جوانه کینوای خشک‌شده با مایکروویو کمترین روشنایی (۶۷/۷۸) و بیشترین شاخص قرمزی (۹/۸۹) و زردی (۲۱/۰۹) را داشت. پودرهای خشک‌شده به روش فروسرخ بیشترین میزان ترکیبات فنلی و ظرفیت آنتی‌اکسیدانی را داشتند. مقادیر ترکیبات فنلی برای پودرهای خشک‌شده با روش‌های همرفتی، فروسرخ و مایکروویو به ترتیب برابر با ۹۱۶/۹۸، ۱۲۶۸/۴۸ و ۱۲۶۲/۴۶ میکروگرم اسید گالیک بر گرم ماده خشک بود. به‌طور کلی، خشک‌کردن با روش فروسرخ به عنوان بهترین روش برای خشک‌کردن جوانه‌های کینوا شناخته شد، چرا که ضمن افزایش سرعت خشک‌کردن، به حفظ بهتر شاخص‌های رنگی کمک کرده و بیشترین میزان ترکیبات مفید را در محصول حفظ می‌کند.

واژه‌های کلیدی: شاخص‌های رنگ؛ ظرفیت آنتی‌اکسیدانی؛ فروسرخ؛ کینوا جوانه‌زده؛ مایکروویو