



Sustainable Optimization of Ohmic Heating–Assisted Extraction of Polyphenolics from Goji Berry (*Lycium barbarum* L.): LC–MS/MS Profiling and Blueness–Greenness Assessment

Harun Kantar¹ · Nesrin Ecem Bayram²

Received: 21 April 2025 / Accepted: 11 June 2025 / Published online: 26 June 2025
© The Author(s) 2025

Abstract

This study aimed to extract bioactive compounds from goji berry (*Lycium barbarum* L.) fruit using the ohmic heating–assisted extraction (OHAE) method and optimize the extraction conditions. In this context, firstly, the extraction conditions to be applied for the OHAE method were determined using the response surface method (RSM)-Box Behnken experimental design. During the study, temperature, holding time, and electrical field strength were determined as independent variables, while the total phenolic compound (TPC), total flavonoid compound (TFC), and antioxidant activity (DPPH) were selected as dependent variables. As a result of the optimization, the optimum conditions were determined to be 60 °C for the temperature, 60 min for the holding time, and 45 V/cm for the electrical field strength, and the composite desirability value of the model was 0.90. The highest experimental results for TPC, TFC, and DPPH were found to be 23.83 mg GAE/g, 7.33 mg QE/g, and 24.53 mg TE/g, respectively. In addition, the polyphenolic profiles of all extracts obtained under different process conditions were determined by LC–MS/MS, and rutin was the phenolic detected at the highest rate in the extracts. In addition, the blueness and greenness of the analytical method used in this study were evaluated using the BAGI and ComplexGAPI metrics, respectively. The results indicate that OHAE is an effective and sustainable method for extracting bioactive compounds from goji berries.

Keywords BAGI · ComplexGAPI · Innovative technology · Phenolic compounds · RSM

Introduction

The goji berry, scientifically known as *Lycium barbarum* L., also called wolf berry, is a species of shrub that sheds its leaves annually. This plant, which belongs to the Solanaceae family, is primarily grown in north-western China (Wang et al. 2011). In recent years, goji berries have gained recognition as superfoods owing to their nutritional profile and bioactive compounds. Its popularity has been growing in

countries outside Asia, particularly Turkey (Yao et al. 2018; Agagunduz et al. 2021). Many nations now regard it as a universally beneficial food owing to its significant health-protective properties. Goji berries contain many bioactive compounds, including 18 different amino acids, 21 different mineral substances, flavonoids, proteins, polysaccharides, and carotenoids (Gong et al. 2018). In addition, goji berries also contain high amounts of vitamins C and E (Karioti et al. 2014; Bertoldi et al. 2019). It is also a good source of various minerals (e.g., Cu, Fe, and P) and has a significant omega-3 fatty acid content (Fattore et al. 2016; Bertoldi et al. 2019). Research has shown that a 100-g portion of fresh goji berries contains 9.12 g of carbohydrates, 4.49 g of protein, 2.33 g of total lipids (fats), 0.23 mg of thiamine, 0.33 mg of riboflavin, and 1.7 mg of niacin (McGuire 1992; Thaipong et al. 2006; Agagunduz et al. 2021). Goji berry fruits have been reported to be used in the treatment of liver, hypercholesterolaemia, diabetes, and heart diseases (Jing et al. 2009). Owing to these bioactive/pharmacological properties, the cultivation area and production yield of goji berry

✉ Nesrin Ecem Bayram
ecem.nesrin@gmail.com; nesrinbayram@bayburt.edu.tr

Harun Kantar
harunkantar@hotmail.com

¹ Department of Organic Agricultural Management, Institute of Graduate Education, Bayburt University, Bayburt, Türkiye

² Department of Food Processing, Aydıntepe Vocational College, Bayburt University, Bayburt, Türkiye

fruit have increased significantly in recent years (Yu et al. 2023). Prior to market distribution, approximately 75–85% of freshly harvested goji berries undergo dehydration. These methods include freeze-drying (lyophilization), conventional hot-air drying, and vacuum-pulse drying techniques (Batu and Kadakal 2021; Ni et al. 2020; Yu et al. 2020, 2023). In addition to dried fruits, goji berries are currently processed into various products, including juice (comprising clear juice, solid drinks, pulp juice, milk drinks, and lactic acid-fermented beverages), wine, and other basic commodities. These products have become the predominant category of goji berry derivatives available commercially market (Wang et al. 2021; Liu et al. 2020; Yu et al. 2023). Owing to its biologically active secondary metabolites, this plant is also marketed to consumers as a dietary supplement, aromatic oil, and health-enhancing food product (Lasekan 2014).

Extraction enables the separation of specific compounds from food products. Traditional extraction methods include percolation, maceration, soxhlet extraction, and decoction extraction. Although traditional extraction methods are simple, easy to use, and inexpensive, they involve long extraction times, high solvent requirements, and extraction of temperature-sensitive components (Sridhar et al. 2021). Owing to these disadvantages, new-generation methods are required.

New extraction techniques have been implemented to overcome the limitations of the conventional approaches. Ohmic heating, one of these methods, has recently become widely used. Ohmic heating is an electroheating method that utilizes electricity to generate heat within food. This technique works by sending an electric current through a food item, which behaves as a resistor. Electrical energy is immediately converted into thermal energy inside the food. Heat production is proportional to the applied current and the food's electrical conductivity (Sastry 2008). Ohmic heating is a rapid heating mechanism, and its speed varies depending on the resistance of the material to be processed and the applied voltage gradient. Because the electric current passes through the homogeneous solvent in this method, it provides homogeneous heating of the materials. The successful implementation of ohmic heating depends on two crucial factors: the speed at which heat is generated, and the food material's overall electrical conductivity (Leizer-son and Shimoni 2005). The application of a higher voltage gradient results in increased heating rates, which consequently shorten the overall heating time (Icier and Ilicali 2005). Ohmic heating technology is not only a heating system, but also creates an electroporation effect that increases extraction rates and decreases gelatinization temperature and enthalpy thanks to the applied electric field. Electroporation leads to increased membrane permeability through pore formation in cell membranes and facilitates substance diffusion (Knirsch et al. 2010a, b; İncedayı et al. 2019). This increased

permeability leads to leakage of cellular compounds, further diffusion of materials and irreversible damage to the cell (Cappato et al. 2017; İncedayı et al. 2019). In addition, product concentration also affects the efficiency and duration of ohmic heating. As the concentration increases, ionic mobility decreases, which decreases electrical conductivity. However, high viscosity liquids are heated faster by the ohmic method than low viscosity ones (İncedayı et al. 2019).

In this study, it was aimed to extract bioactive compounds from goji berry fruit using ohmic heating–assisted extraction (OHAE) method. The experimental design was established by Box-Behnken method using different electric field strengths, holding times, and temperatures, and then the optimum conditions for maximum recovery of bioactive compounds were optimized by response surface method (RSM). Accordingly, the main objective of the study was to optimize the OHAE conditions, to evaluate the efficiency of the extracts obtained according to polyphenolic profile analysis by LC–MS/MS, and also to examine the sustainability of the method with environmental assessment tools such as BAGI and ComplexGAPI. In the study, antioxidant activity (DPPH), total phenolic content (TPC), and total flavonoid content (TFC) were evaluated as dependent variables.

Material and Method

Material and Chemicals

Dry fruit samples of red goji berry (*Lycium barbarum* L.) were stored at +4 °C until analysis. Chemicals used in total phenolic content, total flavonoid content, and antioxidant activity analyses were obtained from Sigma-Aldrich (St. Louis, MO, USA). Solvents such as methanol, acetonitrile, formic acid, and ammonium acetate used in LC–MS/MS analysis were obtained from Isolab (Wertheim, Germany) or Merck (Darmstadt, Germany). Solvents used in spectrophotometric analyses were ACS Reagent pure and solvents used in chromatographic analyses were gradient pure.

Box-Behnken Experiment Design and Optimization with Response Surface Methodology

The Box-Behnken experimental design was used to optimize the operating parameters of the OHAE and to ensure maximum recovery of bioactive compounds. The order of the experiments was randomized to minimize the impact of the external variables. The Box-Behnken design was selected for this research, as it offers meaningful and valuable data through fewer experimental runs, without the need to test every possible combination. The extraction parameters used in this study, such as temperature, time, and electric field strength, were determined based on studies on goji berry

using different extraction techniques (Skenderidis et al. 2017; Tripodo et al. 2018; de Moura et al. 2018) and applications of OHAE in different natural products (Gavahian and Chu 2022; Pereira et al. 2016; Kutlu et al. 2021a). The dependent variables were TPC, TFC, and DPPH. A second-order polynomial equation (Eq. 1) was used to fit the experimental results. In this equation, Y is the dependent variable, b_i is the coefficient, and X_i is the independent variable.

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_1^2 + b_5X_2^2 + b_6X_3^2 + b_7X_1X_2 + b_8X_1X_3 + b_9X_2X_3 \quad (1)$$

Optimization was applied to the data recorded as a result of the analyses performed on the extracts obtained in accordance with the experimental design. During RSM optimization, the TPC, TFC, and DPPH values were maximized to determine the optimum conditions.

Ohmic Heating–Assisted Extraction

The ohmic heating system (CLOH-1000, CLS, Türkiye) used in the extraction stage consisted of a glass heating cell resistant to high temperatures, a power supply, a controller connected to the power supply, and a computer to record temperature/voltage/current data. The temperature of the heating cell was controlled using a Teflon-coated thermocouple. The power supply was designed to provide a maximum voltage of 1000 V at a frequency of 50 Hz. Depending on the experimental design, three different electrical field strength (15, 30, and 45 V/cm), time (20, 40, and 60 min), and temperature (40, 50, and 60 °C) were applied. Following these procedures, the resulting extracts were stored at −18 °C, shielded from oxygen and light exposure until analysis. A 70% (w/w) ethanol–water mixture was used as the solvent. The solid:solvent ratio was determined to be 1:15. Ethanol-to-water ratio and solid:solvent ratio were determined based on He et al. (2018) and Gamage and Choo (2023). The TPC, TFC, and antioxidant properties of the extracted samples were analyzed. In addition, the specific phenolic profile of each extract was evaluated. In the control group, the extraction process was performed by maceration (24 h at room temperature) with the same solvent (70% ethanol–water).

Analyses

Determination of Total Phenolic Content of Extracts

The method described by Magalhães et al. (2010) was employed to measure TPC in the extracted samples. Accordingly, 50 µL of extract, 50 µL of Folin–Ciocalteu reagent (1:5, v/v), and 100 µL of 0.35 M NaOH were added to the microplate well and incubated for 3 min. The absorbance of the extracts was measured at 760 nm wavelength using a

Biotek Instruments Epoch Microplate Spectrophotometer. Using a standard curve generated with gallic acid, the results were determined and presented as mg GAE/g.

Determination of Total Flavonoid Content of Extracts

The total flavonoid content in the goji berry extracts was determined using the methodology described by Kostić et al. (2021). The process involved combining 125 µL of the sample, 625 µL of dH₂O, and 37.5 µL of 5% NaNO₂ solution in a test tube, followed by vortexing. After a 6-min wait, 75 µL of 10% AlCl₃·6H₂O solution was introduced, vortexed, and incubated in the dark for 5 min. Subsequently, 250 µL of 1 M NaOH and 138 µL of distilled water were added to the mixture, which was vortexed and incubated for 20 min. A 200 µL aliquot of the final mixture was transferred to a microplate, and its absorbance was measured at 510 nm using an Epoch Microplate spectrophotometer (Biotek Instruments). The results were calculated using a standard curve equation with quercetin and were expressed as mg QE/g.

Determination of Antioxidant Activity of Extracts

The antioxidant activity of the extracts was evaluated using the radical scavenging activity (DPPH; 1,1-diphenyl-2-picrylhydrazyl) method, adapted from the approach outlined by Bobo-García et al. (2015). The procedure involved combining 50 µL of extract with 150 µL of DPPH (0.1 mM) solution in a microplate, followed by a 20-min dark incubation period. The absorbance was measured at 517 nm using an Epoch Microplate spectrophotometer (Biotek Instruments). The total antioxidant capacity was derived from a Trolox standard curve equation, with the results expressed as mg TE/g.

Determination of Individual Polyphenolic Compound Content of Extracts by LC–MS/MS

The polyphenolic profile of the extracts was analyzed by LC–MS/MS according to the method described by Gercek et al. (2024). To screen for phenolic compounds in the extracts, 100 µL of extract and 900 µL of water:methanol:formic acid (v:v:v, 80:19:1) solution were mixed and centrifuged at 10,000 rpm for 10 min after vortexing for 2 min. The samples were then injected into the LC–MS/MS system for quantitative analysis. LC–MS/MS analyses were performed using the Thermo TSQ Quantis. Data acquisition and processing were performed using Chromeleon 7.1 (Thermo LC–MS software). The substances were separated on a Thermo C18 HPLC column. LC parameters were set as autosampler temperature, 4 °C; column temperature, 30 °C; flow rate, 0.2 mL/min; mobile phases, acetonitrile:methanol (1:1, v:v) solutions containing 5 mM

ammonium acetate (mobile phase A) and 1% acetic acid; injection volume, 5 μ L; and total analysis time, 28 min. MS analyses were performed on tri-polar LC–MS Thermo TSQ Quantis equipped with an electrospray ionization source. MS parameters were set as spray voltage 3 kV in positive and negative mode, sheath gas flow 54 arb, auxiliary gas flow 11 arb, sweep gas 1 arb, ion transfer tube temperature 275 °C, and vaporizer temperature 400 °C.

Blueness and Greeness Assessment of Method

In this study, the environmental and practical sustainability of the analytical method was assessed using the BAGI (Blue Applicability Grade Index) tool developed by Manousi et al. (2023) and the ComplexGAPI (Complementary Green Analytical Procedure Index) tool developed by Plotka-Wasyłka and Wojnowski (2021). The assessments were conducted on online platforms where these tools are available. In addition, the Complex GAPI, available at mostwiedzy.pl/complex-gapi, was utilized to analyze the greenness profile of the method.

Statistical Analyses

The response surface method (RSM) was applied to determine the optimum conditions for goji berry extraction. The effect of extraction conditions on total phenolic compounds, total flavonoid compounds, and antioxidant activity, and the correlation and regression analyses between them were performed using the Minitab 19 package programme at $p \leq 0.05$ confidence level.

Results and Discussion

Optimization of Extraction Parameters

In recent years, the food industry has recognized ohmic heating as one of the most promising methods for the extraction of bioactive components. This technique involves heating food by applying a direct electric current during the extraction process (Knirsch et al. 2010a, b). This method has been considered an innovative alternative to the traditional method in recent years due to its rapid and homogeneous heating of foods, improvement of product quality (preservation of nutritional quality-color-texture), and applicability to different foods (Astráin-Redín et al. 2024). Therefore, in this study, OHAE conditions were optimized for the extraction of bioactive compounds from the fruit of a plant with high bioactive content, such as goji berry, and the total phenolic, flavonoid, and antioxidant activity of the extracts were evaluated. The Box-Behnken experimental design, consisting of 17 runs (including five center points), was used to conduct

OHAE procedures for the extraction of bioactive phytochemicals from goji berry fruit. The effect of three independent variables (X_1 : temperature of ohmic heating cell, °C; X_2 : Holding time in the ohmic heating cell, minutes; and X_3 : electrical field strength, V/cm) on extraction was evaluated. The results for the dependent variables based on the experimental design are presented in Table 1. Table 1 shows that TPC (Y_1 , mg GAE/g) values ranged between 17.924 and 23.826 mg GAE/g, TFC (Y_2 , mg QE/g) values ranged between 6.180 and 7.329 mg QE/g, and DPPH (Y_3 , mg TE/g) values ranged between 13.422 and 24.528 mg TE/g.

The full quadratic regression model, including linear, quadratic, and two-factor interaction effects for the estimation of the process and the obtained statistical parameters, are presented in Table 2.

Research suggests that for a model to be considered a good fit, the minimum R^2 value should exceed 80%, whereas the adjusted (Adj) R^2 values should surpass 70% (Gan et al. 2007; Granato et al. 2010). In this investigation, the equations yielded R^2 values ranging from 91.09 to 93.78% and Adj R^2 values between 76.84 and 83.83%, thus meeting these criteria. Another crucial statistical factor is lack of fit, which represents the error resulting from an unsuitable mathematical model. This value was not expected to be statistically significant (Box and Draper 2007). An examination of Table 2 reveals that the regression model's lack of fit value is statistically insignificant ($p > 0.05$).

Effect of Electrical Field Strength, Temperature, and Time on Total Phenolic Content

When the impact of the different process conditions on TPC was examined, it was found that the most significant independent variable was temperature (Table 2). In addition, the squares of all independent variables and the time $\times$ temperature interaction were statistically significant ($p \leq 0.05$). A positive correlation was found between TPC and temperature, and an increase in temperature had a positive effect on the TPC yield. The variation in TPC with temperature and time is shown in Fig. 1. The maximum TPC was obtained at a high temperature and average time. The highest TPC value was determined as 23.826 mg GAE/g at 60 °C, 40 min, and 15 V/cm (Table 1).

Although the OHAE method used in this study was not used in the literature for goji berry fruit extraction, it has been used for TPC extraction from different natural products (Pereira et al. 2020; Kutlu et al. 2021a, 2021b; Gumustepe et al. 2023). However, there are studies in the literature in which the TPC was evaluated using different extraction methods for goji berry fruit. For example, total phenolic extraction was optimized using an ultrasonically assisted method for goji berries grown in Greece. Based on these results, the TPC of the extracts varied between 153.762 and 406.619 mg GAE/L (Skenderidis et al. 2017). Similarly,

Table 1 Experimental values of dependent variables obtained according to Box-Behnken experimental design

Run	X_1^*	X_2	X_3	Y_1	Y_2	Y_3
1	50	40	30	17.924	6.180	18.606
2	50	40	30	22.445	6.746	18.462
3	50	40	30	23.775	6.935	18.001
4	50	60	45	21.800	7.067	18.554
5	60	60	30	22.493	7.225	18.448
6	60	20	30	19.673	6.881	18.225
7	50	40	30	21.346	6.862	13.909
8	50	60	15	21.226	6.754	13.422
9	40	40	45	22.251	7.012	24.528
10	60	40	45	23.165	6.692	24.212
11	40	20	30	19.705	7.126	24.501
12	40	60	30	19.630	6.865	24.357
13	50	40	30	21.973	6.866	24.357
14	40	40	15	20.319	6.496	24.449
15	60	40	15	23.826	7.329	24.225
16	50	20	15	22.641	6.692	24.449
17	50	20	45	22.828	7.126	24.199

* X_1 , temperature of ohmic heating cell—°C; X_2 , holding time in the ohmic heating cell—min; X_3 , electrical field strength—W/cm; Y_1 , TPC—mg GAE/g; Y_2 , TFC—mg QE/g; Y_3 , DPPH—mg TE/g

Table 2 Equations and statistical parameters obtained from regression analysis

Dependent variable	Model equation	R^2	Adj R^2	Lack of fit
Y_1	$Y_1 = -0.63^* + 1.012X_1^* - 0.156X_2 - 0.188X_3 - 0.01064X_1^{2*} - 0.003325X_2^{2*} + 0.00681X_3^{2*} + 0.00786X_1X_2^* - 0.00432X_1X_3 + 0.00032X_2X_3$	92.93%	77.01%	0.419
Y_2	$Y_2 = 6.34^* + 0.0417X_1 - 0.083X_2 + 0.0642X_3^* - 0.00072X_1^2 + 0.00061X_2^{2*} - 0.000828X_3^{2*} + 0.000756X_1X_2^* - 0.000101X_2X_3$	93.78%	83.83%	0.417
Y_3	$Y_3 = 144.9^* - 4.19X_1 - 0.330X_2^* + 0.902X_3 + 0.0421X_1^{2*} + 0.00004X_2^2 + 0.01287X_3^{2*} - 0.00015X_1X_3 + 0.00448X_2X_3$	91.09%	76.84%	0.674

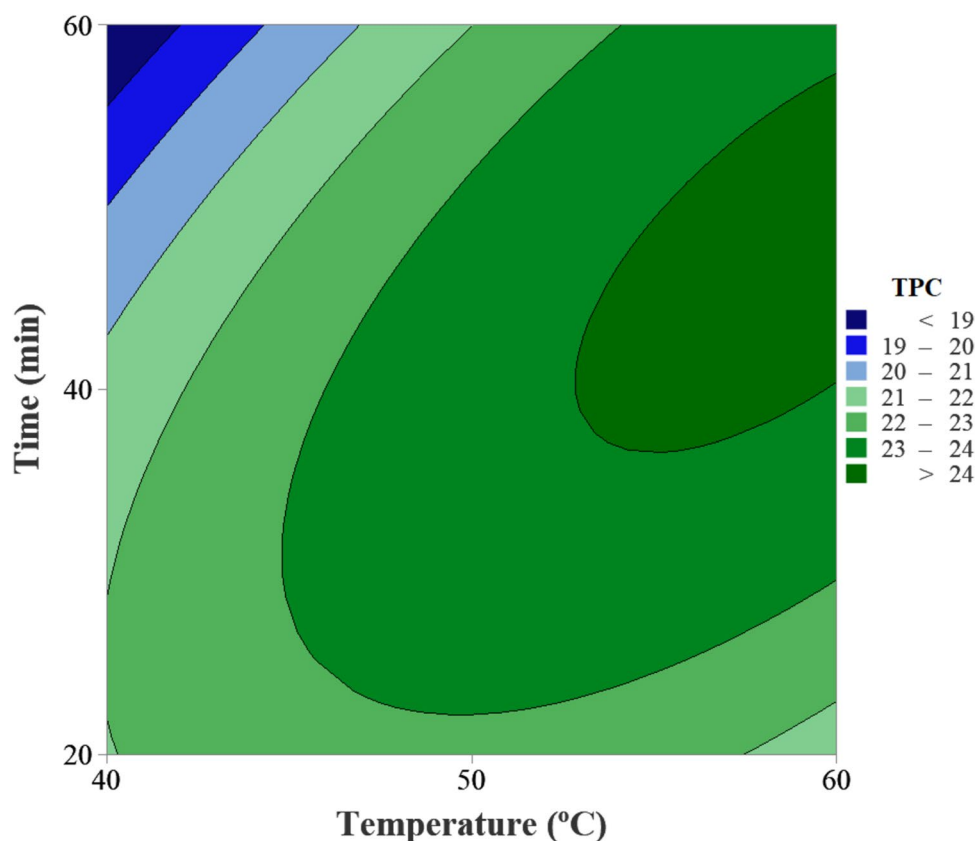
*The term is significant at $p \leq 0.05$; X_1 , temperature of ohmic heating cell—°C; X_2 , holding time in the ohmic heating cell—min; X_3 , electrical field strength—V/cm; Y_1 , TPC—mg GAE/g; Y_2 , TFC—mg QE/g; Y_3 , DPPH—mg TE/g

Tripodo et al. (2018) evaluated the TPC, extraction yield, TFC, and antioxidant activity of goji berry fruits to optimize the extraction conditions for the pressurized liquid extraction method. Researchers reported that the TPC of goji berry fruits was between the lowest 5.72 mg GAE/g and the highest 74.84 mg GAE/g according to the difference in extraction conditions. In our study, we found that the TPC of goji berry fruit varied between 17.924 and 23.826 mg GAE/g under different OHAE process conditions. When the difference between the results of these studies in the literature and our study is evaluated, this may be related to many variables, such as differences in extraction methods and parameters and differences in botanical and geographical origins of fruits. Consequently, to extract highly bioactive compounds from goji berries, it is essential to determine the optimal

extraction conditions using various extraction techniques and parameters.

In previous studies, different foods were extracted using the OHAE method, and the advantages and disadvantages of this method were determined by evaluating the TPC of these foods (Pereira et al. 2020; Kutlu et al. 2021a). Pereira et al. (2020) used the OHAE method in grape skin extraction and reported that the maximum total phenolic yield of the extracts prepared was obtained in the extract prepared by applying an ohmic heating pre-treatment at a temperature of 100 °C for 1 s. According to the results obtained by these researchers, ohmic heating support is important because it increases the yield and reduces energy consumption. Similarly, Kutlu et al. (2021a) used ultrasonic-assisted extraction and maceration methods in addition to OHAE for

Fig. 1 Variation of TPC values with temperature and time



the recovery of pharmacologically active compounds from cranberry fruits. The researchers reported that a higher TPC was recorded with the OHAE method than with the other two methods. The results obtained from different studies show that the OHAE method is promising for the extraction of total phenolic compounds.

Effect of Electrical Field Strength, Temperature, and Time on Total Flavonoid Content

Flavonoids, which belong to the class of phenolic compounds or polyphenols, are the most abundant secondary metabolites in plants. The amount of flavonoids in plants varies according to the growth conditions of the plant, soil, and climate. Interest in the recovery of this group of compounds in food technology continues to grow because of their benefits to human health (Dias et al. 2021). In this study, when the effect of the OHAE process conditions on the TFC was analyzed, it was found that the most effective independent variable was the electrical field strength (Table 2). In addition, the squares of the time, electrical field strength, and time $\times$ temperature interaction were also found to be statistically significant ($p \leq 0.05$). There was a positive correlation between the TFC and the electrical field strength, and the increase in the electrical field strength increased the TFC yield. Figure 2a presents the variation in TFC with

temperature and time, and Fig. 2b presents the variation in TFC with electrical field strength and temperature. In the temperature $\times$ time interaction, it was observed that the TFC yield was high in conditions where both were minimum or maximum. The highest TFC value was obtained as 7.33 mg/g under conditions where the temperature was 60 °C, the time was 40 min, and the electrical field strength was 15 V/cm, as in the TPC value (Table 1).

Similar to this study, the TFC of goji berries has been evaluated in other studies. Islam et al. (2017) conducted a comparative study on the total phenolic, carotenoid, and anthocyanin contents and antioxidant capacity of extracts obtained from red goji berry (*Lycium barbarum*) and black goji berry (*Lycium ruthenicum*) fruits after 3 h of pre-treatment in an orbital shaker and 12-h incubation. The researchers determined the TFC of red goji berries and black goji berries as 2.17–4.48 mg GAE/g and 7.26–9.01 mg GAE/g, respectively. Peixoto et al. (2023) conducted a study on the optimization of extraction of bioactive substances from red goji berries (*Lycium barbarum*) using ultrasonically assisted and maceration methods. The researchers reported that different extraction methods affected the extraction of total flavonoids from goji berries, and the highest TFC was obtained using the ultrasonically assisted extraction method. The researchers found that under optimal ultrasound and maceration extraction conditions, the TFC was

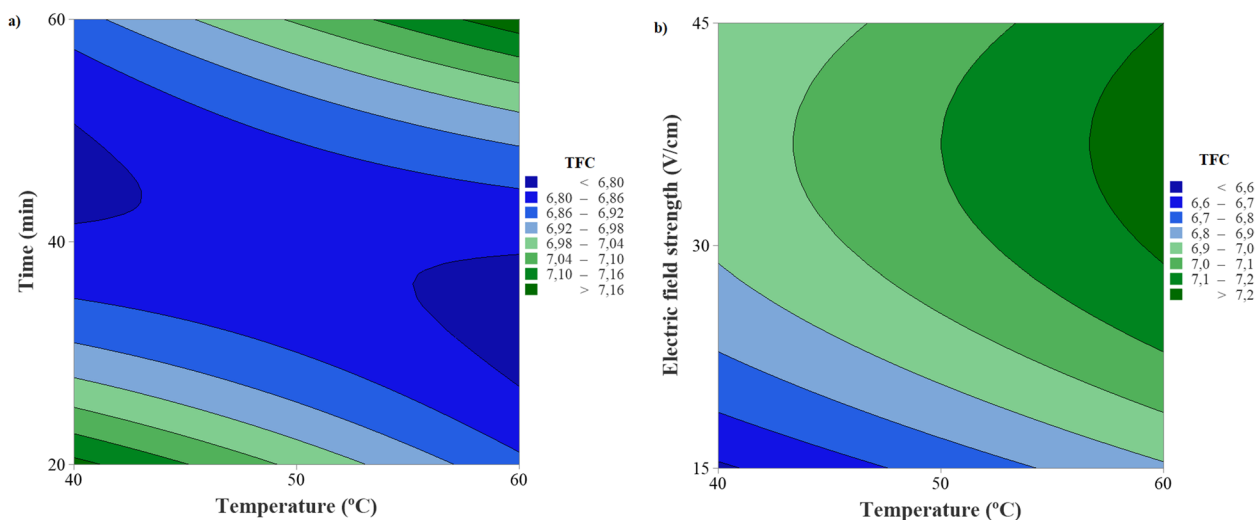


Fig. 2 Variation of TFC Values with **a** time and temperature and **b** electrical field intensity and temperature

3.15 mg QE/g and 2.99 mg QE/g, respectively. Do et al. (2024) extracted bioactive substances from goji berries dried using two different methods using different solvents. The researchers reported that the TFC of the prepared extracts ranged from 13.3 to 31 mg OCE/g. However, in another study by Ferreira-Santos et al. (2024), extraction of bioactive substances from grape pomace was performed using an OHAE method. The effects of different extraction conditions (solid:solvent ratio, time, and temperature) on the extraction of biosolids were evaluated. The researchers reported that the TFC of the extract was higher at 80 °C, 50% ethanol:water, and an extraction time of 30 min. In addition, they determined the TFC as 26.32 ± 1.4 mg CE/g and 37.98 ± 2.3 mg CE/g for the extracts prepared using the traditional method and OHAE method, respectively. This clearly shows that a higher amount of flavonoids was extracted using the OHAE method. In this study, the TFC of goji berry extracts prepared using the OHAE method varied between 6.180 and 7.329 mg QE/g. These results were lower than those obtained by Do et al. (2024) and Ferreira-Santos et al. (2024) but higher than those obtained by Peixoto et al. (2023). However, similar to the TPC extraction yield, the differences and similarities in these results indicate that the variability of the bioactive content of the food product used and also the extraction conditions significantly affect the TFC.

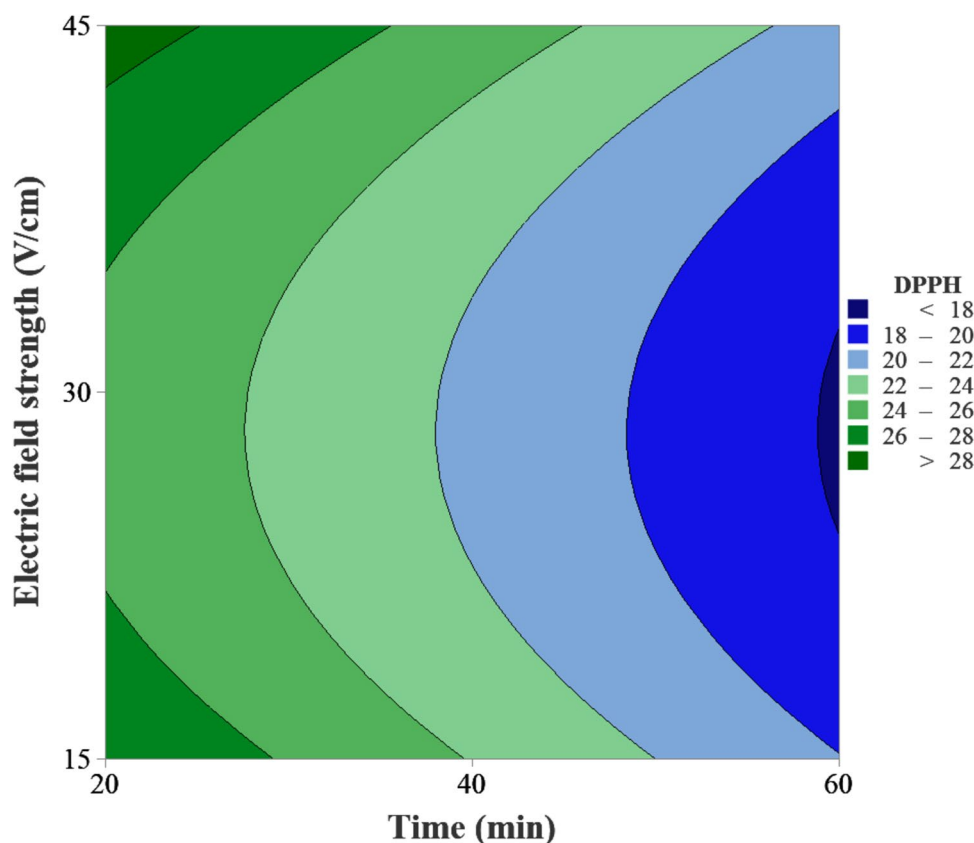
Effect of Electrical Field Strength, Temperature, and Time on Antioxidant Activity

Antioxidants, both in natural and in synthetic forms, can scavenge free radicals and inhibit oxidation in the human body (Ahmad and Langrish 2012). Therefore, it is crucial to maximize the antioxidant contents of various

natural products. The antioxidant potential of the extracts was assessed using the DPPH method. According to the results obtained, when the effect of different OHAE process conditions on DPPH was examined, it was found that the most effective independent variable was holding time (Table 2). In addition, the squares of the temperature and electrical field strength were also statistically significant ($p \leq 0.05$). A negative correlation was found between DPPH and time, and an increase in time decreased the antioxidant activity. The variation in DPPH with electrical field strength and time is shown in Fig. 3. DPPH reached its minimum value with increasing time, as shown in Fig. 3. The highest DPPH value was calculated as 24.43 mg TE/g at 40 °C, 40 min, and 45 V/cm electrical field strength (Table 1).

In different studies, the antioxidant activities of goji berry extracts prepared by extraction methods other than the OHAE method were determined (Skenderidis et al. 2017; Peixoto et al. 2023; Do et al. 2024; Teixeira et al. 2024; Ferreira-Santos et al. 2024). Ozkan et al. (2018) reported the antioxidant activity of goji berry (*Lycium barbarum* L.) fruit extracts prepared by maceration with water and methanol by DPPH to be 90.36% and 70.83%, respectively. According to their results, the antioxidant activity of the methanolic extract was higher. This situation shows that, although the same extraction method is used, the solvent type used at this stage is a significant factor supporting the literature. Similarly, Turan et al. (2023) extracted fresh and dried goji berry samples using an ultrasonic-assisted method in a methanolic solution prepared at a ratio of 1:10. According to the results obtained, the antioxidant potential of fresh goji berry samples measured by DPPH test was determined as 15.70 mg TE/g, while the antioxidant activity of the samples dried by different drying techniques was determined between 23.26 mg TE/g and 29.90 mg TE/g. Likewise, in our study, the

Fig. 3 Variation of DPPH values with electrical field strength and time



DPPH activity of dried goji berry samples extracted under different process conditions was determined to be in a similar range to that reported in the literature and was measured between 13.422 and 24.528 mg TE/g. However, Islam et al. (2017) extracted dried red and black goji berry samples obtained from different locations using the traditional method and acetone/water/acetic acid (70:29.5:0.5:0.5) solution, and the antioxidant potential of the extracts recorded by DPPH was determined between 0.46 mg TE/g and 8.97 mg TE/g. The results obtained by the researchers are lower than the results obtained in this study, and this may be affected by different factors, such as the geographical-botanical origin of the samples, extraction parameters, and the type of solvent used in the extraction. Therefore, when compared with the literature studies, it can be said that the OHAE method presented in this study shows a remarkable success in the recovery of compounds with antioxidant effect from red goji berry fruit.

Optimum Conditions

Optimization of any process is important for achieving the desired goals. In this study, the optimum conditions were identified by maximizing the TPC, TFC, and DPPH values. As a result of the optimization by RSM, the optimum conditions were determined to be 60 °C for the temperature

of the ohmic heating cell, 60 min for the holding time in the ohmic heating cell, and 45 V/cm for the electrical field strength. The composite desirability value (d) of the model was found to be 0.90. The predicted TPC, TFC, and DPPH values obtained under these conditions were 23.83 mg GAE/g, 7.13 mg QE/g, and 22.65 mg TE/g, respectively. The highest TPC, TFC, and DPPH values obtained experimentally in our study were 23.83 mg GAE/g, 7.33 mg QE/g, and 24.53 mg TE/g, respectively. When the predicted and experimental values were compared, it was found that the experimental values were within the predicted confidence intervals; therefore, the values were similar. This finding for the optimum temperature in our study is consistent with literature reports showing that maximum polyphenol yields in some extraction methods are obtained at temperatures between 60 and 80 °C. Higher temperatures above 80 °C are generally not preferred due to solvent losses. However, in order to accurately assess the effect of temperature during the extraction of polyphenols, factors such as solvent type, pH, processing time, and source of plant material need to be taken into account. Different polyphenols can have different degradation temperatures and the extraction temperature can directly affect the type of phenolic compounds obtained. In addition, high temperatures can cause phenolic-polysaccharide or phenolic-protein bonds in plant tissues to break, which can increase the amount of phenolics

that can be extracted. However, at very high temperatures, thermal degradation of heat-sensitive phenolic compounds may occur, leading to a decrease in total yield (Antony and Farid 2022). In addition, it is also reported that the electrical field applied during ohmic heating increases permeability by electroporation of cell membranes, thereby increasing the extraction rate (Kutlu et al. 2021a).

TPC, TFC, and DPPH values of the control group were 21.55 mg GAE/g, 6.87 mg QE/g, and 24.16 mg TE/g, respectively. These values were found to be close to each other when compared to the values obtained with the OHAE. However, these values, which were obtained after 24 h of maceration, were reached after 60 min of OHAE. Therefore, a high time-saving was achieved with the OHAE.

Individual Phenolic Compound Profile

Phenolic compounds in plants have numerous pharmacological activities and thus have beneficial effects on human health (Sun and Shahrajabian 2023). In this study, the individual phenolic compound profiles of the extracts obtained under different experimental conditions were also examined, and the results are presented in Table 3. The total individual phenolic content of the extracts varied between 236.294 and 333.429 mg/kg. However, the total individual polyphenolic content of the control sample was 298.990 mg/kg. In summary, 15 out of 17 different process conditions resulted in higher extraction of polyphenolic compounds compared to the control. This indicates that the OHAE method is more effective than maceration. Except artepillin C and catechol, other polyphenolic compounds were extracted from goji berries at varying concentrations under different extraction conditions. In particular, rutin was detected in goji berry fruit at a considerably higher concentration (208.717–292.843 mg/kg) than other phenolics. Similarly, de Moura et al. (2018) screened individual phenolic compounds in goji berries. In this study, the amounts of caffeic acid, catechin, coumaric acid, ferulic acid, epicatechin, rutin, and myricetin were determined, and rutin (326 mg/kg) was the most dominant phenolic compound. This was followed by 151 mg/kg caffeic acid, 123 mg/kg coumaric acid, 69 mg/kg ferulic acid, and 50 mg/kg catechin. However, epicatechin and myricetin compounds were not detected in goji berry extracts. In addition, Protti et al. (2017) investigated 23 individual phenolic compounds in goji berry fruit and reported that the most dominant phenolic compound was chlorogenic acid ($10,740 \pm 8.3$ and $11,931 \pm 9.4$ mg/kg). Significant amounts of chlorogenic acid, epicatechin, quercetin, rutin, catechin, caffeic acid, ferulic acid, coumaric acid, and zeaxanthin compounds were detected in goji berry fruit. They reported that the lowest amount of phenolic compounds found in goji berry samples were quercitrin (10.8 ± 1.8 – 12.7 ± 1.0 mg/kg) and myricitrin (10.1 ± 0.9 – 13.9 ± 1.6 mg/kg).

Teixeira et al. (2024) examined the amounts of individual phenolic compounds in goji berries and found that the most dominant compound in the phenolic acid group was 3,5-dicaffeoylquinic acid with 5.76 ± 0.29 mg/100 g and the most dominant compound in the flavonoid group was rutin with 192.7 mg/kg, similar to our study. In addition, Wojdyło et al. (2018) conducted individual phenolic compound and carotenoid screening of 21 different goji berry genotypes. They found that the dominant phenolic compound was quercetin dihexoside. The lowest amount of phenolic compounds was found to be kaempferol 3-orutinoside. The TPC was found to be in the range of 254.85–1926.52 mg/kg. Rocchetti et al. (2018) determined the amounts of cyanidin, ferulic acid, catechin, and luteolin in 22 different goji berry genotypes using individual phenolic compound screening. Among the phenolic acids, ferulic acid was the most dominant phenolic. These compounds are followed by flavones and flavonols, respectively. In goji berry samples, average values of 6.45, 0.86, 0.22, and 0.11 mg/g were determined for ferulic acid, catechin, cyanidin, and luteolin equivalents, respectively. In our study, trans-ferulic acid was extracted at the highest rate of 1.307 mg/kg and luteolin at the highest rate of 54.048 mg/kg under different processing conditions. The differences observed in our study and the literature can be explained by the differences in processing procedures, such as extraction method (maceration, microwave-assisted extraction, ultrasonic-assisted extraction, etc.) and extraction parameters (temperature, time, etc.) used during sample preparation for analysis. In addition, factors such as the geographical-botanical origin, harvest time, collection, and storage conditions of these fruits can be said to affect these differences.

Blueness and Greeness Assessment of Method

One of the main objectives of green analytical chemistry is to minimize the harmful effects of analytical methods on humans and the environment. In recent years, different tools such as AGREE, AGREEprep, GAPI, ComplexGAPI, NEMI, the Analytical Eco-Scale, RGB 12 algorithm, AMGS, and BAGI have been used to evaluate the environmental performance of analytical methods used during analyses, including sample preparation. In this study, the BAGI and ComplexGAPI tools were used to assess the environmental impact of sample preparation, and the analytical method used to determine the chromatographic profile of the samples. The BAGI tool was designed to assess the practicality and blueness of the analytical method. This tool evaluates the color shade in the resulting pictogram and the method of scoring. The blue color in the pictogram indicates conformity of the method with the specified criteria (dark blue: high conformity; blue: medium conformity; light blue: low conformity; and white: no conformity). In addition, the

Table 3 Individual polyphenolic compound profile of goji berry extracts obtained under different processing conditions

Phenolics (mg/kg)	1*	2	3	4	5	6	7	8	9
(-)-Epicatechin	0.342 ± 0.014	0.499 ± 0.036	0.563 ± 0.019	0.593 ± 0.019	0.536 ± 0.02	0.567 ± 0.021	0.551 ± 0.019	0.574 ± 0.032	0.735 ± 0.035
Apigenin	0.079 ± 0.001	0.139 ± 0.003	0.063 ± 0.006	0.074 ± 0.004	0.063 ± 0.001	0.052 ± 0.003	0.066 ± 0	0.054 ± 0.007	0.088 ± 0.004
Artepillin C	-	-	-	-	-	-	-	-	-
Caffeic acid phenethyl ester	0.079 ± 0.004	0.296 ± 0.015	0.039 ± 0.004	0.052 ± 0.008	0.039 ± 0.004	0.049 ± 0.003	0.038 ± 0	0.036 ± 0.002	0.084 ± 0.001
Catechin + epicatechin	0.045 ± 0.004	0.141 ± 0.008	0.197 ± 0.016	0.191 ± 0.006	0.054 ± 0.005	0.131 ± 0.001	0.096 ± 0.001	-	0.126 ± 0.002
Catechol	-	-	-	-	-	-	-	-	-
Chlorogenic acid + neochlorogenic acid	5.163 ± 0.357	5.837 ± 0.520	6.194 ± 0.242	5.887 ± 0.156	5.803 ± 0.139	6.601 ± 0.612	6.012 ± 0.301	6.592 ± 0.539	6.263 ± 0.101
Chrysin	0.292 ± 0.009	0.639 ± 0.059	0.189 ± 0.004	0.278 ± 0.023	0.131 ± 0	0.202 ± 0.004	0.163 ± 0.002	0.184 ± 0.028	0.454 ± 0.016
Epicatechin gallate	-	-	-	0.039 ± 0.001	-	0.032 ± 0.001	-	-	-
Galangin	0.128 ± 0.005	0.217 ± 0.010	0.044 ± 0.008	0.118 ± 0.002	0.036 ± 0.002	0.063 ± 0.003	0.056 ± 0.004	0.072 ± 0.002	0.157 ± 0.017
Gallic acid	1.593 ± 0.170	1.663 ± 0.112	1.891 ± 0.046	1.863 ± 0.021	2.787 ± 0.092	2.292 ± 0.205	1.941 ± 0.111	1.887 ± 0.09	1.59 ± 0.029
Gallocatechin + epigallocatechin	0.368 ± 0.057	0.513 ± 0.052	1.146 ± 0.069	1.148 ± 0.128	0.608 ± 0.134	0.58 ± 0.019	0.692 ± 0.055	0.538 ± 0.014	-
Hesperidin	0.388 ± 0.111	0.431 ± 0.073	0.326 ± 0.013	0.436 ± 0.034	0.566 ± 0.039	0.5 ± 0.026	0.469 ± 0.008	0.423 ± 0.025	0.312 ± 0.005
Hyperosid	7.394 ± 0.324	8.717 ± 0.410	9.170 ± 0.393	8.641 ± 0.091	9.584 ± 0.495	8.462 ± 0.729	9.018 ± 0.474	9.556 ± 0.834	7.095 ± 0.031
Kaempferol	-	-	-	-	0.035 ± 0	0.013 ± 0.001	-	-	-
Luteolin	0.049 ± 0.004	0.062 ± 0.001	0.046 ± 0.004	0.097 ± 0.006	0.071 ± 0.007	0.06 ± 0.003	0.045 ± 0.002	0.071 ± 0.002	54.048 ± 53.952
Myricetin	0.625 ± 0.099	1.083 ± 0.107	1.195 ± 0.124	1.005 ± 0.138	1.642 ± 0.124	1.994 ± 0.104	1.481 ± 0.058	1.879 ± 0.016	1.622 ± 0.058
Naringenin	1.517 ± 0.051	1.685 ± 0.024	1.672 ± 0.005	1.773 ± 0.102	1.798 ± 0.013	1.804 ± 0.012	1.7 ± 0.052	1.778 ± 0.021	1.726 ± 0.013
p-Coumaric acid	2.092 ± 0.036	2.361 ± 0.052	2.446 ± 0.002	2.431 ± 0.004	2.493 ± 0.037	2.427 ± 0.015	2.429 ± 0.036	2.545 ± 0.074	2.477 ± 0.018
Pinobanksin	0.235 ± 0.026	0.438 ± 0.024	0.128 ± 0.013	0.221 ± 0.007	0.154 ± 0.003	0.144 ± 0.01	0.132 ± 0.008	0.144 ± 0.001	0.142 ± 0.005
Pinocembrin	0.183 ± 0.016	0.316 ± 0.006	0.099 ± 0.005	0.132 ± 0.003	0.095 ± 0.002	0.115 ± 0.001	0.099 ± 0.005	0.103 ± 0.007	0.148 ± 0.007
Protocatechuic acid	5.817 ± 0.567	10.683 ± 0.480	6.330 ± 0.623	0.719 ± 0.026	11.202 ± 0.165	7.951 ± 0.188	8.544 ± 0.02	6.956 ± 0.65	6.887 ± 1.142
Quercetin	0.368 ± 0.027	0.287 ± 0.026	0.427 ± 0.023	0.377 ± 0.015	0.371 ± 0.026	0.198 ± 0.027	-	0.374 ± 0.009	0.701 ± 0.018
Quercitrin	0.021 ± 0.002	0.035 ± 0.004	0.017 ± 0.002	0.028 ± 0.006	0.02 ± 0	0.019 ± 0.002	0.011 ± 0.001	0.019 ± 0	-
Rutin	208.717 ± 4.756	254.074 ± 4.530	272.134 ± 3.899	266.605 ± 0.504	278.393 ± 1.502	263.786 ± 3.93	264.481 ± 17.21	278.178 ± 6.16	281.024 ± 2.781
t-Cinnamic acid	0.799 ± 0.096	1.011 ± 0.136	1.163 ± 0.108	0.831 ± 0.049	0.895 ± 0.056	1.129 ± 0.016	0.904 ± 0.048	1.028 ± 0.065	1.057 ± 0.067
Trans-caftaric acid	-	-	-	-	0.881 ± 0.044	1.11 ± 0.026	-	-	1.091 ± 0.012
trans-ferulic acid	-	1.032 ± 0.100	0.720 ± 0.008	-	0.862 ± 0.02	0.785 ± 0.004	0.754 ± 0.021	1.267 ± 0.061	1.043 ± 0.059
Total	236.294	292.157	306.200	293.537	319.121	301.068	299.681	314.259	368.871

Table 3 (continued)

Phenolics (mg/kg)	10	11	12	13	14	15	16	17	Control
(-)-Epicatechin	0.553 ± 0.026	0.547 ± 0.016	0.745 ± 0.047	0.467 ± 0.037	0.572 ± 0.021	0.585 ± 0.007	0.674 ± 0.033	0.491 ± 0.044	0.502 ± 0.023
Apigenin	0.119 ± 0.000	0.067 ± 0.008	0.057 ± 0.003	0.05 ± 0.003	0.046 ± 0.002	0.073 ± 0.003	0.059 ± 0.002	0.434 ± 0.021	0.086 ± 0.001
Artepillin C	-	-	-	-	-	-	-	-	0.019 ± 0.002
Caffeic acid phenethyl ester	0.145 ± 0.010	0.042 ± 0.002	0.025 ± 0.001	0.027 ± 0.002	0.025 ± 0.002	0.038 ± 0.005	0.028 ± 0.001	0.748 ± 0.013	0.037 ± 0.003
Catechin + epicatechin	0.19 ± 0.005	-	0.134 ± 0.016	0.034 ± 0.000	0.168 ± 0.003	0.163 ± 0.005	0.071 ± 0.005	-	-
Catechol	-	-	-	-	-	-	-	-	0.588 ± 0.114
Chlorogenic acid + Neochlorogenic acid	6.242 ± 0.384	7.305 ± 0.199	6.649 ± 0.671	6.498 ± 0.589	6.36 ± 0.157	6.411 ± 0.245	7.204 ± 0.389	7.065 ± 0.161	6.106 ± 0.286
Chrysin	0.596 ± 0.029	0.209 ± 0.011	0.164 ± 0.004	0.181 ± 0.010	0.164 ± 0.032	0.169 ± 0.005	0.183 ± 0.003	2.67 ± 0.012	0.196 ± 0.052
Epicatechin gallate	-	-	-	-	-	-	-	-	-
Galangin	0.242 ± 0.002	0.052 ± 0.004	0.025 ± 0.003	0.046 ± 0.004	0.025 ± 0.002	0.04 ± 0.001	0.027 ± 0.000	1.155 ± 0.035	0.053 ± 0.006
Gallic acid	2.796 ± 0.164	1.124 ± 0.026	1.088 ± 0.031	1.986 ± 0.194	0.984 ± 0.080	2.017 ± 0.049	1.713 ± 0.089	1.163 ± 0.069	1.926 ± 0.022
Galocatechin + Epigallocatechin	0.653 ± 0.025	0.776 ± 0.070	0.827 ± 0.070	0.977 ± 0.057	0.703 ± 0.081	0.874 ± 0.098	0.926 ± 0.031	0.815 ± 0.019	0.508 ± 0.004
Hesperidin	0.573 ± 0.048	1.161 ± 0.070	0.647 ± 0.062	0.28 ± 0.001	0.204 ± 0.022	0.365 ± 0.029	0.498 ± 0.005	0.444 ± 0.034	0.431 ± 0.061
Hyperosid	10.218 ± 0.069	10.584 ± 0.392	9.591 ± 0.219	9.168 ± 0.086	8.672 ± 0.230	9.166 ± 0.232	8.944 ± 0.100	9.379 ± 0.213	8.436 ± 0.380
Kaempferol	-	-	-	-	-	-	-	0.109 ± 0.000	-
Luteolin	0.17 ± 0.010	0.1 ± 0.005	0.044 ± 0.000	0.042 ± 0.003	0.05 ± 0.002	0.076 ± 0.002	0.052 ± 0.001	0.784 ± 0.047	0.22 ± 0.007
Myricetin	2.117 ± 0.063	1.587 ± 0.147	1.383 ± 0.299	1.704 ± 0.088	1.324 ± 0.018	1.36 ± 0.155	1.161 ± 0.03	2.206 ± 0.061	1.22 ± 0.100
Naringenin	1.969 ± 0.013	1.8 ± 0.022	1.825 ± 0.08	1.762 ± 0.053	1.53 ± 0.090	1.761 ± 0.085	1.658 ± 0.094	2.022 ± 0.072	1.789 ± 0.091
p-coumaric acid	2.605 ± 0.109	2.667 ± 0.000	2.578 ± 0.043	2.394 ± 0.066	2.31 ± 0.085	2.432 ± 0.010	2.439 ± 0.083	2.509 ± 0.066	2.501 ± 0.055
Pinobanksin	0.354 ± 0.056	0.118 ± 0.009	0.135 ± 0.005	0.119 ± 0.002	0.086 ± 0.005	0.117 ± 0.006	0.162 ± 0.013	1.341 ± 0.057	0.114 ± 0.007
Pinocembrin	0.225 ± 0.012	0.111 ± 0.004	0.093 ± 0.004	0.097 ± 0.007	0.083 ± 0.007	0.102 ± 0.005	0.083 ± 0.002	1.076 ± 0.009	0.126 ± 0.003
Protocatechuic acid	7.731 ± 0.772	8.09 ± 0.055	7.027 ± 0.664	6.694 ± 0.462	10.746 ± 0.37	7.082 ± 0.345	10.651 ± 0.139	6.719 ± 0.029	1.594 ± 0.029
Quercetin	0.662 ± 0.023	0.365 ± 0.041	0.497 ± 0.022	0.399 ± 0.001	0.914 ± 0.098	0.615 ± 0.116	0.298 ± 0.006	0.349 ± 0.042	0.235 ± 0.001
Quercitrin	0.041 ± 0.001	-	0.008 ± 0.001	0.044 ± 0.004	0.017 ± 0.000	0.042 ± 0.001	0.012 ± 0.000	0.024 ± 0.002	0.02 ± 0.002
Rutin	290.514 ± 5.221	292.843 ± 11.635	284.36 ± 4.641	265.576 ± 5.738	254.146 ± 17.237	272.208 ± 7.37	279.284 ± 0.128	289.74 ± 2.936	269.651 ± 7.965
t-cinnamic acid	0.899 ± 0.020	0.943 ± 0.064	1.018 ± 0.145	0.962 ± 0.124	0.892 ± 0.038	1.061 ± 0.095	0.872 ± 0.013	0.878 ± 0.011	0.932 ± 0.063
trans-caffeic acid	-	1.137 ± 0.075	0.993 ± 0.022	1.028 ± 0.014	-	1.084 ± 0.055	-	-	0.973 ± 0.067
trans-ferulic acid	1.048 ± 0.099	0.942 ± 0.064	0.982 ± 0.066	0.794 ± 0.050	0.709 ± 0.084	0.864 ± 0.043	0.771 ± 0.033	1.307 ± 0.007	0.728 ± 0.026
Total	330.662	332.570	320.894	301.327	290.730	308.707	317.770	333.429	298.990

*Runs 1 to 17 represent goji berry extracts obtained under different processing conditions

**“-” indicates the compound was not detected

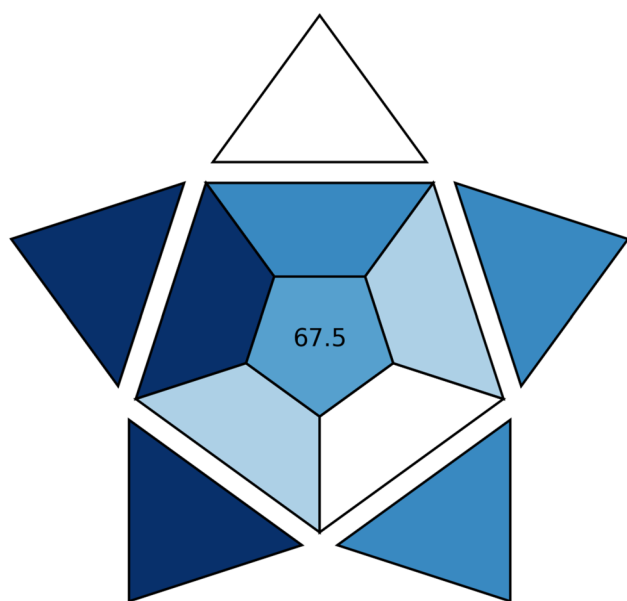
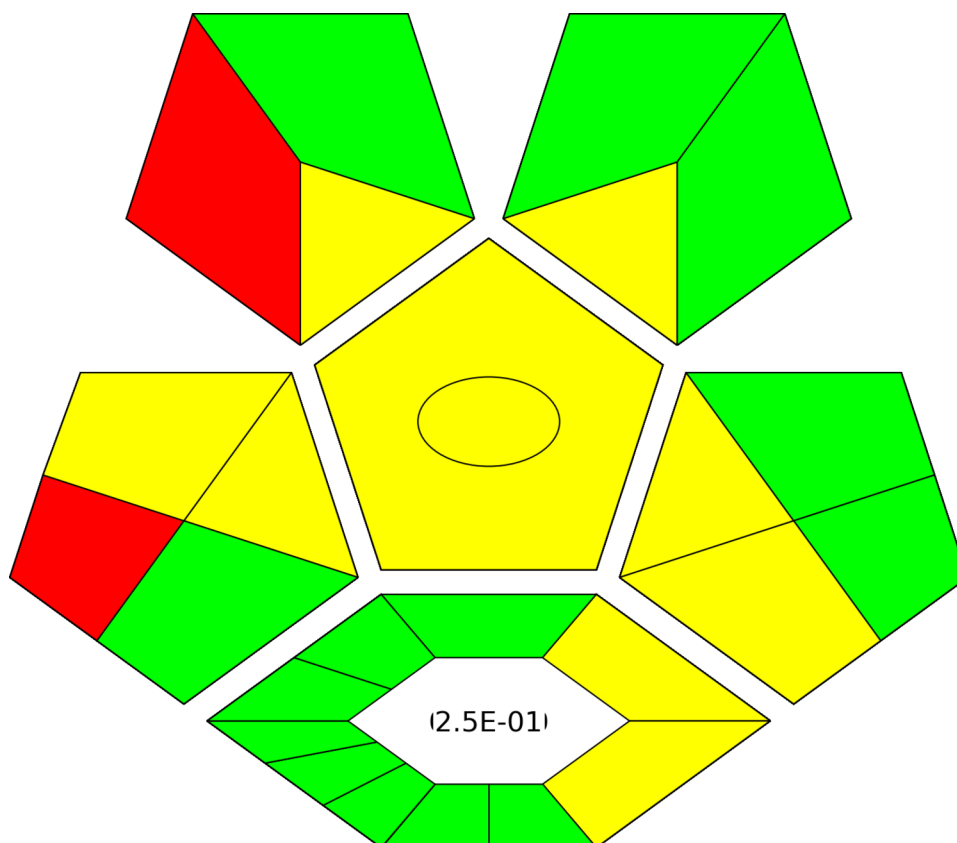


Fig. 4 Blueness assessment by BAGI tool of the method

score in the center of the pictogram is scored between 25 and 100, with a score closer to 100 indicating very good performance. A score above 60 is considered a cutoff score for the method to be considered practical (Manousi et al. 2023).

Fig. 5 Greeness assessment by ComplexGABI of method



The score achieved in this study was 67.5 and, in general, the method used can be considered practical according to the results obtained (Fig. 4). Different studies in the literature have evaluated the practicality of different methods using the BAGI index. For example, the practicality of various micro-extraction techniques used to analyze UV filters in water was evaluated using BAGI, and the scores of six different methods were above 60, indicating that the methods were practical (Wejnerowska and Narloch 2024). Similarly, in a different study, the practicality of a high-performance thin-layer chromatography approach developed for the quantitative analysis of three different anti-*Helicobacter pylori* drugs, omeprazole, tinidazole, and clarithromycin, was evaluated with BAGI and a very high score of 80 was obtained for the method (Mahmoud and Abbas 2024). Again, in different studies, the practicality of different methods was evaluated using the BAGI tool, thus drawing attention to the sustainability profile of the methods used (Abd-ALGhafar et al. 2024; Halim et al. 2024; Katamesh et al. 2024).

Another assessment tool, ComplexGAPI, evaluates all aspects of an analytical procedure, from sample collection-transportation-protection-storage-preparation to final analysis. According to the criteria defined on the tool, a final pictogram is created and colored green, yellow, or red depending on the environmental impact of the criteria (Płotka-Wasyłka and Wojnowski 2021). For the

chromatographic method used in this study, all stages, from sample collection to analysis, were evaluated using the relevant tool, and the resulting pictogram is presented in Fig. 5. This method is a comprehensive method used to evaluate the greenness of the methods used in the studies. The result of this method is a pictogram, just like the BAGI. This inclusive green analytical procedure index allows to assess the green character not only of the sample preparation and final analysis stages (top five large areas) but also of the pre-analytical stages (bottom hexagon). The middle figure is the *E*-factor value, the total mass of waste from process to total mass of product. The green color in the pictogram indicates that the respective stage has a low impact on the environment, yellow a medium impact, and red a high impact (Płotka-Wasyłka and Wojnowski 2021). The *E*-factor value of the pictogram obtained in this study shows that the method is sustainable in terms of efficiency.

Conclusion

In recent years, the need for the research and development of different functional foods has increased because of their effects on nutrition and health. Goji berries are among the functional foods that have become popular worldwide due to their protective/therapeutic effects on health. Accordingly, with increasing technological applications, various forms of this plant are being used raw or as extracts in different food products. However, especially during the extraction of food products, sustainable and environmentally friendly extraction methods that are alternatives to traditional methods are being researched and used at this stage. In recent years, the main purpose of preferring innovative methods in the extraction phase has been to ensure the extraction of the bioactive content of the product with maximum efficiency during the extraction phase, as well as the benefits of these methods in terms of different parameters such as low solvent consumption, time efficiency, and energy saving. Therefore, in this study, goji berries were extracted for the first time using the OHAE method and the extraction conditions were optimized using the RSM-Box Behnken experimental design. According to the obtained results, the optimum conditions were determined to be 60 °C for the ohmic heating cell temperature, 60 min for the holding time in the ohmic heating cell, and 45 V/cm for the electrical field strength. When the predicted TPC, TFC, and DPPH values obtained under these optimum conditions and the highest TPC, TFC, and DPPH values obtained experimentally in our study were compared, we found that the experimental values were within the predicted confidence interval; therefore, the values were similar to each other. In conclusion, this method can be considered a preferable method for the preparation of goji berry fruit extracts due to its advantages such as time and energy saving and remarkable recovery of bioactive

compounds. In addition, it is promising for scale-up in food processing due to rapid and homogeneous heating. However, pilot-scale applications are needed to fully demonstrate the applicability of this method on an industrial scale during the gojiberry extract preparation process. In addition, it is important to evaluate this method in comparison with other extraction techniques in order to clarify its advantages or limitations in terms of cost, time, and energy efficiency. Therefore, pilot-scale studies for gojiberry as well as further studies examining the applicability of this method in the processing of different functional foods are recommended.

Acknowledgements This study includes the results of Harun Kantar's master's thesis. We would like to thank Dr. Yusuf Can Gerçek for his valuable contribution to the phytochemical analysis, and Dr. Aslı Işçi and Dr. Özge Şakıyan Demirkol for providing the ohmic heating system used in this study.

Author's Contribution Harun Kantar: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. Nesrin Ecem Bayram: Writing – review & editing, Resources, Investigation, Formal analysis, Conceptualization, Supervision.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abd-ALGhafar WN, Shabana RA, El-Shaheny R, Tolba MM (2024) A fluorescence switch-off nanosensor for sensitive determination of the antiandrogen drug flutamide in pharmaceutical and environmental samples. *Analytical method greenness, blueness, and whiteness assessment*. *Microchem J* 204:111078
- Agagunduz D, Koseler-Beyaz E, Duman S (2021) Assessment of the physicochemical and antioxidant profile of dried goji berries. *Progr Nutrit* 23(4)
- Ahmad J, Langrish TAG (2012) Optimisation of total phenolic acids extraction from mandarin peels using microwave energy: the importance of the Maillard reaction. *J Food Eng* 109(1):162–174

- Antony A, Farid M (2022) Effect of temperatures on polyphenols during extraction. *Appl Sci* 12(4):2107
- Astráin-Redín L, Ospina S, Cebrián G, Álvarez-Lanzarote I (2024) Ohmic heating technology for food applications, from ohmic systems to moderate electric fields and pulsed electric fields. *Food Eng Rev* 16(2):225–251
- Batu HS, Kadakal Ç (2021) Drying characteristics and degradation kinetics in some parameters of goji berry (*Lycium Barbarum* L.) fruit during hot air drying. *Italian J Food Sci* 33(1):16–28
- Bertoldi D, Cossignani L, Blasi F, Perini M, Barbero A, Pianezze S, Montesano D (2019) Characterisation and geographical traceability of Italian goji berries. *Food Chem* 275:585–593
- Bobo-García G, Davidov-Pardo G, Arroqui C, Vírveda P, Marín-Arroyo MR, Navarro M (2015) Intra-laboratory validation of microplate methods for total phenolic content and antioxidant activity on polyphenolic extracts, and comparison with conventional spectrophotometric methods. *J Sci Food Agric* 95(1):204–209
- Box GE, Draper NR (2007) Response surfaces. *Mixtures Ridge Anal* 649
- Cappato LP, Ferreira MVS, Guimaraes JT, Portela JB, Costa MQ, Freitas ALR, Cunha RL, Oliveria CAF, Mercali GD, Marzack LDF, Cruz AG (2017) Ohmic heating in dairy processing: relevant aspects for safety and quality. *Trends Food Sci Technol* 62:104–112
- De Moura C, dos Reis AS, da Silva LD, de Lima VA, Oldoni TLC, Pereira C, Carpes ST (2018) Optimization of phenolic compounds extraction with antioxidant activity from açai, blueberry and goji berry using response surface methodology. *Emirates J Food Agric* 30(3):180–189
- Dias MC, Pinto DC, Silva AM (2021) Plant flavonoids: chemical characteristics and biological activity. *Molecules* 26(17):5377
- Do S, Kim Y, Yim J, Lee KG (2024) Analysis of volatile compounds, betaine, and antioxidant effect in goji berry (*Lycium barbarum* L.) powder extracted by various drying methods and extraction solvents. *Curr Res Food Sci* 100798
- Fattore M, Montesano D, Pagano E, Teta R, Borrelli F, Mangoni A, Seccia S, Albrizio S (2016) Carotenoid and flavonoid profile and antioxidant activity in “Pomodoro Vesuviano” tomatoes. *J Food Compos Anal* 53:61–68
- Ferreira-Santos P, Nobre C, Rodrigues RM, Genisheva Z, Botelho C, Teixeira JA (2024) Extraction of phenolic compounds from grape pomace using ohmic heating: chemical composition, bioactivity and bioaccessibility. *Food Chem* 436:137780
- Gamage GCV, Choo WS (2023) Effect of hot water, ultrasound, microwave, and pectinase-assisted extraction of anthocyanins from black goji berry for food application. *Heliyon* 9(3)
- Gan HE, Karim R, Muhammad SKS, Bakar JA, Hashim DM, Rahman RA (2007) Optimization of the basic formulation of a traditional baked cassava cake using response surface methodology. *LWT-Food Sci Technol* 40(4):611–618
- Gavahian M, Chu R (2022) Ohmic heating extraction at different times, temperatures, voltages, and frequencies: a new energy-saving technique for pineapple core valorization. *Foods* 11(14):2015
- Gerçek YC, Dagsuyu E, Basturk FN, Kırkinci S, Yıldırım N, Kışkanç G ... Kostić AŽ (2024) Enzyme inhibitory, physicochemical, and phytochemical properties and botanical sources of honey, bee pollen, bee bread, and propolis obtained from the same apiary. *Antioxidants* 13(12):1483
- Gong G, Dang T, Deng Y, Han J, Zou Z, Jing S, Zhang Y, Liu Q, Huang L, Wang Z (2018) Physicochemical properties and biological activities of polysaccharides from *Lycium barbarum* prepared by fractional precipitation. *Int J Biol Macromol* 109:611–618
- Granato D, Ribeiro JCB, Castro IA, Masson ML (2010) Sensory evaluation and physicochemical optimisation of soy-based desserts using response surface methodology. *Food Chem* 121(3):899–906
- Gumustepe L, Kurt N, Aydın E, Özkan G (2023) Comparison of ohmic heating- and microwave-assisted extraction techniques for avocado leaves valorization: optimization and impact on the phenolic compounds and bioactivities. *Food Sci Nutr* 11(9):5609–5620
- Halim MK, Badran OM, Abbas AEF (2024) Greenness, blueness and whiteness evaluated-chemometric approach enhanced by Latin hypercube technique for the analysis of lidocaine, diclofenac and carcinogenic impurity 2, 6-dimethylaniline. *Sustain Chem Pharm* 38:101463
- He Q, Du B, Xu B (2018) Extraction optimization of phenolics and antioxidants from black goji berry by accelerated solvent extractor using response surface methodology. *Appl Sci* 8(10):1905
- Icier F, Ilicali C (2005) The effects of concentration on electrical conductivity of orange juice concentrates during ohmic heating. *Eur Food Res Technol* 220:406–414
- Islam T, Yu X, Badwal TS, Xu B (2017) Comparative studies on phenolic profiles, antioxidant capacities and carotenoid contents of red goji berry (*Lycium barbarum*) and black goji berry (*Lycium ruthenicum*). *Chem Cent J* 11:1–8
- İncedayı B, Seyhan B, Çopur ÖÜ (2019) Ohmik ısıtma destekli işlemlerin gıdalarda kullanımı ve kalite üzerine etkisi. *Bursa Uludağ Üniversitesi Ziraat Fakültesi Dergisi* 33(2):341–354
- Jing L, Cui G, Feng Q, Xiao Y (2009) Evaluation of hypoglycemic activity of the polysaccharides extracted from *Lycium barbarum*. *Afr J Trad Complement Altern Med* 6(4)
- Karioti A, Bergonzi MC, Vincieri FF, Bilia AR (2014) Validated method for the analysis of goji berry, a rich source of zeaxanthin dipalmitate. *J Agric Food Chem* 62(52):12529–12535
- Katamesh NS, Abbas AEF, Mahmoud SA (2024) Four chemometric models enhanced by Latin hypercube sampling design for quantification of anti-COVID drugs: sustainability profiling through multiple greenness, carbon footprint, blueness, and whiteness metrics. *BMC Chemistry* 18(1):54
- Knirsch MC, Dos Santos CA, de Oliveira Soares AAM, Penna TCV (2010a) Ohmic heating—a review. *Trends Food Sci Technol* 21(9):436–441
- Knirsch MC, Santos CA, Vicente AAMOS, Penna TCV (2010b) Ohmic heating- a review. *Trends Food Sci Technol* 21:436–441
- Kostić AŽ, Milinčić DD, Nedić N, Gašić UM, Špirović Trifunović B, Vojt D ... Pešić MB (2021) Phytochemical profile and antioxidant properties of bee-collected artichoke (*Cynara scolymus*) pollen. *Antioxidants* 10(7):1091
- Kutlu N, İsci A, Sakiyan O, Yilmaz AE (2021a) Effect of ohmic heating on ultrasound extraction of phenolic compounds from cornelian cherry (*Cornus mas*). *J Food Process Preserv* 45(10):e15818
- Kutlu N, İsci A, Sakiyan O, Yilmaz AE (2021b) Extraction of phenolic compounds from cornelian cherry (*Cornus mas* L.) using microwave and ohmic heating assisted microwave methods. *Food Bioprocess Technol* 14:650–664
- Lasekan O (2014) Exotic berries as a functional food. *Curr Opin Clin Nutr Metab Care* 17(6):589–595
- Leizerson S, Shimon E (2005) Effect of ultrahigh-temperature continuous ohmic heating treatment on fresh orange juice. *J Agric Food Chem* 53(9):3519–3524
- Liu J, Meng J, Du J, Liu X, Pu Q, Di D, Chen C (2020) Preparative separation of flavonoids from Goji berries by mixed-mode macroporous adsorption resins and effect on Aβ-expressing and anti-aging genes. *Molecules* 25(15):3511
- Magalhães LM, Santos F, Segundo MA, Reis S, Lima JL (2010) Rapid microplate high-throughput methodology for assessment of Folin-Ciocalteu reducing capacity. *Talanta* 83(2):441–447
- Mahmoud SA, Abbas AEF (2024) Greenness, whiteness, and blueness assessment with spider chart solvents evaluation of HPTLC-densitometric method for quantifying a triple combination anti-*Helicobacter pylori* therapy. *Sustain Chem Pharm* 37:101412

- Manousi N, Wojnowski W, Płotka-Wasyłka J, Samanidou V (2023) Blue applicability grade index (BAGI) and software: a new tool for the evaluation of method practicality. *Green Chem* 25(19):7598–7604
- McGuire RG (1992) Reporting of objective color measurements. *HortScience* 27(12):1254–1255
- Ni J, Ding C, Zhang Y, Song Z (2020) Impact of different pretreatment methods on drying characteristics and microstructure of goji berry under electrohydrodynamic (EHD) drying process. *Innov Food Sci Emerg Technol* 61:102318
- Ozkan EE, Ozden TY, Toplan GG, Mat A (2018) Phenolic content and biological activities of *Lycium barbarum* L. (Solanaceae) fruits (Goji berries) cultivated in Konya Turkey. *Trop J Pharmaceut Res* 17(10):2047–2053
- Peixoto FB, Raimundini Aranha AC, Oliveira Defendi R, Tonin LTD, Sipoli CC, Fragoso ÁG, Düsman E, Suzuki RM (2023) Optimization of extraction of bioactive compounds with antiproliferative activity from goji berry and assessment of kinetic models. *J Chem Technol Biotechnol* 98(12):2888–2903
- Pereira RN, Coelho MI, Genisheva Z, Fernandes JM, Vicente AA, Pintado ME (2020) Using ohmic heating effect on grape skins as a pretreatment for anthocyanins extraction. *Food Bioprod Process* 124:320–328
- Pereira RN, Rodrigues RM, Genisheva Z, Oliveira H, de Freitas V, Teixeira JA, Vicente AA (2016) Effects of ohmic heating on extraction of food-grade phytochemicals from colored potato. *Lwt* 74:493–503
- Płotka-Wasyłka J, Wojnowski W (2021) Complementary green analytical procedure index (ComplexGAPI) and software. *Green Chem* 23(21):8657–8665
- Protti M, Gualandi I, Mandrioli R, Zappoli S, Tonelli D, Mercolini L (2017) Analytical profiling of selected antioxidants and total antioxidant capacity of goji (*Lycium* spp.) berries. *J Pharm Biomed Anal* 143:252–260
- Rocchetti G, Chiodelli G, Giuberti G, Ghisoni S, Baccolo G, Blasi F, Montesano D, Trevisan M, Lucini L (2018) UHPLC-ESI-QTOF-MS profile of polyphenols in Goji berries (*Lycium barbarum* L.) and its dynamics during in vitro gastrointestinal digestion and fermentation. *J Function Foods* 40:564–572
- Sastry S (2008) Ohmic heating and moderate electric field processing. *Food Sci Technol Int* 14(5):419–422
- Skenderidis P, Petrotos K, Giavasis I, Hadjichristodoulou C, Tsakalof A (2017) Optimization of ultrasound assisted extraction of goji berry (*Lycium barbarum*) fruits and evaluation of extracts' bioactivity. *J Food Process Eng* 40(5):e12522
- Sridhar A, Ponnuchamy M, Kumar PS, Kapoor A, Vo DVN, Prabhakar S (2021) Techniques and modeling of polyphenol extraction from food: a review. *Environ Chem Lett* 19:3409–3443
- Sun W, Shahrajabian MH (2023) Therapeutic potential of phenolic compounds in medicinal plants—natural health products for human health. *Molecules* 28(4):1845
- Teixeira F, Silva AM, Sut S, Dall'Acqua S, Ramos OL, Ribeiro AB, Ferraz R, Delerue-Matos C, Rodrigues F (2024) Ultrasound-assisted extraction of bioactive compounds from goji berries: optimization, bioactivity, and intestinal permeability assessment. *Food Res Int* 188:114502
- Thaipong K, Boonprakob U, Crosby K, Cisneros-Zevallos L, Byrne DH (2006) Comparison of ABTS, DPPH, FRAP, and ORAC assays for estimating antioxidant activity from guava fruit extracts. *J Food Compos Anal* 19(6–7):669–675
- Tripodo G, Ibáñez E, Cifuentes A, Gilbert-López B, Fanali C (2018) Optimization of pressurized liquid extraction by response surface methodology of Goji berry (*Lycium barbarum* L.) phenolic bioactive compounds. *Electrophoresis* 39(13):1673–1682
- Turan B, Tekin-Cakmak ZH, Kayacan Çakmakoglu S, Karasu S, Kasapoglu MZ, Avci E (2023) Effect of different drying techniques on total bioactive compounds and individual phenolic composition in goji berries. *Processes* 11(3):754
- Wang K, Sasaki T, Li W, Li Q, Wang Y, Asada Y, Kato H, Koike K (2011) Two novel steroidal alkaloid glycosides from the seeds of *Lycium barbarum*. *Chem Biodivers* 8(12):2277–2284
- Wang M, Ouyang X, Liu Y, Liu Y, Cheng L, Wang C, Zhu B, Zhang B (2021) Comparison of nutrients and microbial density in goji berry juice during lactic acid fermentation using four lactic acid bacteria strains. *J Food Process Preserv* 45(1):e15059
- Wejnerowska G, Narloch I (2024) A comprehensive assessment of sample preparation methods for the determination of UV filters in water by gas chromatography–mass spectrometry: greenness, blueness, and whiteness quantification using the AGREEprep, BAGI, and RGB 12 tools. *Appl Sci* 14(17):7690
- Wojdyło A, Nowicka P, Bąbalewski P (2018) Phenolic and carotenoid profile of new goji cultivars and their anti-hyperglycemic, anti-aging and antioxidant properties. *J Function Foods* 48:632–642
- Yao R, Heinrich M, Weckerle CS (2018) The genus *Lycium* as food and medicine: a botanical, ethnobotanical and historical review. *J Ethnopharmacol* 212:50–66
- Yu F, Li Y, Wu Z, Wang X, Wan N, Yang M (2020) Dehydration of wolfberry fruit using pulsed vacuum drying combined with carboxymethyl cellulose coating pretreatment. *Lwt* 134:110159
- Yu J, Yan Y, Zhang L, Mi J, Yu L, Zhang F, Lu L, Luo Q, Li X, Zhou X, Cao Y (2023) A comprehensive review of goji berry processing and utilization. *Food Sci Nutr* 11(12):7445–7457

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.