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MATHEMATICAL MODELLING OF THE SOLAR DRYING OF APRICOT

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Abstract: *Agricultural products provide significant growth in export earnings for many countries and provide food globally. Fruits and vegetables are perishable foods due to their high moisture content. Therefore, most agricultural products require post-harvest processing such as drying to extend the shelf life of fruits and vegetables and maintain nutrient quality. Solar drying is widely used for this purpose. Ambient temperature, humidity and solar radiation affect the drying time and quality of agricultural products, especially apricots, in solar dryers. The experiments were carried out in the same place (Tashkent, Uzbekistan) and in the same time interval. When the mass of apricots decreased from 424 g to 255 g, the water activity in the indirect forced solar drying (IFCSD) system simultaneously decreased from 0.93 to 0.62. The average solar radiation on the day of the experiment was recorded at 625 W/m*^{2}*. The constant values and coefficients of the empirical mathematical models corresponding to the experimental results obtained in this research work were calculated and analyzed. Mathematical models were evaluated by comparing correlation coefficients (*R^2*), reduced chi-square (*X^2*), and root mean square error (RMSE) coefficients. As a result, the Midilli and Kuchuk model was accepted as the closest to the experimental result, and the coefficients turned out to be* R^2*=0.987727,* X^2*=0.000935 and RMSE=0.025437.*

Key words: *Apricot, Solar drying, Solar radiation, Mathematical models, correlation coefficient (*R^2*), reduced chi-square (*X^2*), root mean square error (RMSE), Statistical analysis.*

Annotatsiya: *Qishloq xoʻjaligi mahsulotlari koʻplab mamlakatlar uchun eksport daromadlarini sezilarli darajada oshiradi va global miqyosda oziq-ovqat yetkazib beriladi. Meva va sabzavotlar namlik miqdori yuqori boʻlganligi sababli tez buziladigan oziq-ovqat mahsulotlari hisoblanadi. Shuning uchun, meva-sabzavotlarni saqlash muddatini uzaytirish va ozuqaviy moddalar sifatini saqlab qolish uchun koʻpchilik qishloq xoʻjaligi mahsulotlari quritish kabi hosildan keyin qayta ishlashni talab qiladi. Quyosh energiyasidan foydalangan holda quritish - bu maqsadda keng qoʻllaniladigan usuldir. Quyosh quritgichlarida qishloq xoʻjaligi mahsulotlarini, xususan, oʻrikni quritish vaqti va sifatiga atrof-muhit harorati, namligi va quyosh radiatsiyasi kabi omillar taʼsir qiladi. Tajribalar izchil joyda (Toshkent, Oʻzbekiston) va vaqt oraligʻida oʻtkazildi. Oʻrikning vazni 424 g dan 255 g gacha kamayganligi sababli, bilvosita majburiy quyosh quritish (IFCSD) tizimida suv faolligi bir vaqtning oʻzida 0,93 dan 0,62 gacha kamaygan. Tajriba kunidagi oʻrtacha quyosh nurlanishi 625 Vt/m*^{2} *da qayd etilgan. Ushbu tadqiqot ishida olingan tajriba natijalariga mos keladigan empirik matematik modellar oʻzgarmas qiymatlari va koeffitsentlari hisoblab chiqildi va tahlil qilindi. Matematik modellar korrelyatsiya koeffitsienti (*R^2*), qisqartirilgan chi-kvadrat (*X^2*) va oʻrtacha kvadrat xatolik (RMSE) koeffitsientlarini solishtirish orqali baholandi. Natijada, Midilli va Kucuk modeli tajriba natijasiga eng yaqin model sifatida olindi va koeffitsientlari* R^2*=0.987727,* X^2*=0.000935, va RMSE=0.025437 ekanligi aniqlandi.*

Tayanch soʻzlar: *oʻrik, quyoshda quritish, quyosh nurlanishi, matematik modellar, korrelyatsiya koeffitsienti (*R^2*), kichraytirilgan kvadrat xatolik (*X^2*), oʻrtacha kvadrat xatolik (RMSE), statistik tahlil.*

Аннотация: *Сельскохозяйственная продукция обеспечивает значительный рост экспортных поступлений для многих стран и обеспечивает продовольствием в глобальном масштабе. Фрукты и овощи относятся к скоропортящимся продуктам из-за высокого содержания влаги. Поэтому большинство сельскохозяйственных продуктов требуют послеуборочной обработки, такой как сушка, чтобы продлить срок хранения фруктов и овощей и сохранить качество питательных веществ. Для этой цели широко используется солнечная сушка. Температура окружающей среды, влажность и солнечная радиация влияют на время и качество сушки сельскохозяйственной продукции, особенно абрикосов, в солнечных сушилках. Эксперименты проводились в одном и том же месте (Ташкент, Узбекистан) и в одном и том же временном интервале. При уменьшении массы абрикосов с 424 г до 255 г активность воды в системе непрямой принудительной солнечной сушки (IFCSD) одновременно снизилась с 0,93 до 0,62. Средняя солнечная радиация в день эксперимента была зафиксирована на уровне 625 Вт/м2. Были рассчитаны и проанализированы постоянные значения и коэффициенты эмпирических математических* *моделей, соответствующие экспериментальным результатам, полученным в данной исследовательской работе. Математические модели оценивались путем сравнения коэффициентов корреляции (R^2), приведенного хи-квадрата (X^2) и коэффициентов среднеквадратической ошибки (RMSE). В результате модель Мидилли и Кучука была принята как наиболее близкая к экспериментальному результату, а коэффициенты оказались равными R^2=0,987727, X^2=0,000935 и RMSE=0,025437.*

Ключевые слова: *абрикос, солнечная сушка, солнечная радиация, математические модели, коэффициент корреляции (R^2), приведенный хи-квадрат (X^2), среднеквадратическая ошибка (RMSE), статистический анализ.*

Introduction

Food is a fundamental necessity for all humans. With the growing population, ensuring a stable food supply and minimizing losses in food processing and distribution is becoming increasingly important. Improper processing methods and inadequate storage conditions negatively impact the quantity and quality of produced food products. Consequently, many developing countries face significant losses in the food sector. Approximately 30-40% of fruits and vegetables are lost post-harvest [1]. To reduce these losses and preserve the quality of fruits, vegetables, and other food products, drying methods are utilized [2].

During the drying process, the moisture content of the product is removed, thereby halting biochemical reactions and the development of microorganisms. This allows agricultural products to be preserved for extended periods without compromising their nutritional value. Additionally, by reducing the moisture content, drying not only extends the shelf life of the product but also leads to a reduction in transportation and storage costs [3].

In the food industry, drying is primarily used to preserve the nutritional integrity of fruits and vegetables over time. The efficiency of the drying process is evaluated based on the color, taste, and retention of the nutritional content of the dried product [4]. Additionally, the product's ability to regain moisture when exposed to a humid environment, known as rehydration capacity, is also of significant importance [5].

Fruits and vegetables, and products derived from them in Uzbekistan, stand out for their taste, high quality, and richness in vitamins essential and beneficial to the human body. Among the stone fruits grown in Uzbekistan, apricots hold a leading position. Apricot trees grow in many regions of the world, including Northern India, Iran, Turkey, Italy, Spain, North and South Africa, North America, Australia, as well as Central Asia, the Caucasus, and the southern European parts of Russia. Uzbekistan's climate is very favorable for apricot cultivation. In Uzbekistan, high-yield varieties such as Akhroriy, Subhoniy, Gulungi Luchchak, Mirsanjali, Koʻrsodiq, Khurmoiy, Isfarak, Navoi, Javpazak, White Apricot, Shalakh, Ruhi Juvonon, Mohtobi, and others are mainly grown in the Fergana, Namangan, and Andijan regions [6].

Apricots are mainly grown for fresh consumption, drying, and canning. This fruit has the property of accelerating the digestion process and quickly removing excess water from the body. Dried apricots are very rich in minerals and vitamins, and their content of iron, carotene, phosphorus, magnesium, and vitamin B5 is very beneficial for cardiovascular and kidney-related diseases. If dried apricot juice is given to children, it strengthens the immune system and prevents constipation [7].

Using solar energy to dry agricultural products, such as apricots, is one of the advanced directions in modern technology. Solar energy is recognized as a crucial solution for the drying process due to its widespread availability, stability, and economic efficiency [8].

There are two main types of solar dryers suitable for agricultural applications. These are natural convection solar dryers, which are controlled by thermal gradients, and forced convection dryers, which use an air solar collector to move air. This study focuses on a natural convection solar dryer, where the air is heated using a flat-plate solar collector instead of traditional methods. The heated air is then directed to the drying chamber, where it removes moisture from the product [9, 10].

Many researchers have studied the drying of fruits and vegetables using solar energy. Timoumi et al. (2004) investigated the thermal properties of solar energy in drying, while Vijaya Venkata Raman et al. (2012) focused on the latest technologies for drying in solar radiation [11]. Belessiotis and

Delyannis (2011) discussed the advantages and disadvantages of various solar dryers [12]. Mengesh (2001) analyzed drying times for apricots and cherries at different air temperatures and velocities. To‘g‘rul and Pehlivanlar (2002) examined apricot drying in solar dryers, including the analysis of drying parameters and mathematical models [13]. Other studies have evaluated and examined the effects of temperature, humidity, and drying kinetics on various fruits and vegetables such as figs, onions, tomatoes, mangoes, and others in solar dryers.

The efficiency of solar drying systems depends on the climatic conditions of a specific geographical location. The dry climate and high-altitude geographic setting in Uzbekistan create ideal conditions for utilizing solar energy for drying. Although drying fruits, including apricots, in solar dryers has been studied extensively, the effects of process parameters such as temperature, air humidity, airflow velocity, and empirical model parameters, especially the product's water activity, have not been thoroughly investigated. According to our data, these aspects are still underexplored in scientific literature. Additionally, existing experimental data are often obtained under conditions that are not specific to dry climates and high-altitude geographical settings.

This study focuses on investigating apricots under natural convection solar dryers at temperatures ranging from 33°C to 60°C, relative humidity levels from 18% to 35%, and air velocities from 0.6 to 1.1 m/s. The research is specific to geographic locations with elevations between 380 meters and 515 meters above sea level. The impact of process parameters on the effective diffusion coefficients and kinetic parameters of various empirical models was examined. Changes in the water activity of the dried product were observed to determine the optimal drying time for each condition.

Materials and Methods

In this study, fresh apricots (Subhoniy variety) were purchased during the harvest season from the Chorsu market in Tashkent, Uzbekistan. The apricots were thoroughly washed with cold water and then sorted by size and weight, selecting 0.5 *kg* batches. The average diameter of an apricot was approximately 60 *mm*, and the weight ranged from 35 to 45 grams. The initial moisture content of the apricots selected for drying was measured at 85%. The apricots were then halved and pitted. The prepared apricots were placed on mesh-bottom trays measuring 50 × 80 *cm* and positioned inside the drying chamber. During the drying process, the weight of the apricots was measured every hour using precise scales. The experiments continued until the moisture content of the apricots decreased to less than 20%. *Figure 1* shows a schematic view of the solar dryer used in the experiment.

Figure 1 shows a schematic representation of a forced convection solar dryer powered by renewable solar energy. This forced convection solar dryer consists of a drying chamber, a solar collector, and centrifugal air blowers. The drying chamber measures 1000 × 950 × 500 mm and includes four trays with wire mesh bottoms, each capable of holding 2000 g of apricots. The solar collector measures 1900 × 950 × 200 mm, providing an area of 1.71 m^2, and its interior is coated with black paint to absorb all solar radiation. A centrifugal air blower is installed at the inlet of the solar collector to increase the airflow speed. The centrifugal air blower initially forces external air at ambient temperature into the lower part of the solar air heater. The heated air then enters the drying chamber from the upper part of the solar collector. The hot air removes moisture from the drying product and exits through the top of the drying chamber.

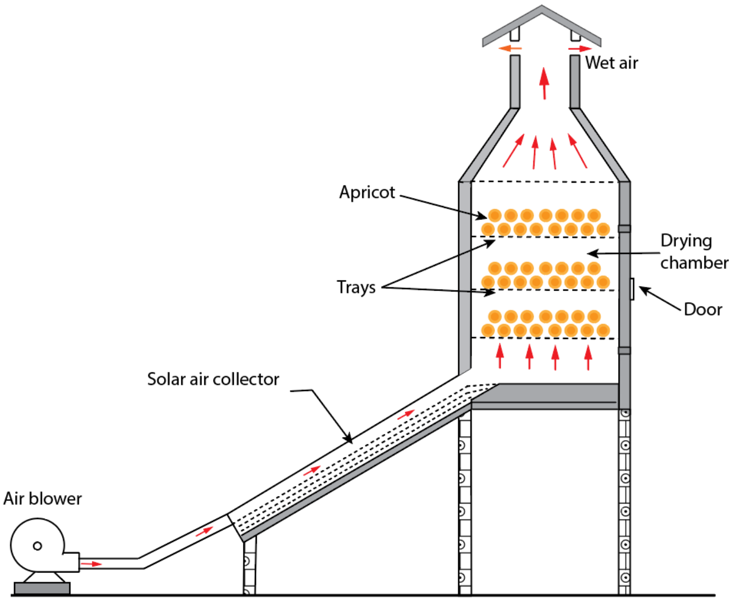

Fig. 1. ***Schematic view of the IFCSD system.***

Mathematical modeling

To date, researchers have proposed mathematical models for drying [14]. The mathematical models for the drying process of apricot products used in this study are provided in table 1.

Table 1.

Mathematical Models of the Drying Process Under Consideration.

Model	Model name
$NN = exp\ (-at)$	Newton [15]
$NN = exp\ (-at^n)$	Page [16]
$NN = exp\ [-(at)]^n$	Modified Page[16]
$NN = b \cdot exp(-at) + g$	Logarithmic [17]
$NN = b \cdot exp\ (-at)$	Henderson and Pabis [18]
$NN = b \cdot exp(-a_0 t) + c \cdot exp(-a_1 t)$	Tow-term [19]
$NN = b \cdot exp(-at) + (1-b) \cdot exp\ (-abt)$	Two term exponentials [14]
$NN = b \cdot exp(-at)^n + c \cdot t$	Midelli at al [18]
$NN = b \cdot exp(-at) + (1-b) \cdot exp\ (-act)$	Approximation of diffusion [20]
$NN = b \cdot exp(-at) + (1-b) \cdot exp\ (-dt)$	Verma et al [15]
$NN = b \cdot \exp\ (-at^n) + c \cdot t$	Midilli and Kucuk [21]

In the aforementioned mathematical models, the moisture ratio (***NN***), drying time (*t*), drying rate constant (*a*), and model coefficients *b*, *c*, *g*, *d*, and n are defined. *Formula 1* is used to calculate ***NN*** during the drying process of apricots. *Formulas 2* and *3* are applied to determine the initial and final moisture content of the dried product [17].

$$NN = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

$$M_0 = \frac{m_i - m_d}{m_d} \tag{2}$$

$$M_f = \frac{m_w - m_d}{m_d} \tag{3}$$

In these formulas: M_b – initial moisture content of the product; M_o – final moisture content of the product; M_t – transient moisture content of the product; M_e – equilibrium moisture content of the product; m_i – total mass (*kg*); m_d – dry mass (*kg*); m_w – mass of water (*kg*).

In identifying the most suitable mathematical models for drying apricots using a solar dryer, three key parameters were considered: the coefficient of correlation (R^2), chi-square (χ^2), and root mean square error (*RMSE*). The R^2 value from *Formula 4* is used to determine the fit between experimental and calculated values. Formula 5 is used to assess the difference between experimental and calculated value models; the smaller the χ^2 value, the better the model fits. The average difference between experimental and calculated value models is determined using *Formula 6* (*RMSE*), which indicates the model's accuracy. The model with the smallest χ^2 and *RMSE* values, and the largest R^2 value, is selected as the best-fitting model.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(NN_{pre,i} - NN_{exp,i})^2}{\sum_{i=1}^{n}(NN_{exp,i} - NN_{exp,ave})^2} \quad (4)$$

$$X^2 = \frac{\sum_{i=1}^{n}(NN_{pre,i} - NN_{exp,i})^2}{K-q} \quad (5)$$

$$RMSE = \sqrt{\frac{1}{K}\sum_{i=1}^{n}(NN_{pre,i} - NN_{exp,i})} \quad (6)$$

In these formulas, $NNexp,i$ represents the normalized moisture ratio observed in the ith experiment, and $NNpre,i$ is the predicted value for that same observation. Moreover, $NNexp,av$ is the average normalized moisture ratio across all experimental data points, K denotes the total number of observations, and q refers to the number of constants in the model.

Results and Discussion

During the days when the experiment was conducted in Tashkent, the solar radiation intensity ranged from 398 to 886 W/m², and the temperature varied from 25.4°C to 39.1°C. The air temperature exiting the solar collector increased from 33°C to 60°C. The heating efficiency of the collector, compared to the ambient temperature, reached a maximum of 88%. The global solar radiation showed lower intensity at the beginning of the day, peaked around midday, and then gradually decreased, as depicted in Figure 2. Based on the measurements, the recorded maximum solar radiation was 862.3 W/m² on the first day, 885.8 W/m² on the second day, and 820.5 W/m² on the third day.

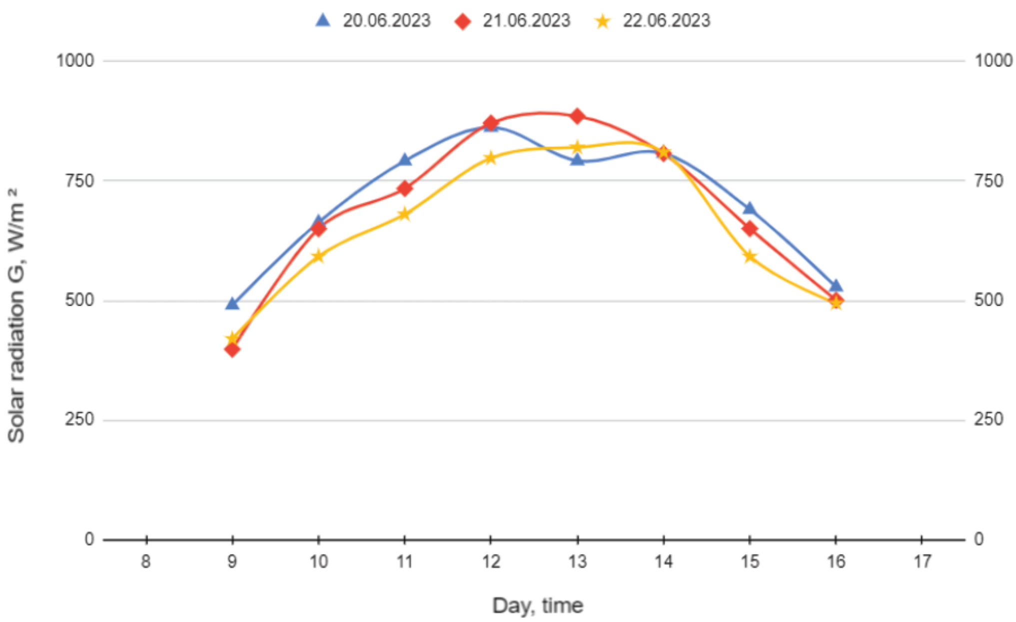

Fig. 2. ***Variation of solar radiation for the time of day.***

In Figure 3, fluctuations in humidity over time are depicted. Initially, there is a gradual alteration in humidity for nearly an hour, followed by a sharp decline. Towards the end of the drying process, the indicator remains relatively stable. It took approximately 24 hours to decrease the initial moisture content of the apricots from 85% to 19%. The timeframe between 10:00 and 16:00 on a given day proves to be optimal for conducting experiments.

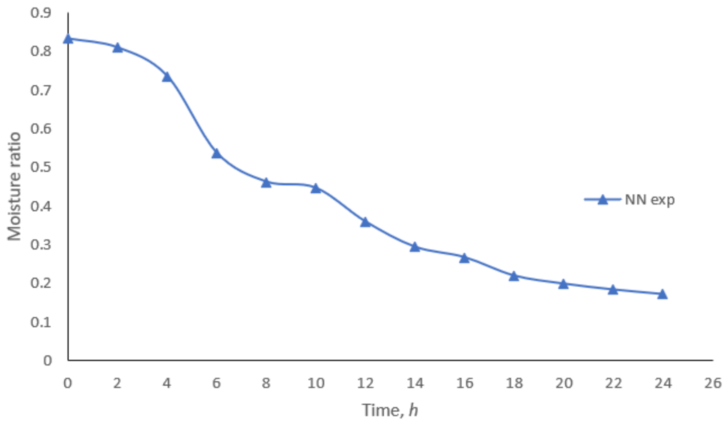

Fig. 3. ***Changes in apricot moisture over time.***

Mathematical model selection

The experimental results obtained are compared with the drying models mentioned above in *Figure 3*. The analysis results are shown in Figure 4 with the most suitable mathematical models. Based on the observations in *Figure 4*, it is clear that drying in the solar drying system occurs under stable conditions, and the variations in experimental data are well represented by the drying models. The experimental data ($NN_{exp\ curve}$) closely matches the calculated theoretical data ($NN_{pre\ curve}$).

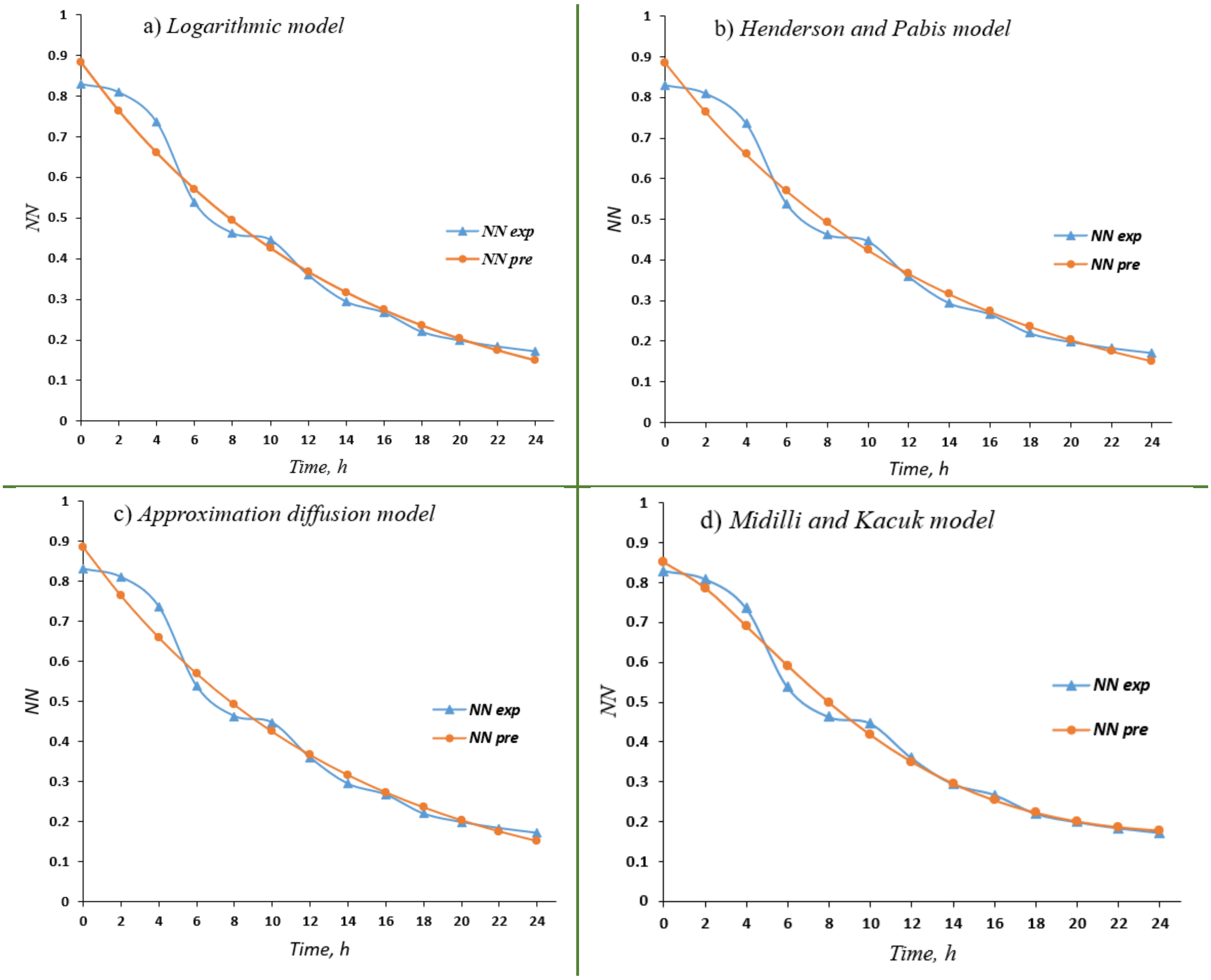

Fig. 4. ***Graphs comparing the experimental and calculated NN with drying time for the Logarithmic, Henderson and Pabis, Approximate diffusion, and Midilli and Kucuk models are shown.***

A statistical analysis was conducted to identify the most suitable drying model for apricots in solar drying systems. Using formulas *4*, *5*, and *6*, the R^2, X^2, and *RMSE* values were calculated to select the appropriate drying model. The constant values (*a*, *n*, *b*, *c*, *g*, *d*) for the drying mathematical models and the three key statistical parameters (R^2, X^2, *RMSE*) were computed in *Excel Solver* based on experimental data. The calculated values of these statistical parameters are presented in *Table 2*.

Table 2.

Coefficients and Statistical Results of Drying Mathematical Models.

№	Model constants	R^2	X^2	*RMSE*
1	*a=0.84996*	*0.999993*	*0.003247*	*0.054743*
2	*a=0.111001, n=0.892552*	*0.947638*	*0.003262*	*0.05254*
3	*a=0.102812, n=0.826708*	*0.941678*	*0.003634*	*0.055449*
4	*a=0.071691, b=0.895283, g=-0.01090*	*0.978647*	*0.001463*	*0.033551*
5	*a=0.073495, b=0.886173*	*0.978611*	*0.001333*	*0.033579*
6	a_0*=0.073495, b=0.886095, c=7.83E-5,* a_1*=0.073382*	*0.978611*	*0.001629*	*0.033579*
7	*a=0.062219, b=0.593501*	*0.977576*	*0.001397*	*0.034383*
8	*a=0.258907, b=0.885617, n=0.282444, c=-8.8E-05*	*0.978614*	*0.001628*	*0.033577*
9	*a=0.073491, b=0.585426, c=0.000162*	*0.978611*	*0.001466*	*0.033579*
10	*a=0.073485, b=0.585426, d=2.4355E-05*	*0.978611*	*0.001466*	*0.033579*
11	*a=0.035451, b=0.850636, n=1.378115, c=0.005304*	*0.987727*	*0.000935*	*0.025437*

All the obtained statistical coefficients are dimensionless, indicating that all drying models effectively represent the experimental data in the drying system with minimal discrepancies. Moreover, the Logarithmic, Henderson and Pabis, Approximation of Diffusion, and Midilli and Kacuk models consistently provided the highest performance among the drying models.

Conclusions

This study investigated the process of drying apricots using a forced solar drying system through experimental and mathematical analyses. During the research, it was found that changes in air temperature, humidity, and air flow rate significantly affect the duration of the drying process and the quality of the dried product. In regions with an arid climate, such as Uzbekistan, issues related to product rehydration are less common, but in areas with higher humidity levels, increased water activity in dried products can lead to microbial growth, posing risks for long-term storage. This study analyzed the statistical coefficients and R^2, X^2, and RMSE values of various empirical models. To determine the optimal drying time for each condition, changes in water activity in the dried product were monitored. In drying apricots, moisture ratio variations analyzed across all 11 models effectively described the experimental data under stable conditions. However, the Logarithmic, Henderson and Pabis, Approximate Diffusion, and Midilli and Kacuk models consistently demonstrated higher efficiency in the IFCSD system compared to the other models considered.

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