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ORIGINAL ARTICLE

Modeling and optimization of bioactive compounds from jujube (*Ziziphus jujuba Mill.*) vinegar using response surface methodology and artificial neural network: Comparison of ultrasound processing and thermal pasteurization

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Abstract

In recent years, vinegar varieties have been preferred by consumers because of their beneficial effects on human health. Vinegar contains different bioactive components and antioxidants according to the fruit or vegetable used as raw materials. In this study, three different samples of jujube vinegar—traditional jujube vinegar (TJV), pasteurized jujube vinegar (PJV), and ultrasound-treated jujube vinegar (UJV)—were studied. Ultrasound parameters were determined as 6.2 min and 60.6% amplitude. Response surface methodology (RSM) and artificial neural network (ANN) showed a high correlation. After ultrasound treatment, the bioactive components in the UJV samples increased compared with the TJV samples. Caffeic and ferulic acids were identified as the dominant phenolic components in jujube vinegar samples. Jujube vinegar samples contained 22–27 volatile compounds. As a result of the study, ultrasound treatment applied to jujube vinegar positively affected phenolic components, organic acids, volatile components, and mineral content, allowing for the development of a new healthy product.

Practical Applications

The effects of ultrasound processing on jujube vinegar were investigated in this study. The bioactive qualities of jujube vinegar were enriched by ultrasound. ANN outperformed RSM in terms of correlation.. Mineral and phenolic compounds were affected by ultrasound treatment. Caffeic and ferulic acids are major phenolics in jujube vinegar. The application of ultrasound to jujube vinegar was found to be effective.

1 | INTRODUCTION

Regular consumption of fruits and vegetables in a healthy diet is critical for the prevention of many chronic diseases (Colabianchi et al., 2021). Fruits and vegetables contain valuable nutrients such as sugars, fibers, vitamins, minerals, antioxidants, phenolic compounds, and numerous bioactive compounds (Duthie et al., 2018). Jujube (*Ziziphus jujuba* Mill.) fruit, which has been grown for food and medicinal purposes for 7000 years in its homeland of China, belongs to the family *Rhamnaceae*, has various health properties, and can be grown in tropical as well as subtropical regions. The plants native habitat includes China, India, Russia, Southern Europe, North Africa, the Middle East, and Anatolia (Ji et al., 2017; Rashwan et al., 2020). The stem, trunk, flower, and fruit of jujubes are used for medical purposes and are known to have anticancer, anti-inflammatory, antidiabetic, antimicrobial, and antioxidant effects due to their bioactive components (Lam et al., 2016). The phenolic compounds in the structure of jujube act as hydrogen donors and provide powerful antioxidant features

to its products (Koley et al., 2011). Additionally, the jujube fruit is a rich source of vitamin C, carotenoids, minerals such as potassium and iron, aroma components, polysaccharides, phenolic acids (hydroxyconic acids and benzoic acids), and flavonoids (Promyou et al., 2012). Used as traditional and functional food, jujube can also be processed into products such as jam, fruit juice, mash, jelly, pickles, liquor, wine, stewed fruit, and vinegar (Wojdyło et al., 2016).

Fruits and vegetables are processed into products using various techniques and made more durable. The most common techniques for inactivation and prolonged preservation of microorganisms in foods are conventional thermal pasteurization and sterilization. In thermal applications, when the temperature rises, undesired changes occur in the nutritional value, as well as the flavor and sensory qualities of the food (Cheng et al., 2020; Wibowo et al., 2015). Nevertheless, with the ultrasound technique, which is among new, non-thermal technologies and is increasingly used today, the loss of flavor and taste in the product is minimum, whereas the nutritional quality of the product is higher (Zhai et al., 2021). Ultrasonic waves used in ultrasound technology, which has been used in solid/liquid food systems, create cavitation by causing a sponge effect in porous products like fruit and increase mass transfer (Azoubel et al., 2015; Soltani Firouz et al., 2019). Ultrasound is one of the most environmentally safe and cost-effective innovative technologies used in food drying, enzyme hydrolysis, freezing and thawing, and microbe inactivation (Fan et al., 2017; Knorr et al., 2004; Xu et al., 2022). The application of ultrasonic technology in the food business allows for the retention and enhancement of bioactive components in products. Ultrasound positively affects the number of antioxidants and phenolic compounds in products such as fruit, fruit juices, and vinegar (Golmohamadi et al., 2013). In literature studies, there was a minimum loss in bioactive components and nutritional properties of the products with ultrasound technology applications, such as pomelo juice (Gupta et al., 2020), citrus fruit juice (Kumar Gupta et al., 2021), purple onion vinegar (Yıkmış et al., 2022), ougan juice (Gao et al., 2021), and tomato juice (Starek et al., 2021). However, when the literature is examined, ultrasound studies are limited to increasing the quality of vinegar (Zhenjiang vinegar) (Wang et al., 2017), sherry vinegar (Jiménez-Sánchez et al., 2020), and verjuice vinegar (Yıkmış et al., 2020).

The study's primary goal was to enrich the bioactive components of jujube vinegar through ultrasound processing. Response surface methodology (RSM) and artificial neural network (ANN) are used to achieve this goal. At the same time, some quality parameters of traditionally produced jujube vinegar, thermal pasteurized jujube vinegar (PJV), and ultrasound-treated jujube vinegar (UJV) will be compared.

2 | MATERIALS AND METHODOLOGY

2.1 | Preparation of vinegar samples

Jujube fruits (*Ziziphus jujuba Mill.*) were collected from ripe fruits in Tekirdag/Turkey. Fully ripe fruits that were dark red were selected. Fruits were cleaned of foreign matter and washed with water. The rotten and damaged parts of the jujube fruits were cleaned, and their size was reduced. They were then mixed with deionized water (1:1 w:w) using a blender (Waring Blender, USA). Jujube vinegar was produced by using the traditional method, as previously described (Yıkmış, 2019). Organic cherry laurel vinegar samples were stored at −20 ± 1°C in 100-ml sterile glass jars for further analysis. The control (traditional jujube vinegar [TJV]) sample was untreated jujube vinegar. Tests were performed in triplicate.

2.2 | Thermal pasteurization and ultrasound treatments

Bottles were pasteurized at 85 ± 1°C in a water bath (Wisd-Model WUC-D06H, Daihan) for 10 s and cooled to 20 ± 1°C and named PJV. Ultrasound treatment was conducted on some of the prepared jujube vinegar for different time durations (2, 4, 6, 8, and 10 min) and amplitudes (40%, 50%, 60%, 70%, and 80%). Finally, 100 ml of jujube vinegar was processed using a 200 W ultrasonic processor (Hielscher Ultrasonics Model UP200St) at a frequency of 26 kHz. The temperature was controlled using ice. Vinegars were stored at −18 ± 1°C until analysis. The UJV sample was coded as a regenerated vinegar sample in the parameters obtained as a result of RSM and ANN optimization. Tests were performed three times.

2.3 | Modeling procedure for response surface methodology and artificial neural networks

The RSM was designed according to the previous method described by Yıkmış et al. (2020). The factor levels used are shown in Table 1. Independent variables were determined as duration within the range of X_1 (time) and X_2 (amplitude). Dependent variables were determined as total phenolic content, total flavonoid content, and total antioxidant (DPPH and CUPRAC) contents. All values were obtained in triplicate and expressed as mean ± standard deviation (SD). RSM was performed using Minitab software (version 19, Minitab software).

For ANN, MATLAB Neural Network Toolbox (MATLAB Version R2020b-Mathworks Inc.) was used, which provides an interactive environment for numerical computing, visualization, and programming. It consists of a hidden layer between the input and output layers and modules using an error backpropagation (BP) algorithm from weight to prediction error. The Levenberg–Marquardt (LM) combined BP algorithm was used to create a feed-forward neural network. The LM algorithm uses 15% of the data as test data, 15% is used as validity transaction data, and 70% as training data. Multilayer perceptron neural network architectures were trained. ANN modeling was also used in the calibration of the entire data set for samples evaluated for use in independent fivefold cross-validations. For the prediction of a non-linear relationship between the input parameters (time, amplitude) and response outputs (TPC, TFC, DPPH, and CUPCAC), an ANN was used. First, it

TABLE 1 Experimental and predicted responses of RSM and ANN and results of TJV and PJV

	Independent variables		Dependent variables											
			TPC (mg GAE/100 ml)			TFC (mg CE/100 ml)			DPPH activity (%)			CUPRAC activity (%)		
Run no	Time (X_1)	Amplitude (X_2)	Experimental data	RSM predicted	ANN predicted	Experimental data	RSM predicted	ANN predicted	Experimental data	RSM predicted	ANN predicted	Experimental data	RSM predicted	ANN predicted
1	6	60	58.75 ± 0.16	58.94	58.99	9.85 ± 0.08	9.83	9.83	47.68 ± 0.34	47.45	47.60	52.88 ± 0.57	52.48	52.49
2	8	50	57.39 ± 0.72	57.48	57.31	9.46 ± 0.08	9.5	9.51	44.84 ± 1.26	44.86	44.67	51.05 ± 0.57	51.10	51.05
3	6	60	59.15 ± 0.42	58.94	58.99	9.80 ± 0.10	9.83	9.83	46.76 ± 1.56	47.45	47.60	52.32 ± 0.14	52.48	52.49
4	10	60	55.12 ± 0.85	55.27	55.24	9.20 ± 0.08	9.22	9.21	44.34 ± 0.62	43.81	43.97	49.92 ± 0.71	49.77	49.92
5	4	70	57.43 ± 0.42	57.17	57.30	9.57 ± 0.07	9.53	9.51	44.40 ± 0.71	44.69	44.40	51.10 ± 0.07	50.65	50.81
6	6	40	56.98 ± 0.89	56.88	57.07	9.32 ± 0.08	9.29	9.29	44.17 ± 0.14	44.44	44.17	49.75 ± 0.28	49.74	49.75
7	6	60	58.75 ± 0.71	58.94	58.99	9.85 ± 0.11	9.83	9.83	47.68 ± 1.50	47.45	47.60	52.88 ± 0.28	52.48	52.49
8	4	50	57.26 ± 0.85	57.50	57.26	9.54 ± 0.06	9.54	9.54	46.64 ± 0.28	46.62	46.49	50.94 ± 0.42	50.65	50.94
9	8	70	57.84 ± 0.85	57.58	57.78	9.64 ± 0.07	9.63	9.63	46.28 ± 1.41	46.81	46.63	51.47 ± 0.14	51.61	51.47
10	6	60	58.75 ± 0.92	58.94	58.99	9.85 ± 0.14	9.83	9.83	47.68 ± 0.42	47.45	47.60	52.88 ± 0.14	52.48	52.49
11	2	60	54.92 ± 0.57	54.87	54.92	9.20 ± 0.10	9.17	9.16	43.72 ± 0.57	43.46	43.72	48.16 ± 0.42	48.35	48.16
12	6	60	58.75 ± 0.30	58.94	58.99	9.80 ± 0.10	9.83	9.83	46.76 ± 0.85	47.45	47.60	52.88 ± 0.57	52.48	52.49
13	4	50	57.26 ± 0.57	57.50	57.26	9.54 ± 0.03	9.54	9.54	46.34 ± 0.76	46.62	46.49	50.94 ± 0.42	50.65	50.94
14	4	70	57.16 ± 0.96	57.17	57.30	9.46 ± 0.06	9.53	9.51	44.40 ± 0.24	44.69	44.40	50.51 ± 0.1	50.65	50.81
15	6	60	59.15 ± 0.28	58.94	58.99	9.85 ± 0.04	9.83	9.83	47.85 ± 0.74	47.45	47.60	52.16 ± 0.14	52.48	52.49
16	10	60	55.36 ± 0.68	55.27	55.24	9.22 ± 0.13	9.22	9.21	43.60 ± 0.13	43.81	43.97	49.92 ± 0.07	49.77	49.92
17	8	50	57.24 ± 0.57	57.48	57.31	9.56 ± 0.08	9.5	9.51	44.50 ± 0.37	44.86	44.67	51.05 ± 0.42	51.10	51.05
18	6	60	59.15 ± 0.86	58.94	58.99	9.85 ± 0.03	9.83	9.83	48.10 ± 0.11	47.45	47.60	52.16 ± 0.28	52.48	52.49
19	6	60	59.15 ± 0.47	58.94	58.99	9.80 ± 0.04	9.83	9.83	48.10 ± 1.23	47.45	47.60	52.16 ± 0.28	52.48	52.49
20	6	40	57.16 ± 0.00	56.88	57.07	9.24 ± 0.04	9.29	9.29	44.80 ± 0.35	44.44	44.17	49.55 ± 0.14	49.74	49.75
21	6	80	56.48 ± 0.21	56.65	56.48	9.42 ± 0.07	9.41	9.42	44.65 ± 0.71	44.45	44.65	50.30 ± 0.06	50.25	50.3
22	6	80	56.48 ± 0.10	56.65	56.48	9.42 ± 0.03	9.41	9.42	44.65 ± 0.71	44.45	44.65	50.30 ± 0.08	50.25	50.3
23	2	60	54.92 ± 0.28	54.87	54.92	9.15 ± 0.04	9.17	9.16	43.37 ± 0.07	43.46	43.72	48.16 ± 0.24	48.35	48.16
24	6	60	58.75 ± 0.38	58.94	58.99	9.85 ± 0.06	9.83	9.83	46.76 ± 1.39	47.45	47.60	52.16 ± 0.40	52.48	52.49
25	8	70	57.72 ± 0.28	57.58	57.78	9.62 ± 0.04	9.63	9.63	46.63 ± 0.28	46.81	46.63	51.37 ± 0.16	51.61	51.47
26	6	60	59.15 ± 0.16	58.94	58.99	9.85 ± 0.07	9.83	9.83	48.10 ± 0.08	47.45	47.60	52.16 ± 0.07	52.48	52.49
Predictive capacity comparison of RSM and ANN models for five response variables			R^2	0.981	0.989		0.985	0.985		0.933	0.939		0.961	0.969
			RMSE	0.19	0.14		0.03	0.03		0.41	0.39		0.26	0.23
			ADD (%)	0.3	0.2		0.25	0.25		0.76	0.44		0.45	0.32
UJV	6.2	60.6	58.94 ± 0.06			9.84 ± 0.14			47.45 ± 0.10			52.52 ± 0.13		
TJV			53.86 ± 0.04			9.12 ± 0.04			42.78 ± 0.18			50.66 ± 0.14		
PJV			52.14 ± 0.16			8.76 ± 0.03			41.16 ± 0.25			48.95 ± 0.57		

Abbreviations: AAD, absolute average deviation; ANN, artificial neural network; CE, catechin equivalent; CUPRAC, cupric-reducing antioxidant capacity; DDPH, radical scavenging activity; GAE, gallic acid equivalent; R^2, coefficient of determination; TFC, total flavonoid content; TJV, traditional jujube vinegar; TPC, total phenolic content; PJV, thermal pasteurized jujube vinegar; RMSE, root mean square error; RSM, response surface methodology; UJV, ultrasound-treated jujube vinegar.

was analyzed with ANN by training the data and selecting the best activation type and a number of neurons that best fit the data (Figure 1).

The generally used main equation for ANN is shown below:

$$n_k^h = \sum_{i=1}^{R} w_{kj}^h p_j + b_k^h, k = 1 \text{to} S \quad (1)$$

where R is the number of input variables, n is a number of data, b^h is the bias of the hidden layer, p is the input variable, S is the number of hidden neurons and w^h is the weight.

To clarify the performance of ANN models, determination coefficient (R^2), root mean square error (RMSE), and absolute average deviation were compared between RSM and ANN models. The formulas are written as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(Y_{\text{Predicded}} - Y_{\text{Expertmental}}\right)^2}{\sum_{i=1}^{n} \left(Y_{\text{Average}} - Y_{\text{Expertmental}}\right)^2} \quad (2)$$

$$\text{RSME} = \left(\frac{1}{n} \sum_{i=1}^{n} \left(Y_{\text{Predicded}} - Y_{\text{Expertmental}}\right)^2\right)^{\frac{1}{2}} \quad (3)$$

$$\text{ADD} = \left(\frac{1}{n} \sum_{i=1}^{n} \left| \frac{Y_{\text{Predicded}} - Y_{\text{Expertmental}}}{Y_{\text{Expertmental}}} \right|\right) \times 100 \quad (4)$$

where $Y_{\text{Expertmental}}$, $Y_{\text{Predicded}}$, Y_{Average}, and n are the experimental value, predicted value, average of data, and number of data points, respectively.

2.4 | Determination of bioactive compounds

Total phenolic content analysis was performed according to the Folin–Ciocalteu method, which is a common method. In the experiment, phenolic substances were determined according to the Folin–Ciocalteu method applied by Singleton and Rossi (1965) (Singleton & Rossi, 1965). Total phenol content used a gallic acid calibration curve and is given as gallic acid equivalent and expressed as milligrams of gallic acid equivalents (mg GAE/100 ml). Total flavonoid concentrations were calculated colorimetrically by UV spectrophotometer according to the method applied by Zhishen et al. (1999) (Zhishen et al., 1999). The results are expressed as mg of (+)- catechin equivalent per 100 ml of vinegar sample. DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging activity was estimated according to the procedure described by Grajeda-Iglesias et al. (2016) with slight modifications (Grajeda-Iglesias et al., 2016). CUPRAC (Cu[II] ion reducing antioxidant capacity) assay was performed according to the method recently developed by Apak et al. (2006) (Apak et al., 2006). In all assays, absorbance measurements were carried out at 25°C in a UV–VIS spectrophotometer (Spectrum Instrument, SP-UV/VIS-300SRB).

2.5 | pH, titratable acidity, Brix, and color

Brix was measured at 20°C using an optical refractometer (ATAGO brand RX-7000α model), and pH was measured with a pH meter (Hanna Instruments HI 2002 pH/ORP). The titration acidity was potentiometrically determined by titration of the samples with 0.1 N NaOH (Sigma-Aldrich) solution to pH 8.1. From the sample, 5 ml was taken, and 50 ml of distilled water was added, and 10 ml of the sample was taken from the filtrate. The results were calculated as total acidity (%).

L, *a*, and *b* values of fruit juices were measured with a Hunter colorimeter (Color Measuring Device PCE-CSM 5). *L* is a measure of light and darkness between 0 and 100, where 0 corresponds to black and 100 corresponds to white. In the color measurement system, positive (+) values of a indicate redness while negative (−) values indicate greenness. The positive (+) values of b indicate yellow and the negative (−) values represent blue. Chroma (C), hue angle (h), and total color change (ΔE) are expressed according to the following equations (5)–(7);

$$\text{Chroma, C} = \left(a^2 + b^2\right)^{1/2} \quad (5)$$

$$h\,(\text{hue angle}) = \tan^{-1}(b/a) \quad (6)$$

$$\Delta E = \left((\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2\right)^{1/2} \quad (7)$$

All determinations were carried out three times per treatment.

2.6 | Determination of organic acid content

Organic acid contents were evaluated by using the AOAC official method (1995) (AOAC, 1995). Samples were filtered through a 0.45-μ nylon membrane to ensure the removal of any particulate impurities that might be present and injected into a Shimadzu LC-20A series HPLC model SPD-20A ultraviolet and visible detector (UV–VIS) system. The mobile phase consisted of 0.2 M KH_2PO_4 (pH 2.4) with a flow rate of 0.8 ml/min. An InertSustain C18 column (5 μm, 4.6 × 250 mm) was used, a 10 μl sample was injected, and peaks were identified by comparing retention times with those of commercially available external standards. Citric, malic, acetic, lactic, tartaric, oxalic, fumaric, and formic acids were used as external standards, and different concentrations of each standard solution were used to draw a linear regression calibration curve. Results are expressed as g of each organic acid equivalent per liter of sample.

2.7 | Phenolic compounds

Phenolic compounds were extracted by methanol according to the method, which is used by Selli (2017) (Selli, 2017), phenolic

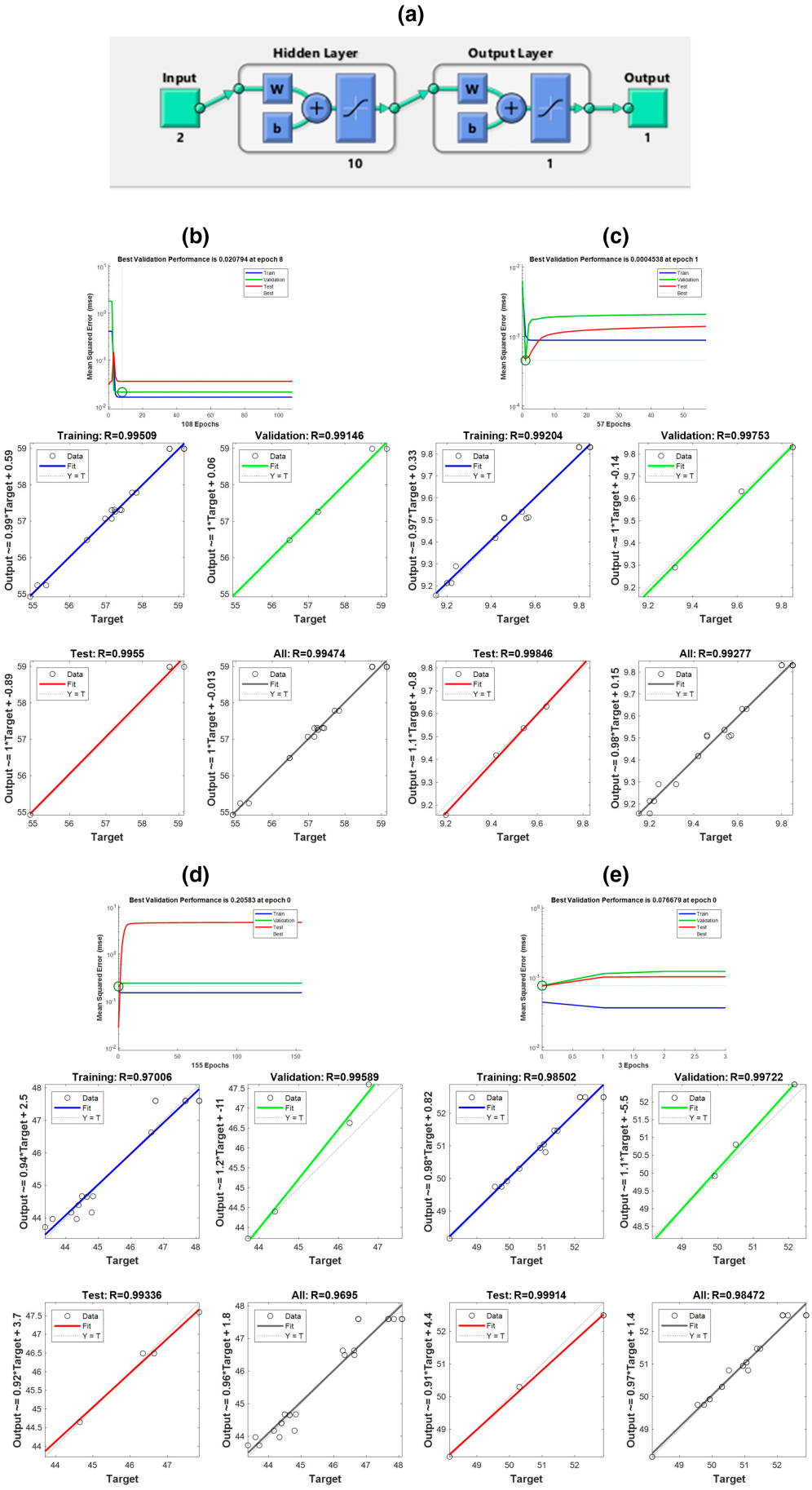

FIGURE 1 Optimal architecture of developed artificial neural network (ANN) model (a) and performance plot for the ANN model (b). (b), total phenolic content; (c), total flavonoid content; (d), radical scavenging activity; (e), cupric-reducing antioxidant capacity.

compounds were extracted with methanol. Samples were filtered through a 0.45-μm pore size membrane filter before injection. An Agilent 1100 HPLC system (Agilent Technologies) operated by Windows NT-based ChemStation software was used. Sigma phenolic component single standards were weighed to 100 mg and dissolved in methanol. Intermediate standards were prepared as calibration standards at 0.5–1–2–5–10 ppm. The HPLC equipment was used along with a diode array detector. The system comprised a binary pump, degasser, and auto sampler. The column used was a Waters inverse phase Hichrom ODS-2 column (150 mm 4.6 mm × 5 μm). The mobile phase consisted of two solvents: 0.2% phosphoric acid (A) and acetonitrile: methanol (B). The limit of detection (LOD) and quantification (LOQ) under the present chromatographic conditions were determined at a signal-to-noise ratio (S/N) of about 3 and 10, respectively.

2.8 | Minerals

Ca, Cu, Fe, K, Mg, Na and Zn content in the samples were determined with an atomic absorption spectrometer (Perkin Elmer Analyst AA800) at wavelengths of 422.7, 324.8, 248.3, 766.5, 285.2, 589.0, and 213.9; C_2H_2 flow (L/min) rate of 2.0, 1.7, 2.0, 2.4, 2.1, 1.9, and 1.8, oxidant airflow (L/min) rate of 18.0, 14.0, 17.0, 13.0, 17.0, 17.0, and 19.3, respectively. A known volume of sample (0.3–0.5 g), 6.5 ml 65% nitric acid solution, and 1.5 ml 30% hydrogen peroxide (H_2O_2) were injected into the Teflon container and then the mix was burned in a microwave oven at temperatures varying between 180°C during 30 min (Anton Paar Multiwave GO). The acid digested samples were diluted with ultra-pure water in 50-ml volumetric flasks, and the mineral contents of samples were determined as mg/kg according to calibration curves which were prepared with Ca, Cu, Fe, K, Mg, Na, and Zn standards (Merck). Phosphorus (P) was determined with a UV–Visible spectrophotometer (Shimadzu, UV-1601) at a wavelength of 400 nm. A known volume of sample (0.3–0.5 g), 6.5 ml 65% nitric acid solution, and 1.5 ml 30% hydrogen peroxide (H_2O_2) were injected into the Teflon container and then the mix was burned in a microwave oven at temperatures varying between 180°C during 30 min (Anton Paar Multiwave GO). The acid-digested samples were diluted with ultra-pure water in 50-ml volumetric flasks. Then, a 5 ml sample solution was mixed with 10 ml of molybdovanadate (Merck) solution, which was prepared by dissolving 1.25 g of ammonium monovanadate and 25 g of ammonium hepta molybdate tetrahydrate in 1 L of ultra-pure water including 70 ml of 65% nitric acid solution. The phosphorus content of samples was determined as mg/kg according to calibration curves which were prepared with the P standard (Merck).

2.9 | Volatile compounds

Analysis of the volatiles was performed using a solid-phase microextraction method described by Yıkmış et al. (2021), with a GC–MS system (Shimadzu Corp.) (Yıkmış et al., 2021). The detections were achieved by comparing the mass spectra of unknown compounds with those in Wiley 8 and NIST 05 mass spectral laboratory.

2.10 | Statistical analysis

All values were obtained in triplicate and expressed as mean ± SD. Jujube vinegar samples were determined by one-way ANOVA at a $p < 0.05$ significance level using Tukey's Honestly Significant Difference test (SPSS 22.0 software, SPSS Inc.). RSM was performed using Minitab software (version 19, Minitab software). RSM and ANN plots were developed using SigmaPlot 12.0 software (Systat Software, Inc.). Cluster analysis (Ward method and hierarchical) and principal component analysis (PCA) were performed using JMP (12.2.0 SAS Institute, Inc.).

3 | RESULTS AND DISCUSSION

3.1 | Optimization of bioactive compounds

Experimental and predictive results for the bioactive component values of jujube vinegar samples at different levels of X_1 and X_2 are given in Table 1. The second-order equation results for the bioactive components in the polynomial regression results are given below.

$$\mathbf{TPC\ (mg\ GAE/L)} = 32.62 + 2.631X_1 + 0.6151X_2 - 0.24199X_1^2 - 0.005442X_2^2 + 0.00537X_1X_2 \quad (8)$$

$$\mathbf{TFC\ (mg\ CE/L)} = 4.446 + 0.3798X_1 + 0.13784X_2 - 0.04018X_1^2 - 0.001213X_2^2 + 0.001812X_1X_2 \quad (9)$$

$$\mathbf{DPPH\ (\%Inhibition)} = 28.99 - 0.001X_1 + 0,6107X_2 - 0,2384X_1^2 - 0.007509X_2^2 + 0.04844X_1X_2 \quad (10)$$

$$\mathbf{CUPRAC\ (\%Inhibition)} = 22.87 + 2.363X_1 + 0.7202X_2 - 0.2137X_1^2 - 0.006211X_2^2 + 0.00631X_1X_2 \quad (11)$$

Table 2 shows the analysis of variance (ANOVA) for TPC, TFC, DPPH, and CUPRAC. The linear effect of the X_2 factor on TPC values as a result of RSM was not statistically significant ($p > 0.05$). However, the linear effect of the X_2 factor on TFC values was statistically significant ($p < 0.001$). The linear effects of X_1 and X_2 factors on DPPH values were not statistically significant ($p > 0.05$). In the 2-way interaction, X_1 and X_2 factors were found to be insignificant only for CUPRAC and TPC values ($p > 0.05$). The effects of X_1 and X_2 factors on bioactive components were found to be statistically significant in cross-interactions ($p < 0.001$). As a result of the RSM model, the R^2 values showed high correlations for TPC, TFC, and TAC with values of 97.59, 97.52, and 99.51, respectively. The interactions of the variables were graphically represented by three-dimensional (3D) response surfaces for RSM and ANN, as shown in Figure 2. As

TABLE 2 Corresponding *p*-values of linear, interaction, and quadratic terms of regression coefficients obtained by RSM of responses for TPC, TFC, DPPH, and CUPRAC experiments

		TPC (mg GAE/100 ml)		TFC (mg CE/100 ml)		DPPH activity (%)		CUPRAC activity (%)	
Source	DF	*F*-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value
Model	5	205.07	0.0000	264.81	0,0000	55.53	0.0000	97.34	0.0000
Linear	2	3.38	0.0550	12.05	0,0000	0.45	0.645	18.72	0.0000
X_1	1	5.07	0.0360	3.52	0,0750	0.9	0.355	33.11	0.0000
X_2	1	1.68	0.2090	20.59	0,0000	0.0000	0.983	4.33	0.0510
Square	2	508.3	0.0000	645.35	0,0000	121.26	0.0000	223.93	0.0000
X_1^2	1	937.62	0.0000	1039.78	0,0000	190.07	0.0000	369.19	0.0000
X_2^2	1	296.37	0.0000	592.66	0,0000	117.91	0.0000	194.89	0.0000
Two-way interaction	1	2.02	0.171	9.24	0,0060	34.26	0.0000	1.41	0.2500
$X_1 \times X_2$	1	2.02	0.171	9.24	0,0060	34.26	0.0000	1.41	0.2500
Error	7								
Lack-of-fit	3	4.72	0.014	0.43	0,7330	1.2	0.34	1.81	0.183
Pure error	4								
Total	12								
R^2		98.09%		98.51%		93.28%		96.05%	
Adj R^2		97.61%		98.14%		91.60%		95.07%	
Pred. R^2		96.73%		97.24%		89.76%		94.15%	

Abbreviations: CE, catechin equivalent; CUPRAC, cupric-reducing antioxidant capacity; DF, degree of freedom; DDPH, radical scavenging activity; GAE, gallic acid equivalent; TPC, total phenolic content; TFC, total flavonoid content; X_1, time; X_2, amplitude;

a result of the RSM model, R^2 values showed high correlations of 98.51, 93.51, 93.28, and 96.05 for TPC, TFC, DPPH, and CUPRAC, respectively (Table 2).

At the end of the optimization, X_1 and X_2 values were determined to be 6.2 min and 66 amplitudes, respectively (Table 1). As a result of ultrasound treatment applied to jujube vinegar samples, the TPC optimization value was determined as 58.94 mg GAE/100 ml, an increase of 8.6% compared with the TJV sample. The TFC value, on the other hand, was found to be 9.84 mg CE/100 ml as a result of the optimization, a 7.3% increase compared with the TJV sample. As a result of the optimization, DPPH activity was determined to be 47.45%. An increase of 9.8% was detected compared with the TVJ sample. The CUPRAC activity was determined as 52.2% as a result of the optimization in addition to an increase of 3.5% compared with the TJV sample. Although reductions were detected in all bioactive components at the end of thermal pasteurization applied to the TJV sample, increases occurred after ultrasound treatment. As in our study, increases in bioactive content are compatible with reports about fruit and vegetable smoothies (Casco et al., 2022), black, red, and white currant juices (Kidoń & Narasimhan, 2022), prebiotic soursop whey beverages (Guimarães et al., 2019), gilaburu vinegar (Erdal et al., 2022), cashew apple bagasse (Patra et al., 2021), beetroot (*Beta vulgaris* L.) juice (Ramírez-Melo et al., 2022) and orange juice whey drink (Oliveira et al., 2022). Factors such as the formation of hydroxyl radicals during the cavitation with the effect of ultrasound, increased mass transfer rates and the formation of micro-voids may cause an increase in bioactive components (Ordóñez-Santos et al., 2017; Wang, Wang, et al., 2019). At the same time, the increase in phenolic substance content and flavonoid substance content with ultrasound treatments can explain the increase in total antioxidants (Figure 3).

The statistical results of the parameters used to compare the RSM and ANN models are shown in Table 1. The R^2 values for the ANN and RSM models were found to provide sufficient experimental fit. R^2 for RSM were 0.981, 0.985, 0.933, and 0.961 for TPC, TFC, DPPH, and CUPRAC, respectively, while R^2 for ANN was 0.989, 0.985, 0.939, and 0.969 for TPC, TFC, DPPH, and CUPRAC, respectively. For the experimental data and the prediction data, ANN had a higher fit, indicating an alternative or better approach than RSM. For RSME and ADD values, both models were equal for TFC, but the ANN model gave better results for the other bioactive values (Table 1). It was concluded that the ANN model is more reliable and has higher accuracy than the RSM model in terms of predictive ability and measured responses for TPC, DPPH, and CUPRAC. Similar results to our study reported that ANN gave better results than RSM modeling for optimization of kidney bean antioxidants (Yang et al., 2019), cashew apple bagasse (Patra et al., 2021), cranberry pomace (Alrugaibah et al., 2021), and ultrasound-assisted extraction of phenolic compounds from garlic (Ciric et al., 2020).

3.2 | Physicochemical, color, and organic acid

The pH, Brix, and total acidity values of TJV, PJV, and UJV samples are given in Table 3. There was no significant difference ($p < 0.05$)

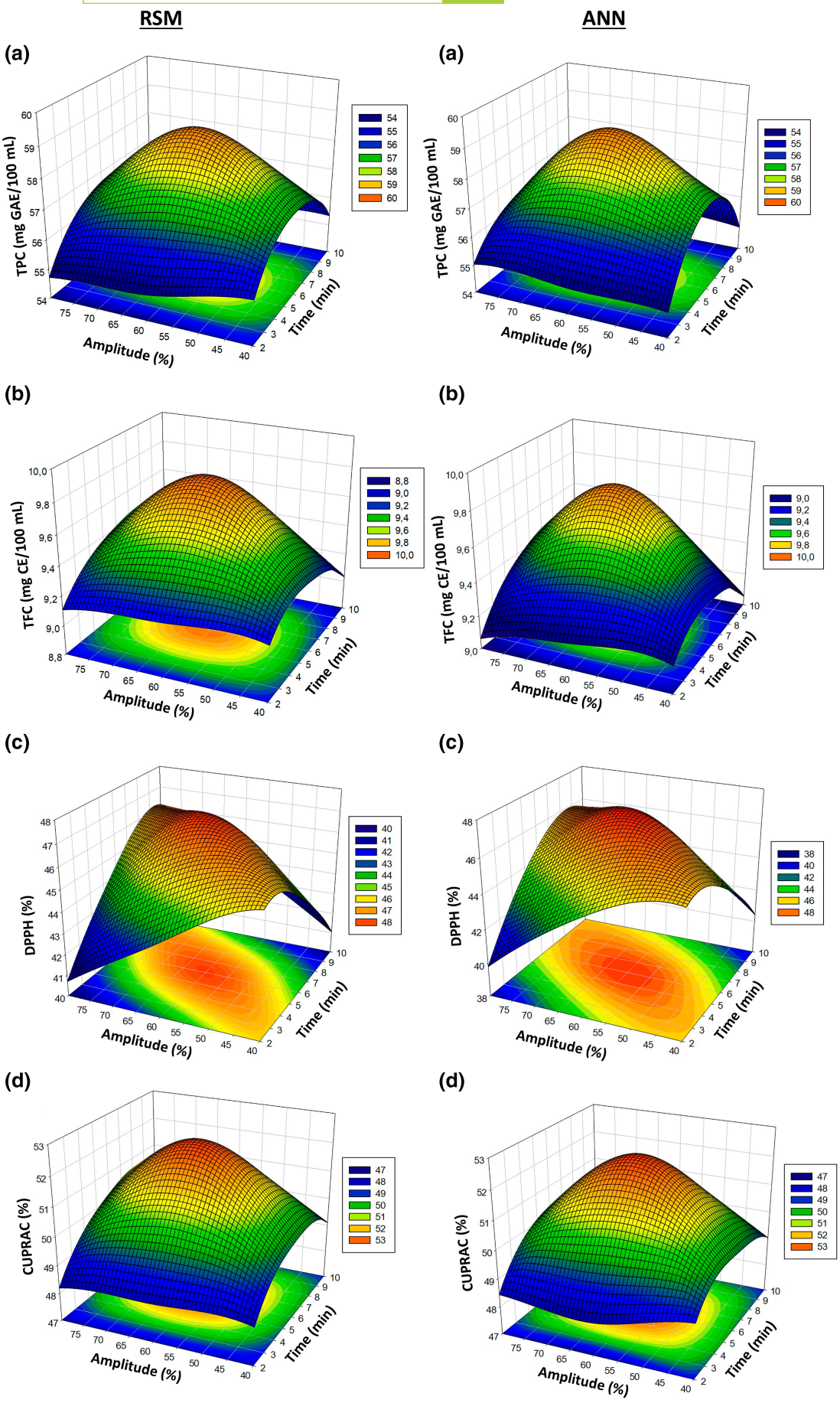

FIGURE 2 Response surface plots (3D) for total phenolic content (a), total flavonoid content (b), DPPH (c), and CUPRAC (d) analysis as a function of significant interaction factors for response surface methodology and artificial neural network.

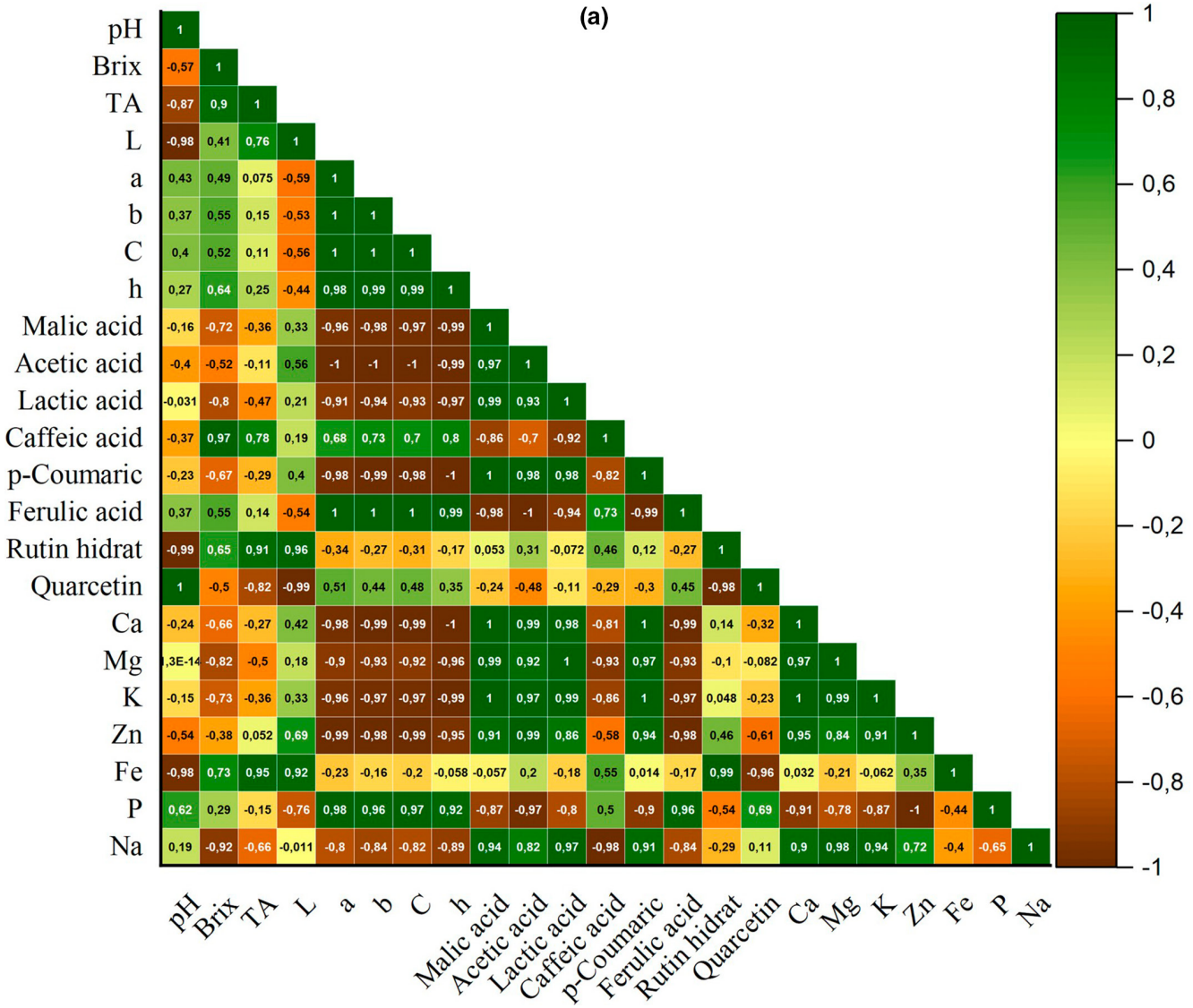

FIGURE 3 (a) Pearson's correlation coefficients of physcochemical, phenolic compounds, and mineral of jujube vinegars.

between the pH, Brix, and total acidity properties of the three vinegar samples. This situation may vary depending on the applied ultrasound application method, energy levels, and molecular structures (Zhai et al., 2021). Similar results regarding pH, Brix, and acidity were observed in prebiotic cranberry juice, crabapple (*Malus asiatica*) vinegar, apple cider, strawberry juice, and apple juice treated with ultrasound treatment (Jiménez-Sánchez et al., 2020; Tiwari et al., 2008; Ugarte-Romero et al., 2006; Zhang et al., 2012). When the color values of all jujube vinegar samples are examined, a significant increase was observed in the L^* value of PJV and UJV compared with the sample with no treatment.

The color values (L^*, a^*, and b^*) and the total color difference (ΔE) of jujube vinegar in the CIELab system are summarized in Table 3. When the color values of all jujube vinegar samples are examined, the L^* value (L^*: 33.97, L^*: 34.48) of PJV and UJV increased significantly ($p < 0.05$) compared with the UJV sample with no treatment. Despite significant differences in L^* color values of samples, no noticeable differences were obtained between the a^* and b^* values of untreated and treated vinegar. Total color change values were calculated for PJV ($\Delta E = 1.19$) and UJV ($\Delta E = 1.60$) samples. The TJV untreated jujube vinegar was a little bit darker compared with the treated samples. Cserhalmi et al. (2006) reported that the L^* values of lemon and orange juices increase, and the L^* values of tangerine and grapefruit juices decrease as a result of pulsed electric field (PEF) treatment (Cserhalmi et al., 2006). Minor variations in color values occurred in our study, as reported in a study about the effect of ultrasound and steam treatments on color parameters in orange-fleshed sweet potato juice (Rios-Romero et al., 2021), and it is difficult to identify the sole source of this. No statistically significant differences were detected ($p < 0.05$).

Vinegar is a product rich in organic acids and contains different bioactive compounds depending on the type of raw material used, processing technique, and fermentation conditions (Xia et al., 2020). When TJV, PJV, and UJV samples are compared in terms of malic and lactic acid contents, PJV samples were found to have higher organic acid content (Table 3). In UJV samples, on the other hand, ultrasound

TABLE 3 Physicochemical, color, organic acid, phenolic compounds, and mineral results of samples TJV, PJV, and UJV

Analyzes		Sample		
		TJV	PJV	UJV
Physicochemical properties	pH	2.69 ± 0.01[a]	2.68 ± 0.02[a]	2.67 ± 0.01[a]
	Brix°	4.53 ± 0.06[a]	4.50 ± 0.10[a]	4.57 ± 0.06[a]
	Total acidity (%)	2.67 ± 0.02[a]	2.67 ± 0.02[a]	2.68 ± 0.01[a]
Color properties	L^*	32.97 ± 0.26[b]	33.97 ± 0.25[a]	34.48 ± 0.14[a]
	a^*	12.29 ± 0.25[a]	12.06 ± 0.09[a]	12.19 ± 0.13[a]
	b^*	12.11 ± 0.44[a]	11.68 ± 0.26[a]	11.95 ± 0.19[a]
	Chroma (C)	17.25 ± 0.44[a]	16.78 ± 0.26[a]	17.06 ± 0.19[a]
	Hue angle (h°)	44.56 ± 0.46[a]	44.09 ± 0.44[a]	44.43 ± 0.18[a]
	ΔE	–	1.19 ± 0.40	1.60 ± 0.27
Organic acid contents (g/L)	Malic acid	0.12 ± 0.00[b]	0.18 ± 0.00[a]	0.13 ± 0.00[b]
	Acetic acid	15.81 ± 0.11[c]	26.07 ± 0.42[b]	19.97 ± 0.12[a]
	lactic acid	0.59 ± 0.01[b]	0.87 ± 0.02[a]	0.60 ± 0.01[b]
	Citric acid	n.d	n.d	n.d
Phenolic compounds (mg/L)	Caffeic acid	3.15 ± 0.39[a]	2.30 ± 0.18[b]	3.65 ± 1.49[a]
	p-Coumaric	1.92 ± 0.14[a]	2.09 ± 0.00[a]	1.96 ± 0.15[a]
	Ferulic acid	3.40 ± 0.36[a]	3.32 ± 0.59[a]	3.37 ± 0.34[a]
	Rutin	1.25 ± 0.09[a]	1.41 ± 0.13[a]	1.64 ± 0.07[a]
	Quarcetin	0.23 ± 0.03[a]	0.19 ± 0.00[a]	0.16 ± 0.00[a]
Minerals (mg/L)	Ca	59.49 ± 0.30[a]	89.35 ± 0.13[c]	67.04 ± 0.06[b]
	Mg	24.74 ± 0.23[a]	35.54 ± 0.30[b]	24.74 ± 0.23[a]
	K	208.60 ± 9.48[a]	361.65 ± 9.48[b]	233.40 ± 4.53[a]
	Zn	0.03 ± 0.00[a]	0.25 ± 0.01[c]	0.15 ± 0.00[b]
	Fe	1.03 ± 0.13[a]	1.23 ± 0.22[a]	1.67 ± 0.33[a]
	P	24.2 ± 0.14[c]	13.8 ± 0.28[a]	17.65 ± 0.35[b]
	Na	44.28 ± 1.39[a]	60.10 ± 1.56[b]	40.18 ± 1.29[a]

Note: Results are presented mean ± standard deviation ($n = 3$). Values with the different letters within line are significantly different ($p < 0.05$).
Abbreviations: PJV, thermal pasteurized jujube vinegar; TJV, traditional jujube vinegar; UJV, ultrasound-treated jujube vinegar;

application caused a significant ($p < 0.05$) increase in acetic acid content. It was stated that the reason for this increase is the removal of trapped compounds due to cavitation after ultrasound treatment (Cheng et al., 2007). The organic acid content of fruits is one of the important features that affect sensory properties and especially taste. In a study examining the organic acid content of jujube fruits, malic, citric, and succinic acid contents were determined, with malic acid being reported as the dominant organic acid (Gao et al., 2021). There was no study investigating the organic acid content of jujube vinegar samples. In our study, the dominant acid in vinegar samples was acetic acid, and small amounts of malic and lactic acids were detected.

3.3 | Phenolic compounds

In the last few years, phenolic compounds derivated from plants have been linked to several bioactivities such as anticancer, antimicrobial, antiallergic, antiviral, and antioxidant. Research into evaluating the nutritional properies of many foods, processing plant based phenolic compounds step also play a significant role (Kumar & Goel, 2019). The amounts of phenolic compounds in jujube vinegar samples are given in Table 3. Except for the decrease in caffeic acid content in UJV samples, ultrasound application, and pasteurization did not cause a significant ($p > 0.05$) change in the amounts of *p*-coumaric, ferulic acid, quercetin, and rutin hydrate phenolic compounds in TJV, PJV, and UJV samples. Wang et al. (2011) reported that cinnamic acid and p-hydroxybenzoic phenolic acids are mostly found in jujube, while six other phenolic compounds and flavonoids were detected, such as caffeic acid, p-coumaric acid, rutin, quercetin, and gallic acid, and protocatechuic acid, which were also detected in jujube vinegar samples in our study (Wang et al., 2011). It was stated that phenolic acids are bound in the water-insoluble form in jujube seeds and peel, and these fractions show high total phenol content and high antioxidant capacity (Gao et al., 2013). The results in Table 2 in our study also support this situation. In the studies, ultrasound technology was recommended to improve the extraction of bioactive compounds,

especially in liquid food systems (Wang, Wang, et al., 2019). Similar results were reported for the increase in the flavonoid and total phenolic contents of kiwi fruit and strawberry juice that were treated with ultrasound. It was reported that the mass transfer to liquid increases with ultrasound treatment, and the dents caused by the cavitation pressure disrupt the cell walls of the fruit tissue and cause an increase in the amount of bioactive components (Chen et al., 2013; Wang, Vanga, & Raghavan, 2019; Wang, Wang, et al., 2019).

3.4 | Minerals

Minerals are one of the important components that determine the quality of fruits, while also affecting the ash content, acidity, pH, Brix and sensory properties (taste–aroma) of the product (Huang et al., 2021). The mineral substance content of TJV, PJV, and UJV samples is given in Table 3. When the jujube vinegar samples are compared, the P mineral content increased significantly ($p < 0.05$) in the ultrasound-treated UJV samples, whereas the mineral content

TABLE 4 Determination of volatile profiles of TJV, PJV, and UJV

Volatile compounds	RI	TJV (μg/kg)	PJV (μg/kg)	UJV(μg/kg)
Ethyl acetate	885	1.41 ± 0.13^{a}	0.87 ± 0.06^{b}	1.04 ± 0.12^{ab}
Ethanol	936	3.06 ± 0.42^{a}	2.10 ± 0.12^{a}	2.33 ± 0.16^{a}
Hexanal	1080	3.46 ± 0.33^{a}	2.31 ± 0.06^{b}	2.60 ± 0.13^{b}
Methyl hexanoate	1179	0.14 ± 0.03^{a}	0.08 ± 0.01^{a}	0.10 ± 0.02^{a}
2-Heptanone	1185	0.21 ± 0.04^{a}	0.08 ± 0.04^{a}	0.16 ± 0.04^{a}
Limonene	1195	0.41 ± 0.06^{a}	0.19 ± 0.03^{a}	0.28 ± 0.06^{a}
2-Hexanal	1223	36.78 ± 1.90^{a}	23.74 ± 0.63^{b}	28.45 ± 1.01^{b}
Styrene	1256	0.08 ± 0.04^{a}	n.d	0.05 ± 0.01^{a}
Octanal	1288	1.97 ± 0.25^{a}	1.09 ± 0.10^{b}	1.42 ± 0.14^{ab}
2-Heptenal	1330	0.43 ± 0.12^{a}	0.24 ± 0.04^{a}	0.32 ± 0.04^{a}
6-Methyl-5-hepten-2-one	1241	0.31 ± 0.10^{a}	0.14 ± 0.05^{a}	0.24 ± 0.04^{a}
1-Hexanol	1357	0.05 ± 0.03^{a}	n.d	n.d
2-Nonanone	1192	0.28 ± 0.10^{a}	n.d	0.13 ± 0.03^{b}
Nonanal	1396	0.42 ± 0.09^{a}	0.23 ± 0.04^{a}	0.21 ± 0.03^{a}
1-Octen-3-ol	1451	0.14 ± 0.02^{a}	0.13 ± 0.03^{a}	0.11 ± 0.02^{a}
Acetic acid	1461	0.52 ± 0.11^{a}	0.32 ± 0.08^{a}	0.37 ± 0.03^{a}
2-Ethyl-1-hexanol	1496	0.18 ± 0.02^{a}	0.11 ± 0.02^{a}	0.14 ± 0.04^{a}
Decanal	1503	0.84 ± 0.13^{a}	0.52 ± 0.06^{a}	0.61 ± 0.09^{a}
Benzaldehyde	1541	1.24 ± 0.16^{a}	0.73 ± 0.11^{a}	0.95 ± 0.09^{a}
Linalool	1546	0.26 ± 0.05^{a}	0.13 ± 0.04^{a}	0.27 ± 0.03^{a}
Methyl benzoate	1631	0.08 ± 0.03^{a}	0.04 ± 0.01^{b}	n.d
Butanoic acid	1636	0.15 ± 0.06^{a}	n.d	0.10 ± 0.03^{a}
Ethyl benzoate	1652	0.17 ± 0.04^{a}	0.09 ± 0.04^{a}	0.14 ± 0.03^{a}
Hexanoic acid	1850	0.22 ± 0.06^{a}	0.17 ± 0.03^{a}	0.19 ± 0.03^{a}
Phenethyl alcohol	1908	0.24 ± 0.06^{a}	0.14 ± 0.03^{a}	0.18 ± 0.04^{a}
Nonanoic acid	2160	0.04 ± 0.02^{a}	n.d	n.d
Decanoic acid	2249	0.12 ± 0.04^{a}	0.08 ± 0.04^{a}	0.12 ± 0.02^{a}
Total (μg/kg)				
Esters		1.80	1.08	1.28
Alcohols		3.93	2.61	3.03
Aldehydes		45.14	28.86	34.56
Ketones		0.80	0.22	0.53
Acids		1.05	0.57	0.78
Terpenes		0.49	0.19	0.33

Note: Results are presented mean ± standard deviation ($n = 3$). Values with the different letters within line are significantly different ($p < 0.05$).

Abbreviations: n.d, not determined; PJV, thermal pasteurized jujube vinegar; RI, retention index; TJV, traditional jujube vinegar; UJV, ultrasound-treated jujube vinegar.

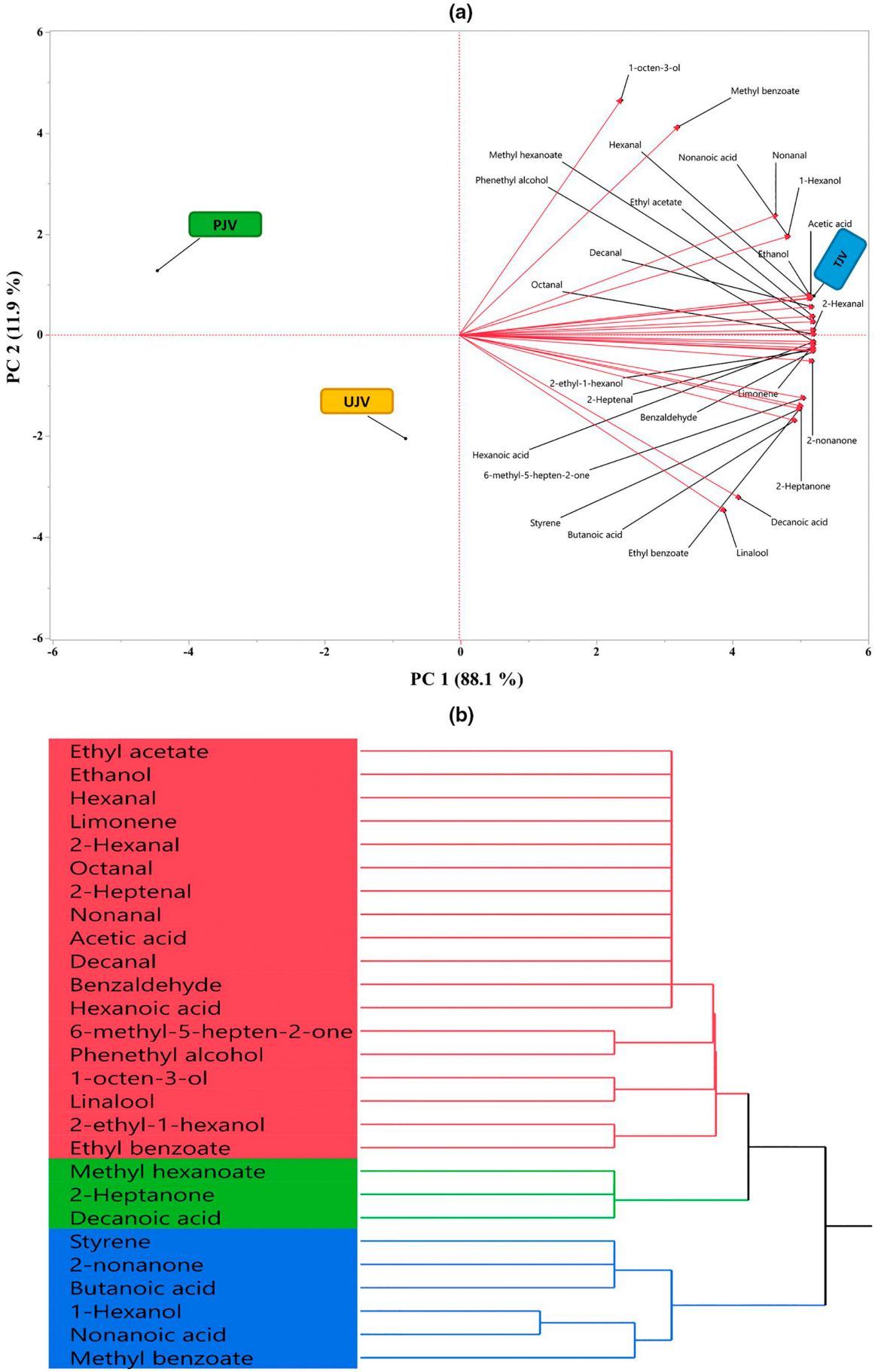

FIGURE 4 (a) Principal component analysis biplot of volatile compounds in jujube vinegar samples (b) dendrogram of hierarchical cluster analysis of samples and identified volatile compounds. The samples were clustered according to them in the form of red, green, and blue.

of Zn, Ca, Mg, K, and Na decreased, and the Fe mineral content was found to be similar in all samples. Mineral contents of PJV and TJV samples were similar. The highest mineral content was determined for potassium, K (250 mg), the lowest for Zn (0.05 mg) in 100 g jujube fruit, with the lowest K (233.40 mg/kg) in jujube vinegar samples, and the lowest mineral content Zn (0.03 mg/kg). Similar to our study, the mineral K was found to be dominant in a study of black vinegar. Components such as amino acids, sugar, and mineral substances in vinegar are stated to be substances that regulate metabolism, provide energy and increase immunity (Chou et al., 2015). Minerals such as K in vinegar regulate the acid–base balance in the blood and play a regulatory role in meeting the daily nutritional needs of the body (Xia et al., 2020). Similar mineral contents were observed in different vinegar samples (Fu et al., 2013; Koyama et al., 2016; Xia et al., 2020). However, no study was found in which the mineral contents of jujube vinegar used in our study were investigated, except for ready-made packaged product information (Rashwan et al., 2020).

3.5 | Volatile profile

Table 4 shows the identified volatile compounds in the TJV, PJV, and UJV samples. Principal component analysis (PCA) was used to evaluate the differences between TJV, PJV, and UJV samples in terms of volatile compounds. The PCA plot in Figure 4a shows the distribution of samples in two principal components. Eigenvector values in the score graph where all jujube samples are evaluated were 100% (PC1 = 88.1% and PC2 = 11.9%). PCA is suitable for distinguishing samples of jujube vinegar and grouping volatile compounds according to their spatial location. TJV was positively charged for PC1 and PC2, and PJV was negatively charged for PC1 and positively charged for PC2. TS-PJ, on the other hand, was negatively charged for PC1 and PC2, and was not grouped for volatile chemicals. Hierarchical cluster analyses (HCA-Ward clustering method) were performed using the data obtained for TJV, PJV, and UJV. The dendrogram clusters of TJV, PJV, and UJV samples are shown in Figure 4b. When the dendrogram is examined, the volatile aroma profiles of the most similar jujube vinegar were first grouped, and the starting groups were combined according to their similarity. In cluster analysis, classification according to distances is separated by colors. The red area (18), green area (6), and blue area (6) are divided into cluster groups.

Jujube vinegar samples contained 22–27 volatile compounds, and the most identified groups were aldehydes (7), alcohols (6), and alcohols (6). The lowest amounts of volatile compounds were found in PJV (33.53 μg/kg), while high amounts of volatile compounds were found in TJV (53.21 μg/kg) and UJV (40.51 μg/kg) (Table 4). Thermal pasteurization was more affected by the total change. 1-hexanol could not be detected in both treatment methods. There were 4 and 3 undetectable aroma compounds for PJV and UJV compared with the TJV sample, respectively. Linalool, responsible for the floral, citrus, and fruity aroma, was more damaged in the PJV sample and increased in the UJV sample. In the studies about the different effects on volatile compounds, as for the thermal pasteurization and ultrasound treatment applied to pomegranate juice, limonene compounds decreased in both treatments, as in our study (Tian et al., 2020). Thermal pasteurization affected the 2-heptanone compound 38.1% more than ultrasound treatment ($p > 0.05$). At the end of the ultrasound applied to jujube vinegar, decreases in the octanal compound were similarly detected as the effect of ultrasound to removing bitterness in citrus fruit juice (Kumar Gupta et al., 2021). Tian et al., 2020 reported that ultrasound treatment preserved total alcohol volatile compounds more than thermal heat treatments, as in our study. Similar results were found for the thermosonication treatment applied to grape juice, with reductions in aldehyde compounds (Ma et al., 2020). 6-methyl-5-hepten-2-one, which makes a significant contribution to the fresh and green sensory properties of most fruits, was detected as 0.14 and 0.14 μg/kg in PJV and UJV samples, respectively ($p > 0.05$). Terpenes, alcohols, aldehydes, ketones, and esters were higher with ultrasound treatment of jujube vinegar than with thermal pasteurization (Table 4). The same effect was detected in ultrasound-treated mandarin (*Citrus unshiu*) juice by Cheng et al. (2020) in a 2020 report. Changes in aroma compounds may cause reductions in some volatile aroma compounds with the effect of micro shock waves generated by cavitation during the ultrasound process.

4 | CONCLUSION

Products obtained from fruits rich in phenolic compounds are frequently chosen by consumers because of their important health benefits. Jujube fruit contains many organic acids, vitamins, and minerals, and also contains other bioactive components such as phenolic compounds with antioxidant activity. Thanks to the bioactive compounds in the jujube fruit used in our study, a product with very high nutritional value were obtained when processed into vinegar. In this study, RSM and ANN were successfully used to determine the optimal experimental parameters for the bioactive properties (total phenolic compound, total flavonoid content, and antioxidant activity) of jujube vinegar. ANN showed superior properties and increased the workable suitability of the dataset. The bioactive properties of jujube vinegar were enriched with ultrasound technology. Ultrasound preserved the aroma profile of jujube vinegar more than thermal pasteurization. Ultrasound treatment caused an increase in Ca, K, Zn, and Fe mineral contents of jujube vinegar. The dominant organic acid in jujube vinegar is acetic acid, and an increase in organic acid content was detected as a result of ultrasound treatment. UJV could potentially be recommended as a functional food ingredient for health-conscious consumers and this could constitute a preliminary study about an industrial process for use in the food industry to enrich products with bioactive compounds. However, the effects of combining ultrasound technology with other innovative non-thermal technologies to provide safe and high-quality jujube vinegar should be explored for their impact on the sensory quality properties of the final product.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in the manuscript.

ETHICS STATEMENT

This article does not contain any studies with human or animal subjects.

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