Effect of Ultrasound-Assisted Thin Bed Drying for Retaining the Quality of Red Bell Pepper and Compare the Predictive Ability of the Mathematical Model with Artificial Neural Network

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Effect of ultrasound-assisted thin bed drying for retaining the quality of red bell pepper and compare the predictive ability of the mathematical model with artificial neural network

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Abstract

Red bell peppers (*Capsicum annuum* L.) are low in calories and high in nutrients, including vitamins A and C. Various factors such as weight loss, senescence, and microbial influence affect their quality during storage. To address this, the present study aims to preserve and retain the quality of red bell peppers using ultrasound-assisted thin-bed drying. The results were analyzed using an Artificial Neural Network (ANN) for more accurate prediction of variables involved in the process. Variations in moisture ratio and moisture content during drying were calculated and predicted. The Midilli model provided satisfactory curve fitting at an air velocity of 1.5 m/s, with $R^2 = 0.9993$, $\chi^2 = 0.0002$, and RMSE $= 0.0134$. The two-term and modified page models fit better with drying curves at air velocities of 2 and 2.5 m/s, with $R^2 = 0.9995$, $\chi^2 = 0.002$, RMSE $= 0.0016$ and $R^2 = 0.9996$, $\chi^2 = 0.00003$, RMSE $= 0.00003$, respectively. However, the trained standard backpropagation ANN algorithm demonstrated excellent predictive ability, outperforming the mathematical models with $R^2 = 0.9989$ (training), MSE $= 0.0001$ (training), and $R^2 = 0.9996$ (testing), MSE $= 0.0002$ (testing). Most importantly, the ultrasound-assisted drying process retains the essential nutrients in red bell peppers, including vitamin C, carotenoids, polyphenols, and flavonoids, across various conditions. The antioxidant potential, as measured by DPPH and FRAP assays, remains largely unchanged compared to untreated samples. However, ABTS activity shows a significant difference at an air velocity of 1.5 m/s and temperatures of 60 and 70°C compared to the control sample.

Practical applications

In terms of vitamins and antioxidants, red bell peppers are a great provider. Interestingly, capsaicin, the substance responsible for spiciness, is found in very little to no quantity in red bell peppers making it appealable to consumers. To achieve a certain level of processing, the quality of the dried product needs to be monitored while fulfilling the needs of consumers. Particularly, the quality-determining parameters were vitamin C, total carotenoids, total polyphenols, total flavonoid content, DPPH, ABTS, and FRAP activity. These qualities were retained after drying with the potential novel combination of ultrasound with thin bed drying at low temperatures and air velocity.

This means that the bioactive compounds responsible for improving the health of humans are readily available in dried form all year round. The drying kinetics were modeled, predicted, and compared with mathematical and ANN models.

KEYWORDS
antioxidant, red bell pepper, thin layer bed drying, ultrasound, vitamin C

1 | INTRODUCTION

The red bell pepper (*Capsicum annuum* L) is a rich source of various vitamins and minerals, particularly vitamins A and C. It is considered an exotic vegetable with substantial economic value (Anaya-Esparza et al., 2021). Many industrialized nations, including China, Mexico, and Turkey, generate significant profits from bell pepper cultivation (Singh & Cotty, 2019). This agricultural product is in high demand due to its savory flavor, vibrant color, nutritional benefits, antibacterial and antioxidant properties, and its role in preventing chronic diseases (Gutiérrez et al., 2015; Sun et al., 2007).

The coloration of red bell peppers is attributed to high concentrations of capsanthin, capsorubin, and capsanthin 5, 6-epoxide (Sun et al., 2007). Yellow-orange bell peppers contain beta- and gamma-carotene, zeaxanthin, lutein, and beta-cryptoxanthin, while green varieties are rich in chlorophyll and carotenoids (Chouaibi et al., 2019; Marín et al., 2004). These natural pigments not only serve as alternatives to artificial food colorings but also contribute to the pepper's multifunctionality and market value (Echegaray et al., 2023; Gomes et al., 2014; Molina et al., 2023).

Red bell peppers are prone to weight loss, senescence, and microbial contamination due to their high moisture content and perishable nature, even when refrigerated (Montoya-Ballesteros et al., 2014). They are commonly used as flavoring agents in the food processing industry (Nasiroglu & Kocabiyik, 2009; Vega-Gálvez et al., 2008). To maximize their utility and extend their shelf life, drying technologies are employed, which also facilitate easier transportation and storage.

Drying is a versatile food preservation technique (Kumar et al., 2014). It involves simultaneous heat and mass transfer, effectively reducing the water content and thereby inhibiting microbial and enzymatic activities (Guiné et al., 2012). Hot air drying is a popular commercial method with advantages such as low cost, controlled parameters, and contamination-free end products (Lin, 2023). However, it is slower than other methods due to low thermal conductivity, and the drying rate is temperature-dependent, affecting both energy consumption and product quality (Ashtiani et al., 2023; Ashtiani, Rafiee, et al., 2020).

Pre-treatments like ultrasound have been shown to accelerate the drying process by creating micro-channels in the food tissues, facilitating moisture migration to the surface for easier removal during drying (Nasiroglu & Kocabiyik, 2009; Ovando-Medina, 2023; Vega et al., 2007). Such pre-treatments improve product quality and reduce energy consumption compared to traditional thermal methods. Previous studies have demonstrated nutrient retention improvements when ultrasound is used as a pre-treatment (Abbaspour-Gilandeh et al., 2021; Feng et al., 2019).

Artificial neural networks (ANN) is a machine learning model inspired by the human brain's neural structure. It is widely used for moisture-related predictions in the drying process. ANN was found to be more productive and precise than the mathematical modeling method for predicting changes in the moisture ratio. Different studies suggested various mathematical models for predicting the drying rates and optimization of drying conditions of agricultural commodities. These models were developed to model the moisture content and quality parameters in the drying process (Nasiroglu & Kocabiyik, 2009; Ovando-Medina, 2023; Vega et al., 2007; Vega-Gálvez et al., 2008). ANN also gained industrial importance as it offered non-linear data handling that involves complex relationships (Motevali et al., 2012).

Therefore, the primary objective of this research is to conduct a comprehensive comparison between traditional mathematical models and ANN for accurately predicting the kinetics involved in ultrasound-assisted thin-bed drying of red bell peppers. A secondary focus will be to rigorously evaluate the retention profiles of key phytonutrients such as polyphenols, flavonoids, carotenoids, vitamin C, and antioxidants across different drying treatments. This will help to identify the most efficacious approaches for enhancing the shelf life of the dried product.

2 | MATERIALS AND METHODS

2.1 | Preparation of sample

The red bell peppers were procured from the locality of Tura, Meghalaya, India, with coordinates of 25° 34′ 4.5768″ N and 90° 13′ 28.0704″ E. Fresh samples with the same maturity indices were graded and manually rinsed with distilled water to eliminate latex from the surface using a 1% potassium permanganate solution. Following the washing process, the flesh of the red bell peppers was manually chopped into 1 cm cubes after being separated from the seeds and placenta. The sample pieces were then given a second wash and spread out in a single layer in a drying atmosphere. All experiments were performed using high-purity, laboratory-grade chemicals purchased from Sigma Aldrich, India.

2.2 | Pre-treatment using ultrasound

A 13 mm probe ultrasonic system (Hielscher model UP 400s) with a power output of 400 W was employed for the pre-treatment of the red bell pepper samples. Each sample, weighing 15 g, was submerged in 400 mL of distilled water contained in a 1000 mL beaker. The samples were then exposed to ultrasound for 10 min at a power density of 400 W/L. After the pre-treatment, the red bell pepper was blotted with paper towels to remove excess water before being transferred to the air dryer.

2.3 | Drying experiment

The drying kinetics of red bell peppers were studied at three different temperature levels (50, 60, and 70°C) and three air velocity levels (1.5, 2, and 2.5 m s^{-1}). Samples weighing 100 g each were evenly spread on a tray and placed in a hot air dryer (Model-25L, Laboratorydeal, India). Given that the samples had a thickness of 1 cm, the drying process is referred to as thin-bed drying. The dryer is equipped with a temperature and air velocity control unit, accurate to ±2°C. The moisture content of the samples was measured both before and after pre-treatment using the standard AOAC 925.10 method. This involved drying 5 g of the sample at 105°C for 6 h, with the process being triplicated to reduce error. The initial moisture content of the red bell pepper was found to be 92.8 ± 1.4% (w.b.). The drying samples were weighed at 30 min intervals using an electronic balance (Model: QUINTIX224-10IN) with an accuracy of 0.01 g, until an equilibrium moisture content was achieved. The dryer was preheated to the predetermined temperatures (50, 60, or 70°C, as applicable) for 30 min to establish steady-state conditions before inserting the samples.

2.4 | Mathematical modeling

The following equation was used to convert drying data measured in terms of dry basis moisture content (gram water/gram dry matter) to dimensionless moisture ratio (Wang et al., 2007).

$$\text{Moisture ratio (MR) of sample, MR} = \frac{M - M_e}{M_o - M_e} \quad (1)$$

where, M_o, initial moisture content; M, moisture content at time (t), and M_e, equilibrium moisture content.

However, M_e was relatively less when observed along with M_o and M during the long drying duration, further simplification of Equation (1) results in $\text{MR} = M/M_o$ (Wang et al., 2007).

The moisture content (MC) was expressed in a dry basis (d.b.) and calculated using Equation (2).

$$\text{MC} = M_o \times MR_t \quad (2)$$

where MR_t is the moisture ratio at time (t).

The experimental data were fitted to selected models (Table 1) using the Generalized Reduced Gradient (GRG) method to accommodate non-linear inequality constraints (Microsoft Office 2016, USA).

TABLE 1 Thin layer drying model for calculation of MR of red bell pepper.

Model	Equation	Reference
Midilli et al. model	$\text{MR} = a\exp(-kt^n) + bt$	Özbek and Dadali (2007)
Approximation of diffusion	$\text{MR} = a\exp(-kt) + (1-a)\exp(-bkt)$	Yaldiz et al. (2001)
Modified page model	$\text{MR} = \exp(-kt)^n$	Wang et al. (2007)
Two term model	$\text{MR} = \text{a}\exp(-k_0 t) + b\exp(-k_1 t)$	Henderson (1974)
Logarithmic model	$\text{MR} = a\exp(-kt) + c$	Motevali et al. (2010)

Note: MR is dimensionless moisture ratio; a is dimensionless drying constant; k is constant of drying velocity (h^{-1}); n is number of constant; t is time (h); b is parameter in case of Midilli model (h^{-1}) or b is dimensionless drying constant in case of approximation of diffusion and two term model; c is constant of external moisture uptake.

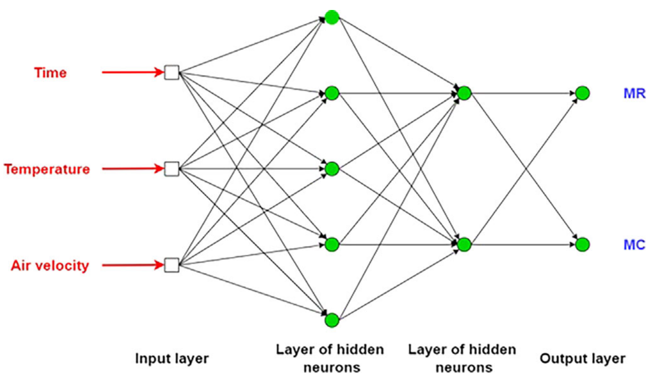

FIGURE 1 Configuration of multilayer neural network for calculation of MR and MC.

2.5 | Neural network design

ANN being a non-linear adaptive technique connects the input and output variables. The multilayer perceptron (MLP) feed-forward network configuration of the static ANN utilized for the prediction of MR and MC values is shown in Figure 1. It has one input layer, two hidden layers, and one output layer. MLP network regulates the weight of neurons during training to bring actual output closer to the desired output (Ashtiani, Rohani, et al., 2020). The use of more than 1 hidden layer brings more complexity in determining the output. However, the first hidden layer only gives a basic combination of the input variables. Using a second hidden layer brings more abstract representations that capture higher-level relationships by using the combinations of the first layer.

In the input layer, independent variables like air temperature (°C), air velocity (m s^{-1}), and drying time (min) were inserted and the variables in the output layer were MR and MC of red bell pepper at any time. Hence, the input layer had 3 neurons and the output layer had 2 neurons. The best prediction by the network was obtained by

TABLE 2 Summary of collected data points at various input parameters.

Sample	Air velocity	Temperature			Total no. of data points
		$T = 50^\circ C$	$T = 60^\circ C$	$T = 70^\circ C$	
Red bell pepper	1.5 m s^{-1}	26	18	14	58
	2 m s^{-1}	21	19	15	57
	2.5 m s^{-1}	24	20	16	60

training and testing the network with the collected experimental data (Table 2). The error is minimized through a gradient descent rule. Various transfer functions including hyperbolic tangent sigmoid, logarithmic, linear functions, and feed-forward back-propagation approach were evaluated. Following the addition of the input values to the model, the distribution of the input patterns for the training and testing data sets was 70% and 30%, respectively. The experimentation was devoid of validation subsets and this might hinder in performing effective hyperparameter tuning (Ashtiani et al., 2021). Hence, the learning rate of 0.1 was adjusted to all the tested networks to simplify the hyperparameter tuning process, since the experimentation is focused on getting a baseline understanding of the networks' performance. It avoids the complexity of hyperparameter search at the beginning.

Levenberg–Marquardt (LM) was selected as the final training algorithm. This model featured two hidden layers with varying distributions of neurons within each layer for better yield. Optimal topologies were determined based on the highest R^2 and the lowest MSE values. The activation function combined logarithmic (Log) and tangent (tan) functions in the hidden and output layers, respectively. The ANN design was executed in the toolbox provided in MATLAB R2015a software.

2.6 | Analysis of total phenolic, flavonoids, carotenoids, and ascorbic acid content

The sample size was adjusted according to moisture content; specifically, one part of the dried sample was equivalent to four parts of fresh or sonicated samples. All analyses were performed in triplicate. The following procedures were adapted for fresh or sonicated samples.

Total phenolic content was analyzed following the method by Wiktor et al. (2019), with slight modifications. In each 10 mL volumetric flask, 4 mg of sample and 0.8 mL of gallic acid solution were added. After 5 min, 1 mL of Folin–Ciocalteu reagent was introduced, followed by 0.8 mL of a 7.5% aqueous sodium carbonate solution. The volume was then made up to 10 mL with distilled water and incubated for 30 min. Absorbance was measured at 765 nm using a UV–Visible spectrophotometer (Genesys-S 10S UV-V, Thermo Fisher, USA). Results were expressed in mg of gallic acid equivalent per 100 g (mg GAE/100 g) of the sample.

Total flavonoids were analyzed as per Saeed et al. (2012), with a slight alteration in the standard used. A 10 mg sample of red bell pepper was mixed with 2.5 mL of an ethanolic $AlCl_3$ solution. The mixture was incubated in the dark at room temperature for 30 min, and absorbance was recorded at 425 nm. Results were expressed as Quercetin Equivalent per 100 g (QE mg/100 g).

Total carotenoid content was determined using the method described by Xie et al. (2019); (Thaipong et al., 2006). A 4 g sample was ground in liquid nitrogen and mixed with 20 mL of acetone containing 0.1% butylated hydroxytoluene. The mixture was centrifuged at 4000 rpm at 4°C, and the supernatant was collected. This procedure was repeated until the residue became colorless. Absorbance was measured at 470 nm, and results were expressed as μg of β-carotene equivalent per 100 g of red bell pepper.

For ascorbic acid content, 5 g of the sample was mixed vigorously in 50 mL of a 3% phosphorous acid solution and filtered. A 2 mL aliquot of the filtrate was combined with 2 mL of acetate buffer and 3 mL of a vitamin C indicator (2, 6-dichlorophenol indophenol solution, 0.0007 M). Xylene (15 mL) was then added, and the mixture was vortexed at 2000 rpm for 10 s. Ascorbic acid concentration was determined at 425 nm and expressed as mg of ascorbic acid per 100 g of bell pepper, following the method by Domínguez-Martínez et al. (2014).

2.7 | Antioxidant analysis

According to do Socorro et al. (2010) and Cortés-Estrada et al. (2020), the antioxidant capability of red bell pepper samples was measured using the DPPH and ABTS radicals, with modifications. The ABTS radical was diluted in 50 mL of ethanol to achieve an absorbance of 0.70 ± 0.02 at 734 nm. A 9 mL aliquot of this diluted solution was transferred to a test tube, and 90 μL of the sample was added. The mixture was vortexed for 6 min, and its absorbance spectra were recorded at 734 nm using a UV–V spectrophotometer (Genesys-S 10S UV-V, Thermo Fisher, USA). A standard curve was constructed, and the results were expressed as μmole equivalents of Trolox per gram of bell pepper (μmol TE/g). For the DPPH analysis, 15.6 mL of a methanolic solution containing 0.06 mM DPPH was mixed with 4 mg of the ground sample. The absorbance was measured after a 20 min incubation at 30°C. The DPPH radical activity was calculated according to Subrahmaniyan et al. (2022) and given in terms of percentage (%). Ferric reducing antioxidant power (FRAP) analysis was conducted according to Thaipong et al. (2006).

2.8 | Statistical analysis

Statistical analysis for goodness of fit was performed using the correlation coefficient (R^2), chi-square (χ^2), and root mean square error

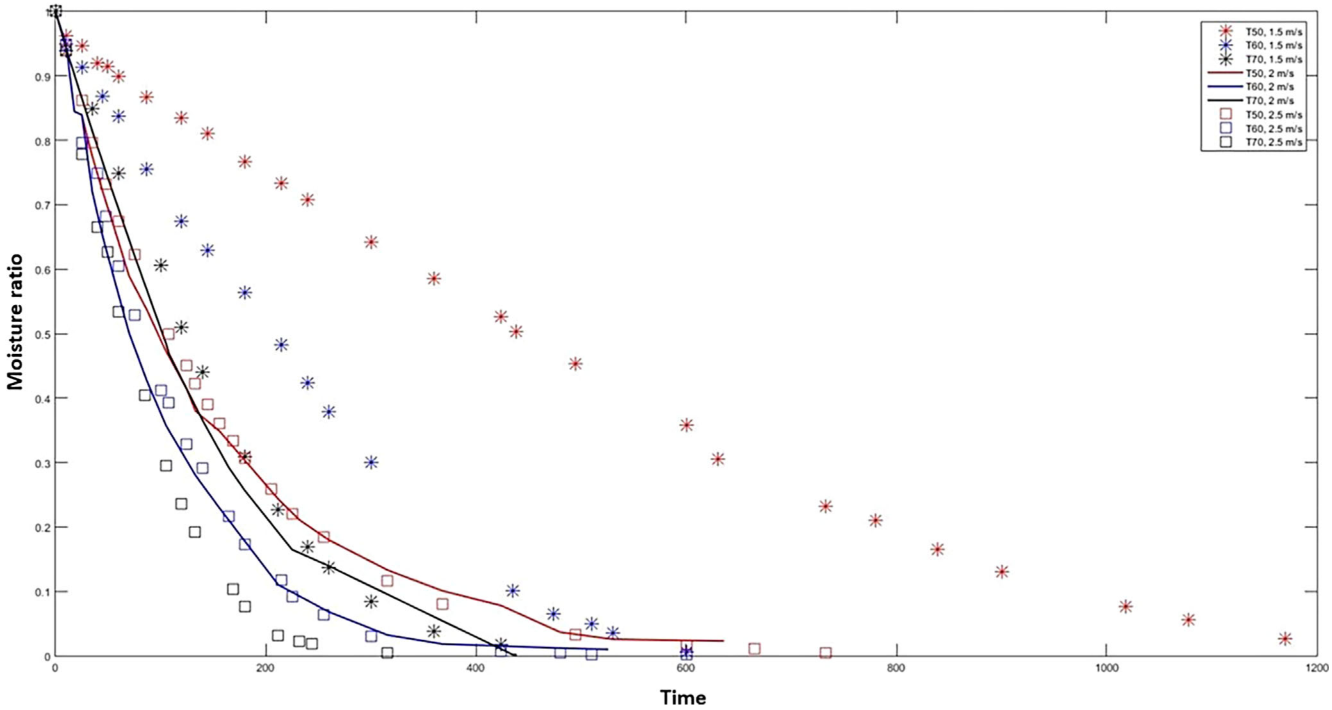

FIGURE 2 Moisture ratio vs drying time curve at different air velocity and temperature.

(RMSE). The R^2 and RMSE values were employed to verify the linearity between the experimental and model-predicted values (Meerasri & Sothornvit, 2022). High R^2 values (closer to unity), the lowest RMSE, and χ^2 indicate the goodness of fit and the proximity of predicted values to experimental ones (Yu et al., 2021). Analyses of total phenolic, flavonoids, carotenoids, ascorbic acid, and antioxidants were statistically evaluated at a 95% significance level. Each set of analyses was also grouped using the Tukey Test in Minitab software (Mangang & Manickam, 2022).

Equations (3), (4), (5) were used to calculate R^2, χ^2, and RMSE, respectively.

$$R^2 = 1 - \frac{\sum_{i=1}^{N} \left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\exp,i}\right)^2}{\sum_{i=1}^{N} \left(\overline{\mathrm{MR}_{pre}} - \mathrm{MR}_{\exp,i}\right)^2} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{N - m} \tag{4}$$

$$\mathrm{RMSE} = \left(\frac{1}{N}\sum_{i=1}^{N} \left(\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2\right)^{1/2} \tag{5}$$

where, $\mathrm{MR}_{\mathrm{pre},i} = i$th predicted moisture ratio, $\mathrm{MR}_{\exp,i} = i$th experimental moisture ratio, $\mathrm{MR}_{\mathrm{pre}}$ = mean of predicted MR, N = number of observations and m = number of constants.

3 | RESULTS AND DISCUSSION

The most popular thin-layer drying models were applied, and the observed data were plotted on a graph with moisture ratio on the *Y*-axis and drying time on the *X*-axis (Figure 2). An increase in air velocity led to a greater reduction rate of MR values. Similarly, temperature rise also had a comparable effect on the drying behavior of the sample (Figure 2). The plots clearly show that as the operating temperature and air velocity increase, the drying curves become steeper, indicating a faster drying rate. This is consistent with previously reported results on bell peppers and other food materials (Kheto et al., 2021; Murthy & Manohar, 2014; Vega et al., 2007). The increased drying rate is attributed to a greater driving force for heat and mass transfer, along with an increase in effective moisture diffusivity resulting from higher drying temperatures (Niamnuy et al., 2011). Similarly, as air velocity increased from 1.5 to 2.5 m s^{-1}, the drying time was significantly reduced due to a faster rate of moisture loss. An increase in air velocity lowers the vapor pressure in the surrounding environment, allowing the product's moisture to escape more easily (El-Mesery & El-Khawaga, 2022). This resulted in a greater drying rate in the current study (Figure 2).

The curve shows that the rate of moisture removal was higher in the beginning and reduced as drying continued and moisture content dropped (Figure 2). This may be due to fewer amount of water molecules present on the surface of red bell pepper, wherein the central portion of water present inside the vegetable takes time to reach the surface (Li et al., 2022). Due to the greater vapor pressure gradient,

TABLE 3 Statistical result obtained for different model at various level of temperature and velocity.

	Temperature (°C)								
	50°C			60°C			70°C		
Air velocity	R^2	RMSE	χ^2	R^2	RMSE	χ^2	R^2	RMSE	χ^2
Midilli model									
1.5 m s^{-1}	0.9993	0.013497	0.00022	0.9954	0.033228	0.001443	0.9877	0.054404	0.004275
2.0 m s^{-1}	0.9928	0.042068	0.002359	0.9969	0.058165	0.004736	0.9927	0.033369	0.00167
2.5 m s^{-1}	0.9843	0.043987	0.00245	0.9905	0.034104	0.00155	0.9851	0.051633	0.003635
Diffusion model									
1.5 m s^{-1}	0.9914	0.048408	0.002649	0.9964	0.0303	0.001101	0.9937	0.048078	0.002942
2.0 m s^{-1}	0.9995	0.03864	0.00171	0.9988	0.04126	0.00202	0.9988	0.01515	0.00029
2.5 m s^{-1}	0.9998	0.0059	0.00004	0.9984	0.02418	0.00068	0.9973	0.03751	0.00173
Modified page model									
1.5 m s^{-1}	0.9914	0.048408	0.002538	0.991	0.057299	0.003693	0.993	0.048078	0.002696
2.0 m s^{-1}	0.9995	0.04131	0.00186	0.9986	0.03888	0.00169	0.9984	0.02665	0.00081
2.5 m s^{-1}	0.9996	0.00003	0.00003	0.9984	0.00058	0.00064	0.9973	0.03751	0.0016
Two term model									
1.5 m s^{-1}	0.9976	0.022872	0.000618	0.9991	0.014348	0.000269	0.9923	0.043797	0.002685
2.0 m s^{-1}	0.9995	0.00166	0.00202	0.9987	0.00164	0.00208	0.9978	0.00052	0.00072
2.5 m s^{-1}	0.9998	0.00526	0.00003	0.9982	0.02056	0.00052	0.9962	0.03176	0.00134
Logarithmic model									
1.5 m s^{-1}	0.9909	0.045123	0.002301	0.999	0.014872	0.000268	0.9975	0.023546	0.00072
2.0 m s^{-1}	0.9995	0.04084	0.00191	0.9987	0.0406	0.00195	0.9987	0.01709	0.00036
2.5 m s^{-1}	0.9998	0.00526	0.00003	0.9982	0.02056	0.00049	0.9962	0.03176	0.00124

Note: R^2 is correlation coefficient, χ^2 is chi square and RMSE is root mean square error.

the initial drying rate is always higher. Opening of cellular matrices, which enables rapid movement and evaporation of water molecules, may have caused the first spike in drying rate. Similar alterations in the drying rate curve's shape were noted (Suna, 2019). Differences in air velocity, mass, and tray load also cause variations in the initial drying rate at different temperatures (Basavarai et al., 2008). The difference in the starting point of the MC curve has resulted from the variation in initial moisture content level in the samples opted in different studies.

3.1 | Data fitting in the model

The experimental data were fitted to five mostly used mathematical models and the goodness of fit was evaluated by determining the statistical parameters (R^2, RMSE, and χ^2). The Midilli model provided the best fit at an air velocity of 1.5 m s^{-1} ($R^2 = 0.9988$, $\chi^2 = 0.00022$ and RMSE $= 0.013497$). At $v = 2$ m s^{-1} and $v = 2.5$ m s^{-1}, the two-term model and modified page model were found to be satisfactorily fitting with the drying curve with $R^2 = 0.9995$, $\chi^2 = 0.00202$, RMSE $= 0.00166$, and $R^2 = 0.9998$, $\chi^2 = 0.00003$, RMSE $= 0.00003$, respectively. The statistical parameters of the models at different air velocities and temperatures were practical (Table 3). Selected models are validated by comparing the experimental values with those of those given by the respective models (Figure 3a,b). Constant parameters of the best models at different temperatures and air velocities were also observed (Table 4).

3.2 | Drying kinetics

As the air velocity and temperature increased, the required drying time for samples to reach the equilibrium moisture content of 0.3 kg water·kg^{-1} d.b., decreased from 1078 to 300 min. As the moisture content decreased, the loss of moisture and thereby the drying rate also reduced for all air velocities, and this effect is more prominent at higher air velocities (Tzempelikos et al., 2014). The highest drying rate, 0.29 kg water·kg^{-1} d.b. min^{-1} was recorded at 70°C and 2.5 m s^{-1} air velocity. At 50°C and an air velocity of 2.5 m s^{-1}, the drying rate is almost six times that of the drying rate at an air velocity of 1.5 m s^{-1}. Similarly, higher air temperature can significantly reduce the drying rate and drying time even at lower air velocity (Misha et al., 2015). Thus, increasing both air velocity and temperature results in rapid loss of moisture and a tremendous reduction in drying time, which is important in obtaining a dried product with minimum loss of nutrient value.

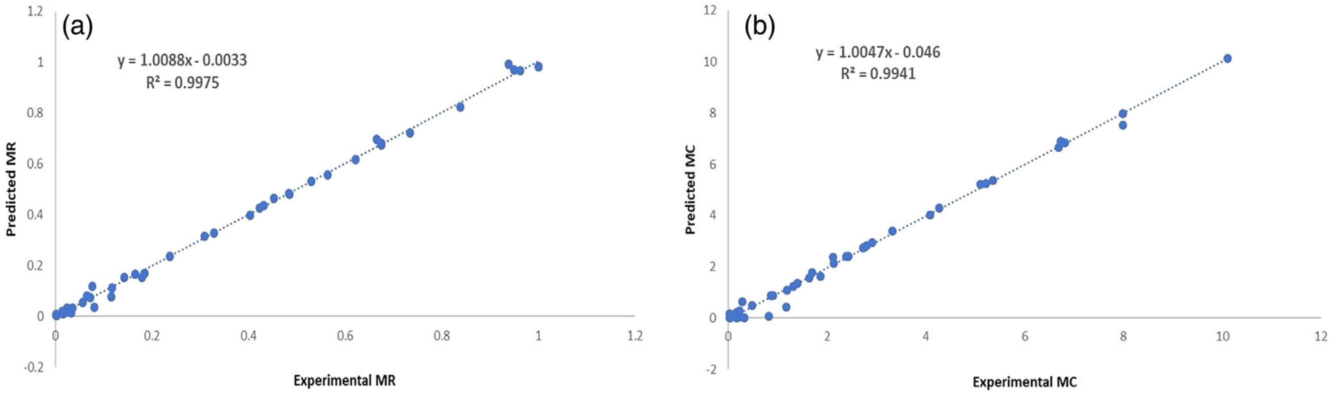

FIGURE 3 Correlation between (a) experimental and predicted MR values by mathematical models, (b) experimental and predicted MC values by mathematical models.

TABLE 4 Model constant of best fitted model.

Air velocity	Temperature	Constants			
Midilli model					
1.5 m s^{-1}	50	$a = 0.30444$	$k = -1.2361$	$n = -0.02125$	$b = -0.00087$
	60	$a = 0.00220$	$k = -6.32994$	$n = -0.01402$	$b = -0.00133$
	70	$a = 0.02365$	$k = -4.14957$	$n = -0.04339$	$b = -0.00159$
Two term model					
2 m s^{-1}	50	$a = 0$	$k_0 = 0.005$	$b = 0.98028$	$k_1 = 0.00794$
	60	$a = 0$	$k_0 = 0.006$	$b = 0.98588$	$k_1 = 0.00815$
	70	$a = 0.01064$	$k_0 = 0.00635$	$b = 1.02092$	$k_1 = 0.00747$
Modified page model					
2.5 m s^{-1}	50	$k = 0.00098$	$n = 6.66461$		
	60	$k = 0.00099$	$n = 8.99117$		
	70	$k = 0.00097$	$n = 11.82602$		

Note: a is dimensionless drying constant; k is constant of drying velocity (h^{-1}) where k_0 indicates initial and k_1 indicate final; n is number of constant; b is parameter in case of Midilli model (h^{-1}) or b is dimensionless drying constant in case of two term model.

3.3 | Prediction of drying kinetics by ANN

The feed-forward back propagation training algorithm was found to be satisfactorily predicting the MR and MC in ANN modeling. After experimenting with various architectural designs, a four-layered back-propagating ANN with 15 neurons and 25 neurons in the first and second hidden layers, respectively, was found to be the best option (Figure 4).

The LM training function with feed-forward backpropagation algorithm was employed to obtain the highest R^2 values of 0.9989 (training), 0.9997 (testing) and MSE values of 0.0001 (training), 0.0002 (testing), implying the development of a robust model and efficiency of ANN in predicting dehydration kinetics of red bell pepper. Various combinations of ANN networks in pursuit of the best prediction topology of drying behavior have been depicted (Table 5). Experimental values of both MR and MC have been plotted against predicted values and shown in Figure 5a,b, which indicates excellent agreement between the predicted and measured values. The LM model was further considered for analysis of the test pattern (Figure 6), which is also satisfactory in terms of similarity between both the experimental and predicted values. The goodness of fit between the experimental and predicted data sets for both MR and MC confirms the excellent simulation capacity of ANN. Thus, ANN can be used to predict complex non-linear processes like drying for the development of efficient and economical technologies for practical applications. ANN prediction of MR at different temperatures and air velocities is illustrated in Figure 6. There are numerous studies on prediction of drying kinetics using ANN for various food materials such as mango ginger (Murthy & Manohar, 2014), pineapple (Sarkar et al., 2020), pomegranate aril, jujube fruit (Motevali et al., 2010, 2012), and onion (Jafari et al., 2016), confirming the competency of ANN as a simulation tool. However, no prior studies on understanding the drying behavior of red bell peppers have been done using ANN. Therefore, an effort has been made through this study to compare the predictive ability of

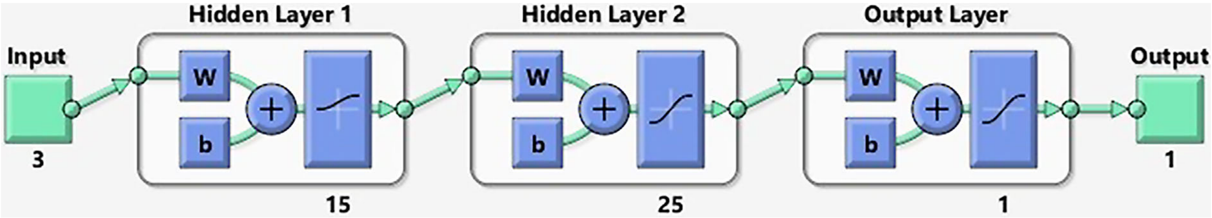

FIGURE 4 Feedforward neural network.

TABLE 5 Summary of ANN networks to evaluate the best determination coefficient (R^2) and mean squared error (MSE).

Activation function	Training rules	Neurons in hidden layer 1	Neurons in hidden layer 2	Training error	R^2 (training)	R^2 (test)	MSE (training)	MSE (test)	Epoch
Log/Tan	Trainlm	20	0	0.00053	0.9978	0.9969	0.0001	0.0007	82
Log/Tan	Trainrp	20	0	0.00168	0.9882	0.9942	0.0008	0.0012	726
Log/Tan	Trainscg	20	0	0.00024	0.9968	0.9981	0.0003	0.0004	522
Log/Tan/Tan	Trainlm	15	25	0.00064	0.9989	0.9996	0.0001	0.0002	27
Log/Tan/Tan	Trainrp	15	25	0.00091	0.9957	0.9972	0.0003	0.0006	846
Log/Tan/Tan	Trainscg	15	25	0.00110	0.9940	0.9882	0.0002	0.0026	474

Note: R^2 is correlation coefficient, and MSE is mean square error.

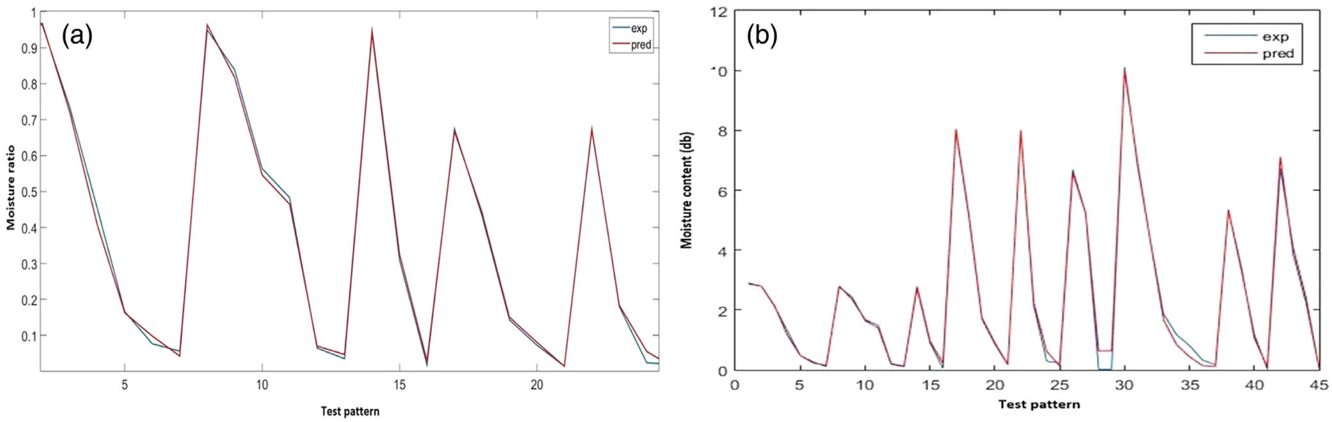

FIGURE 5 Comparison of (a) experimental data and predicted MR values by ANN, (b) experimental data and predicted MC values by ANN.

ANN with various mathematical models, where ANN was found to be better in terms of MSE value (Table 5). As drying data were collected from different studies conducted in different environments, there could be multiple factors influencing the reported values of drying characteristics such as physicochemical and morphological properties of the sample, drying equipment, relative humidity, accuracy of weighing and other equipment used in the experiments. This could potentially be reflected in the final analysis of this study, as data subjected to different conditions has been collated and considered as of identical origin. This might even hinder the predictive ability of various tools employed in this study. However, the ANN application has produced satisfactory results in calculating the red bell pepper's drying behavior, which will help with processing this high-value commodity in the future.

3.4 | Effect of treatments on total phenolic, flavonoids, carotenoids, and ascorbic content

Initially, the polyphenol content was 102.6 mg GAE/100 g of red bell pepper. The total phenolic, flavonoid and carotenoid are present in most green vegetables. In a study by Vega-Gálvez et al. (2009), the total phenolic content was significantly reduced in red bell peppers when air drying alone was employed. However, in this study, with the use of ultrasound as a pre-treatment, the quality of the dried red bell pepper was significantly improved with no significant difference when compared to the control (Table 6). This may be because of ultrasound which has the principle of forming high pressure and heat locally, during cavitation. This may cause all the metabolites to loosen up without destroying the properties leading to the availability of antioxidants in

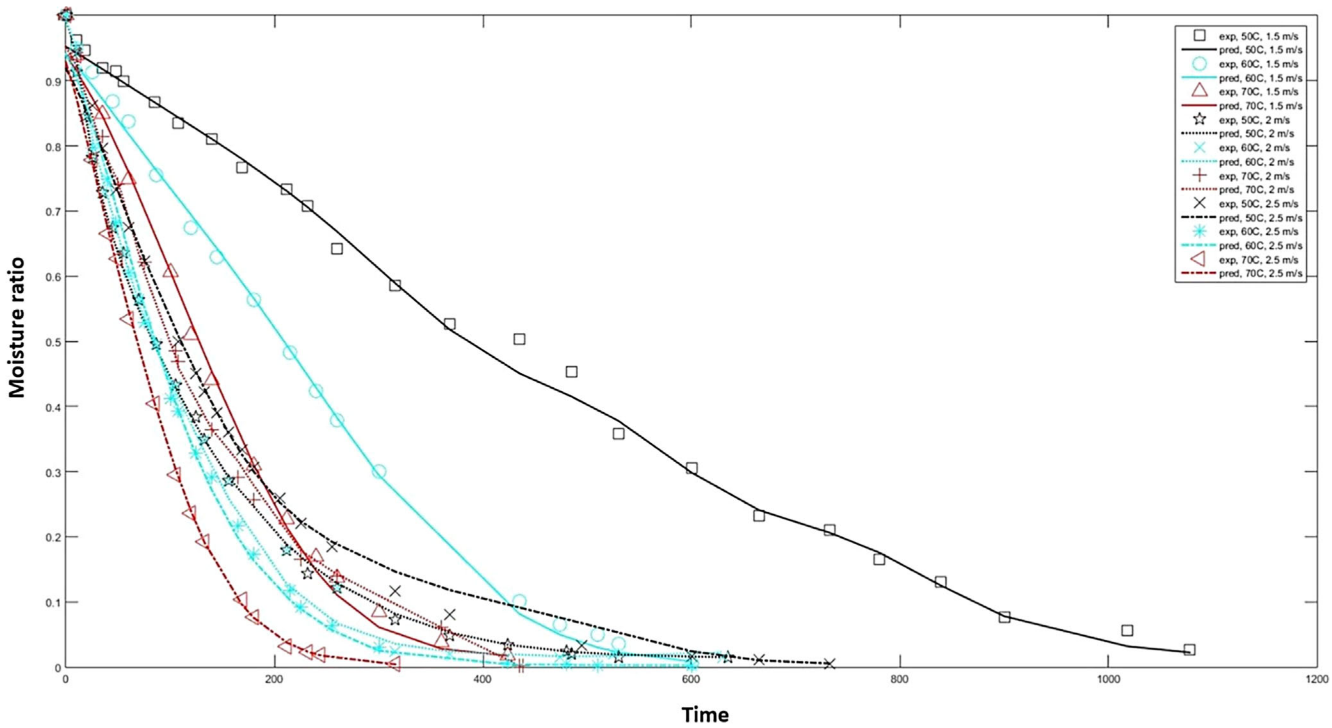

FIGURE 6 ANN prediction of drying curves at three level of air velocity and temperature.

TABLE 6 Vitamin C, total carotenoids, polyphenol, and flavonoids of red bell pepper given as mean ± SD.

Treatments		Vitamin C (mg/ 100 g)	Total carotenoids (μg/100 g)	Total polyphenol content (mg GAE/100 g)	Total flavonoids (QE mg/100 g)
Control		130.1 ± 1.16ab	8695.2 ± 7.13bc	102.6 ± 1.54ab	42.5 ± 0.96ab
Ultrasound pre-treatment (10 min at 400 W/L)		131.9 ± 2.1a (1.4%↑)	8812.3 ± 8.22a (1.3%↑)	108.2 ± 1.78a (5.5%↑)	43.8 ± 0.93a (3.1%↑)
Thin layer drying					
Air velocity	Temperature				
1.5 m s^{-1}	50	128.6 ± 1.2ab (1.2%↓)	8648.9 ± 7.76de (0.5%↓)	102.2 ± 1.12ab (0.4%↓)	41.9 ± 0.11ab (1.4%↓)
	60	126.9 ± 0.9b (2.5%↓)	8632.4 ± 9.87ef (0.7%↓)	101 ± 0.68b (1.6%↓)	39.5 ± 0.64de (7.1%↓)
	70	126.1 ± 1.6b (3.5%↓)	8578.7 ± 7.96h (1.3%↓)	99.8 ± 1.96b (2.7%↓)	37.7 ± 0.78f (11.3%↓)
2 m s^{-1}	50	129.4 ± 1.7ab (0.5%↓)	8671.2 ± 9.41cd (0.3%↓)	103.8 ± 0.98ab (1.2%↑)	42.9 ± 0.49ab (0.9%↑)
	60	127.9 ± 2.1ab (1.7%↓)	8612.7 ± 7.44fg (0.9%↓)	102.8 ± 0.32ab (0.2%↑)	40.6 ± 0.42cd (4.5%↓)
	70	127.1 ± 1.7ab (2.3%↓)	8596.3 ± 11.2gh (1.1%↓)	100.2 ± 1.56b (2.3%↓)	38.7 ± 0.71ef (8.9%↓)
2.5 m s^{-1}	50	129.6 ± 1.9ab (0.4%↓)	8702.2 ± 9.58b (0.1%↑)	105.2 ± 1.46ab (2.5%↑)	43.1 ± 0.42ab (1.4%↑)
	60	129.1 ± 1.1ab (0.8%↓)	8662.9 ± 7.76d (0.4%↓)	104.2 ± 1.44ab (1.6%↑)	42.7 ± 0.17ab (0.5%↑)
	70	127.2 ± 2.1ab (2.2%↓)	8592.7 ± 13.7gh (1.2%↓)	101.4 ± 1.94b (1.2%↓)	39.3 ± 0.21def (7.5%↓)

Note: The data in the column are significantly different ($p < 0.05$) if the small letters corresponding to the data are different to each other.

higher quantity as compared to the control. However, many studies showed that antioxidant escapement from the food increases as cells loosen up due to heat (Fletcher et al., 2005; Sasikumar & Jaiswal, 2022; Tomaino et al., 2005; Wan et al., 2015).

The total flavonoid content in fresh red bell pepper was 42.5 mg QE/100 g, in the current study. However, the use of drying treatment to store the commodity may reduce the quantity of flavonoids. With the use of ultrasound pre-treatment in combination with thin bed drying, there was an increase in flavonoids by 1.4% in ultrasound pre-treated and thin bed dried red bell pepper (2.5 m s^{-1}, air velocity and 50°C temperature). The carotenoids present in the fresh red bell pepper were found to be 8695.2 μg/100 g. They are mainly responsible for the attractive red color pigments. The carotenoid content was slightly increased during ultrasound pre-treatment and decreased during the overall drying process (Table 6). However, the air velocity and temperature combination of 2.5 m s^{-1} and 50°C after ultrasound pre-

TABLE 7 Antioxidant activity of red bell pepper given as mean ± SD.

Treatments		Antioxidant activity DPPH (%)	ABTS (μmol TE/g)	FRAP (μmol Fe_2^+/g)
Control		83.1 ± 2.45[abc]	685.3 ± 5.81[ab]	49.3 ± 1.80[a]
Ultrasound pre-treatment (10 min at 400 W/L)		85.7 ± 3.21[a] (3.1%↑)	693. 6 ± 7.91[a] (1.2%↑)	50.4 ± 1.12[a] (2.2%↑)
Thin layer drying				
Air velocity	Temperature			
1.5 m s^{-1}	50	82.4 ± 1.54[abc] (0.8%↓)	684.9 ± 4.57[ab] (0.1%↓)	48.7 ± 2.24[a] (1.2%↓)
	60	79.6 ± 0.74[c] (4.2%↓)	665.8 ± 4.78[c] (2.8%↓)	47.2 ± 1.77[a] (4.3%↓)
	70	79.1 ± 1.11[c] (4.8%↓)	648.3 ± 5.78[d] (5.4%↓)	46.8 ± 1.43[a] (5.1%↓)
2 m s^{-1}	50	83.4 ± 0.17[abc] (0.4%↑)	684.7 ± 3.81[ab] (0.1%↓)	48.9 ± 3.72[a] (0.8%↓)
	60	81.7 ± 0.98[abc] (1.7%↓)	682.4 ± 5.76[ab] (0.4%↓)	47.3 ± 1.12[a] (4.1%↓)
	70	80.1 ± 0.76[abc] (3.6%↓)	670.1 ± 4.42[bc] (2.2%↓)	47.2 ± 1.89[a] (4.3%↓)
2.5 m s^{-1}	50	84.5 ± 1.75[ab] (1.7%↑)	687.7 ± 2.89[a] (0.4%↑)	49.1 ± 0.91[a] (0.4%↓)
	60	82.9 ± 1.32[abc] (0.2%↑)	679.6 ± 9.41[abc] (0.8%↓)	48.2 ± 1.43[a] (2.2%↓)
	70	81.5 ± 0.72[abc] (1.9%↓)	678.1 ± 3.75[abc] (1.1%↓)	47.7 ± 1.19[a] (3.2%↓)

Note: The data in the column are significantly different ($p < 0.05$) if the small letters corresponding to the data are different to each other.

treatment showed an increase of 0.1% compared to the control. This may be due to the highly enhanced application of ultrasound that can destroy quality degrading enzymes like lipoxygenase which degrades carotenoids (Ercan & Soysal, 2013; Lopez & Burgos, 1995; Xavier & Ansari, 2023).

Red bell peppers are a rich source of antioxidants. It is a known fact that the consumption of foods rich in antioxidants reduces the risk of chronic diseases by scavenging free radicals produced in the human body. The vitamin content of fresh red bell pepper was found to be 130.1 mg/100 g (Table 6). During ultrasound-assisted thin bed drying, the vitamin C content reduced, however, there was no significant difference observed between the fresh sample and treated samples. Interestingly, there is an increase in the vitamin C content by 1.4% during the sonication stage. The reason for this retention is related to the employment of shorter pre-treatment duration (10 min) without increasing the temperature. Similar observations and results were supported by Sasikumar and Deka (2018) in blood fruit, Rashid et al. (2020) in sweet potatoes where the use of lower treatment time retains more vitamin C. Another reason is pressure generation inside the structure caused by the water molecules during cavitation leading to shear disruption. This makes vitamin C readily available increasing the bioavailability. Along with this, there is an increased rate of heat transfer during thin bed drying. The rate of heat transfer is directly proportional to the surface area of the food and to the temperature difference between the food and the air (Sahay & Singh, 1996). With the increase in surface area caused by pore formation during sonication, the heat transfer rate increases. The use of forced convection rather than still air also increases the rate of heat transfer. The high rate of heat transfer allows easy removal of moisture in a non-thermal environment without disturbing the bioactive components. This implies that vitamin C was retained during ultrasound-assisted thin bed drying and has the potential to be used in food processing and preservation.

3.5 | Effect of treatments on antioxidant profile

The DPPH, ABTS, and FRAP activity showed increasing potential from control when ultrasound pretreatment was performed alone (Table 7). After ultrasound-assisted thin bed drying, there was a decrease as well as an increase in its activity, however, DPPH and FRAP activity of all the treatment conditions were insignificant to control ($p < 0.05$). In the ABTS profile, a significant difference was observed at 1.5 m s^{-1} air velocity with temperature conditions of 60 and 70°C. The increase or decrease in antioxidant profile is related to the temperature and air velocity employed. From the study, it can be observed that higher velocity with lower temperature (2.5 m s^{-1} and 50°C) led to the increased profile of DPPH and ABTS activity by 1.7% and 0.4%, respectively.

The carotenoid, flavonoid and phenolic content present in the food are major components of antioxidants acting as free radical terminators (Sasikumar et al., 2021). Phenolic compounds are known to bind with polysaccharides (Tudorache & Bordenave, 2019) and proteins (Yadav et al., 2018). The use of ultrasound as a pretreatment breaks the non-covalent bonds of phenolic compounds bound to water-soluble polysaccharides, and forms pores for faster evaporation of water thereby retaining phenolic compounds in the dried form of red bell pepper. The thickness of red bell pepper also plays an important during retention as the thickness of food (1 cm) is inversely proportional to the rate of drying (Fellows, 2022).

Ferric reducing antioxidant power as the name suggests is the ability of red bell pepper to reduce TPTZ Fe^{3+} to TPTZ Fe^{2+} during FRAP analysis. The amount of reductones was directly correlated to the number of antioxidants present. There was a reduction in FRAP activity in overall treatments (ultrasound-assisted thin bed drying), however, there was no significant difference observed (Table 7). This may be due to minor seepage of reductones along with water when it evaporates. The responsible factor is the temperature used in the overall process as air velocity is non-thermal and there is also an increase in FRAP activity in ultrasound treatment by 2.2%.

4 | CONCLUSION

This study offers a comprehensive analysis of the drying kinetics of red bell peppers using ultrasound-assisted thin-bed drying. The research not only demonstrates a significant reduction in drying time to less than 6 h but also provides compelling evidence for the efficacy of ANN in predicting moisture ratio and moisture content loss. The ANN models outperformed semi-empirical methods, achieving R^2 values close to unity and substantial MSE values. Importantly, the study reveals that this drying technique has minimal impact on the nutritional quality of red bell peppers. Vitamin C content showed negligible reductions, while total polyphenol and flavonoid contents increased under specific velocity and temperature conditions. Furthermore, the total carotenoid content reached its peak at an air velocity of 2.5 m s^{-1}, indicating the method's potential for nutrient retention. Additionally, the study assessed the antioxidant profiles using DPPH and ABTS assays, which showed a slight increase in antioxidant activity. Although the Ferric Reducing Antioxidant Power (FRAP) profile indicated a reduction, it was not statistically significant when compared to fresh samples. Given these findings, it is evident that ultrasound-assisted thin-bed drying emerges as a promising technique for preserving the nutritional and antioxidant qualities of red bell peppers. This research advances our understanding of effective drying methods while setting the stage for future studies aimed at optimizing these techniques for broader applications in food preservation.

AUTHOR CONTRIBUTIONS

Raju Sasikumar: Conceptualization, data curation, funding acquisition, investigation, methodology, resources, supervision, validation; **Irengbam Barun Mangang:** Conceptualization, writing original draft, data curation, formal analysis, methodology; **Kambhampati Vivek:** Writing-review and editing, validation; **Amit K. Jaiswal**: Writing- review and editing, visualization.

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CONFLICT OF INTEREST STATEMENT

There is no conflict interests to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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