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Mathematical Modelling of Convective Hot Air Drying of Garlic Slices

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ABSTRACT

The present study investigates the mathematical modelling and drying kinetics of garlic slices using a laboratory dryer at five drying air temperature levels (45, 50, 55, 60, and 65°C). Comparison was made between untreated and pretreated samples, using a 0.5% w/w sodium metabisulfite ($Na_2O_5S_2$) solution for 10 min. A constant air flow rate of 0.708 m^3/s and slice thicknesses ranging from 2 to 3 mm were used. Ten different drying mathematical models were used to simulate and evaluate the drying data. The models were evaluated based on the coefficient of determination (R^2), standard error (SE), chi-square (χ^2), and root mean square error (RMSE). The results indicated that a three-term exponential model satisfactorily describes the garlic drying behavior at all drying air temperatures, for both treated and untreated garlic slices. The effective moisture diffusivities varied from 2.225×10^{-10} to 3.1187×10^{-10}, and from 2.0517×10^{-10} to 2.9545×10^{-10} for treated and untreated garlic slices, respectively, over the temperature range studied. The activation energy was calculated based on the Arrhenius equation and found to be 15.429 and 16.552 kJ/mol for treated and untreated garlic slices, respectively. Pretreatment with sodium metabisulfite showed a positive effect on the rehydration rate and color, indicating improved product quality.

Keywords: Garlic slices, Mathematical modelling, effective moisture diffusivity, activation energy, rehydration ratio, color parameters

INTRODUCTION

Garlic (*Allium sativum L.*) belongs to the Amaryllidaceae family and has been cultivated in various temperate regions worldwide (Shagun *et al.*, 2024). According to FAO (2023), the global garlic production exceeded 28 million tons in 2023, cultivated around 1.6 million hectares, with an average yield of 17 tons per hectare. According to Food Business Africa (2023), Egypt is among the leading garlic-producing countries in the Middle East and Africa. In 2021, garlic production reached 446,000 tons. In recent years, Egypt has increased its garlic exports, especially to the European Union.

Demiray and Tulek (2014) mentioned that garlic is commonly employed in food preparation and has also been traditionally used for its therapeutic properties. Garlic has been planted for centuries all over the world. Because of its culinary and therapeutic use. It is used as a culinary additive in a variety of food preparations, including salad dressings, beef sausages, stews, pasta, sauce, marinades, and tomato sauce. Zheng *et al.* (2023) stated that besides the use of garlic as a spice, it has many functions, such as regulating blood pressure, treating cardiovascular diseases, and improving immunity, and it has anti-tumor, antimicrobial, and anti-cancer properties.

The intrinsic moisture content of garlic is much more than 65% (w.b.), allowing it to quickly deteriorate due to microbial and enzymatic activities, leading to undesirable consequences such as rotting and germination (El-Mesery *et al.*, 2022). An investigation indicates that drying methods may significantly reduce the water content of food by approximately 90%, reducing spoilage, minimizing degradation reactions, and decreasing transportation costs (Allai *et al.*, 2023, and Shagun *et al.*, 2024).

Drying is one of the most important methods to preserve food products from spoilage, as the moisture content is reduced to a safe degree of microbial activity while maintaining a high quality of the dried product. It is considered a heat and mass transfer process in which heat is transferred to fresh products and subsequently removes moisture from the products (İlter *et al.*, 2018).

Hot-air drying is the most widely used drying method in the food industry; it is more efficient and costs less to operate. Additionally, this technique keeps garlic slices notably stable. However, hot-air drying requires a long time, and the end product's quality deteriorates due to the high temperature. To remediate these issues, garlic can be pretreated before drying to save energy consumption and get a high-quality product (Guo *et al.*, 2023).

Fruits and vegetables have protective layers that prevent moisture from being removed during drying, resulting in an increase in drying times and an overall reduction in product quality. Therefore, pretreatment methods before drying have been researched to handle this issue through enhancing permeability and quickening the rate of drying, resulting in the efficient deactivation of enzymes and the prevention of oxidation (Bassey *et al.*, 2021).

Chemical pretreatment before the drying process is considered an effective step for minimizing drying time, improving energy efficiency, and preserving product quality (Yu *et al.*, 2017). Pre-treatment with sodium metabisulfite is commonly carried out using either sulfur dioxide gas or soluble sulfite salts in water. Upon absorption into the material, sulfur dioxide (SO_2) is transformed into bisulfite ions. At low concentrations, sulfites effectively inhibit both enzymatic and non-enzymatic browning, as well as microbial growth (Deng *et al.*, 2019).

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Drying is a complex process in terms of the phenomena of simultaneous mass and heat transfer. Mathematical models are crucial for dryer design, energy integration, optimization, and control. Physical and thermal properties of agricultural products, such as heat and mass transfer coefficients, moisture diffusion, activation energy, and energy consumption, are required to study the drying process (Khanali *et al*., 2016).

Mathematical modeling or simulation of the drying process of agricultural products has a huge role in industrial drying. In modeling processes, physical features are transformed into numerical quantities and mathematical relationships. The mathematical model, consisting of variables and a set of equations illustrating the relationship between the variables, is used to analyze and predict the behavior of the system before changes occur to the system. It is also used to determine the best drying conditions to obtain a product with a high final quality (Abbaspour-Gilandeh *et al*., 2019 and Kaveh *et al*., 2020).

Demiray and Tulek (2014) investigated the drying kinetics of garlic slices in a cabinet-type convective dryer at a constant air velocity of 0.2 m/s and air temperatures ranging between 55 and 75 °C and a relative humidity of 20 %. They found that garlic was dried at a falling rate period, like most food products, with the absence of a constant drying rate period. The Page and Modified Page models, which gave higher correlation coefficients and lower reduced chi-square and RMSE, were considered the best for explaining the drying garlic slices. The moisture diffusivity of garlic samples ranged between (2.221 × 10^{-10} and 4.214 10^{-10} m^2/s within an air temperature range between 55 and 75°C. Activation energy was also found to be 30.582 kJ mol^1.

This study aims to

- Investigate the mathematical modeling of hot air-drying kinetics of treated and untreated garlic slices.
- Evaluate the effect of sodium metabisulfite pretreatment on the drying behavior of garlic slices.
- Estimate the effective moisture diffusivity and activation energy.
- Assess key quality parameters such as color and rehydration ratio of the dried garlic.

MATERIALS AND METHODS

Preparation of Garlic Samples:

Fresh garlic of good quality was procured from a local market in Dakahlia Governorate, Egypt. The garlic was stored in a refrigerator at a temperature of 4 ºC. Before drying, the white thin papery coverings were removed from the whole bulb and the cloves. The individual cloves were cut into slices of 2-3 mm using a cutting machine. The sliced garlic was divided into two groups. The first group was immersed in a solution comprised of sodium metabisulfite ($Na_2O_5S_2$) at a concentration of 0.5 % w/w for 10 min., at room temperature to prevent both enzymatic and non-enzymatic forms of browning, and the second was left without treatment.

The Experimental Methodology:

For laboratory experiments, a hybrid infrared and hot air thin-layer laboratory dryer was used (Figure 1). The dryer was designed and manufactured at the Food Processing Engineering Laboratory, Faculty of Agriculture, Mansoura University, Egypt. The dryer consists of a centrifugal fan to supply air to the dryer at a constant air flow rate throughout the experiments. The air then passes to the heating unit, which contains two electric spiral heaters, each with a capacity of 1.5 kW, to raise the air temperature from room temperature to the desired drying temperature. The air temperature is controlled by a thermostat located on the control panel to ensure a constant drying air temperature throughout the experiment. The heated air then passes to air distribution pipes made of PVC with a diameter of 76.2 mm and containing 10 mm diameter holes located at the bottom of the drying chamber (Figure 2), allowing the hot air to be evenly distributed under the sample trays. After the air passes over the samples to complete the drying and dehumidification process, the humid air is extracted by two fans installed at the top of the drying chamber. The drying chamber contains two sample trays made of galvanized steel mesh, each measuring 15 x 40 cm. A thin layer of fresh garlic slices weighing 50 g was distributed on each tray inside the drying chamber. One tray contains the pre-treated sample and the other contains the untreated sample. The electronic balance used to monitor the mass of drying samples had of 0.01g precision. The mass of the sample was measured at 5 min. intervals for the first hour, then at 10 minutes. intervals for the second hour and then at 20 min. intervals to the end of the experiment. The moisture contents of the samples during drying were calculated using the mass balance approach.

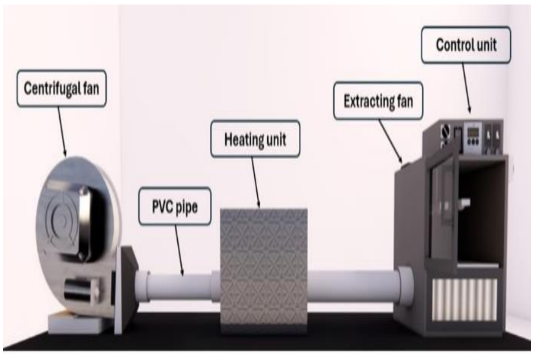

Figure 1. Schematic diagram of the laboratory dryer.

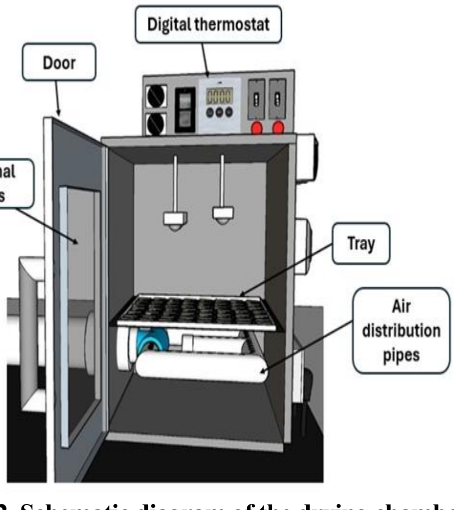

Figure 2. Schematic diagram of the drying chamber.

Moisture Content:

Moisture content of both fresh and dried garlic slices was determined using a hot air oven set at 70 °C for 16 hours, as recommended by AOAC (1990). The initial moisture content of the treated garlic slices was approximately 68.8% (wet basis), while that of the untreated slices was 66.45% (wet basis).

The drying process was operated under five different air temperature levels of (45, 50, 55, 60, 65 °C). A constant air flow rate of 0.708 m³/s and slice thicknesses ranging from 2 to 3 mm were used. Slices were dehydrated until they reached the equilibrium moisture content. To maintain the garlic slices quality, the dried slices were packaged in bags and stored at an ambient temperature until subject to analytical tests. Figure (3) shows the flowchart of the drying process.

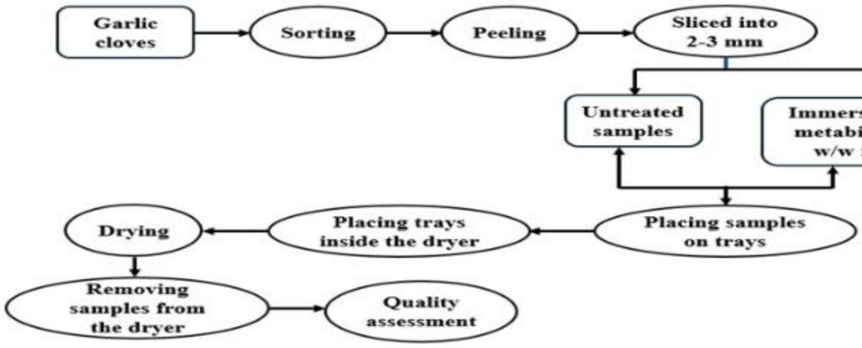

Figure 3. Flowchart of the drying process of garlic slices.

Moisture Ratio and Drying Rate:

The following equation was used to calculate the moisture ratio, MR:

$$MR = \frac{M_t - M_f}{M_0 - M_f} \qquad (1)$$

Where: M_t: moisture content at time t, %(d.b), M_0: initial moisture content, %(d.b), and M_f: final moisture content, %(d.b).

The drying rate (DR) was calculated as follows:

$$DR = \frac{M_1 - M_2}{t_2 - t_1} \qquad (2)$$

Where: M_1, M_2: moisture content, % (d.b) at time of t_1, t_2, min.

Modeling of the drying kinetics:

To study the drying behavior of garlic slices, it is important to model the drying behavior effectively. The experimental drying data were fitted to ten thin layer drying models as listed in Table (1).

Table 1. Thin layer drying mathematical models.

Model	Expression	Reference
Lewis model	$MR = \exp(-K_L t)$	Lewis, (1921)
Henderson and Pabis model	$MR = A_H \exp(-K_H t)$	Henderson and Pabis (1961)
Page model	$MR = \exp(-K_P t^n)$	Page (1949)
Modified page model	$MR = \exp(-K_{mP} t)^n$	Ozdemir and Devres, (1999)
Logarithmic model	$MR = a \exp(-K_{loa} t) + C$	Chandra and Singh, (1995)
Two-term model	$MR = a_T \exp(-K_T t) + b_T \exp(-K_{T1} t)$	Henderson (1974)
Exponential linear combination model	$MR = a_E + b_E \exp(-K_E t) + c_E t$	Elfar *et al*., (2022)
Diamante model	$ln(-ln\ MR) = a_D + b_D\ ln(t) + C_T (\ln(t))^2$	Diamente *et al*, (2010)
Wang and Singh model	$MR = 1 + a_W t + b_W t^2$	Wang & Singh (1978)
Three-term exponential model	$MR = a_{T2} \exp(-K_{T2} t) + b_{T2} \exp(-K_{T3} t) + C_{T2} \exp(-K_{T4} t)$	Karathanos. (1999)

Effective Moisture Diffusivity (D_{eff}):

Fick's second law of diffusion is utilized to describe moisture movement in biological materials, especially during the falling rate stage of drying, as represented mathematically in Equation (3). The analytical solution to Fick's second law for one-dimensional moisture diffusion in a slab geometry, as presented by Crank, (1975) is shown in Equation (4). This solution assumes that moisture transport occurs only by diffusion under constant temperature conditions, with a constant effective moisture diffusivity and negligible material shrinkage during the drying process.

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \qquad (3)$$

$$MR = \frac{M_t}{M_i} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} exp\left[-\frac{(2n-1)^2 \pi^2 D_{eff} t}{4L^2}\right] \qquad (4)$$

Where D_{eff} is the constant effective diffusivity m²/s and L: half of garlic slice thickness, (mm)

Equation (4) can be simplified to

$$MR = \frac{8}{\pi^2} exp\left[-\frac{\pi^2 D_{eff} t}{4L^2}\right] \qquad (5)$$

It can be written in logarithmic form as shown in Equation (6)

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \qquad (6)$$

Plotting Ln (MR) versus time (t), min, the slope (K_0) can be obtained as in Equation (7):

$$K_0 = \frac{\pi^2 D_{eff}}{4L^2} \qquad (7)$$

Determination of The Activation Energy (E_a)

The basis of activation energy (E_a, kJ/mol) determination can be formed in the following form:

$$D_{eff} = D_o \exp\left(\frac{E_a}{RT_a}\right) \qquad (8)$$

Where: T: absolute air temperature, °K, R: universal gas constant (8.314 J/ mol °K) and Do: equation constant, dimensionless.

Equation (8) can be converted into logarithmic form as follows:

$$ln(D_{eff}) = ln(D_o) - \left(\frac{E_a}{RT_a}\right) \qquad (9)$$

Rehydration ratio:

A modified version of the method proposed by Pei *et al.* (2022) was used to determine the rehydration ratio of garlic slices. Two gram of dried garlic slices were immersed in distilled water; the samples were kept at room temperature for 1 h. The samples were filtered, and the moisture from the garlic slices was gently removed using filter paper. An electronic balance was used to weigh the initial and final sample weights. Each measurement was repeated three times. The rehydration ratio was calculated by dividing the mass of the rehydrated sample (g) by the mass of the dried sample (g), as shown in Equation (10).

$$RR = \frac{W_r}{W_d} \qquad (10)$$

Where: RR: rehydration ratio, dimensionless, W_r: weight of rehydrated samples, g and W_d: weight of dried samples, g.

Color Measurement:

The color of fresh and dried garlic samples was evaluated by a colorimeter (NR145, 3NH TECHNOLOGY CO., LTD). Chromatic attributes were measured, where lightness is represented by (L_0) for fresh, (L_d) for dried, redness or greenness is represented by (a_0) for fresh, (a_d) for dried, and yellowness or blueness is represented by (b_0) for fresh, (b_d) for dried according to (Zeng *et al*, 2019 and El-Mesery *et al*, 2024b). The total color difference (ΔE) between the dried and the fresh garlic slices was calculated as shown in Equation (11)

$$\Delta E = \sqrt{(L_0 - L_d)^2 + (a_0 - a_d)^2 + (b_0 - b_d)^2} \quad (11)$$

Statistical Analysis:

To determine each model's drying constants, regression analysis was performed using using Microsoft Excel 365 and sigmaplot 14 software. The best equation expressing the drying kinetics was chosen using the highest coefficient of determination (R^2) and the lowest sum of Standard Error (SE), chi square (X^2) and root mean square error (RMSE) as follows:

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre.i})^2}{\sqrt{\left[\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre.i})\right]^2 \left[\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre.i})\right]^2}} \quad (12)$$

$$X^2 = \frac{\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre.i})^2}{N-n} \qquad (13)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre.i})^2}{N}} \qquad (14)$$

Where: $MR_{exp.i}$: the experimental MR at observation I, $MR_{pre.i}$: the predicted MR at this observation, N, n: number of experimental data points and number of constants respectively.

RESULTS AND DISCUSSION

Drying Curves:

The variations of dimensionless moisture ratio with drying time for treated and untreated garlic slices dried at various drying temperatures are as shown in figure (4). Table (2) represents the moisture content of fresh and dried garlic slices at various air temperature level. The initial moisture contents of fresh garlic were 218.39 % (d.b.) and 198.21% (d.b.) for treated and untreated samples respectively, which reduced to 7.89 to 11.35 % after hot air drying. It is clear that the moisture loss followed an exponential decay and the increase in temperature accelerated the drying process.

It is also noticeable that, as the air temperature increased from 45°C to 65°C, the drying time taken to reach the equilibrium moisture content was shortened from 380 min to 300 min. Therefore, it can be observed that drying time is significantly affected by the increase of air temperature, which saves about 21 % of time required for drying.

Figure (5) shows the relationship between drying rate and moisture content for both treated and untreated garlic slices during drying process at different air temperatures. A faster reduction in moisture content occurred in the early drying stages, after that it reduced as drying time increased. This impact was caused by the significant availability of free moisture, which was easily removed during the initial drying stage. Most drying periods occurred in the falling rate period, while the constant rate period was absent. Treated garlic slices show faster drying rates compared to untreated samples at all air temperatures. This can be attributed to structural changes caused by pre-treatment, such as increased porosity and improved cell permeability, which facilitated moisture transfer. On the other hand, untreated slices maintained a more compact cellular structure, which limited moisture movement and resulted in longer drying time.

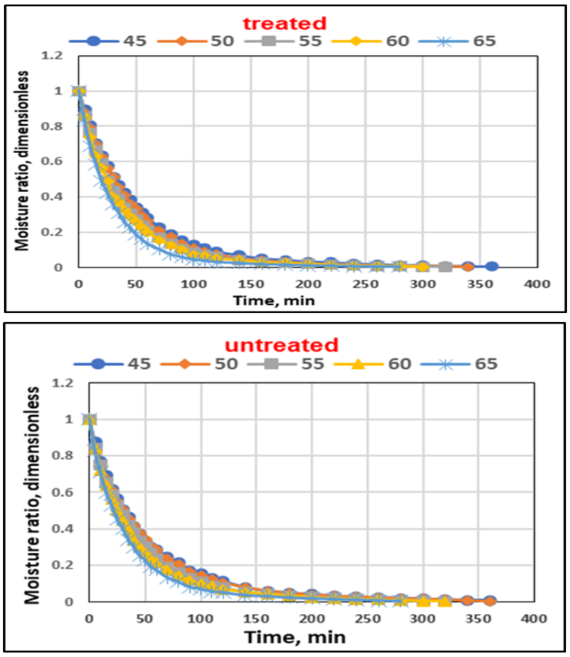

Figure 4. The relationship between moisture ratio and drying time at different air temperatures for treated and untreated garlic slices.

Table 2. Moisture content (d.b, %) of fresh and dried garlic slices.

MC, %(d.b.)	Drying air temperature, °C					
	Fresh	**45**	**50**	**55**	**60**	**65**
Treated	218.39	11.17	10.53	8.38	8.11	7.89
untreated	198.21	11.35	11.05	9.04	8.51	7.95

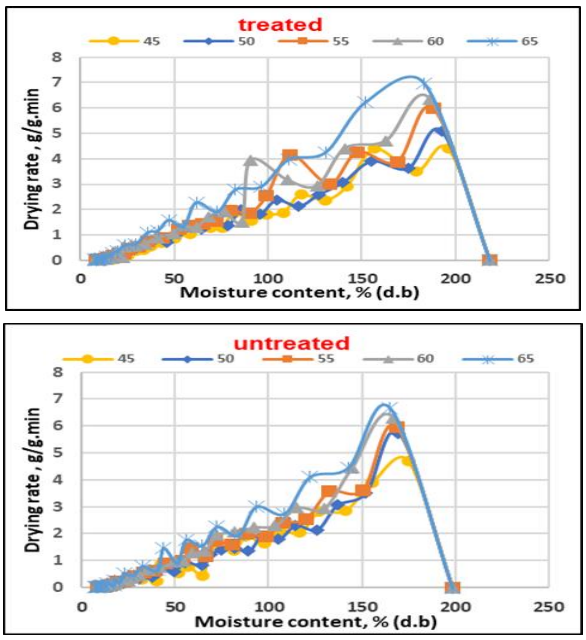

Figure 5. The relation between moisture content (MC) and the drying rate (DR) for the treated and untreated garlic slices.

Mathematical Modelling:

Ten Mathematical models from literature (Lewis, Henderson and Pabis, Page, modified Page, logarithmic, two-term, Exponential linear combination, Diamante, Wang and Singh, and three-term exponential) which are listed in Table (1) were used to describe the drying behavior of garlic. Four statistical measures (R^2, $\mathcal{X}^2$, SE, and RMSE) were used to evaluate them. The optimal model was selected by higher coefficient of determination (R^2), lower standard error (SE), chi-square ($\mathcal{X}^2$) and root mean square error (*RMSE)*. Tables (3 and 4) represent the constants, coefficients and parameters of the statistical evaluation of the tested models for treated and untreated garlic slices, respectively.

Table 3. Statistical results obtained from the modelling of treated garlic slices.

Model	T_a,°c	Constants						R^2	SE	X^2	RMSE
		k_L									
Lewis	45	0.0161						0.9891	0.04043	0.0044	0.0653
	50	0.0178						0.9921	0.03278	0.0031	0.0551
	55	0.0204						0.9895	0.03772	0.0037	0.0599
	60	0.0214						0.9890	0.03889	0.0041	0.0630
	65	0.0238						0.9777	0.05106	0.0068	0.0810
Average								0.9875	0.04018	0.00444	0.06488
		k_H	A_H								
Henderson and Pabis	45	0.0147	0.7222					0.9813	0.0375	0.00683	0.0800
	50	0.0163	0.7492					0.9852	0.0323	0.00652	0.0781
	55	0.0189	0.7939					0.9827	0.0350	0.00568	0.0728
	60	0.0196	0.8245					0.9810	0.0362	0.00581	0.0736
	65	0.0205	0.8579					0.9568	0.0409	0.01445	0.1159
Average								0.9774	0.0364	0.00786	0.0841
		k_P	n								
Page	45	0.031689	0.887					0.9988	0.0128	0.00021	0.0140
	50	0.033081	0.8937					0.9991	0.0102	0.00014	0.0116
	55	0.039752	0.882					0.9988	0.0119	0.00017	0.0128
	60	0.044704	0.8659					0.9991	0.0107	0.00014	0.0113
	65	0.057654	0.8425					0.9756	0.0463	0.00621	0.0759
Average								0.9943	0.01839	0.00137	0.02512
		k_{mP}	n								
Modified Page	45	0.020414	0.887					0.9961	0.0254	0.00160	0.0387
	50	0.022054	0.8937					0.9975	0.0194	0.00107	0.0317
	55	0.025821	0.882					0.9963	0.0235	0.00134	0.0354
	60	0.027626	0.8659					0.9959	0.0249	0.00159	0.0385
	65	0.03382	0.8425					0.9987	0.0136	0.00040	0.0193
Average								0.9969	0.02134	0.0012	0.03273
		k_{Log}	a	c							
Logarithmic	45	0.0218	0.9758	0.0148				0.9997	0.0071	0.00005	0.0069
	50	0.0227	0.9793	0.0093				0.9999	0.0047	0.00002	0.0046
	55	0.0269	0.9763	0.0125				0.9996	0.0081	0.00007	0.0078
	60	0.0284	0.9656	0.0145				0.9993	0.0105	0.00011	0.0101
	65	0.0346	0.9757	0.0115				0.9997	0.0065	0.00004	0.0063
Average								0.9996	0.00736	0.00006	0.00714
		K_T	K_{T1}	a_T	b_T						
Two term	45	0.0244	0.0082	0.8743	0.1239			0.9999	0.0045	0.00002	0.0044
	50	0.0234	0.0053	0.9559	0.0352			0.9999	0.0041	0.00002	0.0040
	55	0.031	0.0118	0.8385	0.1595			0.9998	0.0052	0.00003	0.0050
	60	0.0383	0.0105	0.641	0.3541			0.9997	0.0066	0.00005	0.0064
	65	0.0378	0.0117	0.9065	0.0873			0.9999	0.0043	0.00002	0.0042
average								0.9998	0.00495	0.00003	0.00479
		K_E	a_E	b_E	c_E						
Exponential linear combination	45	0.0231	0.048	0.9485	-0.0001			0.9998	0.0048	0.00004	0.0063
	50	0.0232	0.0229	0.968	-5.387E-05			0.9999	0.0040	0.00002	0.0039
	55	0.0286	0.0465	0.949	-0.0002			0.9994	0.0066	0.00011	0.0096
	60	0.0307	0.0559	0.0326	-0.0002			0.9996	0.0075	0.00006	0.0073
	65	0.0361	0.0325	0.9593	-0.0001			0.9998	0.0046	0.00002	0.0046
Average								0.9997	0.0055	0.00005	0.00633
		a_D	b_D	c_D							
Diamante	45	1.6147	-0.4155	0.0227				0.9859	0.04448	0.0020	0.0427
	50	1.6038	-0.4178	0.023				0.9836	0.04759	0.0023	0.0457
	55	1.6511	-0.4753	0.0316				0.9850	0.04233	0.0018	0.0405
	60	1.6231	-0.4735	0.032				0.9870	0.03881	0.0015	0.0370
	65	1.6973	-0.5535	0.0439				0.9865	0.03600	0.0013	0.0343
Average								0.9856	0.04184	0.0018	0.04004
		a_W	b_W								
wang and singh		0.010374	0.01027					0.9381	0.14308	0.0275	0.1606
		0.011058	0.01031					0.9400	0.14207	0.0271	0.1592
		0.012073	0.01176					0.9210	0.16255	0.0357	0.1825
		0.012835	0.01199					0.9216	0.16267	0.0357	0.1823
		0.014276	0.01377					0.8961	0.18071	0.0429	0.1996
Average								0.9234	0.15821	0.03378	0.17683
		K_{T2}	K_{T3}	K_{T4},	a_{T2}	b_{T2}	c_{T2}				
Three term exponential	45	0.1034	0.0229	0.0066	0.0234	0.9013	0.0774	0.9999	0.00438	0.00002	0.00428
	50	0.0228	18.9401	0.0032	0.9633	1.73E-02	1.94E-02	0.9999	0.00340	0.00001	0.00331
	55	0.031	0.031	0.0118	0.4162	0.4224	0.1595	0.9998	0.00519	0.00003	0.00502
	60	0.0862	0.0292	0.0107	0.0851	0.808	0.1055	0.9997	0.00637	0.00005	0.00616
	65	0.0345	0.1735	0.0063	0.9273	0.0434	0.0305	0.9999	0.00341	0.00001	0.00329
Average								0.9998	0.00455	0.00003	0.00441

Table 4. Statistical results obtained from the modelling of untreated garlic slices.

Model	T_a,°c	constants						R^2	SE	X^2	RMSE
		k_L									
Lewis	45	0.0151						0.9866	0.04741	0.00680	0.08115
	50	0.0163						0.9921	0.03695	0.00477	0.06794
	55	0.0188						0.9916	0.03555	0.00417	0.06346
	60	0.0199						0.9894	0.04020	0.00482	0.06827
	65	0.0219						0.9840	0.04661	0.00613	0.07691
Average								0.9887	0.04135	0.00534	0.07155
		k_H	A_H								
Henderson and Pabis	45	0.0135	0.6965					0.9768	0.04215	0.00688	0.08031
	50	0.0151	0.7114					0.9871	0.03540	0.00302	0.05319
	55	0.0173	0.7433					0.9853	0.03411	0.00447	0.06462
	60	0.0184	0.7575					0.9830	0.03728	0.00399	0.06103
	65	0.0194	0.7917					0.9704	0.04106	0.00850	0.08886
Average								0.9805	0.038	0.00537	0.0696
		k_P	n								
Page	45	0.040591	0.8265					0.9993	0.00999	0.00012	0.01070
	50	0.042814	0.8227					0.9998	0.00529	0.00003	0.00522
	55	0.043322	0.8473					0.9997	0.00676	0.00005	0.00709
	60	0.048791	0.8327					0.9996	0.00755	0.00006	0.00758
	65	0.055084	0.8297					0.9989	0.01103	0.00016	0.01200
Average								0.9995	0.00812	0.00008	0.00852
		k_{mP}	n								
Modified Page	45	0.020716	0.8265					0.9942	0.03268	0.00310	0.05395
	50	0.021711	0.8227					0.9962	0.02675	0.00257	0.04905
	55	0.024604	0.8473					0.9969	0.02308	0.00180	0.04101
	60	0.026596	0.8327					0.9955	0.02746	0.00224	0.04567
	65	0.030382	0.8297					0.9946	0.02864	0.00224	0.04559
Average								0.9955	0.02772	0.00239	0.04705
		k_{Log}	a	c							
Logarithmic	45	0.0215	0.942	0.023				0.9989	0.01402	0.00021	0.01366
	50	0.0212	0.9287	0.0196				0.9987	0.01449	0.00022	0.01410
	55	0.0243	0.9482	0.0152				0.9993	0.01088	0.00012	0.01057
	60	0.0266	0.9423	0.0187				0.9988	0.01331	0.00019	0.01292
	65	0.0309	0.9557	0.0176				0.9993	0.01009	0.00011	0.00978
Average								0.9990	0.01256	0.00017	0.01221
		K_T	K_{T1}	a_T	b_T						
Two term	45	0.0373	0.013	0.4859	0.5066			0.9998	0.00572	0.00004	0.00558
	50	0.0838	0.0169	0.1942	0.7979			0.9997	0.00673	0.00006	0.00700
	55	0.112	0.021	0.132	0.8639			0.9997	0.00585	0.00005	0.00630
	60	0.041	0.0154	0.5582	0.4257			0.9997	0.00652	0.00005	0.00630
	65	0.0382	0.0141	0.7635	0.2229			0.9998	0.00590	0.00004	0.00569
average								0.9997	0.00614	0.00004	0.00618
		K_E	a_E	b_E	c_E						
Exponential linear combination model	45	0.0246	0.0926	0.8862	-0.0003			0.9993	0.00945	0.00014	0.01114
	50	0.0241	0.0865	0.8749	-0.0003			0.9989	0.01135	0.00022	0.01379
	55	0.0265	0.0618	0.9103	-0.0002			0.9995	0.00808	0.00007	0.00781
	60	0.0229	0.0787	0.8951	-0.0003			0.9994	0.00894	0.00012	0.01016
	65	0.0334	0.0585	0.9231	-0.0002			0.9997	0.00641	0.00005	0.00627
Average								0.9994	0.00885	0.00012	0.00983
		a_D	b_D	c_D							
Diamante	45	1.525	-0.377	0.0191				0.9894	0.03796	0.00146	0.03636
	50	1.4623	-0.3515	0.0163				0.9884	0.03920	0.00156	0.03757
	55	1.5237	-0.3991	0.0221				0.9867	0.04114	0.00172	0.03932
	60	1.5444	-0.4287	0.0268				0.9879	0.03739	0.00132	0.03572
	65	1.5975	-0.4789	0.0336				0.9871	0.03738	0.00142	0.03559
Average								0.9879	0.03861	0.00149	0.03691
		a_W	b_W								
wang and singh		0.010272	0.00002					0.9391	0.14535	0.02984	0.16727
		0.010308	0.00002					0.9392	0.14434	0.03022	0.16831
		0.011754	0.00003					0.9339	0.14466	0.02903	0.16461
		0.011984	0.00003					0.9205	0.15812	0.03448	0.17940
		0.013771	0.00004					0.9175	0.16559	0.03669	0.18457
Average								0.9300	0.15161	0.03205	0.17283
		K_{T2}	K_{T3}	K_{T4},	a_{T2}	b_{T2}	c_{T2}				
Three term exponential	45	0.2343	0.0299	0.0113	0.0364	0.5988	0.365	0.9998	0.00515	0.00003	0.00499
	50	0.2832	0.0232	0.009	0.0848	0.7408	0.1744	1.0000	0.00277	0.00001	0.00273
	55	0.3767	0.0254	0.0089	0.0611	0.8396	0.0992	0.9999	0.00298	0.00001	0.00294
	60	0.4691	0.0312	0.0115	0.0539	0.74	0.2062	0.9999	0.00342	0.00001	0.00338
	65	0.442	0.0327	0.0093	0.0445	0.865	0.0905	0.9999	0.00366	0.00002	0.00354
Average								0.9999	0.0036	0.00002	0.0035

For treated garlic slices, as observably in Table (3), tested models have coefficient of determination (R^2) ranging from 0.9234 to 0.9998, which is significant in that all tested models are able to describe garlic drying behavior successfully under all drying air temperature levels. Two term model and three term exponential model displayed the highest average values of coefficient of determination (R^2 =0.9998) confirming their superior performance in fitting the experimental drying data..

When comparing Two term model and three term exponential model in term of other statistical measures values (χ^2, SE, and RMSE), The three-term exponential model recorded the lowest average values for standard error (SE = 0.00455), chi-square (χ^2 = 0.00003), and root mean square error (RMSE = 0.00441), indicating superior model performance. Figure (6) shows comparison between the calculated and the observed moisture ratio of Two term model and three term exponential model for treated garlic slices.

For untreated garlic slices, as shown in Table (4), drying behavior could be acceptably described by all tested models. The models have coefficient of determination (R^2) ranging from 0.9300 to 0.9999. This confirms that all evaluated models adequately described the drying behavior of garlic across the range of drying air temperatures. The three-term exponential model achieved the highest mean coefficient of determination (R^2 = 0.9999), along with the lowest average values for standard error (SE = 0.0036), chi-square (χ^2 = 0.00002), and root mean square error (RMSE = 0.0035) across all drying temperatures under hot air-drying conditions**.** Figure (7) shows comparison between the calculated and the observed moisture ratio of Two term model and three term exponential model for treated garlic slices.

So, it was reasonable to assume that three term exponential model represented the drying behavior of garlic slices in a hot air dryer accurately and it was followed by two term model.

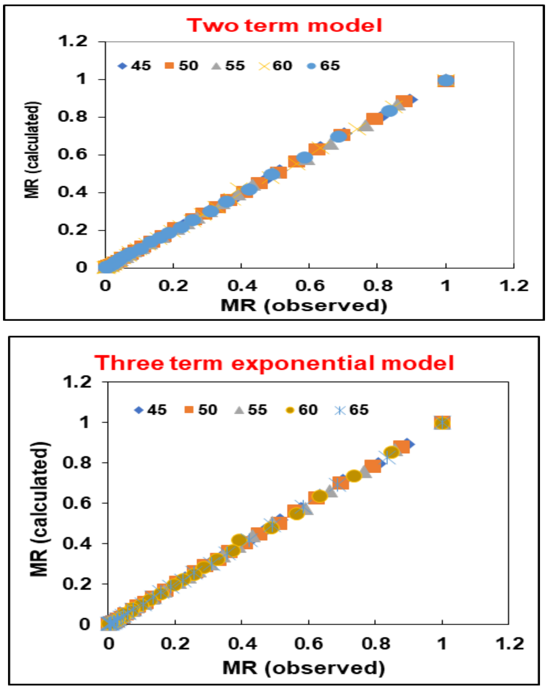

Figure 6. Relationship between calculated and observed moisture ratio of two Term model and Three term exponential model for treated garlic slices.

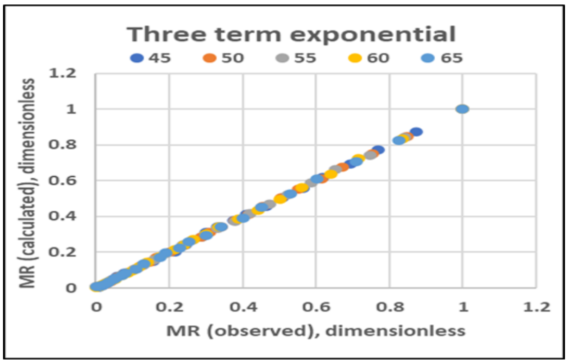

Figure 7. Relationship between calculated and observed moisture ratio of Three term exponential model for untreated garlic slices.

Calculation of the Effective Moisture Diffusivity (D_{eff}):

The values of ln (MR) were plotted against the drying time (t) of treated and untreated garlic slices under different air temperature as presented in Figure (8) and were found to be ranged between (2.225 – 3.1187) × 10^{-10} and (2.0517 – 2.9545) × 10^{-10} m^2/s for treated and untreated garlic slices, respectively.

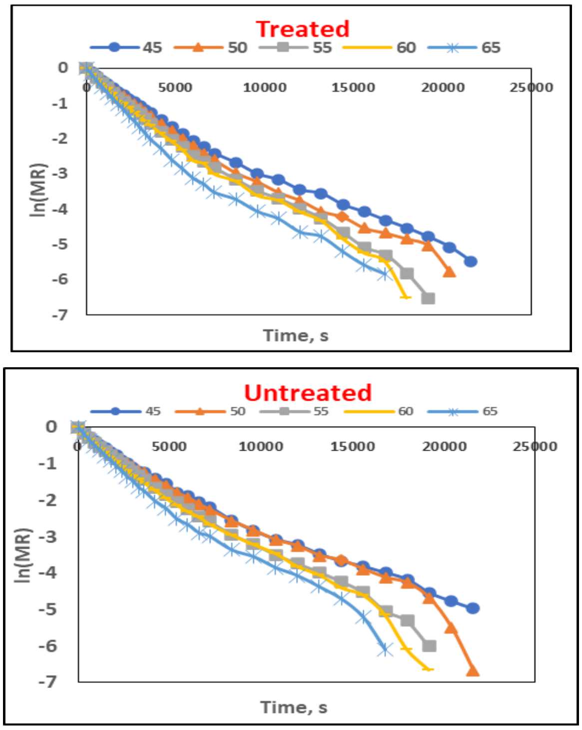

Figure 8. Diffusivity curve for treated and untreated garlic slices at different levels of air temperature.

It also can be seen that the values of effective moisture diffusivity increased by increasing the drying air temperature as presented in Tables (5 and 6). This can be explained by the fact that the increased heat to raise the drying temperature improves the movement activity of water molecules, thus increasing the rate of water diffusion.

Table 5. Values of (D_{eff}) for treated garlic slices at different levels of air temperatures.

T, °C	Linear equation	R^2	D_{eff}, m^2/s
45	Ln(MR) = -0.3255 -0.000244 t	0.9855	2.2250 x10^{-10}
50	Ln(MR) = -0.3159 -0.000271 t	0.9824	2.4712 x10^{-10}
55	Ln(MR) = -0.3094 -0.000314 t	0.9902	2.8633 x10^{-10}
60	Ln(MR) = -0.3251-0.000326 t	0.9868	2.9728 x10^{-10}
65	Ln(MR) = -0.5484 -0.000342 t	0.9649	3.1187 x10^{-10}

Table 6. Values of (D_{eff}) for untreated garlic slices at different levels of air temperatures.

T, °C	Linear equation	R^2	D_{eff}, m^2/s
45	Ln(MR) = -0.3617 -0.000225 t	0.9843	2.0517×10^{-10}
50	Ln(MR) = -0.2595 -0.000252 t	0.9765	2.2980×10^{-10}
55	Ln(MR) = -0.2967 -0.000288 t	0.9907	2.6262×10^{-10}
60	Ln(MR) = -0.2910 -0.000306 t	0.9863	2.7904×10^{-10}
65	Ln(MR) = -0.4130 -0.000324 t	0.9787	2.9545×10^{-10}

It is noticeable that, under the same drying conditions, the effective moisture diffusivity D_{eff} values for pre-treated samples are higher than those for untreated samples. Pretreatment with sodium metabisulfite ($Na_2O_5S_2$) causes a partial chemical breakdown of the sample skins, which improves the water permeability and causes an increase in effective moisture diffusivity D_{eff} as reported by (Doymaz and Ismail, 2011).

Calculation of Activation Energy:

The activation energy was determined using Arrhenius equation by plotting ln (D_{eff}) versus the reciprocal of the air temperature ($1/T_a$) as presented in Figure (9).

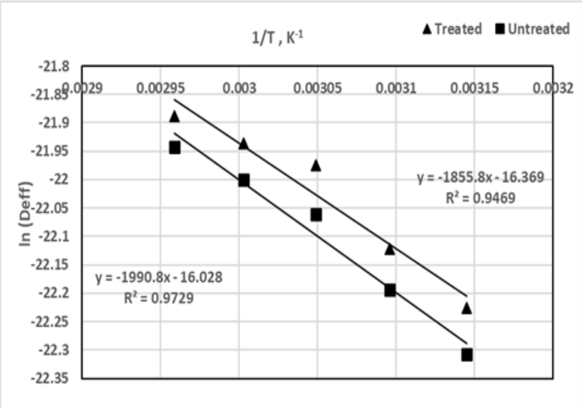

Figure 9. Relationship between logarithm of effective diffusivity and reciprocal absolute air temperature for treated and untreated garlic slices.

As shown in Equations (15 and 16) the air temperature has a noticeable effect on the effective moisture diffusivity (D_{eff}) of treated and untreated garlic slices.

$$D_{eff} = 7.781 * 10^{-8} exp\left(-\frac{1855.8}{T_a}\right) \quad R^2 = 0.9469 \quad \text{(Treated)} \quad (15)$$

$$D_{eff} = 10.943 * 10^{-8} exp\left(\frac{-1990.8}{T_a}\right) \quad R^2 = 0.9728 \quad \text{(Untreated)} \quad (16)$$

The activation energy was found to be 15.429 kJ/mol and 16.552 kJ/mol for treated and untreated garlic slices, respectively. Zogzas *et al.* (1996) documented that the activation energy associated with drying food and agricultural products typically ranges from 12.7 to 110 kJ/mol. The activation energy values that obtained, correspond with the results of previous investigations. EL-Mesery *et al.* (2022) stated that the activation energy of garlic slices under HAD was (18.1 kJ/mol). Demiray and Tulek (2014) stated that the value of the activation energy for garlic slices was (30.582 kJ/mol). Elfar (2022) reported that the activation energy for tomato slices pretreated with 5% sodium chloride was 32.94 kJ/mol.

The results also indicated that the activation energy required for moisture diffusion was lower in treated samples (15.429 kJ/mol) compared to untreated ones (16.552 kJ/mol), suggesting that the sodium metabisulphite pretreatment enhanced moisture transfer during drying.

Rehydration Ratio (RR):

The rehydration ratio (RR) is a critical parameter used to assess the quality of dried garlic slices, in terms of their ability to regain moisture after drying. The results for the rehydration ratio were calculated from Equation (10) and plotted against drying temperature, as shown in Figure (10).

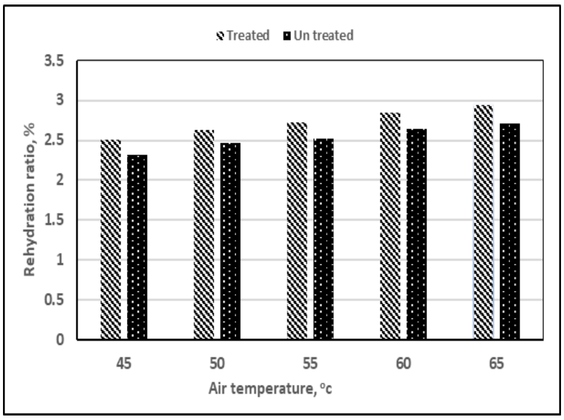

Figure 10. Variation in rehydration ratio of garlic slices subjected to different drying air temperatures, comparing sodium metabisulphite-treated and untreated samples.

The rehydration ratio (RR) of dried garlic slices ranged from (2.51 to 2.95) for samples treated with sodium metabisulphite, and from (2.31 to 2.70) for untreated samples. It significantly affected by both the drying temperature and pretreatment with sodium metabisulfite. Treated samples show higher (RR) values compared to untreated ones, indicating improved rehydration capacity and better structural preservation during drying. This suggests that sodium metabisulfite pretreatment enhances the quality of dried garlic slices by improving their ability to absorb water during rehydration. This result is agreed with (**Liu *et al.*, 2022**), they reported that pretreatment can improve the rehydration behavior of dried vegetables by preserving cellular structure and reducing drying damage.

Color Parameters:

Color is an important parameter commonly used in the quality evaluation of food products (Kose and Erenturk, 2010). The color parameters brightness (L), redness (a), yellowness (b) of fresh and dried treated and untreated garlic slices were analyzed to calculate the color difference as presented in Table (7). Also Figure (11) shows the effect of air temperature on the color difference (ΔE) for treated and untreated garlic slices.

Fresh garlic recorded 86.46, - 0.85, and 9.82 for L, a, and b, respectively. (L) The value of the dried garlic slices decreased with the increase of air temperature in both treated and untreated garlic slices. For treated garlic slices that dried at 45°C and 50°C, recorded L values were higher than the fresh sample; this result proves that sodium metabisulfite pretreatment enhances the color. (a) Values in the dried treated and untreated garlic slices increase when compared to the fresh sample. (b) Values were following the similar trend.

The results illustrated that the color difference (ΔE) values of treated and untreated garlic slices increased significantly after hot air drying. As shown in Table (7), the color difference (ΔE) of treated garlic slices is lower than that in untreated ones at all levels of drying air temperatures. This implied that pretreatment with sodium metabisulfite prior to the drying process decreases browning. Changes in color of the dried garlic slices are a consequence of both enzymatic and nonenzymatic processes (Maillard reaction) caused by dark pigments. İZLİ, (2016) mentioned that pretreatment may strongly affect pigment degradation, especially the degradation of carotenoids.

Table 7. Effect of drying air temperature on color parameters of treated and untreated garlic slices

Garlic	Temperature, °C	Color parameters			
		L	a	b	ΔE
Fresh		86.46	-0.85	9.82	
Treated	45	88.76	1.84	18.37	9.253572
	50	88.55	2.24	18.63	9.567251
	55	85.23	2.73	19.98	10.84227
	60	85.31	2.61	20.04	10.85092
	65	76.39	2.96	20.92	15.46386
Untreated	45	83.59	2.98	19.23	10.55717
	50	82.59	3.75	21.84	13.43939
	55	78.39	3.75	22.66	15.84773
	60	77.72	3.26	22.98	16.32376
	65	76.45	3.64	22.86	17.04118

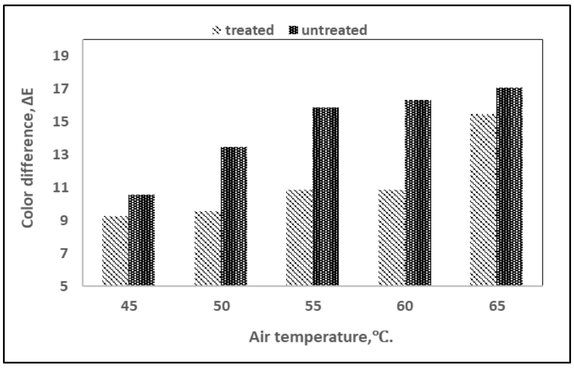

Figure 11. Effect of air temperature on the color difference (ΔE) of dried garlic slices.

CONCLUSION

Hot air-drying kinetics of treated and untreated garlic slices were studied at a constant air flow rate of 0.708 m^3/s, and air temperatures ranged from 45 to 65°C. Treated and untreated garlic slices were dried during the falling drying rate period at all temperature levels, and the constant rate was absent. While drying times increased, the drying rates decreased in all drying air temperatures. Ten mathematical models were tested to determine the drying kinetics of treated and untreated garlic slices. Among the models, the three-term exponential model, which has a higher coefficient of determination and lower SE, $\mathcal{X}^2$ and RMSE, was considered the best for describing the drying kinetics of treated and untreated garlic slices. The effective moisture diffusivity increased with the increase in air temperature, and values for sodium metabisulfite pretreated samples are higher than those for untreated samples. The activation energy required for moisture diffusion was lower in treated samples (15.429 kJ/mol) compared to untreated ones (16.552 kJ/mol). The rehydration ratio and color were considered as important attributes for dried garlic products. The rehydration ratio for treated samples shows higher values compared to untreated ones. It was found that with an increase in the drying air temperature, the color became darker, implying that more browning occurred in the garlic slices. Color difference increased with the increase in the drying air temperature. Overall, sodium metabisulfite-pretreated samples performed better in terms of moisture content, effective moisture diffusivity, activation energy, rehydration ratio, and color at all drying air temperatures investigated.

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النمذجة الرياضية لتجفيف شرائح الثوم بالهواء الساخن

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الملخص

تم اجراء هذا البحث لدراسة النمذجة الرياضية وحركية التجفيف لشرائح الثوم باستخدام مجفف معملي عند خمسة مستويات مختلفة من درجة حرارة الهواء وهي ٤٥ و ٥٠ و ٥٥ و ٦٠ و ٦٥ °م. تمت المقارنة بين شرائح ثوم غير معاملة وأخرى تم معاملتها مسبقا باستخدام ميتابيسلفيت الصوديوم بتركيز ٠,٥ ٪ وزن/ وزن لمدة ١٠ دقائق . تم استخدام معدل ثابت لسريان الهواء ٠,٧٠٨ م^{٣}/ث وسمك ثابت لشرائح الثوم في مدى ٢-٣ مم قبل التجفيف. تم اختبار عشرة نماذج رياضية مختلفة لوصف سلوك التجفيف كما تم تقييمها باستخدام اربع معاملات احصائية اشتملت على معامل الارتباط R^2 و الخطأ المعياري SE و χ^2 وجذر متوسط الخطأ التربيعي RMSE للمقارنة بين النماذج الرياضية موضع الدراسة. أظهرت النتائج أن نموذج Three term exponential model كان الأفضل في وصف سلوك التجفيف لشرائح الثوم المعاملة والغير معاملة . كما بينت النتائج أنه مع زيادة درجة حرارة هواء التجفيف ، زاد معدل انتشار الرطوبة D_{eff}. حيث تراوح معدل انتشار الرطوبة من ٢,٢٢٥ إلى ٣,١١٨٧ ١٠$^{-١٠}$ م^{٢} / ثانية للشرائح المعاملة ومن ٢,٠٥١٧ إلى ٢,٩٥٤٥ ١٠$^{-١٠}$ م^{٢} / ثانية للشرائح الغير معاملة بينما كانت قيمة طاقة التنشيط E_a ١٥,٤٢٩ كيلوجول / مول للشرائح المعاملة و ١٦,٥٥٢ كيلو جول/ مول للشرائح الغير معاملة. أظهرت النتائج أيضا أن المعاملة المسبقة بميتابيسلفيت الصوديوم كان لها تأثيرا إيجابيا على نسبة اعادة التشرب واللون ، مما يشير إلى تحسن جودة المنتج.

الكلمات الدالة : شرائح الثوم ، النمذجة الرياضية ، انتشار الرطوبة ، طاقة التنشيط ، نسبة إعادة الترطيب ، صفات اللون