Vol. 24, No. 1(2025) Alim24400
Revista Mexicana de Ingeniería Química
Ingeniería de alimentos

Modeling of dehydration, polyphenol thermal degradation, and rehydration of instant germinated VD20 rice: Mathematical and artificial intelligence model

Modelado de la deshidratación, degradación térmica de polifenoles y rehidratación del arroz VD20 germinado instantáneo: Modelo matemático y de inteligencia artificial

L.T.K. Loan[1], T.Q. Tat[2], P.D.T. Minh[1], V.T.T. Thao[1], P.T.M. Hoang[1], T.T.Y. Nhi[3], B.L. Giang[3], D.T. Phat[3], C. Mansamut[4], N.V. Tai[5]*

[1] Faculty of Agriculture and Food Technology, Tien Giang University, My Tho city, Tien Giang Province, Viet Nam.

[2] Faculty of Technology and Engineering, Dong Thap University, Pham Huu Lau Street, Cao Lanh City, Dong Thap, Vietnam.

[3] Institute of Applied Technology and Sustainable Development, Nguyen Tat Thanh University, Ho Chi Minh City, Vietnam

[4] Faculty of Sciences and Technology, Dhonburi Rajabhat University, Bangkok 10600, Thailand

[5] School of Food Industry, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand

Received: August 20, 2024; Accepted: October 16, 2024

Abstract

VD20 rice, a local rice variety in Vietnam, is currently undergoing restoration and provides limited information about product development. In order to produce the instant germinated VD20 rice, the study on kinetics of dehydration, polyphenol thermal degradation, and rehydration of the instant product was carried out. Different temperatures were applied in this study, including 50^{o}C, 55^{o}C, 60^{o}C, and 65^{o}C. Various models were developed to describe these changes. The Page model provided the best fit for the sample's dehydration properties, with the moisture diffusivity (D_{eff}) ranging from 7 x 10^{-12} to 1.19 x 10^{-11} m^2/s and an activation energy of 31.70 kJ/mol. A zero-order model described the change in polyphenol during the drying process. The half-life values ranged from 3.737 h to 5.723 h. Also, the ANN model was used. This is an intelligent model made of an artificial neural network. It worked better and faster than earlier models like the Page model for dehydration behavior and the zero-order model for degradation property. The rehydration ratio of instant germinated rice also fitted well with the exponential model. These developed insights could facilitate further optimization and production on a larger scale, thereby enabling farmers to produce more products from this rice.

Keywords: rice, artificial neural network, drying, modeling, antioxidant.

Resumen

El arroz VD20, una variedad local de arroz en Vietnam, está actualmente en proceso de restauración y proporciona información limitada sobre el desarrollo del producto. Para producir el arroz VD20 instantáneo germinado, se llevó a cabo un estudio sobre la cinética de deshidratación, la degradación térmica de polifenoles y la rehidratación del producto instantáneo. Se aplicaron diferentes temperaturas en este estudio, incluyendo 50°C, 55°C, 60°C y 65°C. Se desarrollaron varios modelos para describir estos cambios. El modelo de Page proporcionó el mejor ajuste para las propiedades de deshidratación de la muestra, con una difusividad de humedad (D_{eff}) que varió de 7 x 10^{-12} a 1.19 x 10^{-11} m^2/s y una energía de activación de 31.70 kJ/mol. Un modelo de orden cero describió el cambio en los polifenoles durante el proceso de secado. Los valores de vida media variaron de 3.737 h a 5.723 h. Además, se utilizó el modelo de red neuronal artificial. Este es un modelo inteligente hecho de una red neuronal artificial. Funcionó mejor y más rápido que modelos anteriores como el modelo de Page para el comportamiento de deshidratación y el modelo de orden cero para la propiedad de degradación. La relación de rehidratación del arroz germinado instantáneo también se ajustó bien al modelo exponencial. Estos conocimientos desarrollados podrían facilitar una mayor optimización y producción a gran escala, lo que permitiría a los agricultores obtener más productos de este arroz.

Palabras clave: arroz, red neuronal artificial, secado, modelado, antioxidante.

**Corresponding author. E-mail*: ngovantai1509@gmail.com;
https://doi.org/10.24275/rmiq/Alim24400
ISSN:1665-2738, *issn-e*: 2395-8472

1 Introduction

Rice, scientifically referred to as *Oryza sativa* L., is commonly acknowledged as the predominant staple food in Asian countries. Because of its high nutritional value, a significant portion of the population consumes it every day. Recently, the rapid pace of modern life has resulted in the emergence of innovative applications for basic rice in the production of instant rice, which is prepared by either fully or partially cooking and dehydrating it. It simply takes 3-5 minutes of rehydration before it can be ingested. Various forms of rapid rice products, such as frozen and dried options, were created to meet the needs of the market (Yu *et al*., 2017). Instant rice has become widely popular worldwide because of its convenience and long shelf life, especially for use in tourism, business travel, fast-food businesses, and military rations. Typically, the process of preparing ordinary rice requires at least thirty minutes or more to wash and cook (Loan *et al*., 2023). On the other hand, instant rice is frequently produced by partially or fully heating it and then eliminating the water using a dehydration method. The food can be rapidly prepared for eating by either rehydrating or heating it for a short period (Yadav *et al*., 2024). Instant rice, like conventional rice, has a range of macronutrients, including starch, protein, fat, and a moderate amount of fiber. Instant rice, while convenient, offers a less satisfactory eating experience compared to normal rice. This is because the process of preparing instant rice results in a loss of sensory perception and nutritional characteristics. The quality of instant rice depends on the basic materials and the exact circumstances used during the drying process. The drying phase is the pivotal step in the production of instant rice (Yadav *et al*., 2024).

Instant rice is produced by hydrating and/or precooking raw rice to gelatinize the starch. The treated rice is then dried to obtain the necessary moisture level. The physicochemical properties of rice have a significant impact on the structure of instant rice and its ability to rehydrate (Rewthong *et al*., 2011). Nevertheless, it also altered the characteristics related to the loss and regain of water. Most research used hot air drying and faced the problem of extended dehydration time and slow rehydration rate (Pavkov *et al*., 2021). Therefore, the instant rice does not meet the quality expectations of consumers. The accepted criteria for high-quality instant rice include white color, non-sticky and well-separated cooked grains, reduced rehydration time, similar sensory properties to freshly cooked rice, minimal broken or damaged grains, increased volume expansion ratio, and absence of a hard core or ungelatinized center (Loan *et al*., 2023; Rewthong *et al*., 2011; Yadav *et al*., 2024). Furthermore, the process of drying also had an impact on the polyphenol levels in rice (Finocchiaro *et al*., 2007). Aiming to forecast the changes in attributes such as dehydration, rehydration, and polyphenol degradation in instant VD20 rice, a modeling curve was developed. This curve takes into account the variations in temperature and time. This study aims to give essential information for optimizing the process of producing VD20 instant rice with both excellent quality and reasonable cost. Various mathematical models have been suggested to optimize the drying process and develop efficient dryers. Furthermore, accurate estimation of drying rates for different types of dryers and determination of moisture diffusion parameters for fruit items are crucial elements in drying simulation models. These factors are necessary for conducting an effective analysis of moisture transfer. Many drying qualities and qualitative and quantitative indicators can be accurately described by ANNs for a wide range of agricultural products (Ait Hmazi *et al*., 2024; Rasooli Sharabiani *et al*., 2021). ML (machine learning) is recommended over physics-based models in drying processes (Martynenko & Misra, 2020), favoring real-time quality control with machine vision. According to Khan *et al*. (2022), ML can revolutionize food drying technology by utilizing predictive modeling for drying kinetics, property prediction, and process optimization. Further, Kaveh *et al*. (2023) evaluate moisture content and ratio in apricots dried using various methods utilizing five machine-learning methods. Jebri et al. (2018) showed that ANNs may enhance drying process characterization and optimization by analyzing numerous quality metrics. Chasiotis *et al*. (2020) demonstrated that ANNs possess the ability to model quince slice moisture content during convective drying, capturing complicated drying dynamics.

Rehydration can be seen as an indicator of the damage inflicted on the material due to the drying process and the preceding treatment before dehydration (Krokida & Philippopoulos, 2005). The rehydration of dried plant tissues involves three simultaneous processes: the absorption of water into the dried material, the expansion of the material, and the removal of soluble substances (Krokida & Maroulis, 2001). Research conducted by Krokida and Maroulis (2001) demonstrated that the swelling of biological materials, also known as volume changes, is frequently directly proportional to the quantity of water absorbed. In their study, Li *et al*. (2020) discovered that the increase in volume resulting from water absorption was equal to the volume of water absorbed. However, the increase in size caused by moisture in soybean and pigeon pea grains was consistently smaller than the amount of water absorbed.

The extent of rehydration is commonly acknowledged to be contingent upon the extent of cellular and structural disturbance. During the drying process, the cells experienced irreversible rupture and displacement. This led to a loss of structural integrity and the formation of a dense structure consisting of collapsed and significantly shrunken capillaries. As a result, the capillaries exhibited reduced hydrophilic properties, which means they were unable to absorb enough water to fully rehydrate. Moreover, as the study of Loan *et al*. (2024), germination could enhance the quality of its product. It was also the first study on instant germinated rice. The aim of this study was to evaluate the drying behavior, degradation properties of polyphenol and rehydration of instant germinated VD20 rice. This is the first study on the change of moisture content and polyphenol during drying process of germinated VD20 rice, which could further develop to optimize and produce on a large scale.

2 Materials and methods

2.1 Materials

Rice grain of VD20 variety was obtained from a farmer in Tien Giang, Vietnam. The paddy samples underwent a meticulous cleaning process to eliminate dust particles and were then dehusked. Subsequently, they were polished in preparation for further analysis.

2.2 Preparation of instant rice

The sample was first germinated as optimal conditions of Loan *et al*. (2024) and instant rice was prepared by the method described by Loan *et al*. (2023). For optimal cooking conditions, 400 mL of water was combined with 200 g of rice. A Sharp electric cooker (KS-IH191V-GL, Korea) was employed in this investigation. A measurement was taken of the initial moisture content of cooked brown rice. The sample was applied to the stainless steel tray with a thickness of 3 cm. Subsequently, the sample was dehydrated at varying temperatures to facilitate assessment.

2.3 Drying experiment

The sample underwent a drying process at temperatures of 50°C, 55°C, 60°C, and 65°C until it achieved a state of moisture content equilibrium. The sample's weight was monitored periodically at 30-minute intervals throughout the drying process to ascertain the moisture content at different time intervals. Three separate experiments were performed for each drying condition and the average moisture content data was used.

2.4 Model fitting

Before the model was fitted, the moisture ratio value (MR) was calculated using Equation 1. The variables in the equation are M_e, which stands for the equilibrium moisture content on a dry basis, M_i, which stands for the starting moisture content on a dry basis, and M^t, which is the moisture content at time t expressed as a percentage on a dry basis.

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{1}$$

Five typical thin-layer models, namely Page, two-term exponential, Logarithmic, Wang and Sign, Newton, were chosen to accurately fit the actual MR data, as presented in Table 1. The equation with the highest coefficient of determination (R^2) and the lowest mean square error (MSE) values was chosen as the most acceptable equation to describe the drying kinetics of instant germinated rice.

2.5 Drying behavior

The effective diffusivity (D_{eff}) was calculated using the simplified form of Fick's Diffusion equation (Equation 2) (Demiray & Tulek, 2017).

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 t D_{eff}}{4L^2}\right) \tag{2}$$

The rate at which moisture diffuses through a substance is measured by the effective moisture diffusivity (Deff). It is computed as square meters per second (m^2/s) by dividing the moisture flow by the moisture gradient. The drying time (t), expressed in minutes, is the amount of time needed for the drying process to finish. The thickness (L), which is measured in meters (m), indicates how far or how much of the material is being dried. The diffusivity values were determined through the computation of the ln(MR) versus time (t) plot's slope. Equation 3, or the Arrhenius equation, was utilized to explain the relationship between temperature and moisture diffusivity. Plotting the natural logarithm of the effective diffusion coefficient ($\ln(D_{eff})$) against the reciprocal of the absolute temperature (T, K) was necessary to determine the activation energy (Ea, kJ/mol).

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{3}$$

where, D_0 is the Arrhenius factor, E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 kJ/mol.K) and T is the drying temperature (K).

2.6 Determination of total phenolic content

The total polyphenol content (TPC) of instant germinated rice at different time points were analyzed followed the method of Shen *et al*. (2015). The change of TPC was fit with three common models, including zero-order, first-order and second-order model. Moreover, the half-life and activation energy also calculated.

2.7 *Artificial neural network (ANN)*

A multi-layer feed forward back propagation model was used in this investigation. Temperature and drying time were fed into the model as input signals. The moisture content and moisture ratio were the model's outputs. The number of hidden layers (HLs) in the model was limited to one in order to simplify it. For the hidden layer (HL), the transfer function, or TANSIGMOID, was used, and its relative performance was evaluated (Loan *et al*., 2023). MATLAB v.2023b and the Levenberg-Marquardt (LM) training routines were used to train the model. Seventy percent of the available data were used for the model training. Testing and validation accounted for thirty percent of the remaining data set, divided equally between the two. The maximum number of iterations and validation tests was set at 1000 in order to maximize processing time. The criteria of lowest Mean Squared Error (MSE), highest correlation coefficient (r), and lowest complexity were used to choose the ANN infrastructure.

2.8 *Water gain percentage/Rehydration ratio*

The approach given by Sharma *et al*. (2024) with little modification was used to estimate the percentage of weight increase. A 0.2 g sample of dehydrated instant rice was placed in a beaker containing 4 mL of water heated to 95 °C. The mixture was let to sit for 5 minutes. The samples were collected at regular five-minute intervals. The surplus water was removed. The weight of the rice was measured before and after cooking at each interval using a precise electronic weighing scale. The water gain % was determined by dividing the increase in weight at each interval by the initial weight of the dry rice, and then multiplying by 100. The rehydration kinetics of the quick rice samples were characterized using three empirical models.

3 Results and discussion

3.1 *Dehydration models for instant germinated VD20 rice*

The drying procedure of VD20 rice, which had been germinated instantly, was conducted within a temperature range of 50-65°C. The original moisture content (MC) of the raw material before drying is 89.54±1.39%. During the drying process, the moisture content of the sample decreases till it reaches the desired level. This discrepancy arises from the variation in moisture content (MC) between the inside of the raw material and the surrounding drying conditions (Vu *et al*., 2022). Figure 1 demonstrates a significant reduction in the moisture ratio of the instant rice sample during the initial stage of the drying process. Increasing the drying temperature resulted in a greater decrease in moisture content (Meng *et al*., 2024). The readings experienced a marginal decrease following a 2-hour drying period. Extending the duration of the drying process results in a reduction in MR. The temperature range examined was between 50 and 65°C, and there was a significant decline in MR during the initial 2.5 hours of drying. Subsequently, the MR exhibits a gradual drop. At a temperature of 50°C, the magnetic resonance (MR) value exhibited a gradual drop as the time increased from 0 to 5 hours. At low temperatures, there is a minimal disparity between the moisture content (MC) in the raw material and the drying medium. Consequently, the rate at which moisture moves out of the material is sluggish. Various temperature conditions necessitate varied durations of drying in order to attain a consistent moisture content. It takes around 5 hours to reach a constant moisture ratio (MR) when drying the material at a temperature of 50°C. Similarly, the minimal duration for the MR to remain constant is 4.5 hours, 4 hours, and 3 hours at temperature milestones of 55°C, 60°C, and 65°C, respectively. Drying at 50°C requires approximately 1.7 times the amount of time needed for drying at 65°C. The results demonstrate the strong correlation between time and temperature during the drying process of raw materials. As the drying temperature increases, the amount of moisture in the air decreases. There is a significant disparity between the moisture content inside and outside the raw material. This enhances the rate of moisture conduction to the external environment by utilizing the principle of moving matter from regions with high concentration to regions with low concentration. Consequently, drying at elevated temperatures is more efficient in reducing drying time compared to drying at lower temperatures (Meng *et al*., 2024). The findings align with a prior investigation in which higher air temperatures were found to decrease the duration of the drying process (Önal *et al*., 2019; Randriamiarintsoa *et al*., 2024). When drying at temperatures of 55 and 60°C, the drying curve has a greater slope compared to that at 50°C. At a drying temperature of 65°C, the drying curve exhibits a gradual reduction, and the moisture ratio (MR) does not experience a sudden decrease. This phenomenon can be attributed to the inadequate energy and temperature levels (50 and 55°C) during the drying process. These conditions are not enough

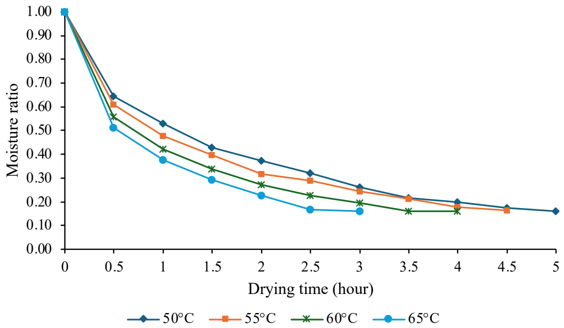

Figure 1. The change of moisture ratio of instant rice during drying process.

to consistently transfer moisture from the inner part of the material to the external environment. As a result, the moisture content (MC) phase diffuses within the material, leading to a high concentration of moisture in the cell layer near the surface before eventually reaching the surface. This is evident in the longer drying time of 1-2 hours at 60°C and the shorter drying time of 0.5 hours at 65°C. The movement of moisture from the flesh at the surface to the material's surface is rapid. As soon as moisture is transported to the surface, there is a quick loss of moisture, with little or no more moisture being displaced to the material's surface (de Lima *et al*., 2002). The drying process at 65°C is characterized by a significant amount of energy. This is due to the phenomenon of cell shrinkage, which aids in the efficient removal of moisture from the material. Additionally, the diffusion rate during this process is quick and continuous (de Lima *et al*., 2002; Randriamiarintsoa *et al*., 2024). The material has a negligible time for moisture diffusion. Hence, it is challenging to perceive this phase.

In order to describe the drying behavior of instant germinated rice, five mathematical models were applied and the model constant was calculated as shown in Table 1. Among five models, the most fitness was found in order Page > Logarithmic > Two-term exponential > Newton > Wang and Sign. The Page model shows the best fit to present the change in moisture ratio of instant germinated rice following the time at different temperatures. The R^2 and MSE were the highest and lowest values, respectively, compared to other models. Gutiérrez-Martínez *et al.* (2024) also reported that the Page model could describe the dehydration behavior of potato slices using a real-time convective drying machine. The change in moisture content of kiwi fruits was also used in the Page model (Simal *et al*., 2005). The benefit of analyzing the drying kinetics is crucial for optimizing the drying conditions. The drying process can be analyzed using drying kinetic analysis to establish particular characteristics such as moisture diffusivity and drying activation energy. This study allows for the empirical determination of the drying rate (Cai *et al*., 2017). The derived empirical relationships are typically utilized in algorithms that imitate the real-world behavior of a dryer (Cai *et al*., 2017).

Table 1. Mathematical model development for drying process of instant germinated rice.

Name and equation of model	Temperature (°C)	Model constant	R^2	MSE
Page MR = exp(ktn)	50	k = 0.6537; n = 0.6446	99.60	0.00012
	55	k = 0.7381; n = 0.5936	99.82	0.00004
	60	k = 0.8699; n = 0.5708	99.80	0.00005
	65	k = 0.9909; n = 0.5825	99.42	0.00013
Two-term exponential: MR = a.exp(-kt) + (1-a)exp(-kat)	50	a = 0.1955; k = 1.9958	97.57	0.00174
	55	a = 0.2029; k = 2.1666	96.33	0.00271
	60	a = 0.2195; k = 2.4787	96.13	0.00323
	65	a = 0.2215; k = 3.0976	97.32	0.00281
Logarithmic MR = a.exp(-kt)+b	50	a = 0.7990; k = 0.7563; b = 0.1642	98.55	0.00117
	55	a = 0.7860; k = 0.9657; b = 0.1859	98.52	0.00125
	60	a = 0.8055; k = 1.2240; b = 0.1750	98.87	0.00110
	65	a = 0.8163; k = 1.5102; b = 0.1719	99.00	0.00131
Wang and Sign $MR = 1 + at + bt^2$	50	a = -0.4269; b = 0.0544	92.35	0.00548
	55	a = -0.4842; b = 0.0698	90.36	0.00713
	60	a = -0.5794; b = 0.0966	90.29	0.00810
	65	a = -0.7425; b = 0.1599	92.90	0.00746
Newton MR = a.exp(-kt)	50	a = 0.8974; k = 0.4260	95.48	0.00324
	55	a = 0.8908; k = 0.4778	93.73	0.00464
	60	a = 0.9011; k = 0.6079	93.21	0.00567
	65	a = 0.9302; k = 0.8000	94.55	0.00572

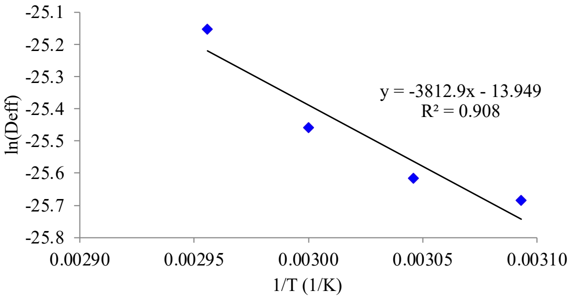

Figure 2. The graph of $\ln(D_{eff})$ versus 1/T.

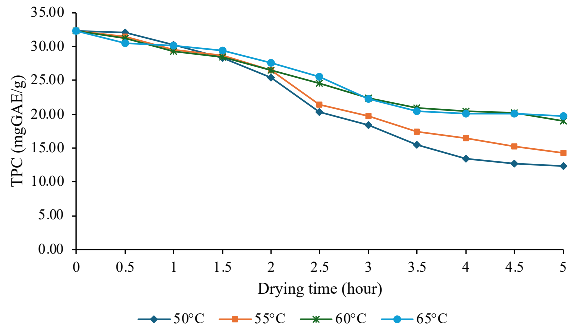

Figure 3. Change in TPC content of instant germinated rice during drying process.

The effective moisture diffusivity for instant germinated rice was measured by plotting the natural logarithm of the moisture ratio (MR) versus time, using Fick's second law of diffusion, at different temperatures. The curves were fitted using a linear regression model, resulting in R^2 values more than 90% as shown in Figure 2. This suggests that the drying process is mostly controlled by moisture diffusion. The moisture diffusivity (D_{eff}) of samples increased from 7 x 10^{-12} to 1.19 x 10^{-11} m^2/s as the temperature climbed from 50 to 65°C. The findings exhibited a decrease in comparison to the research conducted by (Espinosa-Solares & Domínguez-Puerto, 2023) . Figure 2 illustrates the correlation between the logarithm of D_{eff} (effective diffusion coefficient) and the inverse of temperature for instant germinated rice exposed to different drying temperatures. The correlation between effective moisture diffusivity and temperature is clearly demonstrated by the linear curve, which exhibits a clear Arrhenius dependency. The graph facilitated the determination of the activation energy (E_a) as 31.70 kJ/mol.

3.2 Polyphenol thermal degradation the model during drying process

Polyphenol content of instant VD20 rice also changed during the drying process at different temperatures. At the initial stage, at four levels of drying temperature, the TPC reduced as the same trend at the first 2 hours. However, then it remarkable reduced at the low temperature used. The oxidation process might be the main factor that degrades the phenolic compounds in instant germinated rice. Long drying time with mid-heat could activate some enzymes, which resulted in a reduction in antioxidant compounds. Moreover, the browning reaction as well as the formation of some new compounds, which also might be the reason for reducing TPC in the sample (Dias *et al.*, 2020; Rodríguez-Arzuaga *et al.*, 2019).

Three types of models, including the zero-order model, first-order model and second-order model, to describe the degradation of polyphenol during the drying process, were applied to find the model constant and best fit model. The results were shown in Table 2. Among the three models, the zero-order model presented the goodness of fit to describe the change of TPC during the drying process. The coefficient of determination (R^2) of this model at different temperatures from 50 to 65°C, were 0.9843, 0.9883, 0.9925, 0.9833, respectively. The value of haft-life of TPC's degradation at different temperatures reached a value of 3.737 h, 4.236 h, 5.595 h, and 5.723 h for 50°C, 55°C, 60°C, and 65°C, respectively. It was confirmed by the previous results, that low temperatures could promote the reduction of the content of biological compounds. Elevated temperatures can enhance the solubility of phenolic compounds, resulting in the disintegration of cellular structures and facilitating the release of phenolic compounds that were previously attached to the macromolecules of the cell wall (Multari *et al.*, 2018). The literature has minimal information regarding the impact of hot drying on the phenolic content of cereals and pseudocereals. However, a same pattern can be observed by analyzing experiments conducted on various matrices. According to Jing *et al.* (2010), the amount of phenolic compounds in sweet potatoes increased thrice when they were dried at a temperature of 65°C. It is acknowledged that elevated temperatures often enhance the solubility of phenolic compounds. This is because the heat causes the disintegration of cellular structures, which in turn promotes the liberation of phenolics that are attached to the macromolecules of the cell wall (Guido & Moreira, 2017). However, the application of hot air at temperatures equal to or more than 40°C can result in the degradation or reduction of free phenolic compounds, as stated by Rodríguez *et al.* in 2016. The activation energy for degradation of polyphenol was also achieved at a value of 46.04 kJ/mol. The obtained result was higher than that of dried pomegranate aril by using vacuum drying (Karaaslan *et al.*, 2014). While it is also lower when compared to the drying process of apple peel by using drum-drying (Henríquez *et al*., 2014).

Table 2. Mathematical model development for drying process of instant germinated rice.

Model	Temperature (ºC)	Model constant	R^2	$t_{1/2}$ (hour)
Zero-order model	50	4.3212	0.9843	3.737
	55	3.8124	0.9883	4.236
	60	2.8866	0.9925	5.595
	65	2.8220	0.9833	5.723
First-order model	50	0.1924	0.9759	3.603
	55	0.1607	0.9831	4.313
	60	0.1100	0.9933	6.301
	65	0.1075	0.9794	6.448
Second-order model	50	0.0093	0.9546	3.329
	55	0.0071	0.9690	4.361
	60	0.0043	0.9901	7.200
	65	0.0042	0.9725	7.371

3.3 ANN development for predicting the change of moisture ratio and polyphenol content of instant germinated VD20 rice

The ANN model was utilized to forecast the moisture ratio and degradation of polyphenol under various drying circumstances. The model incorporated two input factors, namely temperature and time, and two output parameters, namely moisture ratio and TPC. Figure 4 presents the statistical outcomes of the test, validation, and training. The correlation coefficient (r) between the training and testing models exhibits an increase, as depicted in the table. This indicates that incorporating a greater number of hidden layers could potentially enhance the model's ability to accurately represent the data. The study conducted by Selvi *et al*. (2022) revealed a correlation between the presence of neurons in the innermost layers of participants' bodies and the likelihood of network formation. Consequently, the occurrence of underfitting was due to a smaller number of neurons, whereas the occurrence of overfitting was due to an excessive number of neurons, resulting in an excessive degree of fitting (Loan *et al*., 2023). In order to determine the most precise method of multi-layer modeling using neural networks, the training datasets were utilized to identify the optimal configuration of neuronal and hidden layer quantities. The ANN model with ten hidden layers was chosen to be the ideal structure for instant germinated rice kinetic modeling, as it achieved the lowest MSE and maximum R^2. The structure matrix of weight and bias of input and output layer as shown in Equations 4-7.

$$b_1 = \begin{bmatrix} -4.1023 \\ 3.0905 \\ 2.0445 \\ -0.6498 \\ -0.0205 \\ 1.3363 \\ -1.8815 \\ 2.2904 \\ -2.1778 \\ -4.9173 \end{bmatrix} \tag{4}$$

$$w_1 = \begin{bmatrix} 1.7294 & 4.2005 \\ -1.5486 & 3.2238 \\ -3.2473 & -4.2251 \\ 1.6126 & -4.3321 \\ -3.9482 & 0.9984 \\ 4.2778 & 3.0415 \\ -0.8995 & -4.4034 \\ 3.5284 & -3.6522 \\ -1.1287 & 5.4397 \\ -4.2076 & 0.7908 \end{bmatrix} \tag{5}$$

$$b_2 = \begin{bmatrix} -0.4781 \\ -0.3292 \end{bmatrix} \tag{6}$$

$$w_2 = \begin{bmatrix} -0.8698 & 0.8830 & -0.0213 & -0.0571 & 0.0114 & 0.1702 & 0.8569 & -0.5255 & -0.2239 & 1.1762 \\ -0.5393 & 0.64352 & -0.0955 & -0.1012 & 0.2844 & -0.1186 & 0.4316 & 0.0372 & 0.3412 & 0.1089 \end{bmatrix} \tag{7}$$

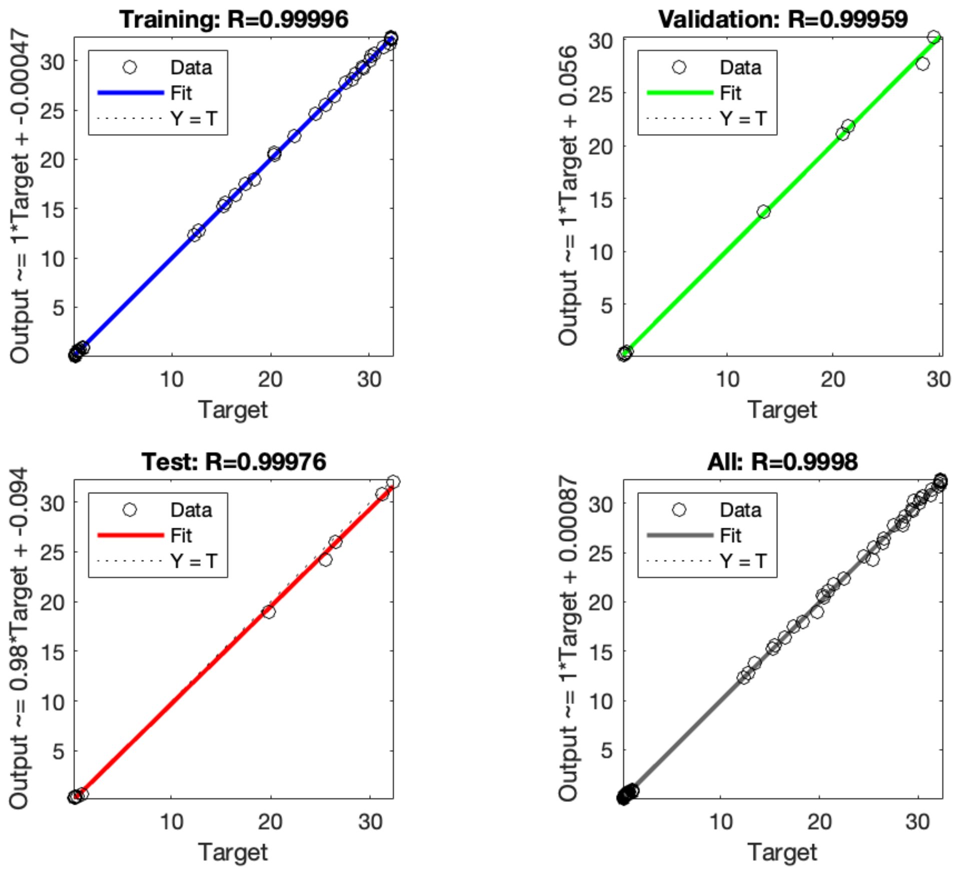

Figure 4. ANN performace to predict the change of moisture ratio and total phenolic content.

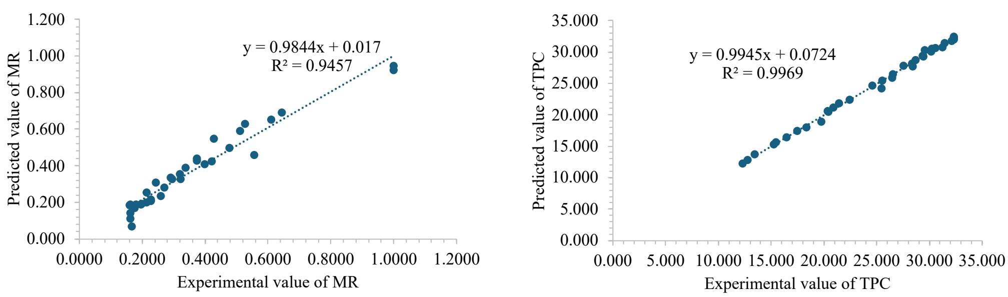

Figure 5. Experimental value verus predicted value by ANN model.

The best fit of ANN model also shown by the goodness of fit between predicted values and experimental values. As shown in Figure 5, the coefficient determination value reached at value above 0.94, which present the high accuracy of model.

3.4 Rehydration model of instant rice samples after drying at various temperatures

Rehydration is an important quality index for dried products. The rehydration ratio of instant rice samples were about 3 times. Figure 6 displays the moisture content uptake data of quick germinated rice during rehydration, plotted against the rehydration time. From the figure, it is evident that drying the sample at a higher temperature leads to an increase in the moisture content uptake of dried quince. Furthermore, nearly all curves exhibited the characteristic rehydration pattern, wherein the first stage of the process demonstrated a rapid uptake of water followed by a gradual drop in absorption rate until reaching a state of equilibrium moisture. The swift initial absorption of water was probably caused by the saturation of capillaries on the sample's surface. As the process of water absorption continues, the rate at which the water is being soaked

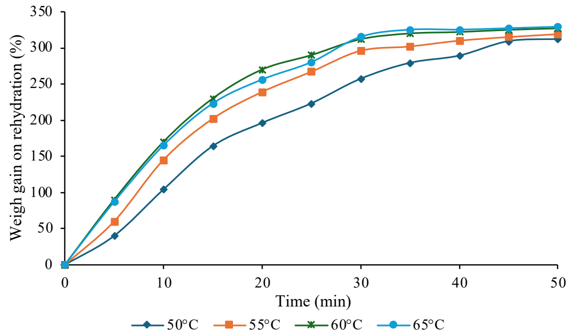

Figure 6. Rehydration curve of different instant germinated rice samples.

starts to decrease because the free capillaries and gaps between cells are becoming filled with water (Yadav *et al.*, 2024). While the sample exhibited microchannels that could potentially facilitate water diffusion throughout the rehydration process, the water diffusivity of the samples dried at low temperatures reduced. The decrease can be attributed to the adhesive nature of the grain's structure. The prolonged drying process during gelatinization results in the infiltration of certain compounds into the microchannel, causing saturation and a reduction in pore size (Rewthong *et al.*, 2011). This leads to additional resistance for water diffusion during rehydration, resulting in a significant decrease in the rate of moisture absorption. The structural qualities of the samples affect their ability to rehydrate. A higher rehydration ratio indicates that the sample absorbed moisture through its capillaries, which is closely related to the porosity and cavities in its microstructure.

Peleg model and Exponential, and Exponential related model were used to determine moisture uptake kinetics. Linear regression was employed to determine all the model's parameters as shown in Table 3. Among three models, exponential model showed the best fit with R^2 higher than 99%.

Table 4. Rehydration model constant by different equation.

Model	Temperature (°C)	Model constant	R^2	MSE
Peleg WG = [t/(b+dt)]	50	b = 0.1184; d = 0.1664	99.15	0.01122
	55	b = 0.0750; d = 0.2088	98.52	0.02010
	60	b = 0.0553; d = 0.2248	98.72	0.01733
	65	b = 0.0607; d = 0.2160	98.90	0.01519
Exponential WG = a-[a.exp(-bt)]	50	a = 3.9306; b = 2.0260	99.36	0.00839
	55	a = 3.4825; b = 3.3602	99.21	0.01071
	60	a = 3.4338; b = 4.3295	99.61	0.00531
	65	a = 3.5104; b = 3.9321	99.58	0.00583
Exponential Related Equation WG = a[1-exp(-at))	50	a = 3.1810	97.36	0.03132
	55	a = 3.4490	99.20	0.00977
	60	a = 3.6329	99.02	0.01192
	65	a = 3.6125	99.44	0.00684

Conclusion

The drying temperatures had an impact on the dehydration, polyphenol degradation, and rehydration kinetics of instant rice. Empirical models with broad applicability were suggested to characterize the kinetics of dehydration, degradation of polyphenols, and rehydration. The dehydration, polyphenol degradation, and rehydration rate constant all exhibited a linear rise in response to air temperature. The constructed models accurately predicted the processes of dehydration, polyphenol degradation, and rehydration. Furthermore, the ANN model demonstrated superior and expedited prediction of dehydration characteristics and TPC fluctuations throughout the drying process. The rise in temperature expedited the process of dehydration kinetics and the breakdown of polyphenol. Based on this knowledge, one might further analyze and improve the optimization of quality changes within the spectrum of experimental settings that were evaluated.

References

Ait Hmazi, F., Bagar, H., Madani, A., & Mrani, I. (2024). A novel approach for modelling and predicting the drying kinetics of couscous grains using artificial neural networks. *Journal of Food Composition and Analysis*, *132*, 106301. https://doi.org/10.1016/j.jfca.2024.106301

Cai, J., Yang, Y., Cai, W., & Bridgwater, T. (2017). Drying Kinetic Analysis of Municipal Solid Waste Using Modified Page Model and Pattern Search Method. *Waste and Biomass*

Valorization, *8*(2), 301-312. https://doi.org/10.1007/s12649-016-9570-9

Chasiotis, V. K., Tzempelikos, D. A., Filios, A. E., & Moustris, K. P. (2020). Artificial neural network modelling of moisture content evolution for convective drying of cylindrical quince slices. *Computers and Electronics in Agriculture*, *172*, 105074. https://doi.org/10.1016/j.compag.2019.105074

de Lima, A. G. B., Queiroz, M. R., & Nebra, S. A. (2002). Simultaneous moisture transport and shrinkage during drying of solids with ellipsoidal configuration. *Chemical Engineering Journal*, *86*(1), 85-93. https://doi.org/10.1016/S1385-8947(01)00276-5

Demiray, E., & Tulek, Y. (2017). Effect of temperature on water diffusion during rehydration of sun-dried red pepper (Capsicum annuum L.). *Heat and Mass Transfer*, *53*, 1829-1834. https://doi.org/10.1007/s00231-016-1940-0

Dias, C., Fonseca, A. M., Amaro, A. L., Vilas-Boas, A. A., Oliveira, A., Santos, S. A., Silvestre, A. J., Rocha, S. M., Isidoro, N., & Pintado, M. (2020). Natural-based antioxidant extracts as potential mitigators of fruit browning. *Antioxidants*, *9*(8), 715. https://doi.org/10.3390/antiox9080715

Espinosa-Solares, T., & Domínguez-Puerto, R. (2023). Influence of power density and geometry of young cactus cladodes (Opuntia ficus-indica (L.) Mill.) on intermittent microwave drying kinetics. *Revista Mexicana de Ingeniería Química*, *22*(1), Alim2965. https://doi.org/10.24275/rmiq/Alim2965

Finocchiaro, F., Ferrari, B., Gianinetti, A., Dall'Asta, C., Galaverna, G., Scazzina, F., & Pellegrini, N. (2007). Characterization of antioxidant compounds of red and white rice and changes in total antioxidant capacity during processing. *Molecular nutrition & food research*, *51*(8), 1006-1019.

Guido, L. F., & Moreira, M. M. (2017). Techniques for extraction of brewer's spent grain polyphenols: A review. *Food and Bioprocess Technology*, *10*, 1192-1209. https://doi.org/10.1007/s11947-017-1913-4

Gutiérrez-Martínez, S., Hernández-Varela, J., Chanona-Pérez, J., Méndez-Méndez, J., González-Martínez, H., Perea-Flores, M. d. J., Mendoza-Vázquez, S., & González-Victoriano, L. (2024). Study of drying, thermal, shrinkage, and color kinetics using digital and thermographic imaging of potato slices under real-time convective drying. *Revista Mexicana de Ingeniería Química*, *23*(3), Alim24322. https://doi.org/10.24275/rmiq/Alim24322

Henríquez, C., Córdova, A., Almonacid, S., & Saavedra, J. (2014). Kinetic modeling of phenolic compound degradation during drum-drying of apple peel by-products. *Journal of Food Engineering*, *143*, 146-153. https://doi.org/10.1016/j.jfoodeng.2014.06.037

Jebri, M., Tarrazó, J., Bon, J., Desmorieux, H., & Romdhane, M. (2018). Intensification of the convective drying process of Salvia officinalis: Modeling and optimization. *Food Science and Technology International*, *24*(5), 382-393. https://doi.org/10.1177/1082013218759363

Jing, Y., CHEN, J.-f., ZHAO, Y.-y., & MAO, L.-c. (2010). Effects of drying processes on the antioxidant properties in sweet potatoes. *Agricultural Sciences in China*, *9*(10), 1522-1529. https://doi.org/10.1016/S1671-2927(09)60246-7

Karaaslan, M., Yilmaz, F. M., Cesur, Ö., Vardin, H., Ikinci, A., & Dalgiç, A. C. (2014). Drying kinetics and thermal degradation of phenolic compounds and anthocyanins in pomegranate arils dried under vacuum conditions. *International Journal of Food Science & Technology*, *49*(2), 595-605. https://doi.org/10.1111/ijfs.12342

Kaveh, M., Çetin, N., Khalife, E., Abbaspour-Gilandeh, Y., Sabouri, M., & Sharifian, F. (2023). Machine learning approaches for estimating apricot drying characteristics in various advanced and conventional dryers. *Journal of Food Process Engineering*, *46*(12), e14475. https://doi.org/10.1111/jfpe.14475

Khan, M. I. H., Sablani, S. S., Joardder, M. U. H., & Karim, M. A. (2022). Application of machine learning-based approach in food drying: opportunities and challenges. *Drying Technology*, *40*(6), 1051-1067. https://doi.org/10.1080/07373937.2020.1853152

Krokida, M., & Philippopoulos, C. (2005). Rehydration of dehydrated foods. *Drying Technology*, *23*(4), 799-830. https://doi.org/10.1081/DRT-200054201

Krokida, M. K., & Maroulis, Z. B. (2001). Structural properties of dehydrated products during rehydration. *International Journal of Food Science & Technology*, *36*(5), 529-538. https://doi.org/10.1046/j.1365-2621.2001.00483.x

Li, C., Dhital, S., Gilbert, R. G., & Gidley, M. J. (2020). High-amylose wheat starch: Structural basis for water absorption and pasting properties. *Carbohydrate polymers*, *245*, 116557. https://doi.org/10.1016/j.carbpol.2020.116557

Loan, L. T. K., Tat, T. Q., Minh, P. D. T., Thao, V. T. T., Hoang, P. T. M., Nhi, T. T. Y., Giang, B. L., Phat, D. T., & Tai, N. V. (2024). Prediction of the Germination Rate and Antioxidant Properties of VD20 Rice by Utilizing Artificial Neural Network-Coupled Response Surface Methodology and Product Characterization. *Journal of Food Measurement and Characterization*. https://doi.org/10.1007/s11694-024-02835-w

Loan, L. T. K., Thuy, N. M., & Van Tai, N. (2023). Mathematical and artificial neural network modeling of hot air drying kinetics of instant "Câm" brown rice. *Food Science and Technology*, *43*, e27623. https://doi.org/10.5327/fst.27623

Martynenko, A., & Misra, N. N. (2020). Machine learning in drying. *Drying Technology*, *38*(5-6), 596-609. https://doi.org/10.1080/07373937.2019.1690502

Meng, L., Sun, X., Zhang, Y., & Tang, X. (2024). Effects of high temperature and high relative humidity drying on moisture distribution, starch microstructure and cooking characteristics of extruded whole buckwheat noodles. *Journal of Future Foods*, *4*(2), 159-166. https://doi.org/10.1016/j.jfutfo.2023.06.007

Multari, S., Marsol-Vall, A., Keskitalo, M., Yang, B., & Suomela, J.-P. (2018). Effects of different drying temperatures on the content of phenolic compounds and carotenoids in quinoa seeds (Chenopodium quinoa) from Finland. *Journal of Food Composition and Analysis*, *72*, 75-82. https://doi.org/10.1016/j.jfca.2018.06.008

Önal, B., Adiletta, G., Crescitelli, A., Di Matteo, M., & Russo, P. (2019). Optimization of hot air drying temperature combined with pre-treatment to improve physico-chemical and nutritional quality of 'Annurca' apple. *Food and Bioproducts Processing*, *115*, 87-99. https://doi.org/10.1016/j.fbp.2019.03.002

Pavkov, I., Radojčin, M., Stamenković, Z., Kešelj, K., Tylewicz, U., Sipos, P., Ponjičan, O., & Sedlar, A. (2021). Effects of osmotic dehydration on the hot air drying of apricot halves: Drying kinetics, mass transfer, and shrinkage. *Processes*, *9*(2), 202. https://doi.org/10.3390/pr9020202

Randriamiarintsoa, N., Ryser, E. T., & Marks, B. P. (2024). Effect of Air Temperature and Velocity on Listeria monocytogenes Inactivation During Drying of Apple Slices. *Journal of Food Protection*, *87*(4), 100253. https://doi.org/10.1016/j.jfp.2024.100253

Rasooli Sharabiani, V., Kaveh, M., Abdi, R., Szymanek, M., & Tanaś, W. (2021). Estimation of moisture ratio for apple drying by convective and microwave methods using artificial neural network modeling. *Scientific Reports*, *11*(1), 9155. https://doi.org/10.1038/s41598-021-88270-z

Rewthong, O., Soponronnarit, S., Taechapairoj, C., Tungtrakul, P., & Prachayawarakorn, S. (2011). Effects of cooking, drying and pretreatment methods on texture and starch digestibility of instant rice. *Journal of Food Engineering*, *103*(3), 258-264. https://doi.org/10.1016/j.jfoodeng.2010.10.022

Rodríguez-Arzuaga, M., Ríos, G., & Piagentini, A. M. (2019). Mild heat treatments before minimal processing reduce browning susceptibility and increase total phenolic content of low-chill apple cultivars. *Journal of Food Processing and Preservation*, *43*(11), e14209. https://doi.org/10.1111/jfpp.14209

Selvi, K. Ç., Alkhaled, A. Y., & Yildiz, T. (2022). Application of Artificial Neural Network for Predicting the Drying Kinetics and Chemical Attributes of Linden (Tilia platyphyllos Scop.) during the Infrared Drying Process. *Processes*, *10*(10), 2069. https://doi.org/10.3390/pr10102069

Sharma, S., Semwal, A. D., Srihari, S. P., Govind Raj, T., & Wadikar, D. (2024). Effect of salt pretreatments on physico-chemical, cooking and rehydration kinetics of instant rice. *Journal of Food Science and Technology*, *61*(4), 770-781. https://doi.org/10.1007/s13197-023-05877-y

Shen, S., Wang, Y., Li, M., Xu, F., Chai, L., & Bao, J. (2015). The effect of anaerobic treatment on polyphenols, antioxidant properties, tocols and free amino acids in white, red, and black germinated rice (Oryza sativa L.). *Journal of*

Functional Foods, *19*, 641-648. https://doi.org/10.1016/j.jff.2015.09.057

Simal, S., Femenia, A., Garau, M., & Rosselló, C. (2005). Use of exponential, Page's and diffusional models to simulate the drying kinetics of kiwi fruit. *Journal of Food Engineering*, *66*(3), 323-328. https://doi.org/10.1016/j.jfoodeng.2004.03.025

Vu, N. D., Tran, N. T. Y., Le, T. D., Phan, N. T. M., Doan, P. L. A., Huynh, L. B., & Dao, P. T. (2022). Kinetic Model of Moisture Loss and Polyphenol Degradation during Heat Pump Drying of Soursop Fruit (Annona muricata L.). *Processes*, *10*(10), 2082. https://doi.org/10.3390/pr10102082

Yadav, G. P., Kumar, D., Dalbhagat, C. G., & Mishra, H. N. (2024). A Comprehensive Review on Instant rice: Preparation Methodology, Characterization, and Quality Attributes. *Food Chemistry Advances*, *4*, 100581.

Yu, L., Turner, M., Fitzgerald, M., Stokes, J., & Witt, T. (2017). Review of the effects of different processing technologies on cooked and convenience rice quality. *Trends in food science & technology*, *59*, 124-138. https://doi.org/10.1016/j.tifs.2016.11.009