

Thin-layer drying characteristics of black solo garlic: Mathematical and ANN modelling, diffusivity, and antioxidant enhancement

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ABSTRACT

Drying is a critical step in processing black solo garlic to enhance its stability and broaden its applications. This study investigated the effects of drying temperature (50–70 °C) on the convective oven drying kinetics, energy consumption, physicochemical properties, and antioxidant activity of black solo garlic slices. Drying behaviour, effective moisture diffusivity, and activation energy were evaluated. Several thin-layer models and an artificial neural network (ANN) were applied to describe the drying kinetics. Increasing drying temperature increased the drying rate, reduced drying time and energy consumption. The effective moisture diffusivity ranged from 4.16×10^{-10} to $7.45 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$, with an activation energy of $27.07 \text{ kJ mol}^{-1}$. Drying occurred entirely in the falling-rate period, indicating internal moisture diffusion as the dominant mechanism. The ANN model demonstrated excellent predictive performance comparable to that of the thin-layer models ($R^2 > 0.99$; RMSE < 0.02). Higher drying temperatures promoted melanoidin formation and increased antioxidant activity (6.91–9.13 mg AAE/g db) while preserving phenolic content, although rehydration capacity decreased. Among the investigated conditions, 70 °C provided the best overall balance for the production of dried black solo garlic as a functional food ingredient. These findings demonstrate the potential of combining thin-layer mathematical modelling and ANN to optimise industrial drying processes for black solo garlic.

KEYWORDS

black solo garlic, artificial neural network, drying kinetics, effective moisture diffusivity, antioxidant activity

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1. INTRODUCTION

Black garlic (BG) is a product obtained through thermal processing of garlic (*Allium sativum* L.), which is produced through prolonged exposure to high temperature and humidity. During this process, complex Maillard reactions and chemical transformations occur, leading to a substantial increase in bioactive compounds such as organosulfur compounds, polyphenols, flavonoids, and alkaloids (Ahmed and Wang, 2021). The composition and functional properties of black garlic are strongly influenced by the garlic variety used. Solo garlic (*A. sativum* L. var. *solo*), a single clove variety that undergoes alteration of bulb formation due to environmental stress and genetic traits, has attracted increasing attention due to its higher concentration of bioactive compounds compared to multi-clove garlic (Naji et al., 2017). As a result, black solo garlic (BSG) obtained by thermal processing of solo garlic contains elevated levels of S-allyl cysteine, flavonoids, and total phenolic compounds (Qiu et al., 2020). Despite being frequently consumed in its fresh form, the practical application of BSG remains constrained by its high moisture content (50–70% on a wet basis) and large bulb size (Chang et al., 2023). Furthermore, there is a growing market demand for black garlic in versatile forms, such as powders for functional food ingredients, culinary seasonings, and nutraceutical capsules.

Previous studies related to drying of BG primarily focused on changes in bioactive compounds, antioxidant activity, and colour development using different drying techniques and conditions (Sari and Herdyastuti, 2024; Wijayanti et al., 2024). One particular study investigated the drying kinetics of BG (Masztalerz et al., 2023). However, it was conducted using multiple bulb BG and did not explore moisture transfer behaviour, effective moisture diffusivity, activation energy, and energy consumption during drying. In recent years, artificial neural networks (ANN) have been successfully applied in various food drying studies to predict moisture ratio and drying behaviour with higher accuracy than traditional mathematical models (Chasiotis et al., 2020). In contrast with conventional models, ANNs show greater flexibility without requiring predefined equations. Despite its advantages, the application of ANN in modelling the drying kinetics of BSG remains limited.

Therefore, this study investigated the drying kinetics of BSG, determined effective moisture diffusivity and activation energy, and evaluated energy consumption. ANN and thin-layer drying models were employed to predict drying behaviour. In addition, the effects of drying temperature on physical properties, rehydration behaviour, total phenolic content, and antioxidant activity were assessed.

2. MATERIALS AND METHODS

2.1. Materials

BSG used in this study was obtained from Karanganyar, Central Java, Indonesia. The reagents used included DPPH (Pro Analysis, Sigma-Aldrich, Missouri, USA), Folin–Ciocalteu reagent, sodium carbonate, ascorbic acid, gallic acid (Pro Analysis, Merck, Darmstadt, Germany), absolute ethanol, and hexane (Pro Analysis, Smart Lab, Tangerang, Indonesia).

2.2. Sample preparation

After removing the outer skin, BSG samples were cut into slices with 2 mm thickness using an adjustable mandoline slicer. The initial moisture content of BSG was determined gravimetrically according to the AOAC 925.10 method (AOAC, 2005).

2.3. Drying apparatus and procedure

The drying of BSG slices was conducted in a convective oven (UN55 plus, Memmert, Germany) at temperatures of 50, 55, 60, 65, and 70 °C under forced-air circulation with an air velocity of 5 m s^{-1} , corresponding to an estimated airflow rate of $0.80 \text{ m}^3 \text{ s}^{-1}$ based on the chamber cross-sectional area. Drying experiments were conducted in an air-conditioned environment with a relative humidity of $50 \pm 5\%$. Evenly spaced BSG slices weighing $88 \pm 2 \text{ g}$ were placed on a single-layer stainless-steel mesh tray. Sample mass was continuously monitored using an internal weighing system consisting of a three-kilogram load cell with a resolution of 0.01 g, HX711 analogue-to-digital converter, and ESP32 microcontroller. The weighing system was calibrated against 12 standard weights to ensure accuracy. The data logging was conducted at 1-min intervals using a Python program (Version 3.13) running on a computer.

2.4. Drying curve and kinetics

Drying curves were obtained by plotting the moisture ratio (MR) as a function of drying time in min (t). The moisture content at time t was determined from the recorded mass loss, assuming that all mass loss during drying was attributable to water evaporation, as commonly reported for thin-layer drying under convective conditions (El-Mesery et al., 2022). The drying rate is defined as the rate at which moisture is removed from a product over a given period. The drying rate was calculated as the change in moisture content over time according to Guo et al. (2023).

2.5. Mathematical modelling

The obtained plots of MR against time were fitted to five common drying models frequently used to describe the drying process of food products, namely, the Two-term exponential, Verma et al., Midilli et al., logarithmic, and Page models (Guo et al., 2023). Simple single-term models such as the Newton model were not considered, as preliminary analysis indicated multi-stage drying behaviour characterised by an initial rapid removal of moisture followed by a prolonged diffusion-controlled period.

2.6. Artificial neural network modelling

An artificial neural network (ANN) was developed to predict the moisture ratio (MR) of BSG slices using the neuralnet package in R (RStudio, version 2024.04.2). A feedforward multilayer perceptron (MLP) architecture consisting of two input neurons (drying temperature and drying time), one hidden layer with four neurons, and one output neuron (MR) was implemented. Prior to model training, all variables were normalised to a range of 0–1 using min–max normalisation. The dataset was randomly divided into training (80%) and testing (20%) subsets using the “createDataPartition” function from the caret package with a fixed random seed (set.seed(123)) to ensure reproducibility. The hidden layer employed the default logistic sigmoid activation function, whereas a linear activation function was used in the output layer

(linear.output = TRUE). Model training was performed using the default resilient backpropagation algorithm implemented in the neuralnet package, with a maximum number of training steps (stepmax) set to 1×10^6 . The optimal hidden layer size (four neurons) was selected from preliminary trials (1–10 neurons) based on the highest coefficient of determination (R^2), lowest root mean square error (RMSE), and avoidance of overfitting. Model performance was evaluated using both the training and independent testing datasets.

2.7. Effective moisture diffusivity (D_{eff}) and activation energy (E_a) determination

The effective moisture diffusivity of BSG samples was calculated based on Fick's second law of diffusion. Based on the Arrhenius equation, the activation energy was calculated by plotting $\ln(D_{\text{eff}})$ versus $1/T$, where the slope corresponds to $-E_a/R$ (El-Mesery et al., 2022).

2.8. Specific energy consumption

The energy required for drying was measured using an energy meter (Taffwaree KWE-PM01, Indonesia) attached to the dryer. Specific energy consumption was expressed as kWh kg^{-1} .

2.9. Quality evaluation of dried BSG slices

2.9.1. Water activity. Water activity of dried BSG slices was analysed using a water activity meter (Landtek WA-60A, China). One g of the sample was placed in an acrylic plate and put inside the instrument to be measured.

2.9.2. Rehydration ratio. Rehydration ratio was assessed by submerging approximately 2 g of the sample in 50 mL distilled water at room temperature for 2 h. The rehydration ratio was calculated according to Liu et al. (2023).

2.9.3. Colour and melanoidin analysis. The colour of dried BSG samples was analysed using a colour reader (CHNSpec CS-10, China) in the CIELAB colour space inside a white box with controlled lighting after calibration using standard black and white references. To confirm colour analysis, melanoidin of dried BSG was analysed using UV–Vis spectrophotometer (Shimadzu UV1800, Japan) in accordance with Wang et al. (2023). The absorbance of defatted extracts was then analysed at 280, 325, and 420 nm in a quartz cuvette using distilled water as a blank.

2.9.4. Total phenolic content and antioxidant activity assay. Total phenolic content was determined using the Folin–Ciocalteu assay, while antioxidant activity was determined using the DPPH radical scavenging assay according to Lu et al. (2017). Total phenolic content was expressed as mg gallic acid equivalent (GAE) per g sample based on a calibration curve of $y = 0.0049x + 0.0268$ ($R^2 = 0.9989$), where y is the absorbance at 760 nm and x is the concentration of gallic acid ($\mu\text{g mL}^{-1}$). Antioxidant activity was expressed as mg ascorbic acid equivalent (AAE) per g sample based on a calibration curve of $y = 0.0027 + 0.0444x$ ($R^2 = 0.9894$), where y is the absorbance at 517 nm and x is the concentration of ascorbic acid ($\mu\text{g mL}^{-1}$).

2.10. Statistical analysis

RStudio (version 2024.04.2) was used for statistical analysis as well as for plotting the data. The goodness of fit of the drying models was determined by R^2 , χ^2 , and RMSE. For quality evaluations, differences between samples were considered statistically significant at $P < 0.05$ and were determined using one-way analysis of variance (ANOVA) followed by Tukey HSD test. All quality evaluations were done in triplicate.

3. RESULTS AND DISCUSSION

3.1. Effect of drying temperature on drying kinetics of BSG

Fresh BSG (Fig. 1a) exhibited a high initial moisture content of $131.65 \pm 1.49\%$ (db). Unlike fresh garlic, which can typically be dried to moisture contents below 8% (db) (Liu et al., 2023), BSG retained relatively high residual moisture even after drying (48.77, 49.94, 36.45, 34.26, and 32.10% (db) at drying temperature of 50, 55, 60, 65, and 70 °C, respectively (Fig. 1b). Yuan et al. (2018) reported a substantial decrease in fructan level accompanied by an increase in fructose content during thermal processing of BG. The accumulation of low-molecular-weight sugars is likely to increase the proportion of bound water, thereby reducing the fraction of freely evaporating moisture. Similar temperature-dependent moisture reduction behaviour has been reported for thermally processed plant materials such as beetroot peels (Khater et al., 2025) and malacca fruit (Raaf et al., 2021).

The drying behaviour of BSG at different temperatures is illustrated in Fig. 2a. Higher drying temperatures resulted in steeper drying curves, indicating accelerated moisture removal. A rapid decrease in moisture ratio was observed during the initial 100 min, followed by a progressively slower drying phase approaching an asymptotic equilibrium, consistent with diffusion-controlled drying behaviour. This trend agrees with observations reported for BG dried at comparable temperature ranges (Masztalerz et al., 2023).

Drying rate curves (Fig. 2b) further confirm the influence of temperature on the moisture removal kinetics. Higher temperatures produced higher initial drying rates, while all drying conditions exhibited only falling-rate periods, with no constant-rate period detected. The absence of a constant-rate period suggests that surface free water was minimal and that internal moisture diffusion governed the mass transfer throughout the drying process. Similar drying characteristics have been reported for garlic and BG products (El-Mesery et al., 2022; Guo et al., 2023).

3.2. Mathematical and ANN modelling of BSG drying

The fitting results for all models at different drying temperatures are summarised in Table 1. The Page model, despite its widespread application for agricultural products, showed comparatively lower fitting accuracy ($R^2 = 0.931$ – 0.947). This model does not explicitly account for structural shrinkage or changing diffusion pathways, which limits its ability to describe drying behaviour in materials undergoing severe matrix collapse (Simpson et al., 2017).

At drying temperatures of 50 and 70 °C, the Two-Term Exponential model provided the best agreement with experimental data. This model incorporates two exponential terms, suggesting the coexistence of at least two distinct moisture-transfer mechanisms. This behaviour is

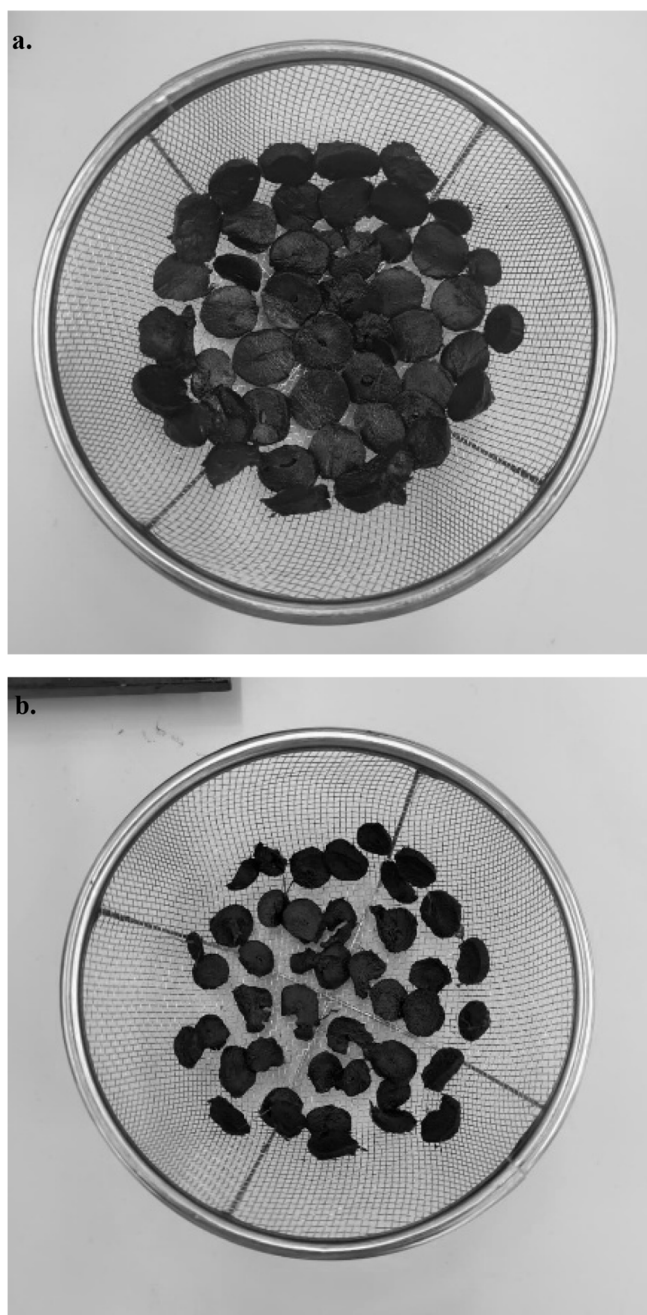


Fig. 1. Visual appearance of a) fresh and b) dried black solo garlic slices

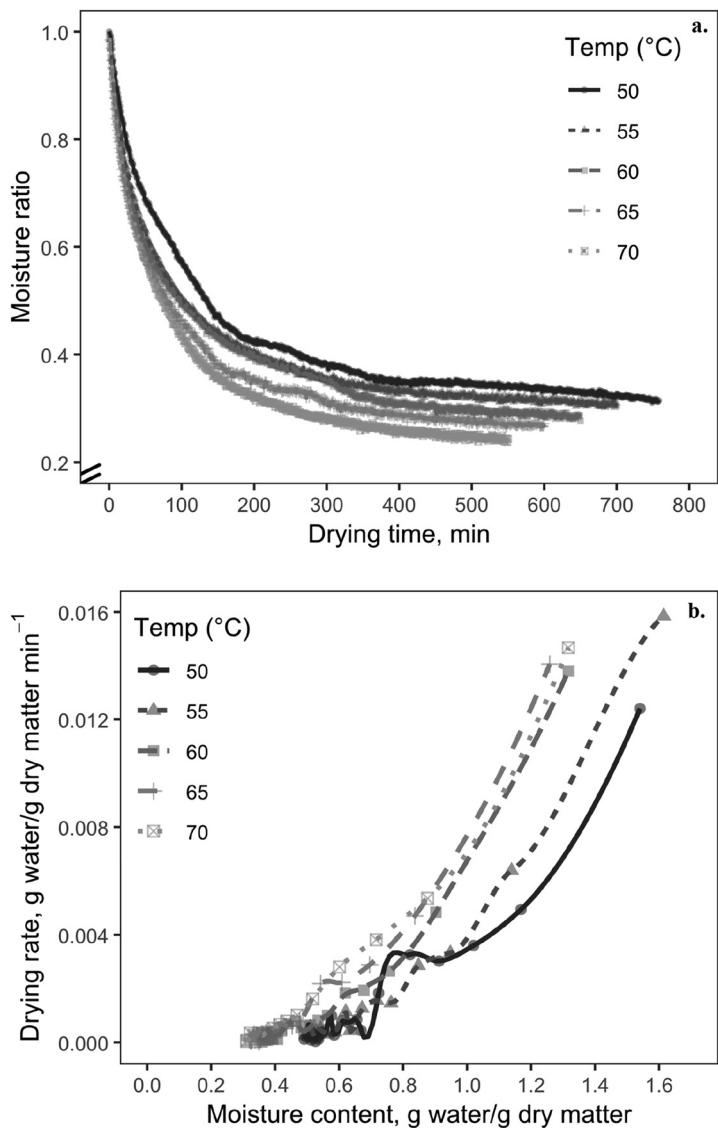


Fig. 2. a) Drying curve and b) drying rate of black solo garlic at different temperatures

consistent with the drying rate curves, which exhibited a more pronounced second falling-rate period at both temperature extremes. In contrast, for intermediate drying temperatures (55–65 °C), the Midilli model consistently yielded the lowest χ^2 and RMSE values. This indicates a smoother transition between drying stages, where moisture diffusion and structural changes occur concurrently without abrupt shifts in drying mechanisms. The superior performance of multi-term models further supports the conclusion that moisture migration in BSG is governed by internal diffusion with varying resistance rather than a single-rate evaporation mechanism.

Table 1. Mathematical model constants and fitting for BSG drying

Temp (°C)	Model	k	n	a	c	b	k ₁	R ²	RMSE	χ ²
50	Two-Term Exponential	0.0116		0.5602		0.3934	2.79 × 10 ^{−4}	0.9965	0.0080	0.0862
	Verma	0.0133		0.5873			3.58 × 10 ^{−4}	0.9939	0.0106	0.1439
	Midilli	0.0529	0.5603	1.0755		2.83 × 10 ^{−4}		0.9938	0.0107	0.2038
	Exponential	0.0094		0.5979	0.3348			0.9933	0.0111	0.1926
	Page	0.0904	0.4001					0.9366	0.0341	1.9195
55	Midilli	0.0883	0.4844	1.1046		2.65 × 10 ^{−4}		0.9962	0.0079	0.0861
	Two Term Exponential	0.0158		0.5385		0.4042	4.37 × 10 ^{−4}	0.9943	0.0097	0.1317
	Verma	0.0190		0.5767			5.25 × 10 ^{−4}	0.9909	0.0122	0.2239
	Exponential	0.0112		0.5784	0.3229			0.9857	0.0153	0.3172
	Page	0.1199	0.3665					0.9400	0.0313	1.5151
60	Midilli	0.1213	0.4183	1.1221		1.49 × 10 ^{−4}		0.9951	0.0084	0.1589
	Two Term Exponential	0.0137		0.5217		0.3759	4.06 × 10 ^{−4}	0.9879	0.0132	0.3794
	Verma	0.0190		0.5964			5.09 × 10 ^{−4}	0.9793	0.0173	0.7105
	Exponential	0.0085		0.5538	0.2824			0.9731	0.0197	0.7860
	Page	0.1462	0.3353					0.9466	0.0277	1.8563
65	Midilli	0.1274	0.4304	1.1325		1.79 × 10 ^{−4}		0.9929	0.0102	0.2373
	Two Term Exponential	0.0156		0.5631		0.3547	4.04 × 10 ^{−4}	0.9927	0.0104	0.1953
	Verma	0.0199		0.6337			4.94 × 10 ^{−4}	0.9852	0.0148	0.4264
	Exponential	0.0108		0.5897	0.2697			0.9791	0.0175	0.6479
	Page	0.1608	0.3332					0.9310	0.0319	2.2983
70	Two Term Exponential	0.0163		0.6075		0.3261	5.32 × 10 ^{−4}	0.9966	0.0079	0.1005
	Midilli	0.1058	0.4815	1.1252		2.01 × 10 ^{−4}		0.9931	0.0112	0.2814
	Verma	0.0193		0.6570			6.21 × 10 ^{−4}	0.9928	0.0115	0.2230
	Exponential	0.0117		0.6437	0.2441			0.9852	0.0164	0.5747
	Page	0.1377	0.3771					0.9372	0.0338	2.4234

Note: k, n, a, b, c, and k₁ represent empirical constants specific to the respective thin-layer drying models; R²: coefficient of determination; RMSE: root mean square error; χ²: reduced chi-square.

The predictive performance of the ANN model is presented in Fig. 3. The ANN model showed a strong agreement between predicted and experimental values, with data points closely distributed along the parity line. The performance of the ANN model was found to be comparable to that of the best-performing thin-layer drying models, particularly the Two-Term Exponential and Midilli models. These results indicate that both approaches can accurately describe the drying behaviour of BSG. While thin-layer models rely on predefined mathematical equations to describe drying kinetics, the ANN model offers greater flexibility in capturing complex and nonlinear relationships between drying variables without predefined assumptions (Chasiotis et al., 2020). This makes ANN particularly useful for predictive applications under varying drying conditions.

3.3. Effective moisture diffusivity and activation energy

Given that the drying behaviour was dominated by falling-rate periods and was accurately described by diffusion-based empirical models, effective moisture diffusivity was quantified to further characterise internal mass-transfer resistance. The calculated D_{eff} values are presented in Table 2.

The D_{eff} of BSG increased from 4.16×10^{-10} to $7.45 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ as the drying temperature increased from 50 to 70 °C, indicating enhanced moisture mobility at higher temperatures. These values fall within the typical range reported for fruits and vegetables (10^{-7} – $10^{-12} \text{ m}^2 \text{ s}^{-1}$). Comparable D_{eff} values have been reported for fresh garlic under hot-air drying, ranging from 1.4×10^{-10} to $2.0 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ at 40–60 °C (El-Mesery et al., 2022) and from 1.5×10^{-9} to $5.31 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ at 50–70 °C (Guo et al., 2023). Rahman et al. (2009) reported D_{eff} values between 1.1×10^{-9} and $1.81 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ for drying temperatures of 50–105 °C. The comparatively lower D_{eff} values observed for BSG suggest that structural changes induced during thermal processing may reduce porosity and increase internal mass-transfer resistance, thereby hindering moisture diffusion.

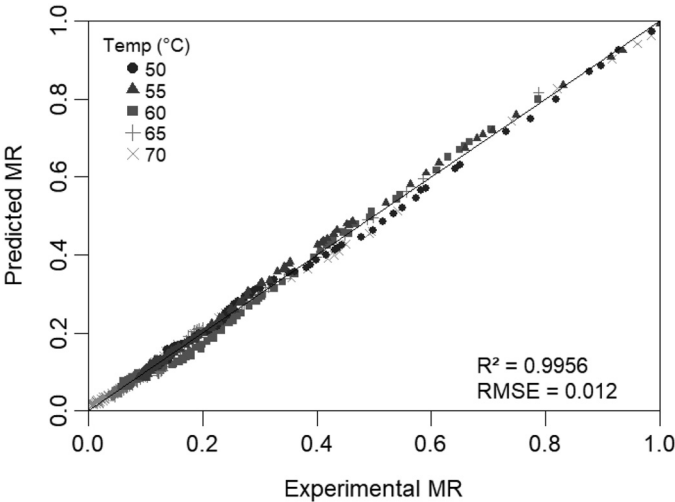


Fig. 3. Comparison of experimental and predicted moisture ratio using artificial neural network modelling

Table 2. Effective moisture diffusivity and energy consumption

Temp (°C)	D_{eff} ($\text{m}^2 \text{s}^{-1}$)	Fitting equation	R^2	Ea (kJ mol^{-1})	Drying time (min)	SEC (kWh kg^{-1})
50	4.16×10^{-10}	$\ln(D_{\text{eff}}) = -11.56 - 3255.55/T$	0.968	27.07	366	6.41
55	4.42×10^{-10}				303	5.98
60	5.43×10^{-10}				303	5.72
65	6.01×10^{-10}				195	4.88
70	7.45×10^{-10}				159	4.51

Note: D_{eff} : effective moisture diffusivity; Ea: activation energy; SEC: specific energy consumption.

A lower Ea is generally associated with higher drying efficiency and shorter drying times. In this study, the Ea of BSG was determined to be $27.07 \text{ kJ mol}^{-1}$ (Table 2). This value is higher than those reported for garlic dried using hot-air drying (18.1 kJ mol^{-1}) (El-Mesery et al., 2022) and fluidised-bed drying ($12.16\text{--}12.8 \text{ kJ mol}^{-1}$) (Sampangi et al., 2022), indicating that moisture removal from BSG requires a higher energy input. This behaviour suggests that BSG drying may benefit from pretreatment strategies or alternative drying technologies to reduce internal mass-transfer resistance and improve process efficiency.

3.4. Specific energy consumption

In BSG drying, the final MR was found to be temperature-dependent (Table 2). Therefore, drying time and energy consumption were evaluated at a fixed endpoint of $\text{MR} = 0.35$ to allow a fair comparison across different drying temperatures. As shown in Table 2, the specific electrical energy consumption during BSG drying ranged from 4.51 to 6.41 kWh kg^{-1} . Increasing the drying temperature resulted in a reduction in total energy consumption, despite the higher instantaneous energy input required to maintain elevated air temperatures. This behaviour can be attributed to the reduction in drying time at higher temperatures, which ultimately lowered the cumulative energy demand of the system (Khater et al., 2025). This trend is consistent with the shorter duration required before the drying rate entered a pronounced falling-rate period at higher drying temperatures (Fig. 2) as well as the higher effective moisture diffusivity at higher temperatures (Table 2). Similar observations were reported by El-Mesery et al. (2022), who found a 37.8% reduction in energy consumption accompanied by a 36.7% decrease in drying time when increasing the drying temperature from 40 to 60°C for garlic.

3.5. Quality analysis of dried BSG

3.5.1. Physical and physicochemical properties of dried BSG. Water activity (a_w) is widely used as an indicator of product shelf stability, as microbial growth is strongly inhibited at a_w values below 0.60 (İlter et al., 2018). All dried BSG samples exhibited a_w values below this threshold, indicating good microbiological stability (Table 3). Significant differences ($P < 0.05$) in a_w were observed among drying temperatures. However, no significant difference was detected between the samples dried at 65 and 70°C , suggesting that the material approached equilibrium moisture conditions at higher temperatures. Fresh black garlic has been reported to exhibit a_w values ranging from 0.58 to 0.88 depending on processing duration (Chang et al.,

Table 3. Physical and physicochemical properties of dried black solo garlic slices

Temp (°C)	a_w	RR	L^*	a^*	b^*	A_{280}	A_{325}	A_{420}
50	0.56 ± 0.01 ^a	1.83 ± 0.04 ^a	38.5 ± 0.61 ^a	−5.24 ± 1.06 ^a	0.72 ± 1.53 ^b	0.293 ± 0.0006 ^c	0.184 ± 0.0006 ^c	0.070 ± 0.0006 ^c
55	0.53 ± 0.01 ^{bc}	1.84 ± 0.04 ^a	39.1 ± 0.50 ^a	−4.93 ± 0.50 ^a	2.57 ± 0.14 ^a	0.366 ± 0.0032 ^d	0.232 ± 0.0017 ^d	0.090 ± 0.0015 ^d
60	0.53 ± 0.01 ^b	1.58 ± 0.04 ^b	39.3 ± 0.34 ^a	−4.33 ± 0.15 ^a	3.47 ± 0.13 ^a	0.409 ± 0.0006 ^c	0.276 ± 0.0006 ^c	0.106 ± 0.0006 ^c
65	0.51 ± 0.01 ^c	1.64 ± 0.04 ^b	39.1 ± 0.67 ^a	−4.22 ± 0.08 ^a	3.03 ± 0.24 ^a	0.553 ± 0.0020 ^b	0.375 ± 0.0031 ^b	0.148 ± 0.0006 ^b
70	0.51 ± 0.01 ^c	1.63 ± 0.05 ^b	39.4 ± 0.34 ^a	−3.90 ± 0.39 ^a	2.67 ± 0.67 ^{ab}	0.594 ± 0.0006 ^a	0.413 ± 0.0006 ^a	0.168 ± 0 ^a

Note: Values in the same column with different superscript letters differ significantly ($P < 0.05$). a_w : water activity; RR: rehydration ratio; A_x : absorbance at specific wavelength.

2023). To the authors' knowledge, no previous study has reported a_w values for dried BSG, although dried garlic has been reported to exhibit a_w values of approximately 0.40 (Poojitha and Athmaselvi, 2023).

The rehydration ratio of dried BSG differed significantly ($P < 0.05$) among drying temperatures (Table 3), with a marked decrease observed at temperatures above 60 °C. Compared with conventional garlic, BSG exhibited lower rehydration ratios. Previous studies have reported rehydration ratios of up to 2.89 for dried garlic slices (Guo et al., 2023), whereas values ranging from 0.81 to 0.87 have been reported for garlic dried using different drying systems (Poojitha and Athmaselvi, 2023). The relatively low rehydration capacity observed in the present study may be associated with structural changes induced during the thermal aging and drying processes, which could reduce the ability of the tissue to absorb water during rehydration. However, because no microstructural characterisation (e.g., SEM or microscopy) was performed, this explanation remains speculative and warrants further investigation.

The inherently dark brown to black colour of BSG originates from intensive Maillard reactions occurring during thermal ageing. No significant differences ($P > 0.05$) were observed in lightness (L^*) and redness-greenness (a^*) values among samples dried at different temperatures (Table 3). In contrast, A_{420} increased significantly ($P < 0.05$) with drying temperature (Table 3), indicating enhanced formation of melanoidins, which are recognised as final-stage Maillard reaction products.

The absence of pronounced visual colour differences despite increased absorbance suggests that the initial pigment concentration in BSG was already high, masking further chromatic changes detectable by colorimetric analysis, while still allowing changes to be detected by spectroscopic methods. In addition, samples dried at 50 °C exhibited lower b^* values, indicating reduced yellowness. This behaviour may be associated with the predominance of low-molecular-weight Maillard reaction products, which tend to impart lighter yellowish hues (Wang et al., 2025). Consistent increases in absorbance at 280 and 325 nm were also observed, suggesting the presence of early Maillard reaction products and intermediate compounds alongside melanoidins detected at 420 nm.

3.5.2. Phenolic compound and antioxidant activity of dried BSG. Total phenolic content (TPC) of BSG expressed on a wet basis showed significant differences ($P < 0.05$) among drying temperatures. In contrast, TPC expressed on a dry basis did not differ significantly ($P > 0.05$) (Fig. 4a). The higher TPC observed on a wet basis is primarily attributable to moisture removal during drying, which concentrates phenolic compounds per unit wet weight rather than reflecting the formation of additional phenolic compounds. These results suggest that convective drying at 50–70 °C largely preserved the phenolic compounds present in BSG, with no indication of substantial thermal degradation of phenolic compounds. Similarly, Zhang et al. (2016) reported that black garlic processed at temperatures up to 80 °C exhibited high retention of phenolic compounds during thermal processing. However, the TPC of BSG observed in the present study was lower than the values reported for BG (14.90–24.05 mg GAE g⁻¹ DM) (Ahmed and Wang, 2021). This difference may be attributed to variations in garlic cultivar, processing conditions during black garlic production, extraction procedures, and analytical methods.

Although TPC on a dry basis remained relatively unchanged after drying, antioxidant activity increased significantly ($P < 0.05$) with drying temperature, suggesting that phenolic compounds were not the sole contributors to the enhanced antioxidant capacity (Fig. 4b). Compared with BG, which has been reported to exhibit antioxidant activity of approximately 1.44 mg AAE/g db (Farhat et al., 2023), BSG demonstrated higher antioxidant capacity (4.48 mg AAE/g db) even before drying. Drying further amplified this activity, highlighted by the significant increase in antioxidant activity on a dry basis. The enhancement of antioxidant capacity with increasing drying temperature is likely associated with the increased formation of melanoidins, the final products of the Maillard reaction, as indicated by the increased absorbance at 420 nm (Table 3). Melanoidins possess strong free radical scavenging activity and exhibit high thermal stability, allowing them to persist and accumulate during thermal processing (Kim, 2020). The stable TPC and significant increase in antioxidant activity suggest that the enhancement of antioxidant capacity was not solely dependent on phenolic compounds but was also influenced by newly formed Maillard reaction products during drying.

From an industrial perspective, drying at 70 °C provided the most favourable balance between drying efficiency, energy consumption, and product quality. This temperature resulted in the highest effective moisture diffusivity ($7.45 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$), the shortest drying time (159 min), and the lowest specific energy consumption (4.51 kWh kg⁻¹). In addition, drying at 70 °C produced the highest antioxidant activity while maintaining total phenolic content on a dry basis, indicating that the improved functional properties were achieved without significant phenolic degradation. Although the rehydration ratio decreased at higher drying temperatures, this limitation is less critical for BSG intended for use as a powdered functional ingredient, seasoning, or food additive. Therefore, among the investigated conditions, 70 °C can be considered the optimum drying temperature for industrial production of dried black solo garlic.

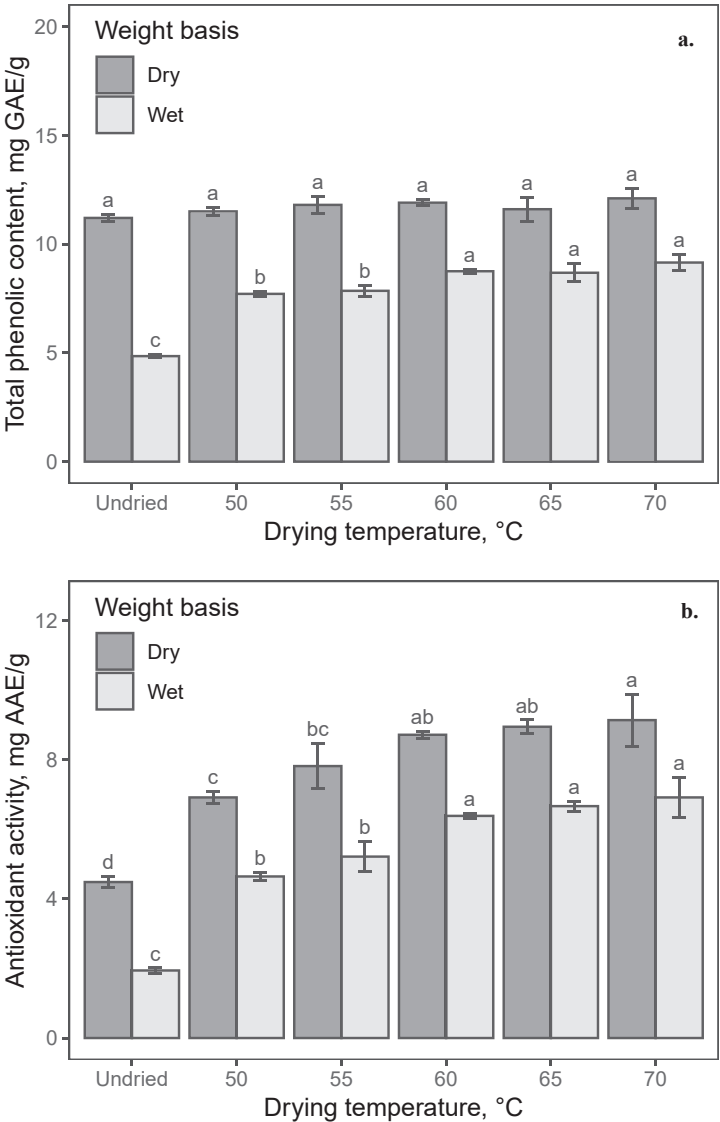


Fig. 4. a) Total phenolic content and b) antioxidant activity of black solo garlic
Error bars represent standard deviation ($n = 3$). AAE: ascorbic acid equivalent; GAE: gallic acid equivalent.
Different lowercase letters indicate significant differences among treatments ($P < 0.05$)

4. CONCLUSIONS

The convective drying of BSG slices was governed entirely by the falling-rate period, indicating that internal moisture diffusion was the dominant moisture transport mechanism. Increasing the drying temperature enhanced effective moisture diffusivity ($4.16\text{--}7.45 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$), reduced drying time and specific energy consumption, and yielded an activation energy of $27.07 \text{ kJ mol}^{-1}$. The Midilli and Two-Term Exponential models most accurately described the drying behaviour, while the ANN model provided comparable predictive performance. The optimum drying temperature was 70°C with the lowest drying time (159 min), minimum energy consumption (4.51 kWh kg), and highest antioxidant activity (9.13 mg AAE/g db). These findings provide practical guidance for industrial drying process optimisation and demonstrate that the combined application of thin-layer mathematical models and ANN offers a robust framework for predicting drying behaviour and supporting process design for black solo garlic and similar functional food materials.

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