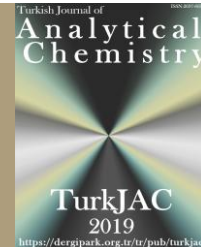




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Use of ohmic heating assisted evaporation in sumac syrup production: Effects on quality and process efficiency

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Abstract

This study investigates the effects of ohmic heating assisted evaporation on the production of sumac syrup. Both conventional evaporation and ohmic heating assisted evaporation methods were used to produce sumac syrup. Two different voltage gradients (20 V/cm and 25 V/cm) were applied during the ohmic heating assisted evaporation process. The physicochemical properties, HMF (5-hydroxymethylfurfural) content, antioxidant properties, rheological characteristics of sumac syrup were evaluated and compared with conventional evaporation process. There were no significant differences in the antioxidant properties or HMF levels between the samples produced with ohmic heating assisted and conventional evaporation methods. However, the energy consumption during the ohmic heating assisted evaporation process (121.93 ± 5.98 and 95.00 ± 3.08 kJ for 20 and 25 V/cm, respectively) was approximately eleven times lower than the conventional evaporation method (1331.00 ± 101.82 kJ). Overall, the findings demonstrate that ohmic heating assisted evaporation preserves the quality attributes of sumac syrup while significantly reducing energy consumption and CO₂ emissions.

Keywords: HMF, ohmic heating, sumac syrup, vacuum evaporation

1. Introduction

Rhus coriaria L. (*Anacardiaceae* family) is known as sumac, and it is a highly valued spice in many cuisines around the world [1]. Sumac is mostly grown in the Mediterranean region, especially in the Middle East. In addition to being a flavorful spice, the sumac also boasts numerous health benefits and medicinal properties. Sumac has been used as a medicine in traditional practice for centuries due to its antibacterial, antifungal, antioxidant, and analgesic effects [2]. Dried and ground fruits are the most commonly consumed part of the Sumac plant [3]. In addition to being used in popular foods in Turkey such as dishes, salads, and kebabs, sumac is also used as sumac syrup. Sumac syrup is often utilized in local dishes, especially in southern Anatolia [4].

Traditionally, sumac syrup is produced by extracting the sumac fruit with water several times until its sourness is transferred into the water. The resulting sour extract is left to stand for 7–8 hours, allowing the sediment to settle to the bottom. After the clarification

process, the sour water is separated from the sedimentary part and concentrated under the sun or in a pot [5]. In the industry, sumac syrup is concentrated through evaporation instead of the sun or boiling in the pot, as is traditional.

In food industry, evaporation is one of the largest scale and energy-intensive processes [6]. Among the various methods, vacuum evaporation is the most widely used technique in the food industry. However, this method can negatively affect product quality, since extended exposure to elevated temperatures promotes the breakdown of aroma compounds [7]. Compared with classical open pan evaporation which characterized by uneven heating and susceptibility to atmospheric contamination, vacuum evaporation offers advantages, yet it still demands substantial energy to maintain the vacuum and power the heating system. This requirement significantly increases operating costs, creating a major economic challenge, particularly when scaling up to industrial levels [8]. To address these

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limitations, researchers have investigated alternative heating technologies aimed at minimizing quality losses and preventing the formation of undesirable components during the evaporation process [7].

One of the methods developed to overcome the aforementioned limitations is the ohmic heating assisted vacuum evaporation. Ohmic heating is a process of passing electric current through food, which causes the food's electrical resistance to produce heat [9]. Unlike conventional heating methods, which rely on conduction, convection, and radiation, ohmic heating produces heat directly within the material, leading to a rapid temperature rise. The main advantages of ohmic heating include uniform heating of food materials, improved product quality, reduced energy costs and consumption, higher energy efficiency, and accelerated processing [10]. Compared with traditional methods, ohmic heating minimizes thermal degradation of heat-sensitive compounds, thereby preserving organoleptic quality while reducing energy losses (reported savings of 82–97%) [11]. Its effectiveness has been demonstrated in seawater desalination for potable water production [8], and in the concentration of fruit juices, yielding products of higher quality than those obtained by conventional evaporation [7,9]. Furthermore, successful applications in the production of tomato concentrates and grape molasses (pekmez) have been reported [6,12]. The process makes these products more appealing to health-conscious consumers by improving physicochemical qualities and bioactive content of products [6].

To the best of our knowledge, there is no literature on the use of ohmic heating assisted evaporation in the production of sumac syrup. This study evaluated the feasibility of using ohmic heating assisted evaporation method to produce sumac syrup. The physicochemical properties, HMF contents, antioxidant properties, rheological characteristics, and energy consumptions of sumac syrup produced by ohmic heating assisted evaporation were compared with the conventional evaporation method.

2. Materials and methods

2.1. Materials

Sumac seeds were purchased from a local market in İstanbul, Turkey. Sumac extract was obtained from sumac seeds before the evaporation process. To produce sumac extract, 1:2.5 ratio of sumac: water was mixed with a magnetic stirrer for 24 hours. It was filtered using a filter paper to remove solid particles from the extract. The suspension was kept in the refrigerator overnight for the residue of the extract to settle to the bottom. The soluble solid content of the clear solution was set to 2 °Bx after the suspension was filtered again via filter paper. All of the reagents and chemicals used in the study were of analytical grade.

2.2. Evaporation methods

Sumac syrup was produced using two methods: conventional evaporation (CE) and ohmic heating assisted evaporation (OHAE) (Fig. 1). For the conventional evaporation method, a rotary evaporator

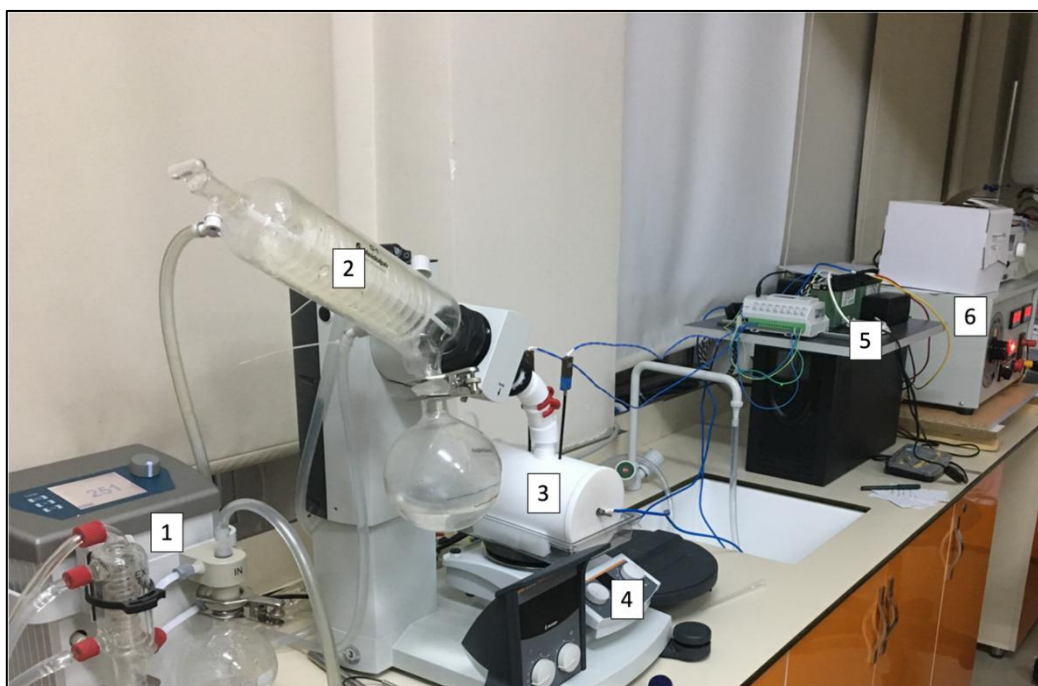


Figure 1. Ohmic heating assisted vacuum evaporation system 1; Vacuum pump, 2; Condenser, 3; Ohmic heating cell, 4; Magnetic stirrer, 5; Data acquisition unit, 6; Isolated variable transformer

was utilized. 200 mL of the sumac extract (2 °Bx) was evaporated at 120 mbar until it reached 50 ± 1 °Bx, using the heating bath set to 80 °C. The parts of the ohmic heating assisted evaporation system included a power supply, an isolated variable transformer (Varsan Elektrik, 0-360V, 5kVA, İstanbul, Turkey), a data logger (Novus, Fieldlogger, Porto Alegre, Brazil) connected to a computer, a voltage transducer (Ohio Semitronics, VT8-10D, Ohio, USA), a current transducer (Ohio Semitronics, CTRS-050D, Ohio, USA), thermocouples (T type, PTFE coated, Sigma Aldrich Inc., Missouri, USA), a vacuum pump (Ilmvac, LVS 105 T-10 ef, Ilmenau, Germany), a condenser, a magnetic stirrer (MR Hei-Standard, Heidolph, Schwabach, Germany) and an ohmic heating cell. The ohmic heating cell was a titanium-type electrode-equipped cylindrical PTFE with an inner diameter of 0.1 m. The distance between the electrodes was 0.094 m. Data on temperature, voltage, and current have been recorded using a data logger at 10-second intervals. 20 and 25 V/cm voltage gradients were used to operate ohmic heating assisted evaporation. Preliminary tests were used to select these voltage gradients. Overflow and foaming issues were observed at high voltages. At lower voltages, it was observed that much longer times were required than with the conventional method. At a constant pressure of 120 mbar, 200 mL of sumac extract (2 °Bx) was evaporated till it reached 50 ± 1 °Bx. The magnetic stirrer was running at 1000 rpm during the evaporation process.

2.3. Total soluble solids

Total soluble solids of sumac extract and sumac syrup were measured with a digital refractometer at 25 °C (Hanna, HI96801, Italy).

2.4. Color

The L, a, and b values were determined from the Konica Minolta Chromameter (Japan), which was used to evaluate color. The color parameters were as follows: -a (greenness) to +a (redness), -b (blueness) to +b (yellowness), and L = 0 (black) to L = 100 (white). Samples (30 mL) were measured at in sample jar. Three measurements of the sumac syrup and extract samples were taken from various locations.

2.5. pH

The pH values of samples were determined by diluting them 1:1 with water with pH meter at 20°C (Hanna EDGE, Italy).

2.6. Titratable acidity content

The titration method using 0.1 N NaOH was used to perform a titratable acidity analysis. 5 g sample was

weighed and volume was brought up to 50 mL using distilled water. 5 mL of solution was titrated with 0.1 N NaOH. Eq. (1) was used to calculate titratable acidity in terms of tartaric acid.

$$\text{Titratable acidity (\%)} = \frac{V \times f \times E}{m} \times 100 \quad (1)$$

Eq. (1) expresses that V is volume of 0.1 N NaOH used, mL, f is factor of NaOH, E is equivalent acid amount of 1 mL 0.1 N NaOH (for tartaric acid 0.007505 g) and m is amount of sample, g.

2.7. Glucose, fructose and sucrose contents

A modified version of method described by Tunç et al. [6], was applied to determine the amount of glucose, fructose and sucrose contents in sumac extract and sumac syrup samples. Glucose and fructose contents of samples were measured with HPLC (TSP P4000 pump, TSP AS 3000 autosampler, TSP SN 4000 controller, TSP degasser, Thermo Finnigan, USA). One gram of sumac syrup dissolved in 8 mL deionized water. 5 mL methanol was added and then it was completed to 20 mL with deionized water. After filtering the sample solution with a 0.45 µm PTFE filter, it was directly injected using a carbohydrate column (150 mm × 4.6 mm) into an HPLC equipped with a refractive index (RI) detector. Acetonitrile and water (3:1) were used as the mobile phase, with a flow rate of 1.4 mL/min an injection volume of 10 µL. A standard calibration curve was used to determine the glucose, fructose and sucrose contents of the samples. Glucose, fructose and sucrose contents of sumac syrups are given as percentages, %.

2.8. Antioxidant properties

The antioxidant activity of sumac extract and sumac syrups was assessed using two different assays (DPPH and FRAP). The free radical scavenging activity of samples was assessed using the DPPH assay [13]. After mixing 50 µL of the diluted sample with 1 mL of 100 µM DPPH solution, the solutions were kept dark for 30 minutes, and the absorbance at 515 nm was measured. The findings are presented as mg Trolox equivalent/mL [14].

The ferric reducing activity of samples was determined using a modified FRAP assay [15]. In summary, 50 µL of sumac extract and 0.95 mL of FRAP reagent (300 mM acetate buffer, pH 3.6, 10 mM TPTZ in 40 mM HCl, and 20 mM FeCl₃, 10:1:1 v/v/v) were mixed. The absorbance at 593 nm was measured after the mixture was left in the dark for five minutes. The results are given in mM Fe eq [14].

2.9. Total phenolic compounds

The Folin-Ciocalteu spectrophotometric technique was used to measure the total phenolic content of sumac syrup samples [16]. Samples were diluted with deionized water in a 1:100 ratio. One milliliter of 0.2 N Folin-Ciocalteu reagent was combined with 200 microliters of diluted sample, and the combination was let to stand in the dark for eight minutes. Following that, 2 mL of saturated sodium carbonate (75 g/L) was added, and the mixture was agitated and stored in the dark. Using a UV-vis spectrophotometer (UV-1800, Shimadzu, Japan), the absorbance of each sample was measured at 760 nm following a 2-hour reaction at room temperature. The results were given as mg GAE/mL.

2.10. Anthocyanin content

Anthocyanin content of sumac syrups were determined using a UV-Vis spectrophotometer (UV-1800, Shimadzu, Japan) according to the pH differential method [17]. Measurements were carried out at 510.5 nm, the wavelength of maximum anthocyanin absorbance. By measuring at 700 nm, errors caused by chemicals that might be suspended in the medium were identified. Using the following Eq. (2) and Eq. (3), the total content of anthocyanins in the samples was determined in milligrams of cyanidin-3-glucoside/L.

$$A = (A_{510} - A_{700})_{pH1} - (A_{510} - A_{700})_{pH4.5} \quad (2)$$

$$TA \text{ (mg/L)} = \frac{A \times MW \times DF \times 100}{\epsilon \times 1} \quad (3)$$

A: Calculated absorbance difference, MA: Molecular weight (449.2 for cyanidin-3-glucoside), SF: Dilution factor, ϵ : Molar absorption coefficient (26.900 for cyanidin-3-glucoside).

2.11. HMF content

HMF content of sumac syrup samples was ascertained with HPLC (TSP P4000 pump, TSP UV 1000 detector (285 nm), TSP AS 3000 autosampler, TSP SN 4000 controller, TSP degasser, Thermo Finnigan, USA). Five grams of sample were dissolved with 5 mL of deionized water and then volume of solution was completed to 25 mL with deionized water in a volumetric flask. The solution was then injected into an HPLC system using a carbohydrate column (C18, 150 mm $\times$ 4.6 mm) after being filtered using a 0.45 μ m PTFE filter. The mobile phase had an injection volume of 20 μ L and a flow rate of 0.7 mL/min, with 1% acetic acid and methanol (9:1). An external calibration curve was used to calculate the quantity of HMF [6]. HMF contents of sumac syrup samples were calculated in mg/kg.

2.12. Rheological properties

Flow curve tests were used to investigate the rheological characteristics of sumac syrups. A rheometer (Anton Paar MCR 102, Thermo Scientific, Germany) with a parallel plate system (diameter 35 mm, spacing 1.000 mm) was used for all measurements, which were conducted at 20 °C. The flow tests were carried out with a shear rate between 1 and 100 s⁻¹ under steady-shear conditions.

2.13. Energy analysis

Energy efficiency and consumption were determined using energy balance equations [18]. The general energy balance was written as given in Eq. (4);

$$\sum E_1 = \sum E_2 + Q_{loss} \quad (4)$$

The system boundary is taken into account for the energy analysis. The energy of heat supplied to the system was represented by E_1 (Eq. 5), whereas the total energy of the product, air, and water removed from the sample was represented by E_2 (Eq. 6).

$$E_1 = (m_1 c_{p1} \Delta T) + E_{consumption} \quad (5)$$

$$E_2 = (m_2 c_{p2} \Delta T) + (m_{water} h_{fg}) \quad (6)$$

For CVE (Conventional Vacuum Evaporation, rotary) energy balance was written in Eq. (7) and Eq. (8) respectively. W_{vacuum} was expressed as the work done required (J) to obtain constant vacuum pressure desired in the system during the evaporation process (Eq. (9)).

$$E_{consumption} = Q_{heat} \quad (7)$$

$$E_{consumption} = Q_{heat} + W_{vacuum} \quad (8)$$

$$W_{vacuum} = \int m_{air} \frac{(P_{atm} - P_{vacuum})}{\rho_{air}} dt \quad (9)$$

For Ω VE energy balance was written in Eq. (10). Q_{heat} was taken as Q_{ohmic} for Ω VE method, while it was expressed as Q_{heater} for VE (Vacuum Evaporation) method.

The Q_{ohmic} was determined using experimental data (voltage, current) collected throughout the Ω VE process during a time period (dt) of 1 s, since the conversion of electrical energy to heat energy was about 99%. $W_{agitator}$ was determined as Watt by using the wattmeter (Lutron, DW-6163, Taiwan) at 1000 rpm agitation.

$$E_{consumption} = Q_{ohmic} + W_{vacuum} + W_{agitator} \quad (10)$$

$$Q_{ohmic} = \int V I dt \quad (11)$$

Energy efficiency was expressed as Eq. (12);

$$\eta_{energy} = \left(1 - \frac{Q_{loss}}{E_1}\right) \times 100 \quad (12)$$

2.14. Statistical analysis

Sumac syrup production was performed with three replicates for each method. All analyses were carried out in three independent replicates. Data were subjected to statistical analysis using SPSS software (version 24, SPSS inc) for the analysis of variance (ANOVA). The differences between means were compared with post hoc-Tukey tests with a 95% confidence level.

3. Results and discussion

3.1. Physicochemical properties

Acidity and pH parameters are shown in Table 1. Sumac syrups had pH values ranging from 2.63 ± 0.00 to 2.65 ± 0.00 . The different evaporation methods used did not affect the samples' pH or acidity levels. Turkmen et al. [19] reported that homemade and commercial sumac syrup's pH values were found to be 3.29 ± 0.01 and 2.84 ± 0.04 , respectively. As reported by Ozkanli et al. [20], sumac concentrate had a pH of 3.2. Foods can be categorized based on their pH values as low-acid (pH > 5.3), medium-acid (pH 4.6 – 5.3), acid (pH 3.7–4.6), or high-acid (pH < 3.7) [21]. Due to pH values ranging from 2.63 to 2.65 in our investigation, sumac syrups are in the high acidity group. Findings by Ozkanli et al. [20] and Turkmen et al. [19], align with our study's findings. Acidity of sumac syrups changed between 2.47-2.97% (Table 1). It can be observed that acidity and pH are not significantly ($p > 0.05$) affected by the evaporation process. Ohmic heating was used to concentrate sour cherry juice by Sabanci et al. [22], who obtained comparable results, revealing no significant differences in pH or acidity.

The color characteristics of sumac syrup were evaluated based on the L (lightness), a (red-green), and b (yellow-blue) values. The results are presented in Table 1. There were no statistically significant changes ($p > 0.05$) in the color values (L, a, b) of the sumac syrups obtained with different methods. In addition to being important in terms of customer preference, food colors can provide insight on the phenolic and antioxidant compounds that foods contain. Anthocyanins and other phenolic compounds, which are common in sumac, are

the main factors that affect color. In the study by Sabanci et al. [7], sugar and compounds produced from sugar residues could have enhanced the degradation of anthocyanin compounds and non-enzymatic browning reactions.

Table 1 shows the percentages of fructose, glucose, and sucrose of sumac syrups. The primary carbohydrates present in the various plant organs of sumac are glucose, fructose, xylose, and sucrose [23]. It was found that the voltage gradient and utilized method had no statistically significant ($p > 0.05$) effect on the fructose, glucose, and sucrose content. The findings of several investigations that have been published in the literature support this conclusion [6]. Our results are in line with the findings of Parmar et al. [24], who reported that ohmic heating applied for milk concentration did not cause substantial changes in the carbohydrate composition when compared with conventional methods. In a study on various food products, including jams, it was reported that glucose and fructose concentrations were equivalent in samples treated by ohmic and conventional heating [25].

Table 1. Physicochemical properties and sugar content of sumac syrups

	Rotary	Ohmic – 20 V/cm	Ohmic – 25 V/cm
pH	2.63 ± 0.00^a	2.65 ± 0.00^a	2.64 ± 0.00^a
Acidity, %	2.49 ± 0.14^a	2.47 ± 0.06^a	2.97 ± 0.90^a
L	26.52 ± 1.15^a	26.25 ± 0.54^a	26.21 ± 0.63^a
a	-0.32 ± 0.36^a	-0.21 ± 0.26^a	-0.25 ± 0.29^a
b	1.52 ± 0.22^a	1.49 ± 0.19^a	1.50 ± 0.12^a
Fructose, %	17.37 ± 0.04^a	18.43 ± 0.17^a	17.12 ± 0.01^a
Glucose, %	12.72 ± 0.04^a	13.30 ± 0.09^a	12.62 ± 0.03^a
Sucrose, %	5.58 ± 0.04^a	5.89 ± 0.04^a	5.41 ± 0.02^a

In each row, means with different letters are significantly different ($p < 0.05$).

3.2. Rheological properties

Flow curves of sumac syrups are shown in Fig. 2. The flow behavior was analyzed using the Newtonian model ($\tau = \mu \cdot \dot{\gamma}$). There was more than 97% acceptance the Newtonian model (Fig. 2). Sumac syrups exhibit Newtonian flow behavior. The viscosity of Newtonian fluids remains constant regardless of the shear rate. The connection between shear rate and shear stress in these fluids is linear [6]. Viscosity curves show that sumac syrups obtained by different methods had similar flow behavior. Ozkanli et al. [20], indicated that viscosity of Newtonian fluids is strongly affected by concentration. In this study all methods were applied to same brix value, therefore viscosity did not change by method. Since the brix values of the sumac syrups produced using various techniques were the same, the method had no effect on the viscosity values in the present study. Akar et al. [26], observed similar results, noting that high

brix and high sucrose content result in high viscosity values of pomegranate sours.

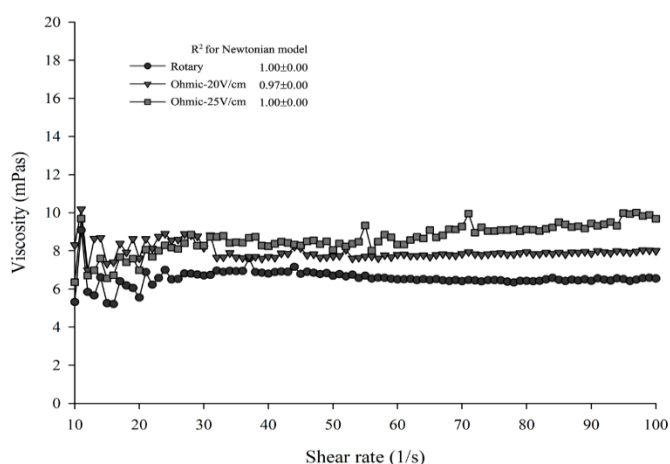


Figure 2. Viscosity curves of sumac syrups obtained by different methods

3.3. HMF content

The Maillard reaction produces a compound known as HMF, which is one of the undesirable components that are restricted in many products by regulation [9]. The HMF value was restricted to a maximum of 20 mg/L in fruit juices and 25 mg/kg in concentrates by the European Fruit Juice Association (AIJN) community [9]. Although there is no specified limit for sumac concentrate, The Turkish Standardization Institute TSE 12720 specifies that the HMF content should not be more than 50 mg/kg in pomegranate concentrates [26].

HMF content of sumac syrups varied between 8.49 ± 2.79 – 12.46 ± 6.20 mg/kg (Table 2). There was no statistically significant difference ($p > 0.05$) between the HMF content of sumac syrups produced with rotary and ohmic heating assisted evaporation methods. Despite the shorter production times, it was found that the HMF content of the samples produced through ohmic heating assisted evaporation was not significantly different.

Table 2. HMF, Total phenolic content and antioxidant properties of sumac syrups

	Rotary	Ohmic – 20 V/cm	Ohmic – 25 V/cm
HMF mg/kg	10.23 ± 4.26^a	8.49 ± 2.79^a	12.46 ± 6.20^a
Total phenolic, mg GAE/mL	79.60 ± 3.91^a	83.19 ± 4.44^a	82.24 ± 8.37^a
FRAP, mM Fe eq	1123.54 ± 59.18^a	1150.54 ± 45.17^a	1090.39 ± 89.76^a
DPPH, mg Trolox eq/mL	246.42 ± 17.98^a	230.84 ± 18.38^a	248.97 ± 21.94^a
Anthocyanin, mg C3G eq/L	665.17 ± 17.25^a	655.43 ± 30.87^a	645.00 ± 32.25^a

In each row, means with different letters are significantly different ($p < 0.05$).

According to reports, the electrochemical reactions that occur in the product may intensify as the voltage rises. This behavior might be explained by electrochemical reactions in the sample during ohmic heating assisted evaporation [6]. According to a study by Turkmen et al.

[19], the HMF values of commercial and homemade sumac concentrates were found to be 209.95 and 446.51 mg/L, respectively. Öztürk [27], reported that HMF values of different commercial sumac syrups changed between 3.39–8117.65 mg/kg. Öztürk [27], noted that variations in the HMF amount result from the composition of syrup, storage conditions, and temperature of manufacturing. The results provides future opportunities to investigate the mechanism and molecular level science accountable for confirming the true cause of HMF formation due to the electrochemical reactions during ohmic heating, as the current body of literature remains limited in providing a comprehensive explanation [28].

3.4. Total phenolic and antioxidant properties

Total phenolic and antioxidant content of sumac syrups produced by different evaporation methods is shown in Table 2. Phenols are important constituents of foods and aromatic plants. Therefore, their loss or reduction in focus will significantly affect the sensory qualities of food. Processing setting, treatment method, and phenolic type all influence phenolic retention and degradation [29]. Total phenolic content of sumac syrups was found between 79.60 ± 3.91 – 83.19 ± 4.44 GAE/mL. Zannou et al. [3], reported that TPC values of sumac extracts extracted by different methods and solvents were found to ranges of 44.52 ± 3.81 – 124.96 ± 3.43 mg GAE/g and 36.34 ± 0.89 – 114.53 ± 0.38 mg GAE/g for ultrasound and homogenate assisted extractions, respectively. Turkmen et al. [19] indicated that total phenolic contents of commercial and homemade sumac syrups were found $3,098.97 \pm 74.23$ and $93,543.81 \pm 1,533.51$ mg/L, respectively. According to Çiftçi Yegin [30], samples of sour sumac from different regions had total phenolic contents ranging from 13.01 to 18.22 mg/g. Jain et al. [31] compared the effects of ohmic and conventional heating by ohmic heating sweet orange juice at five different voltages (120, 150, 180, 210, and 240 V). As a result of the study, they reported that there was no difference in phenolic contents between commercial and ohmic heating-assisted applications at different voltages.

DPPH values of sumac syrup samples vary between 230.84 ± 18.38 – 248.97 ± 21.94 mg Trolox eq/mL. There was no significant differences ($p > 0.05$) between conventional and ohmic evaporation methods. Álvarez-Chávez et al. [32], evaluated the antioxidant activity using the DPPH assay on mezcal samples treated with ohmic heating and observed that ohmic heating did not affect the DPPH values of the free phenolic fraction. Similarly, Ríos-Ríos et al. [33], applied ohmic and conventional heating to garlic samples in their study, and the data showed no significant differences in DPPH and total phenolics values. FRAP analysis results were

found to range from 1090.39 ± 89.76 to 1150.54 ± 45.17 mM Fe eq. The results did not differ significantly ($p > 0.05$) depending on the production method. The release of metal ions during ohmic heating as a result of the electrodes' electrochemical corrosion [34]. Despite the shorter production times at the ohmic heating evaporation process, the lack of difference compared to the rotary method can be attributed to electrochemical degradation. Suathong et al. [35], evaluated the FRAP results on antioxidant activities of green curry paste samples. They reported no significant difference in FRAP values between conventional heat treatment and ohmic heating treatment (non-conductive package).

The anthocyanin content of sumac syrups produced by conventional method was determined 665.17 ± 17.25 mg C3G eq/L. In ohmic evaporation, anthocyanin values were found to be 655.43 ± 30.87 and 645.00 ± 32.25 mg C3G eq/L for 20 V/cm and 25 V/cm, respectively. Although conventional method indicating higher anthocyanin content, there was not statistically significant difference ($p > 0.05$) between the samples. According to Mercali et al. [36], anthocyanin degradation in acerola pulp was not notably affected by either conventional heating or ohmic heating, similarly our research. Sarkis et al. [37], reported that anthocyanin degradation decreased by low voltage gradient application. Anthocyanin levels were not significantly changed despite shorter time heat exposure. Similar outcomes have been noticed by Sarkis et al. [37], when they used ohmic heating to produce blueberry pulp and Mercali et al. [38], when they used it to produce Jaboticaba fruit juice. The percentage of anthocyanin degradation was similar or even lower than those obtained with conventional heating when the ohmic heating process was used with low voltage gradients. When higher voltage gradients were applied, the levels of degradation were greater for the ohmic-heated pulp. These results might be explained by electrochemical reactions that are catalyzed by high voltages. The results emphasize the importance of the use of inert materials in electrodes and electrode coatings or the use of high frequency power to limit electrochemical reactions [37,38].

Table 3. Process conditions and energy analysis of different methods

	Rotary	Ohmic –20 V/cm	Ohmic – 25 V/cm
Voltage, V	—	188	235
Reach to boiling point (min)	3.19 ± 1.00^b	0.85 ± 0.30^a	0.53 ± 0.09^a
Total process time (min)	33.16 ± 0.95^c	23.50 ± 1.65^b	19.03 ± 0.42^a
Energy consumption, kJ	1332.00 ± 101.82^b	121.93 ± 5.98^a	95.00 ± 3.08^a
Total power, kWh	0.370 ± 0.03^b	0.034 ± 0.00^a	0.027 ± 0.00^a
Emitted CO ₂ , g CO ₂	296.00 ± 22.63^b	27.10 ± 1.33^a	21.11 ± 0.68^a

In each row, means with different letters are significantly different ($p < 0.05$)

3.5. Energy analysis and process conditions

Process conditions and energy analysis of different evaporation methods are displayed in Table 3. The time to reach boiling point time for the rotary evaporator was found to be 3.19 ± 1.00 min. It was found that there is a statistically significant difference ($p < 0.05$) in the reach to boiling time between the rotary evaporation and the ohmic heating assisted evaporation. The ohmic heating assisted evaporation at 25 V/cm brought the sample to boiling nearly six times faster than the rotary evaporation method, demonstrating its superior heating efficiency. When the voltage gradient increased, the boiling time reduced (0.85 min and 0.53 min for 20 V/cm and 25 V/cm, respectively). Saxena et al. [39], reported that at higher voltage gradients, come up time diminished in sugarcane juice (for reaching 60°C at 24 V/cm, 32 V/cm, and 40 V/cm, come up times were 0.98 min, 2.12 min, and 0.20 min, respectively). The total process time was calculated from the beginning of the process until the sumac extract reached 50° Brix. It was demonstrated that the rotary evaporator had a statistically higher ($p < 0.05$) total process time (Table 3).

The energy consumption and total power of conventional and ohmic heating assisted methods are significantly different based on energy analysis. In ohmic heating assisted evaporation, energy consumption was calculated as 121.93 kJ at 20 V/cm and 95.00 kJ at 25 V/cm, whereas the rotary method required significantly higher energy, approximately 12 times more (1332.00 kJ). Nevertheless, it was seen that when the voltage changed, the energy values were not substantially changed. Darvishi et al. [34], reported that the energy efficiency of continuous ohmic heating at 30 V/cm (71.5–74.5 %) was 10.7 to 16 % lower than at 15 V/cm. Based on the data that Hamzah et al. [40], provided, ohmic heating was found to use significantly less energy when compared to Soxhlet extraction. Date syrup was produced using ohmic heating at various voltage gradients (9, 10 and 11 V/cm) by Al-Hilphy et al. [41]. It has been observed that shortening the applied time by an increase in the voltage gradient lowers the total energy consumption. Total consumption was reported to have decreased by 85.78% when compared to the conventional method. Researchers note that the yearly savings cost was 10431.75 dollars, which indicates that the ohmic heating can save costs by 85.78% [41]. The total power values were significantly higher in the conventional rotary method, which is consistent with these findings. 800 g of CO₂ will be released into the atmosphere during the combustion of fossil fuels to generate 1 kWh from coal or fuel [42]. Conventional method showed the highest amount of carbon dioxide emitted to the atmosphere, 296.00 ± 22.3 g CO₂, followed by ohmic assisted evaporation at 20 V/cm and ohmic assisted evaporation at 25 V/cm, which are 27.10 ± 1.33 g

CO₂ and 21.11 ± 0.68 g CO₂, respectively. The findings indicated that, even at high voltage levels, a short process time reduced CO₂ emission.

Karakavuk et al. [9], applied ohmic heating at different voltage gradients to bring the water amount of apple juice from 5.25 kg water (W)/kg dry matter to 0.95 kg water (W)/kg dry matter. Researchers reported that the conventional method (1248.6 kJ) consumed approximately 2.5 times more energy than the ohmic heating assisted evaporation method (534.3-565.0 kJ). Additionally, they noted that the use of high voltage significantly decreased energy consumption [9]. Rocha et al. [43], reported that conventional heating leads to higher energy consumption than ohmic heating. Also, when voltage gradient gets higher, energy consumption increases.

4. Conclusion

In this study, the effects of ohmic heating assisted evaporation on sumac syrup production were investigated and compared with the conventional evaporation method. The results demonstrated that ohmic heating effectively preserved the quality attributes of the sumac syrup, including antioxidant properties and HMF content, with no significant differences compared to the conventional method. Importantly, ohmic heating enabled substantial reductions in energy consumption, approximately eleven-fold lower than conventional evaporation, as well as decreases in CO₂ emissions and key process parameters. Significant differences were observed, particularly in the process conditions. The time to reach the boiling point was 3.19 ± 1.00 minutes in the conventional method, whereas it ranged from 0.8 ± 0.30 to 0.55 ± 0.09 minutes in the ohmic heating method. Moreover, increasing the voltage gradient further reduced the boiling time, consequently lowering the energy consumption. These findings suggest that ohmic heating assisted evaporation is a promising alternative to conventional evaporation methods. In particular, the reduction in operation costs is an important advantage of ohmic heating. Future research may focus on optimizing operational parameters such as voltage gradient, pressure and scaling up the process to industrial levels to further validate these benefits.

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