Zeszyty Problemowe Postępów Nauk Rolniczych
nr 598, 2019, 29–39
DOI 10.22630/ZPPNR.2019.598.14

THE EVALUATION OF DRYING KINETICS AND WATER ACTIVITY OF RADISH SPROUTS PROCESSED BY DIFFERENT DRYING METHODS

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Summary. Radish sprouts are rich in bioactive compounds and usually consumed as raw or slightly cooked. Due to their high water activity, they are perishable and the microorganisms can grow very easily. Moreover, sprouts have been associated with numerous foodborne outbreaks worldwide. Thus, there is a need to develop efficient methods to preserve all the healthy valuable compounds and limiting the contamination of sprouts with foodborne pathogens. One of the ideas is to use drying as one of the oldest methods of food preservation. However, the high temperature of traditional drying negatively influences the quality of agricultural products and this process is energy-intensive. The different methods of drying can be used in order to shorten the drying time and improve the quality of dried plant tissue. The aim of this work was to compare the drying kinetics of different drying techniques such as convective drying (air-drying, CD), microwave--assisted convective drying (MV-CD) and infrared-assisted convective drying (IR-CD) of radish sprouts. Convective drying was conducted using temperature of air equal to

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60°C and airflow set at 1 $m \cdot s^{-1}$. Microwave-assisted convective drying was set on microwave power equal to 200 W, the airflow 1 $m \cdot s^{-1}$ and the temperature was equal to 30°C. In infrared-assisted convective drying was used the power of infrared emitter equal 7.875 $kW \cdot m^{-2}$, and airflow was set at 1 $m \cdot s^{-1}$. Fresh radish sprouts contained 88.64% of water and their water activity was equal to 0.94. Drying time was calculated as the time necessary to reach a moisture ratio equal to 0.0014. The shortest drying time (92 min) was noted for the convective drying compared to infrared-assisted (127 min) and microwave-assisted (152 min) air-drying methods. The highest value of drying rate was noticed for the samples dried by the convective method. For microwave-assisted convective drying and infrared-assisted convective drying rates were reduced by 45.2% and 27.6%, respectively. After the drying process, water content was reduced to the range of 4.53–5.65%, whereas water activity was reduced to the range of 0.330–0.401. This means that all of the dried products exhibited water activity below 0.6 which ensures their microbiological stability and improves the safety of radish sprouts.

Key words: radish sprouts, microwave drying, infrared drying, drying kinetics, water activity

INTRODUCTION

Radish sprouts are rich in bioactive compounds and usually consumed as raw or slightly cooked. Due to their high water activity, they are perishable and the microorganisms can grow very easily. Moreover, sprouts have been associated with numerous food-borne outbreaks worldwide. Thus, there is a need to develop efficient methods to preserve all the healthy valuable compounds and limiting the contamination of sprouts with food-borne pathogens [Michino et al. 1999, Li et al. 2016, Zhang et al. 2016]. One of the ideas is to use drying as one of the oldest methods of food preservation [Lewicki 2006].

The drying technique is based on the physical principle of removing water by evaporation, reducing the water activity of the food matrix. The decrease of water content allows the inhibition of microbial activity and reduces the enzymatic and chemical reaction rate that occurs in the food matrix. Consequently, it is of great importance to control the complex glucosinolates–myrosinase in some of the plant origin materials. However, one of the main drawbacks of conventional drying is the use of high temperatures during long drying times, thus promoting the degradation of thermolabile antioxidant compounds [Ndawula et al. 2004, Timoumi et al. 2007, Nowacka et al. 2012]. Therefore, there is a need to optimize and/or to develop processing technologies which can reduce the detrimental effects of conventional drying.

Technologically, the drying procedure can be divided into three steps: (1) pre-drying processing, (2) dehydration and (3) post-drying handling (e.g. packaging) [Lewicki 2006]. The aim of the pre-treatment is to disrupt the cellular structure in order to reduce the diffusion mass transfer resistance, which facilitates the drying process. Some conventional techniques based on mechanical and/or thermal processes have been used to improve cell disruption and subsequently improving the drying process. However, in some cases, they cannot be used as they change the physical properties of the material (e.g. fragmentation changes the geometry of the product) or they are associated with high energy and water consumption that can cause losses of soluble solids (e.g. blanching) [Jayaraman and Das Gupta 2006].

In the last decades, microwave and infrared processing technologies have been used for improving drying of food products, obtaining promising results [Figiel 2007, Pereira et al. 2007, Kowalski and Rajewska 2009]. For instance, microwave- and infrared-assisted convective drying can facilitate the moisture transfer from the material resulting in increasing the effective water diffusion coefficient. Furthermore, in the literature, it is reported that these technologies prior to drying can improve the effective water diffusion coefficient in comparison to that of the intact material [Maskan 2001, Praveen Kumar et al. 2005, Markowski et al. 2007]. Therefore, the aims of the present work were to evaluate and compare drying kinetics of different drying techniques such as convective drying (CD, air-drying), microwave-assisted convective drying (MV-CD) and infrared-assisted convective drying (IR-CD) and assess the water activity of obtained products.

MATERIAL AND METHODS

Radish (*Raphanus sativus* var. *sativus*) seeds used in the current study were purchased at a local market in Warsaw (Poland). Sprouting was carried out in a special sprouting vessel (Bio-natura, Poland) – Figure 1. The vessel consisted of a lid, sprouting dishes (d = 20 cm) with drainage channels, siphons and the overflow tank. The sprouts were irrigated twice a day by pouring 500 cm^3 water in the first sprouting dish. Afterward, the water flows through the siphons to the next sprouting dish levels. The surplus of water was collected in the overflow tank. In order to ensure the proper circulation of air, three ventilators were placed in the lid and in each sprouting dish. The radish sprouts were harvested on the fourth day after seeding. These conditions were selected according to preliminary studies (unpublished data). The dry matter of all samples was determined according to AOAC method 920.15 [Horwitz 2002].

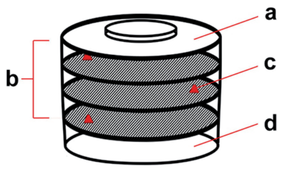

Fig. 1. Scheme of the sprouting vessel: a – lid; b – sprouting dishes with drainage channels; c – siphon; d – overflow tank

Rys. 1. Schemat kiełkownicy: a – pokrywa; b – płyty do kiełkowania z kanałami odsączającymi; c – syfon; d – zbiornik przelewowy

During each drying process, the mass of the material was recorded continuously with the accuracy of ±0.1 g. The material was dried until moisture ratio (MR) was ≈ 0.001 [(see eq. (1)]. The processing parameters were selected on the basis of preliminary studies, which are not presented in this paper and were not published before. Moreover, the drying air temperature was selected so as not to cause total degradation of myrosinase [Oliviero et al. 2014]. After the process, the dried material was vacuum packed (30% of air) into a laminate packaging (BOPA/PE 1540 FF) and stored at room temperature, with limited light exposition.

Convective (air) drying (CD) and infrared-assisted convective drying (IR-CD)

The conventional convective (air) drying and innovative infrared-assisted convective drying were carried out using the same prototype dryer, equipped with nine lamps emitting the infrared radiation (Fig. 2). However, depending on the desired conditions, the dryer could function with enabled or disabled source of IR light. The infrared radiation sources were arranged in series of three rows. The power and the diameter of each lamp were 175 W and 125 mm, respectively. The total power of infrared emitter was 7.875 $kW \cdot m^{-2}$. The distance between the infrared source and the material was equal to 20 cm and the parallel airflow was set at 1 $m \cdot s^{-1}$. The dryer was loaded with 0.5 $kg \cdot m^{-2}$ and the material was placed on a sieve positioned in parallel to the airflow. The dryer was coupled with a balance (with 0.100 ±0.001 g accuracy) and data acquisition software that allowed recording the mass continuously (every 1 min) during the drying process. The temperature of the hot air in the case of CD was equal to 60°C, whereas in the case of IR-CD, the air was supplied at room temperature (20 ±2°C). Drying experiments were performed at least in duplicate.

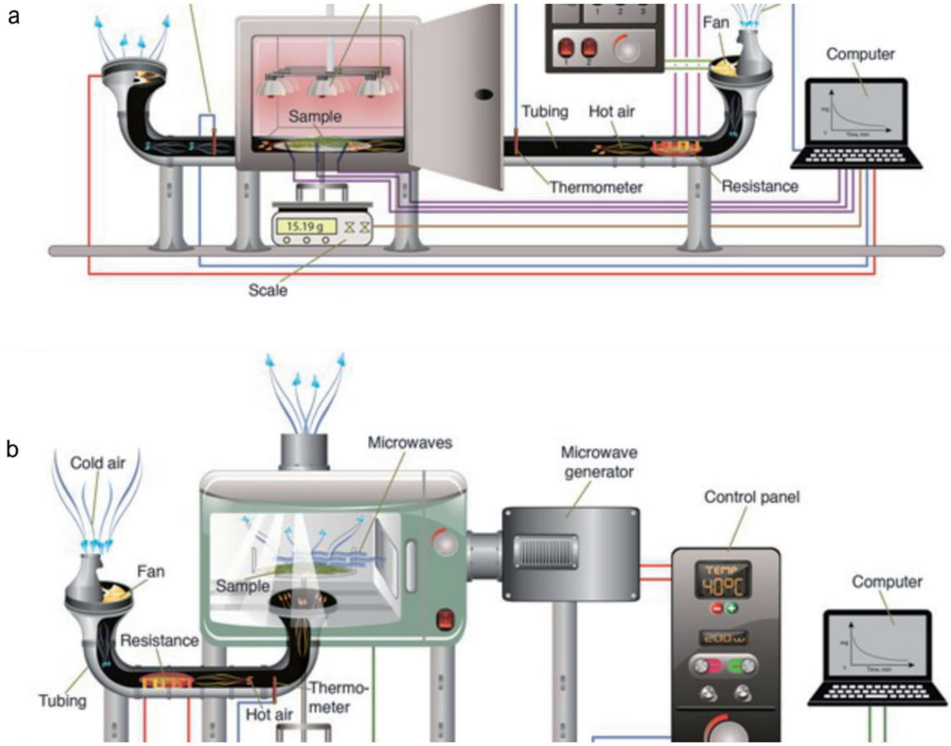

Fig. 2. Experimental set-up for drying processes: a – convective drying and infrared-assisted convective drying set-up; b – microwave-assisted convective drying set-up

Rys. 2. Schemat zestawów użytych w eksperymencie: a – zestaw do suszenia konwekcyjnego oraz promiennikowo-konwekcyjnego; b – zestaw do suszenia mikrofalowo-konwekcyjnego

Microwave-assisted convective drying (MW-CD)

Sprouts were dried in a laboratory prototype microwave-assisted convective dryer (Promis, Wrocław), coupled with balance (0.100 ±0.001 g accuracy) and computer data acquisition software (Fig. 2). The mass changes during drying were registered every 2 min. During mass recording, the drying was stopped for 15 s to collect the data, and then restarted immediately afterwards. The dryer was loaded with 0.673 $kg \cdot m^{-2}$ whereas the microwave power was equal to 200 W. The airflow was set at 1 $m \cdot s^{-1}$ and the temperature was equal to 30 ±2°C. The sieve was positioned perpendicular to the air flow. The drying experiments were performed at least in duplicate.

Determination of drying kinetics

Drying time was determined as the time necessary to reach *MR* of 0.0014, calculated based on equation (1):

$$MR = \frac{u_\tau}{u_0} \tag{1}$$

where:
u_τ – moisture content at τ moment of the process [kg $H_2O \cdot kg^{-1}$ d.m.],
u_0 – initial moisture content [kg $H_2O \cdot kg^{-1}$ d.m.].

The drying curves were described using the model developed by Midilli et al. [2002] presented by equation (2):

$$MR = a \cdot e^{-k \cdot \tau^c} + b \cdot \tau \tag{2}$$

where:
a, b, c – coefficients of the equation;
k – drying coefficient [min^{-1}];
τ – drying time [min].

The effective water diffusion coefficient (D_{eff}) was estimated by the regression analysis based on the simplified Fick's second law of diffusion, which could be expressed according to equation (3) for an unsteady diffusion and in an infinite slab.

$$MR = \frac{8}{\pi^2} \cdot e\left(\frac{\pi^2 \cdot D_{eff} \cdot \tau}{4 \cdot L^2}\right) \tag{3}$$

where:
τ – drying time [s];
L – half of the thickness [m].

Statistical analyses

An one-way analysis of variance (ANOVA) was applied to the results obtained in order to verify whether the differences were significant in the drying parameters studied (differences at $p < 0.05$ were considered significant). A Tukey test was applied to indicate the samples between which there were relevant differences. All statistical analyses were performed using SPSS software v22 (IBM® SPSS® Statistics, USA). Regression analysis was carried out by TableCurve 2D v5.01 software (Systat Software Inc., Chicago, USA). The fit of mathematical modeling process was evaluated on the basis of *RMSE* and χ^2 parameters as described by Sledz et al. [2017].

RESULTS AND DISCUSSION

Drying kinetics

After harvesting (4th day of sprouting), radish sprouts were of 53.2 mm average long (in the elongated state) and they have an average mass of 0.9 g per 20 fresh sprouts. In the literature, it can be found that the best length of sprouts intended for consumption depends on the type and species of the sprouts and varies between 20 and 60 mm [Lewicki 2010]. Fresh radish sprouts contained 88.64% of water and their water activity was equal to 0.94. After the drying process, water content was reduced to the range of 4.53–5.65%, whereas water activity was reduced to the range of 0.330–0.401 (the table). It means that all of the dried products exhibited water activity below 0.6, which ensures their microbiological stability.

Table. Water content, water activity of fresh and dried radish sprouts and drying time of sprouts dried with different method

Tabela. Zawartość wody, aktywność wody oraz czas suszenia kiełków wysuszonych różnymi metodami

Sample Próbka	Water content Zawartość wody [%]	Water activity Aktywność wody	Drying time Czas suszenia [min]
Fresh	88.63 ± 0.63^{a}	0.940 ± 0.002^{a}	–
CD	5.65 ± 0.23^{b}	0.330 ± 0.002^{b}	92
IR-CD	4.53 ± 0.22^{c}	0.401 ± 0.012^{c}	127
MW-CD	4.88 ± 0.73^{bc}	0.372 ± 0.004^{d}	152

[a–c] Different lowercase letters in the same column indicate significant differences ($p < 0.05$) as a function of the applied treatment: CD – convective drying, IR-CD – infrared-assisted convective drying, MW-CD – microwave-assisted convective drying.

[a–c] Różne małe litery w tej samej kolumnie wskazują na statystycznie istotne różnice ($p < 0,05$) w odniesieniu do różnych metod suszenia: CD – suszenie konwekcyjne, IR-CD – suszenie promiennikowo-konwekcyjne, MW-CD – suszenie mikrofalowo-konwekcyjne.

The drying time of the radish sprouts varied between 92 and 152 min, depending on the process technology. The shortest time was noted for the convective (air) drying. What is worth emphasizing is that the use of infrared-assisted air-drying or microwave-assisted air-drying did not result in any significant reduction of drying time. These results are in contrast with some studies reported that the use of these methods could reduce the drying time, compared to conventional convective drying [Mascan 2001, Praveen Kumar et al. 2005, Figiel 2007, Kowalski and Rajewska 2009]. However, it should be noted that these experiments were carried out on raw materials different than sprouts and no data were reported regarding sprout drying. The differences are probably due to the specific morphology and structure of the material.

Due to the fact that radish sprouts are very thin (especially in the epicotyl part) and the thickness determines the mass transfer during the drying process, the application of microwave was probably negligible. The efficiency of microwave power utilization in order to enhance the drying process depends also on the water content of the material. Generally, the materials which consist of more water are more prone to microwave exposition which is linked to the influence of the microwaves on the plant material and the values of the dielectric constant [Wiktor et al. 2012]. The results of the analysis of the drying curve for the MW-CD sprouts are in accordance with this explanation. At the beginning of the drying process, when the moisture content was high, the drying kinetics of MW-CD was enhanced in comparison to the convective drying. This behavior is also expressed as a faster initial drying rate (up to *MR* = 0.75) presented in Figure 3.

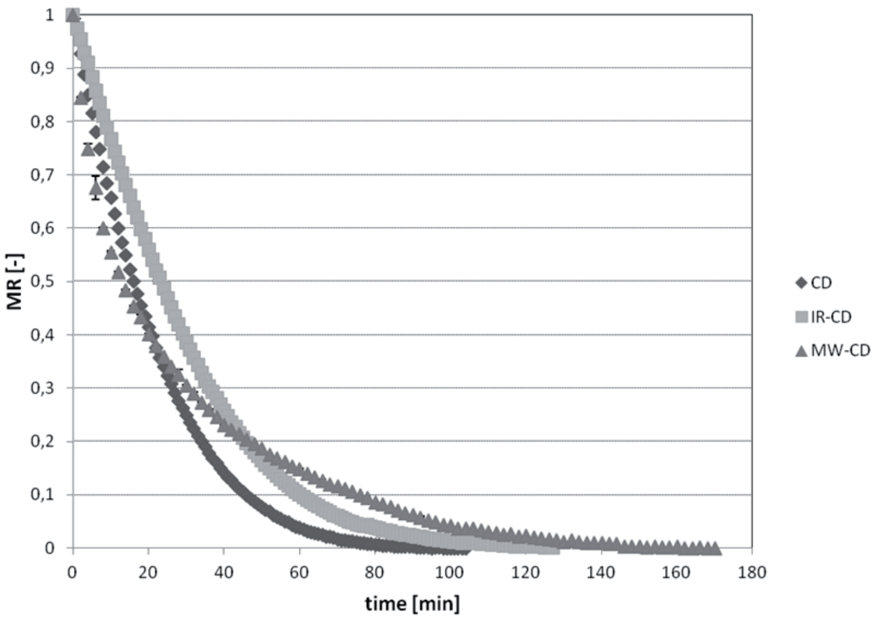

Fig. 3. The drying curves of radish sprouts dried by the different methods: CD – convective air-drying, IR-CD – infrared-assisted convective drying, MW-CD – microwave-assisted convective drying

Rys. 3. Krzywe suszenia kiełków rzodkiewki wysuszonej różnymi metodami: CD – suszenie konwekcyjne, IR-CD – suszenie promiennikowo-konwekcyjne, MW-CD – suszenie mikrofalowo-konwekcyjne

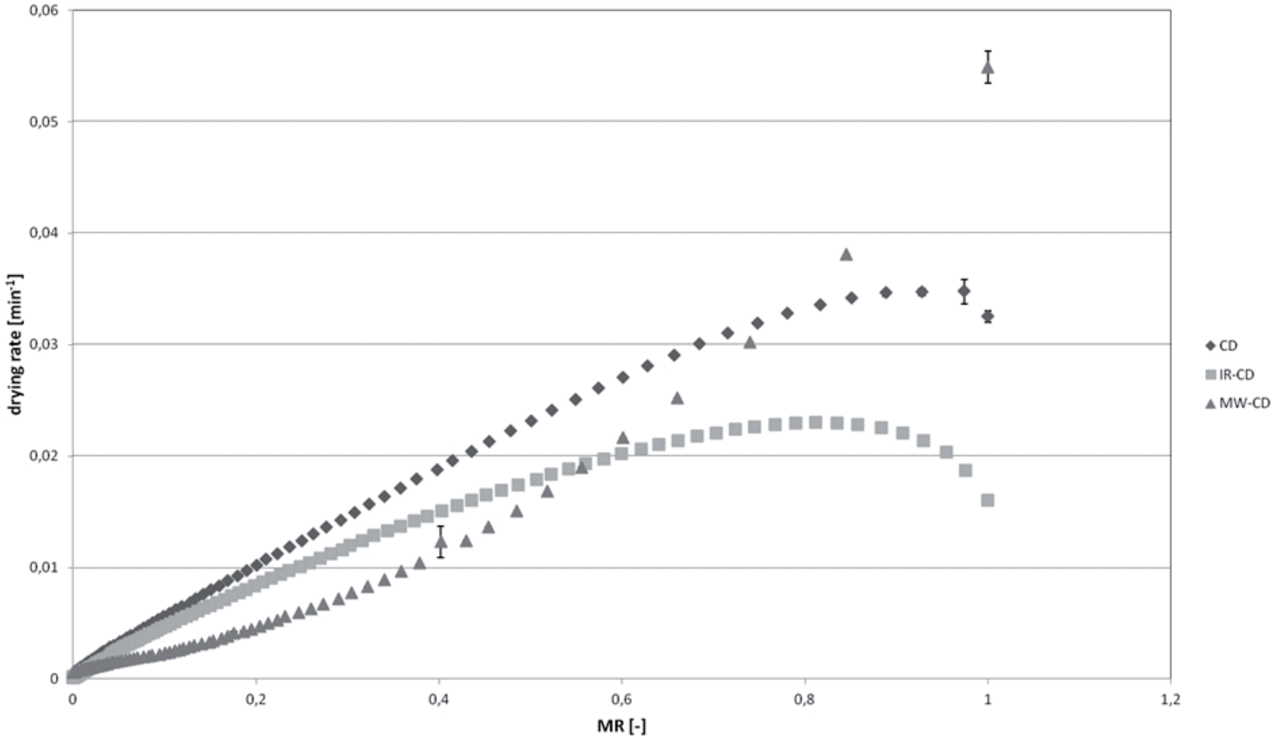

Fig. 4. Drying rate of radish sprouts computed based on Midilli et al. [2002] model: CD – convective air-drying, IR-CD – infrared-assisted convective drying, MW-CD – microwave-assisted convective drying

Rys. 4. Szybkość suszenia kiełków rzodkiewki wyznaczona na podstawie modelu Midilliego i in. [2002]: CD – suszenie konwekcyjne, IR-CD – suszenie promiennikowo-konwekcyjne, MW-CD – suszenie mikrofalowo-konwekcyjne

The drying rate was calculated according to equation (2). This model was proved to be the most suitable to describe the thin-layer drying kinetics for many different raw materials [Vega-Galvez et al. 2008, Kucuk et al. 2014]. The highest average value of drying rate was observed for the samples dried by the convective method (0.0106 min^{-1}). Average drying rates for MW-CD and IR-CD were reduced by 45.2% and 27.6%, respectively (Fig. 4).

In the case of IR-CD and CD, a very short period of the first stage of drying was observed. Moreover, the maximum drying rate in these cases was found for the MR = 0.81 (IR-CD) and MR = 0.93 (CD). However, the MW-CD kinetics exhibited only the falling stage of drying with the maximum of drying rate at the MR = 1.0. The drying rate of MW-CD samples was higher than IR-CD in the range of MR from 1 to 0.58. The low drying rate in the case of IR-CD process could be due to the color of the radish sprouts, which inhibited the absorption of the infrared radiation. In turn, high drying rate and the presence of only the falling stage in the case of MC-CD samples is linked to the mechanism of microwave radiation applied during drying. The effect of microwave support is the strongest when the moisture content in the material is the highest because of the dipole excitation and rapid movement. During drying, water content in the product drops which contributes to the drop of the drying rate either.

CONCLUSIONS

1. Drying, despite of utilized method, allows to obtain product characterized by water activity below 0.6, which prevent against microbial growth.
2. Convective drying seems to be the most effective drying technique in terms on time consumption. Surprisingly, application of microwave radiation during drying did not enhance the drying kinetics of radish sprouts in comparison to convective drying, which can be linked to a very thin structure of the radish sprouts hypocotyl and root.

Acknowledgements

This work was funded by a statutory activity subsidy of the Polish Ministry of Science and Higher Education for the Faculty of Food Sciences of Warsaw University of Life Sciences – SGGW. Francisco J. Barba was supported from the Union by a postdoctoral Marie Curie Intra-European Fellowship (Marie Curie IEF) within the 7th European Community Framework Programme (project number 626524 – HPBIOACTIVE – Mechanistic modeling of the formation of bioactive compounds in high pressure processed seedlings of Brussels sprouts for effective solution to preserve healthy compounds in vegetables). Shahin Roohinejad would like to acknowledge the Alexander von Humboldt Foundation for his postdoctoral research fellowship award.

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WPŁYW RÓŻNYCH METOD SUSZENIA KIEŁKÓW RZODKIEWKI NA PRZEBIEG PROCESU

Streszczenie. Celem badań było określenie kinetyki procesu suszenia kiełków rzodkiewki, wykorzystując tradycyjne suszenie, tj.: konwekcyjne, mikrofalowo-konwekcyjne i promiennikowo-konwekcyjne. Świeże kiełki charakteryzują się zawartością wody wynoszącą 88,64% i aktywnością wody równą 0,94. Czas suszenia niezbędny do uzyskania wysuszonych kiełków rzodkiewki (MR = 0,0014) był najkrótszy w przypadku suszenia konwekcyjnego (92 min) w porównaniu do mikrofalowo-konwekcyjnego (127 min) i promiennikowo-konwekcyjnego (152 min). Oznacza to, że najszybciej suszenie przebiegło przy zastosowaniu technologii konwekcyjnej. Po procesie suszenia zawartość wody w kiełkach rzodkiewki uległa obniżeniu od 4,53 do 5,65%. Aktywność wody została obniżona od 0,330 do 0,401. Osiągnięcie wartości poniżej 0,6 zapewnia stabilność mikrobiologiczną i bezpieczeństwo kiełkom rzodkiewki.

Słowa kluczowe: kiełki rzodkiewki, suszenie mikrofalowe, suszenie konwekcyjne, suszenie promiennikowe, kinetyka suszenia, aktywność wody