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Investigation of Drying Kinetics of Turkey Breast Meat Using Vacuum and Ultrasound-assisted Vacuum Drying

M. Ali ÇAKIR[1], Emre KABİL[2], Barış YALINKILIÇ[3], Mehmet BAŞLAR[4]

[1]Department of Nutrition and Dietetics, Faculty of Health Science, Kırklareli University, 39000 Kırklareli, Türkiye
[2]Department of Food Processing, Armutlu Vocational College, Yalova University, 7500 Yalova, Türkiye
[3]Department of Gastronomy and Culinary Arts, Faculty of Architecture and Design, İstanbul Gedik University, 34876 İstanbul, Türkiye
[4]iPeak Academy Ltd., Mildenhall, Suffolk, IP28 7DE, United Kingdom

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Corresponding Author
Muhammet Ali Çakır
m.ali.cakir@klu.edu.tr

Author ORCID
[1]https://orcid.org/0000-0001-5066-1956
[2]https://orcid.org/0000-0002-2574-196X
[3]https://orcid.org/0000-0002-6195-7821
[4]https://orcid.org/0000-0002-8369-0769

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Abstract

Various drying techniques are employed for the dehydration of fresh meat, and the evaluation of drying kinetics is crucial for determining parameters such as drying rate and energy efficiency. Recent studies have focused on developing innovative drying techniques, among which ultrasound-assisted vacuum drying (UAVD) has gained prominence. In this study, the drying process of turkey breast meat was investigated using both vacuum drying (VD) and UAVD at different temperatures (50°C, 60°C, and 70°C). The drying kinetics were analyzed using six different thin-layer drying models. Samples were dried until their moisture content fell below 20%, and the obtained drying data were successfully fitted to the six thin-layer drying models, with R^2 values ranging from 0.983 to 0.999. The logarithmic drying model was identified as the best-fitting model, and UAVD was found to be more effective than conventional vacuum drying. Moreover, drying efficiency in UAVD improved with increasing temperature, demonstrating its potential as an advanced drying technique for poultry meat processing.

Keywords: Turkey meat, Ultrasound, Vacuum drying, Dehydration kinetics, Moisture diffusivity

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INTRODUCTION

The term poultry describes the domesticated birds such as chicken, guinea fowl, and ostrich that have low fat and high quality protein in their muscles (Scanes and Christensen, 2020). According to Food and Agriculture Organization, poultry meat has the highest rate in the world meat market in terms of production and trade with an increasing trend (FAO, 2022), and the average poultry meat consumption rate per capita in OECD member countries in 2021 was 31.8 kg (OECD, 2022). Along with chicken, turkey represents one of the most main sources of poultry meat. On a global scale, Europe, North and South America come into prominence on turkey meat production. Turkey meat is sold fresh or frozen and is also marketed in various processed forms, including cured, smoked, and emulsified products (Scanes and Christensen, 2020).

Drying is a method of food preservation that has been used for centuries to extend the shelf life of delicate foods. Moreover, it takes a long time to remove water from meat during the drying process due to the interaction of myofibrillar proteins with water molecules. However, the microbiological and biochemical changes that may occur during the prolonged drying process could result in the product being discarded (Gailani et al., 1987; Aykın-Dinçer, 2021).

Drying, once a traditional method used by local producers to preserve food through sun-drying, has now evolved into an industrial-scale field of food engineering in which simultaneous heat and mass transfer are precisely controlled. For high-quality production, monitoring moisture content on a dry basis, as opposed to the wet basis commonly used in commercial operations, is of critical importance. Therefore, in order to ensure effective process control in drying operations, drying kinetics and drying models based on dry-basis moisture content have gained prominence. A high degree of agreement between drying kinetics and models enables food engineers or food technologists responsible for production to accurately monitor the process. Moreover, drying data can serve as a benchmark in the development of different processes. For these reasons, research based on drying kinetics and drying models has become increasingly important in drying operations (Michailidis and Krokida, 2014; Inyang et al., 2018).

As a matter of fact, different drying techniques were studied on meat products, either individually (vacuum drying, ultrasonic drying, freeze-drying, microwave drying, cold drying, etc.) or in combination (vacuum radio frequency drying, vacuum-assisted ultrasonic drying, Far-infrared Assisted Heat Pump Drying, etc.), and the drying kinetics of these techniques were investigated (Deng et al., 2014; Baslar et al., 2015; Aykın and Erbaş, 2016; Aykın-Dinçer and Erbaş, 2019; Ran et al., 2019). Among these techniques, ultrasound-assisted vacuum drying has gained popularity in recent years due to its ability to reduce drying time (Baslar et al., 2014). Attempts to dry turkey meat have previously been made only using hot air, freeze drying, and microwave methods in previous studies (Elmas et al., 2020; 2021; Yıldırım Yalçın and Şeker, 2016).

Ultrasound-assisted vacuum drying (UAVD) has been successfully applied to the drying of various meat products (Baslar et al., 2015; Aksoy et al., 2019); however, in the literature, its application to poultry meat has only been reported for chicken (Baslar et al., 2014), and no studies have investigated its use for other poultry products including turkey meat. In muscle tissue, individual muscle fibres, bundles of fibres, and the entire muscle are enveloped by connective tissue sheaths located in the endomysial, perimysial, and epimysial regions, respectively (Warriss, 2000). During drying, the removal of water necessitates its diffusion through these connective tissue barriers. The content of connective tissue proteins in breast meat can vary considerably among different breeds of chicken and turkey, and the myofibre diameter within this region may also differ (Fernandez et al., 2001; Nakamura et al., 2004). Furthermore, comparative studies have shown that collagen derived from turkey breast exhibits lower solubility than that from chicken breast (Voutila et al., 2009). Since variations in myofibre diameter, collagen content, and collagen solubility are likely to influence the rate and extent of moisture diffusion during breast meat drying, it is crucial to assess the applicability of the UAVD technique specifically for turkey meat. This study aims to fill this research gap by evaluating the effects of UAVD on the drying characteristics of turkey breast meat, with the hypothesis that ultrasound would enhance drying performance compared to conventional vacuum drying because of its ability to accelerate simultaneous mass and heat transfer. This study examines the effectiveness of the ultrasound-assisted vacuum drying method compared to vacuum drying method on turkey breast meats dried at different temperatures (50 °C, 60 °C, and 70 °C) using various drying models.

MATERIALS AND METHODS

Raw Material Supply and Sample Preparation

Raw turkey (Meleagris gallopavo) breast meat samples were obtained from a local butcher shop (commercial supplier) in Kırklareli province, Türkiye. Only pectoralis major parts were selected.They were stored in a refrigerator (4 ± 1 °C) until analysis. During sample preparation, visible fat and connective tissues on the surface of the meat were removed and the meat was sliced into rectangular slices of approximately 50 x 50 x10 mm ± 0.5 mm thick slices. The average surface area of each slice was approximately 25 ± 1 cm², and dimensions were measured using a digital caliper (Mitutoyo, Japan). Each sample was weighed to approximately 20 ± 0.5 g. After surface moisture was removed with sterile absorbent papers, the samples were subjected to the drying process.

Preliminary Trials

Preliminary trials were conducted to determine the experimental parameters. As a result of these trials, it was determined that temperatures of 50 °C, 60 °C, and 70 °C were suitable in terms of both drying time and product quality. Ultrasound frequency and power were fixed at 40 kHz and 180 W, respectively. These parameters were chosen based on previous studies on meat drying, which reported enhanced mass transfer and moderate structural changes under ultrasound-assisted vacuum drying conditions (Baslar et al., 2015; Aykın-Dinçer & Erbaş, 2019).

Drying Processes

Vacuum Drying (VD)

Vacuum drying processes were carried out using a laboratory vacuum dryer (Daihan Scientific WOV-30, South Korea). The pressure inside the device was kept constant at 60 ± 2 mbar during the drying period. Drying temperatures were set at 50 ± 1 °C, 60 ± 1 °C, and 70 ± 1 °C. Samples were placed in a single layer in the drying chamber without contacting each other. During drying, the weights of the samples were measured every 10 minutes using an analytical balance (Radwag AS 220.R2, Poland) with a precision of ±0.001 g. Three parallel experiments were performed for each temperature condition, and all measurements were reported as mean ± standard deviation (SD).

Ultrasound-Assisted Vacuum Drying (UAVD)

Ultrasound-assisted vacuum drying was conducted using an ultrasonic water bath (Isolab TU-520H, Germany) integrated with a vacuum pump. The ultrasound frequency was set to 40 kHz and the power output to 180 W. The ultrasonic power density was calculated to be approximately 0.35 W/cm². During the UAVD processes, the pressure inside the device was kept constant at 60 ± 2 mbar and the drying temperatures were set at 50 °C, 60 °C, and 70 °C. The samples were placed at equal distances from the ultrasound module and weight measurements were made at 10-minute intervals. In both drying methods, the samples were dried until the moisture content decreased below 20%. Methodological comparisons were ensured by keeping time, temperature, pressure, and equipment placement constant in the experimental protocols. The drying procedures were designed to keep all variables constant except ultrasound application, ensuring methodological comparability between VD and UAVD.

Moisture Content Determination and Moisture Ratio Calculation

Moisture contents were determined using a laboratory oven (Memmert UFP400, Germany) at 105°C for 24 hours according to AOAC 950.46 standard. The moisture ratio (MR) was calculated using the following equation:

$MR = (M_t - M_e) / (M_0 - M_e)$

Mt: Moisture content at any time (kg water/kg dry matter)

M_e: Equilibrium moisture content

M_0: initial moisture content (kg water/kg dry matter)

Since the equilibrium moisture content (M_e) is very low, it was neglected, and the simplified form was used:

$MR = M_t / M_0$

Thin Layer Drying Models

Experimental data were fitted to various thin-layer drying models. The mathematical expressions of each model and their corresponding literature sources are presented in Table 1. Nonlinear regression was used to calculate the regression parameters.

Table 1. Equations utilized to model the data collected from the dehydration process of turkey meat.

Model names	Model names	Reference
Lewis	$MR = \exp(-k \cdot t)$	Bruce (1985)
Page	$MR = \exp(-k \cdot t^n)$	Madamba, Driscoll and Buckle (1996)
Henderson and Pabis	$MR = a \exp(-(k \cdot t))$	Henderson and Pabis (1961)
Logarithmic	$MR = a \exp(-(k \cdot t)) + c$	Togrul and Pehlivan (2002)
Wang and Singh	$MR = 1 + a \cdot t + b \cdot t^2$	Wang and Singh (1978)
Weibull	$MR = \exp(-(t/\alpha)^\beta))$	Baslar et al. (2015)

MR: Moisture ratio; a, b, c, and n are drying coefficients; and k, k_0 and k_1 are drying constants.

The parameters of each model were estimated using the least squares method. Model performances were evaluated by the coefficient of determination (R^2), root mean square error (RMSE), and chi-square (χ^2) values. The most suitable model was selected based on the highest R^2 value and the lowest RMSE and χ^2 values.

Determination of Effective Moisture Diffusion Coefficient (D_{eff}) and Activation Energy (E_a)

The effective moisture diffusivity (D_{eff}) during the drying process was calculated based on Fick's second law. The relationship between D_{eff} and temperature was analyzed using the Arrhenius equation:

$D_{eff} = D_0 \times \exp(-E_a / (R \times T))$

where D_0 is the pre-exponential factor, R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature (K). Arrhenius plots were constructed using logarithmic transformation, and Ea and D0 values were obtained through regression analysis.

Statistical Analysis

All experiments were conducted in triplicate, and results were reported as mean ± standard deviation (SD). SPSS Statistics 25.0 (IBM Corp., Armonk, NY, USA) software was used for data analysis. One-way ANOVA was applied to compare drying temperatures and drying methods (VD vs UAVD) within each model in terms of drying parameters such as D_{eff} and model fitness values. A significance level of $p < 0.05$ was considered.

RESULTS AND DISCUSSION

Dehydration rate

The drying characteristics of turkey breast meat processed by vacuum drying (VD) and ultrasound-assisted vacuum drying (UAVD) with temperatures of 50 °C, 60 °C, and 70 °C are shown in Figure 1. According to Figure 1, all drying processes exhibited a logarithmic decrease in moisture content, and the resulting drying curves followed a generally similar trend. The curves obtained in Figure 1 are similar to the findings of other studies conducted on food materials (Baslar, 2023). The drying time and the drying rate were significantly lowered by increasing the temperature. This is due to the fact that there is increased vapor pressure and heightened molecular activity with increasing temperature, thereby speeding up the migration of the moisture from the surface of the sample (Figure 2, Table 2). Across all conditions, a biphasic drying trend was observed, characterized by high initial drying rates (e.g., 0.067 g/min at 70 °C UAVD) followed by a declining phase, where the drying rate decreased below 0.015 g/min. This drying behavior is typical for biological materials, where rapid surface water evaporation in the early stages gives way to the slower diffusion of bound water trapped within the tissue matrix (Nathakaranakule et al., 2007).This pattern of drying has also been described in research with meat and vegetable tissues, where there is subsequent limiting by innermost diffusion of the water after the early stage (Aykın-Dinçer and Erbaş, 2018; Baslar et al., 2024). In particular, UAVD at 70 °C shortened the drying time by approximately 22% compared to VD (90 min vs. 115 min), supporting its efficiency. These findings are in line with previous literature in verifying the usual drying pattern of high-moisture biological materials under different thermal conditions (Nathakaranakule et al., 2007; Aykın-Dinçer and Erbaş, 2018; Baslar et al., 2024).

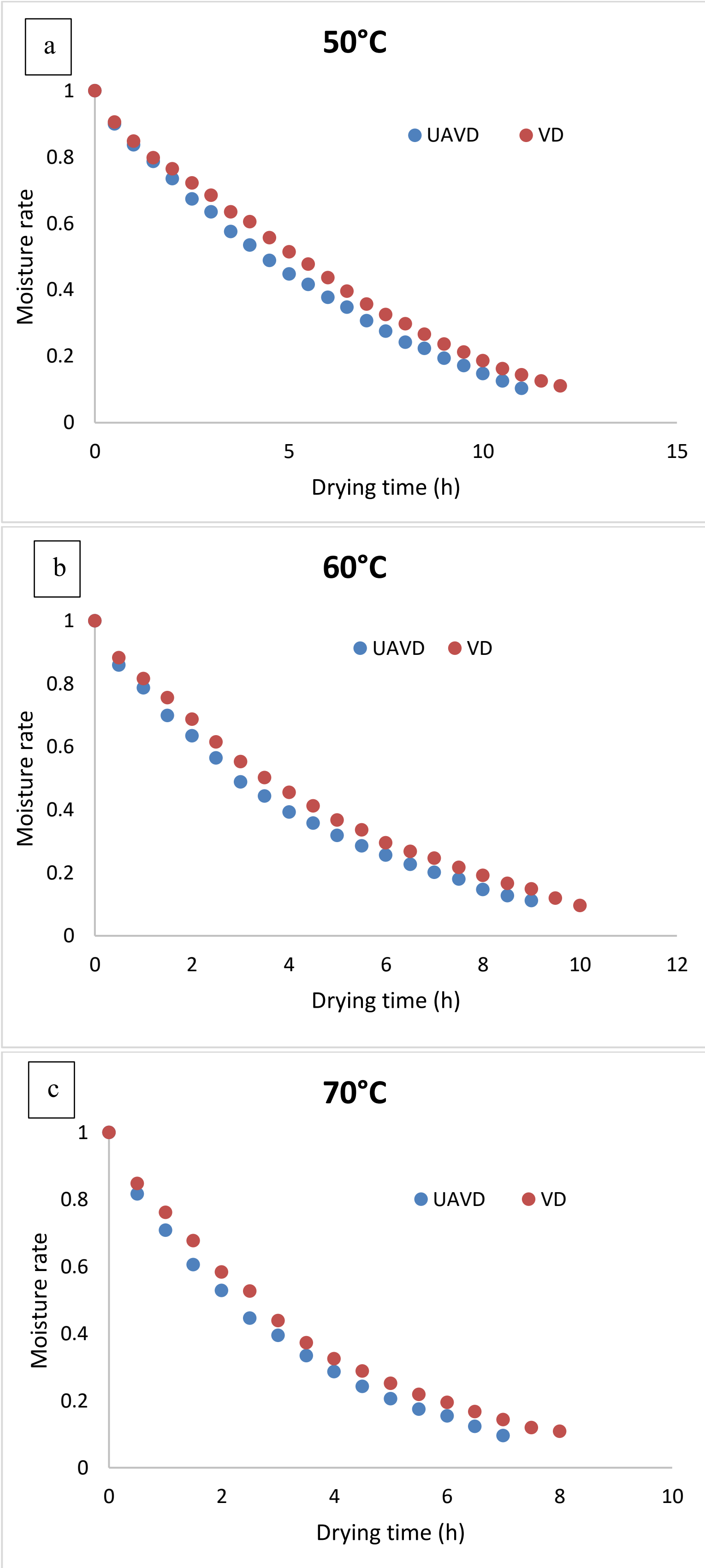

Figure 1. Drying curves of turkey breast meat dried using vacuum drying (VD) and ultrasound-assisted vacuum drying (UAVD) at different temperatures: (a) 50 °C, (b) 60 °C, and (c) 70 °C

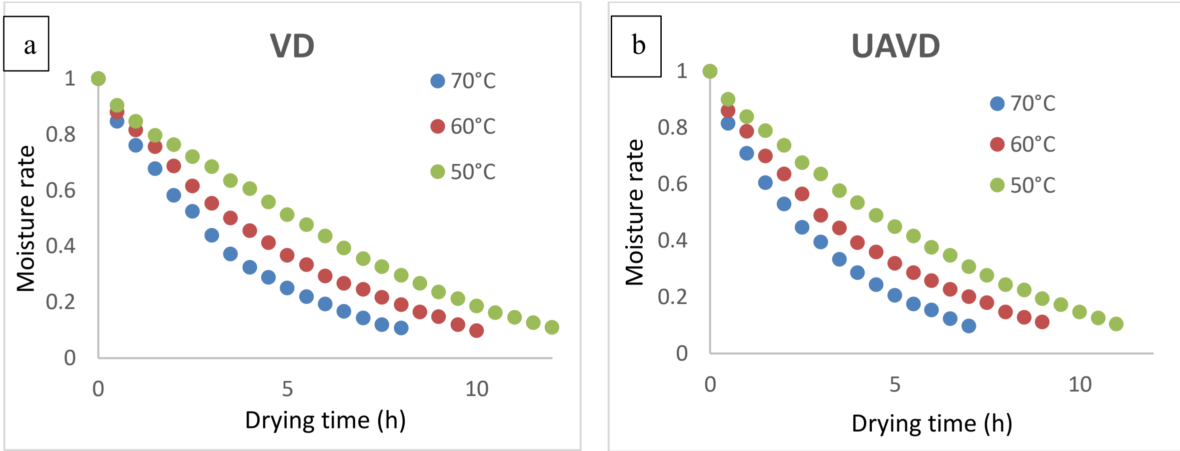

Figure 2. Drying behavior of turkey breast meat at 50 °C, 60 °C, and 70 °C under vacuum (a) and ultrasound-assisted vacuum drying (b) conditions.

Figure 2 illustrates the drying efficiency of VD and UAVD methods with regards to distinct temperatures. UAVD demonstrated a significant rise in drying efficiency against standard vacuum drying in all conditions. For instance, drying time at 60 °C decreased from 102 min (VD) to 82 min (UAVD), indicating a 19.6% improvement. This enhancement is attributed to mechanical effects of ultrasound, including cavitation, acoustic streaming, and microchannel formation, which facilitate moisture removal by disrupting the cellular structure and increasing water mobility (Baslar et al., 2014; Nowacka et al., 2012). The ultrasonic effect was greater at high temperatures, where softening of meat tissue down to the structural level likely enhances the efficiency and extent of ultrasound wave penetration. With increasing temperature, ultrasound synergistically enhances internal moisture diffusion so that drying becomes more uniform and rapid (Aksoy et al., 2019). These studies are in support of previous studies that emphasized the advantages of ultrasound methods in shortening drying time and maintaining product quality, specifically in high-moisture meat products (Baslar et al., 2014; Baslar et al., 2015; Aksoy et al., 2019).

Modeling of drying kinetics

Moisture rate of breast meat versus time was in accordance with the six drying models shown in Table 1. Among these, the Logarithmic model provided the best fit for UAVD samples across all temperatures. Table 2 displays the model parameters estimated from applying drying models to the breast meat.

R^2 values approaching 1.000 suggest that the dependent variable is effectively modeled as a function of the relevant parameter. This indicates high alignment between experimental and predicted values. To evaluate the precision, both the RMSE value, which reflects discrepancies between the experimental and predicted data, and the χ^2 values should be near zero (Baslar et al., 2024). These metrics have been computed and are detailed in Table 2. An analysis of the data presented in Table 2 reveals that among the six different models, the Logarithmic model showed the best fit the UAVD of breast meat. The R^2 value for this model ranged from 0.998 to 0.999, approaching 1, while the RMSE (0.00574–0.01072) and χ^2 (0.00003–0.00012) values were closer to zero. Upon examining the results, it is possible to determine the moisture content of the turkey meat at any moment during the dehydration process through this model.

D_{eff} values of drying techniques at different temperatures are presented in Table 3. D_{eff} increased with temperature, ranging from 2.79×10^{-5} m²/s (VD-50 °C) to 1.10×10^{-4} m²/s (UAVD-70 °C), indicating enhanced diffusion. The UAVD method showed higher D_{eff} values than the VD method at every temperature. From this, it is understood that UAVD is a more efficient drying technique in terms of diffusion. Similar enhancements in moisture diffusivity and drying efficiency through ultrasound-assisted vacuum drying have been reported in meat matrices by Aksoy et al. (2019) and Baslar et al. (2014).

Arrhenius equation parameters calculated for D_{eff} values are presented in Table 4. D_0 values reveal the potential moisture mobility at infinite temperature; here, UAVD showed a ~3.7-fold higher D_0 than VD (4.23×10^{-3} vs 1.15×10^{-3} m²/s), indicating a greater intrinsic capacity for water diffusion under elevated energy input.Activation energy (E_a) of the effective moisture diffusivity (D_{eff}) for vacuum and ultrasound assisted vacuum drying techniques was detected as 29,556 kj/mol and 32,814 kj/mol, respectively. Although the UAVD method required slightly higher energy to initiate moisture diffusion, this higher Ea suggests stronger interactions within the tissue matrix, which are likely disrupted more efficiently by ultrasonic cavitation.Based on the obtained results, it has been concluded that the ultrasound-assisted drying method is more sensitive compared to the vacuum drying method. These results align with the literature. Likewise, studies employing both vacuum drying and ultrasound-assisted vacuum drying methods have reported similar findings as determined in this study (Baslar et al., 2014; 2015). The R^2 values were determined as 0.999 for the ultrasound-assisted vacuum drying technique and 1.000 for the vacuum drying technique. This result indicates that the applied model effectively explains the relationship between the D_{eff} value and the drying temperature, demonstrating a high degree of compatibility with the experimental data. The effective moisture diffusivity (D_{eff}) is a critical parameter used to understand how moisture is transported during the drying process (Minaei et al., 2012). However, the perfect R^2 value (1.000) in VD may reflect model overfitting or high linearity within the tested range, and should be interpreted cautiously.

Table 2. Estimated Parameters Obtained from Kinetic Models for Breast Meat

Models	Parameters	UAVD			VD		
		50°C	60°C	70°C	50°C	60°C	70°C
Lewis	k	0.169	0.232	0.320	0.148	0.202	0.274
	R^2	0.992	0.999	0.998	0.983	0.997	0.999
	χ^2	0.00049	0.00010	0.00016	0.00122	0.00021	0.00010
	RMSE	0.02177	0.00992	0.01236	0.03427	0.01413	0.00974
Page	k	0.138	0.237	0.339	0.106	0.185	0.269
	n	1.114	0.985	0.952	1.180	1.056	1.014
	R^2	0.996	0.999	0.999	0.992	0.998	0.999
	χ^2	0.00025	0.00010	0.00010	0.00055	0.00013	0.00010
	RMSE	0.01543	0.00964	0.00964	0.02295	0.01117	0.00948
Weibull	a	0.964	0.987	0.989	0.944	0.980	0.990
	k	0.114	0.226	0.328	0.075	0.170	0.260
	n	1.194	1.007	0.969	1.326	1.091	1.031
	R^2	0.997	0.999	0.999	0.996	0.999	0.999
	χ^2	0.00017	0.00009	0.00009	0.00031	0.00010	0.00009
	RMSE	0.0128	0.009	0.00912	0.01736	0.00997	0.00908
Henderson & Pabis	a	1.017	0.989	0.980	1.025	1.007	0.999
	k	0.172	0.229	0.313	0.153	0.204	0.274
	R^2	0.992	0.999	0.999	0.984	0.997	0.999
	χ^2	0.00046	0.00009	0.00010	0.00113	0.00020	0.00010
	RMSE	0.02102	0.00903	0.00986	0.03294	0.01386	0.00973
Logarithmic	a	1.232	1.007	0.984	1.443	1.083	1.015
	k	0.113	0.217	0.309	0.078	0.169	0.261
	c	-0.251	-0.024	-0.005	-0.467	0.094	-0.022
	R^2	0.999	0.999	0.999	0.998	0.999	0.999
	χ^2	0.00003	0.00007	0.00010	0.00012	0.00005	0.00009
	RMSE	0.00574	0.00830	0.00981	0.01072	0.00700	0.00899
Wang & Singh	a	-0.136	-0.195	-0.265	-0.116	-0.166	-0.228
	b	0.005	0.011	0.020	0.004	0.008	0.015
	R^2	0.997	0.992	0.988	0.997	0.996	0.995
	χ^2	0.00016	0.00055	0.00088	0.00021	0.00029	0.00036
	RMSE	0.01240	0.02290	0.02863	0.01429	0.01670	0.01849

R^2: Coefficient of determination; *χ^2: Chi-square; RMSE: Root Mean Square Error; k, n, a, b, c: Drying constants and model coefficients.*

Table 3. D_{eff} values of drying techniques at different temperatures

Temperature (°C)	UAVD D_{eff} (m^2/s)	VD D_{eff} (m^2/s)
50	4.11×10^{-5}	2.79×10^{-5}
60	6.91×10^{-5}	4.75×10^{-5}
70	1.10×10^{-4}	7.58×10^{-5}

D_{eff}: Effective moisture diffusivity (m^2/s).

Table 4. Arrhenius equation parameters calculated for D_{eff} values

Drying Technique	Arrhenius parameters		
	D_0 (m^2/s)	E_a (kj/mol)	R^2
UAVD	4.23×10^{-3}	32.814	0.999
VD	1.15×10^{-3}	29.556	1.000

D_0: Frequency factor (m^2/s); *Ea:* Activation energy (kJ/mol); *R^2:* Coefficient of determination.

CONCLUSION

Turkey meat is highly perishable due to its biological structure, making drying a relevant method for shelf-life extension. Various technological methods, including drying, are utilized to extend its shelf life. In this study, the effectiveness of ultrasound-assisted vacuum drying was examined alongside conventional vacuum drying. The findings revealed that this innovative approach dehydrates turkey breast meat in a shorter time compared to vacuum drying alone. Additionally, increasing the drying temperature from 50°C to 70°C further accelerated the drying rate. The results indicate that ultrasound-assisted vacuum drying can be successfully applied for drying turkey breast meat. However, future studies should also investigate the effects of this technique on physicochemical, microstructural (e.g., SEM imaging), and sensory attributes of the dried meat to better understand the changes induced during the drying process. Moreover, the scalability of UAVD for industrial-level applications remains to be explored. Given that the present study was conducted at laboratory scale, future research should assess the energy efficiency, operational costs, and feasibility of integrating UAVD into continuous drying systems used in meat processing facilities.

Compliance with Ethical Standards

Peer Review

This article has been reviewed by independent experts in the field using a rigorous double-blind peer review process.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

M. Ali Çakır: Conceptualization, Methodology, Resources, Investigation, Project administration.
Emre Kabil: Data curation, Calculations, Formal analysis, Writing – original draft.
Barış Yalınkılıç: Validation, Writing – original draft, Review & editing
Mehmet Başlar: Supervision, Calculations, Review & editing.

Ethics Committee Approval

Ethical approval was not required for this study.

Consent to Participate / Publish

Not applicable.

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Data Availability

Not applicable.

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