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ORIGINAL ARTICLE

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Electric field applications on dried key lime juice quality with regression modeling

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Abstract

Key lime (*Citrus aurantifolia* L.) is an important source of juice and vitamins. A continuous nonthermal juice pasteurizer (CNTJP) using electric field with alternating current was designed and constructed. The effect of electric field was investigated on dried (black) lime juice using voltage gradients (X_1) of 24–88 V/cm and mass flow rates (X_2) of 12–50 kg/hr. The treated juice was evaluated for physicochemical properties, phytochemical compounds with antioxidant capacity, and microbial quality. The results showed that there were no significant effects ($p > .05$) between CNTJP treatment and both the thermal treatment and the control sample regarding the total soluble solids and pH values. However, the titration acidity value of dried juices in thermal treatment was significantly higher ($p < .05$) compared to the control and CNTJP samples. There was a significant difference ($p < .05$) between CNTJP samples and both the control and the thermal treatment samples regarding the total phenolic content, ascorbic acid content, and antioxidant activity (1,1-diphenyl 2-picrylhydrazyl). Also, the results showed that coliform bacteria, yeast, and mold were not capable of growing in control samples (fresh juice) or all samples treated by CNTJP treatments or thermal treatments. However, the total viable count of CNTJP samples varied between 1.93 and 4.79 (Log10 CFU/mL), whereas the total viable counts of the control sample and thermal treatment were 5.99 and 3.82 (Log10 CFU/mL), respectively. At the optimum conditions of mass flow rate of 28.24 kg/hr and voltage gradient of 82.38 V/cm, the highest electrical conductivity was 0.65 S/m.

Practical applications

Nonthermal, high-throughput pasteurization systems are highly desirable as alternatives to overcome the negative effects of thermal pasteurization. Electric field (EF) is one potential alternative technology. Although this study did not focus on effectiveness of log reduction of pathogens, EF resulted in fewer pathogenic indicators than nontreated dried lime juice. Electric field did demonstration superiority over thermal pasteurization for maintaining total phenolic content, ascorbic acid, and antioxidant activity in dried lime juice. Maximizing healthy characteristics of fruit juice during pasteurization can lead to a product with a higher retail value than traditional thermal processing. This potential higher economic value for EF-treated juice could offset implementation and processing costs. The EF system described in this study can be readily scaled up by having parallel lines of size similar to this study or by increasing the tubing and electrode sizes or both.

1 | INTRODUCTION

Key lime (*Citrus aurantifolia* L.) is a fruit crop of the family of *Rutaceae* (Alu'datt et al., 2017). Limes as a group are a polyphyletic group of 15 species. Limes are an important horticultural crop. When combined with lemons, the total world production during 2016–2017 was estimated to be 7.2 MMT (USDA, 2017). Limes and lemons were ranked worldwide as the third crop in the citrus industry (Mu et al., 2012). Lemon is planted throughout the world especially in temperate climates such as the western United States, Argentina, Italy, Thailand, and Spain

(Jittanit, Suriyapornchaikul, & Nithisopha, 2013). Limes are highly sensitive to cold weather and are mostly cultivated in tropical climates (USDA, 2017). Other warm and dry climates are suitable to cultivate lime such as those in Egypt, Iran, and Iraq. In arid climates, key limes dry under ambient conditions and are commonly available and referred to as black limes. Dried key limes can be crushed and reconstituted as juice or used to create black lime or loomi, which is a flavoring typical of Persian and Iraqi cuisine.

Iraq is essentially classified as an agricultural country with about 438 317 km^2 of agricultural land (Stephan, El-Behadli, Antoon, & Al-Zahroon, 1989). Approximately, 81.5% of agricultural land was used to cultivate wheat, barley, rice, and maize, whereas 18.5% of agricultural land was employed to plant a wide variety of crops such as date palm, stone fruits, sugarcane, citrus, vegetables, tobacco, and grapes (Stephan et al., 1989). Iraqi production of lime and lemon was 26 600 T in 2002 but it gradually decreased to 7,577 T in 2014 (FAO, 2017). Countries such as Iraq could benefit from the production of more limes to diversify agricultural crops and produce a fruit with highly desirable medicinal traits.

Key limes are green in color when immature and turn yellow at maturity. Lime has a smooth surface and contains citric acid, flavonoids, carotenoids, essential minerals, and dietary fiber (Hanif, Padmanabhan, Waly, & Al-Maskari, 2017; Hunlun, de Beer, Sigge, & Van Wyk, 2017; Ubando-Rivera, Navarro-Ocaña, & Valdivia-López, 2005). Lime like other citrus contains high amounts of antioxidants especially ascorbic acid (AA). As AA cannot be synthesized in the human body, people get 90% of their AA by consuming fruits and vegetables (Lee & Kader, 2000). The studies have found that the risk of cardiovascular diseases and some cancers can be reduced through consuming fruits and vegetables with high antioxidant content (Del Rio et al., 2013; Lee & Kader, 2000). Recently, fresh citrus and lime juices have gained consumers' attention and become the most popular drink worldwide owing to potential health benefits and nutritional value (Esparza-Martínez, Miranda-López, & Guzman-Maldonado, 2016; Xu et al., 2008).

Typically, limes are fresh squeezed for use during food preparation. Although lime juice products are commercially processed and sold in the marketplace, they are often considered unacceptable because of the addition of artificial acids and flavors (Jittanit et al., 2013). As a result, consumers desire to purchase either fresh limes or dried limes to obtain high-quality lime juice. However, consumers face problems with maintaining and extending the shelf life of juice. Therefore, numerous studies have been conducted to develop technology that can improve the quality of juice and extend its shelf life.

Thermal pasteurization processes such as ultra-high-temperature sterilization (Jittanit, Wiriyaputtipong, Charoenpornworanam, & Songsermpong, 2011), microwave treatments (Barba, Calabretti, d'Amore, Piccinelli, & Rastrelli, 2008), ohmic heating (Saxena, Makroo, & Srivastava, 2016), and infrared heating (Aghajanzadeh, Kashaninejad, & Ziaiifar, 2016) were the most common methods studied to ensure food safety and extend shelf life (Sulaiman, Farid, & Silva, 2017). However, high-temperature processing could negatively affect citrus juices by changing the color, flavor, odor, and reducing antioxidants compounds and vitamins (Espachs-Barroso, Van Loey, Hendrickx, & Martín-Belloso, 2006). For instance, Aguilar-Rosas, Ballinas-Casarrubias, Nevarez-Moorillon, Martin-Belloso, and Ortega-Rivas (2007) reported a 22–100% loss of volatile flavor compounds in apple juice with thermal treatment at 90 °C for 30 s and the juice became considerably more turbid than fresh unprocessed juice when thermal processing was extended to 100 s at 90 °C (Krapfenbauer, Kinner, Gössinger, Schönlechner, & Berghofer, 2006).

Owing to these disadvantages of thermal processing, nonthermal processes such as high-pressure processing (Evelyn & Silva, 2015), pulsed electric fields (Elez-Martinez & Martin-Belloso, 2007), ultrasound treatment (Bhat, Kamaruddin, Min-Tze, & Karim, 2011), and ultraviolet radiation (Keyser, Müller, Cilliers, Nel, & Gouws, 2008) have been explored and applied to improve shelf life of fresh fruit juices. Among these technologies, electric field (EF) was deemed an effective nonthermal process for liquid food owing to low-energy utilization, low temperature, and inactivation of pathogenic microorganisms (Peng et al., 2017).

In spite of the advantages of EF and increasing consumer awareness regarding the health benefits of lime juice, no reports are available on the application of EF to enhance the quality of dried (or black) lime juice. Therefore, the main objectives of this research were (a) to construct a continuous nonthermal juice pasteurizer (CNTJP) using EF with alternating current and (b) to study the effect of voltage gradients (X_1) ranging from 24 to 88 V/cm and mass flow rates (X_2) ranging from 12 to 50 kg/hr on the physicochemical properties of phytochemical compounds with antioxidant capacity and antimicrobial activity of dried lime juice. Conventional thermal pasteurization with a water bath at 90 °C for 15 min was used to compare the efficiency of EF method at optimized conditions.

2 | MATERIALS AND METHODS

2.1 | Sample preparation

Black limes (*C. aurantifolia*) that were dried under ambient conditions were purchased from a local market (Basrah, Iraq) and kept at room temperature until the experiments were conducted. Dried limes were crushed to yield 100 g of fine powder and passed through a 40-mesh sieve to remove seeds, impurities, and particles. The powder was then soaked in 3 L of distilled water and kept for 24 hr at room temperature. Then, the mixture was filtered using muslin cloth and centrifuged at 3,000 *g* to obtain 2.6 L of clear juice. The prepared juice was immediately processed using conventional thermal treatment and EF methods, whereas control samples were immediately refrigerated at 4 °C.

2.2 | Conventional thermal processing

Dried lime juice in the amount of 100 mL was promptly poured into each of three clean 250-mL glass bottles and heated in water bath at 90 °C for 15 min. Then, the pasteurized black lime juice was cooled in an ice water bath to minimize the negative effects of heating on physicochemical properties. The juice was kept at 4 °C until physicochemical analysis.

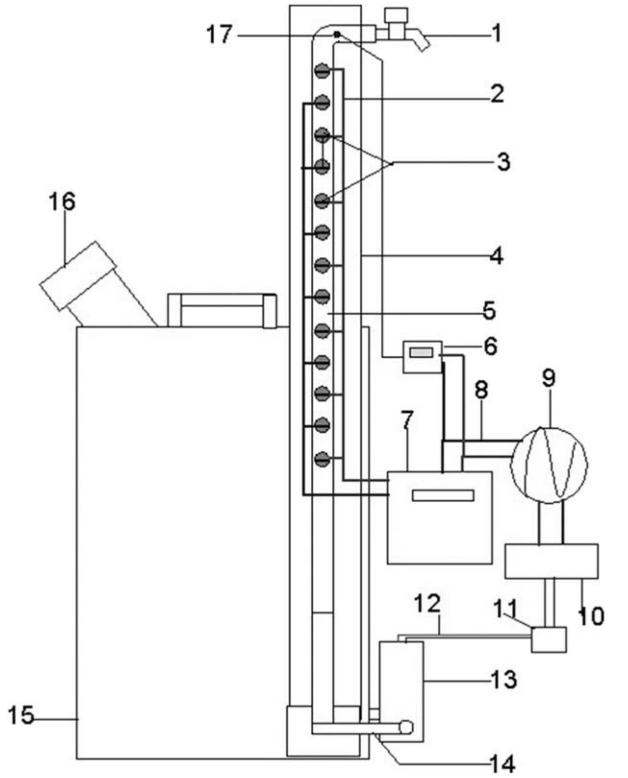

FIGURE 1 Schematic diagram of CNTJP using AC EF consisting of: 1, tap; 2, electric wire; 3, electrodes; 4, plastic tube cover; 5, pasteurization tube; 6, digital temperature gauge; 7, Variac; 8, electric cable; 9, 220 VAC power source; 10, 220 VAC to 12 VDC power converter; 11, electrical connector; 12, electric cable; 13, DC centrifugal pump; 14, pipe; 15, plastic reservoir; 16, reservoir cap; and 17, thermocouple

2.3 | Nonthermal juice pasteurizer

A CNTJP using EF with alternating current (Figure 1) was designed and constructed in our food engineering laboratory (Department of Food Science, College of Agriculture, University of Basrah, Basrah, Iraq). The CNTJP consisted of a pasteurization tube of 0.5 m length and 1 cm internal diameter with 13 stainless steel (Type 316) electrodes (diameter = 0.4 cm, length = 2.5 cm; Figure 2) inserted perpendicularly into the pasteurization tube with 2.5 cm spacing between electrodes. A centrifugal pump (12 VDC, 0.5A, 2,500 rpm, 50 L/hr), powered by a 220 VAC to 12 VDC power converter, moved lime juice from a 1-L plastic reservoir through the pasteurization tube. A variable autotransformer (GeneralRadio, North Reading, MA) provided variable voltage output (0–230 VAC) for the electrodes.

2.4 | Physicochemical analysis

2.4.1 | Total soluble solids (brix) and pH

The total soluble solid values of the juice samples were estimated at room temperature using a refractometer (Bellingham, England). A conversion table was used to convert all recorded refractive indexes to Brix value. The refractometer prism was cleaned using distilled water

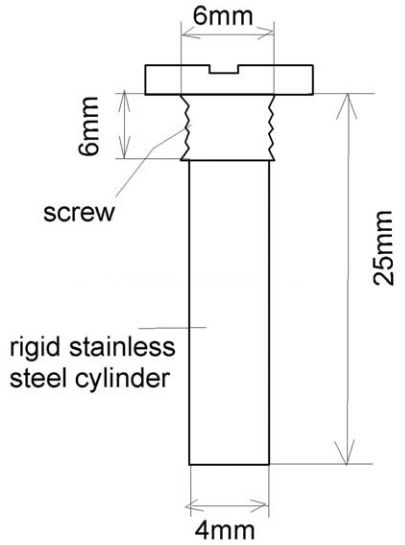

FIGURE 2 Schematic diagram of electrode

(Teerachaichayut & Ho, 2017). A pH meter (Lovibond Sensodirect pH200, Germany) was used to record pH values of juice samples. Buffer solutions of pH 4 and 7 were used to calibrate the pH meter for accurate readings. Approximately, 10 mL of juice was transferred to a small beaker and manually stirred before measuring pH at 25°C (Sulaiman et al., 2017).

2.4.2 | Titratable acidity

Titratable acidity was determined using a titration method (Ordóñez-Santos, Martínez-Girón, & Arias-Jaramillo, 2017) with minor modification. Distilled water (50 mL) was added into a beaker containing 10 mL of juice sample and was gently stirred. For analysis, the mixture was titrated against freshly prepared 0.1 N sodium hydroxide and three to five drops of phenolphthalein as an indicator until it reached a pink color. The total acidity was expressed as the citric acid content (%) and calculated using the following equation:

$$\text{Titratable acidity}\,(\%\ \text{citric acid}) = \frac{\text{mL of NaOH}\,(0.1\ \text{N}) \times 0.067 \times 100}{10} \tag{1}$$

with factors based on the studies of Bhat et al. (2011) and Redd, Hendrix, and Hendrix (1992).

2.4.3 | Ascorbic acid content determination

An iodine titration method (Kashyap & Gautam, 2012) was applied with slight modifications for determining AA content in juice samples. In the first step, the iodine solution was prepared by dissolving 5 g of potassium iodide (KI) and 0.268 g of potassium iodate (KIO_3) with 200 mL of distilled water into a beaker. About 30 mL of 3 M sulfuric acid (H_2SO_4) was added and more distilled water was added for a total volume of 500 mL. The second step was to prepare a fresh starch solution 1% (w/v) as an indicator. Finally, 150 mL of distilled water was added to a beaker containing 20 mL of the lime juice and gently mixed. Titration with prepared iodine solution was performed until it reached a clear dark-blue color owing to the starch–iodine complex. Ascorbic acid contents were determined using the following equation:

$$\text{Ascorbic acid content}\,(\text{mg}/100\ \text{mL sample}) = 0.88 \times \text{iodine solution}\,(\text{mL}) \quad (2)$$

2.4.4 | Total phenolic content

The total phenolic content (TP) of juice samples was measured by the previously reported Folin–Ciocalteu method (Aadil et al., 2015) with slight modifications. For measurement, a solution of 3 mL dried lime juice, 1 mL of freshly prepared 10% (w/v) Folin–Ciocalteu reagent, and 2 mL of 20% (w/v) sodium carbonate were mixed vigorously for 2 min and left in the dark for 50 min at room temperature. The absorbance of the mixture was precisely measured at 760 nm using a spectrophotometer (Jenway, Model 6305, United Kingdom). The calibration curve of Gallic acid was prepared and the results were expressed as milligrams of Gallic acid equivalent per gram of sample.

2.4.5 | Antioxidant activity

The antioxidant activity of the dried lime juice was measured based on the 1,1-diphenyl 2-picrylhydrazyl (DPPH) method (Klimczak, Małecka, Szlachta, & Gliszczyńska-Świgło, 2007) with some modifications. The DPPH solution was prepared by dissolving 25 mg of DPPH radical in 80% v/v methanol and mixed gently using a vortex. Then, 1 mL of the freshly prepared DPPH solution was placed into a test tube containing 1 mL of dried lime juice and mixed and left in the dark for 25 min at room temperature. The absorbance of the samples was estimated using a spectrophotometer at a wavelength of 517 nm. The antioxidant activity was expressed as the DPPH radical scavenging activity and calculated using the following equation:

$$\text{Antioxidant activity}\ (\%) = \left\{\frac{A_c - A_{LS}}{A_c}\right\} \times 100 \quad (3)$$

where A_c was the absorbance of the control and A_{LS} was the absorbance of the lime juice sample.

2.4.6 | Microbiological analysis

In brief, 1 mL of dried lime juice was placed into a sterilized test tube containing 9 mL of peptone water solution and mixed thoroughly to make serial dilution (10^{-1} to 10^{-3}) for determining the total viable count (TVC), coliform bacteria, yeast, and mold. In total, 1 mL of each of the different juice dilutions was placed on nutrient agar plates and incubated at 35 °C for 24–48 hr for measuring the total count of bacteria. The same procedure was used for counting coliform bacteria except that nutrient agar was replaced with MacConkey agar. All petri dishes were incubated at 37 °C for 24–48 hr. The yeast and mold count were estimated using potato dextrose agar and then incubated at 37 °C for 3 days. The results were expressed as log colony forming units (CFU/mL) of dried lime juice. All treatments were performed with three replicates and the average of triplicate microbial analysis was used (Keyser et al., 2008).

2.4.7 | Electrical conductivity

Electrical conductivity was calculated as follows (Icier, Yildiz, & Baysal, 2008)

$$\sigma = \frac{I\ d}{V\ A} \quad (4)$$

where σ is the electrical conductivity (S/m), I is the electrical current (ampere), d is the distance between electrodes (m), A is the section area (m^2), and V is the voltage (V).

2.5 | Experimental design and data analysis

Two independent variables and three coded levels (−1, 0, and +1) were used as follows: X_1 (flow rate, kg/hr) ranged from 12 to 50 kg/hr and X_2 (voltage gradient, V/cm) ranged from 24 to 88 V/cm, whereas the dependent variables (response variables) were the physicochemical properties of phytochemical compounds with antioxidant capacity and microbial quality. These ranges of independent variables were selected based on the preliminary data and were guided by prior research using moderate electrical field up to 60 V/cm (Demırdöven, Yildiz, İçıer, & Baysal, 2017; Machado, Pereira, Martins, Teixeira, & Vicente, 2010). A central composite design (CCD) was employed to achieve the optimal extraction conditions. The following second-order polynomial model was used to determine the relationship between the two independent variables and each response variable.

$$Y_i = B_0 + b_1X_1 + b_2X_2 + b_{12}X_1X_2 + b_{11}{X_1}^2 + b_{22}{X_2}^2 \quad (5)$$

where Y_i is the predicted response, B_0 is a intercept, b_1 and b_2 are the estimated coefficients of flow rate (X_1) and voltage gradient (X_2), respectively; b_{11} and b_{22} are quadratic effects and b_{12} is interaction effect of independent variables. The statistical software Design Expert 10.6 (State-Ease Inc., Minneapolis, Minnesota) was employed to analyze the experimental results.

3 | RESULTS AND DISCUSSION

3.1 | Effects of CNTJP application on physicochemical properties of dried lime juice

Total soluble solids (Brix), pH, and titratable acidity are listed in Table 1. There were no significant differences in total soluble solids among the control, thermal, and CNTJP treatments. The total soluble solid values of CNTJP samples varied between 6.81 and 6.85, whereas the total soluble solid values of the control sample and thermal treatment were 6.85 and 6.82, respectively. These results were in agreement with Demırdöven et al. (2017), who found no changes in total soluble solids by using moderate electric treatment application. Also, there was no statistically significant difference ($p > .05$) among the pH of the control, CNTJP, and thermal treatment samples. The pH values of dried lime juice of CNTJP samples were between 2.29 and 2.33 (Table 1). A similar result in the titration acidity values of dried lime juice in CNTJP samples compared to the control sample was obtained. However, the titration acidity value of dried juices in thermal treatments was significantly higher ($p < .05$) at 1.08 compared to the control samples and

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TABLE 1 Experimental design and the responses of physicochemical properties, phytochemical compounds with antioxidant capacity and microbial quality

Run	Independent variables: Mass flow rate (kg/hr)	Independent variables: Voltage gradient (V/cm)	Electrical conductivity (S/m)	TA	Brix	pH	AA	DPPH	TP	TVC
1	12	88	0.68[a]	0.87[a]	6.83[b]	2.32[a]	34[b]	52.62[c]	255.22[a]	2.41[c]
2	31	56	0.58[e]	0.81[d]	6.83[b]	2.31[a]	35.08[a]	55.85[a]	256.53[a]	3.36[b]
3	12	24	0.52f	0.82[d]	6.85[a]	2.32[a]	34.97[a]	52.45[c]	256.96[a]	4.79[a]
4	12	56	0.60[d]	0.84[b]	6.84[ab]	2.32[a]	34.91[a]	53.88[b]	256.36[a]	3.60[b]
5	50	56	0.56[d]	0.82[cd]	6.81[cd]	2.31[a]	34.84[a]	53.8[b]	257.06[a]	3.12[b]
6	50	88	0.64[c]	0.82[cd]	6.81[cd]	2.32[a]	34.89[a]	51.97[c]	257.12[a]	1.93[d]
7	31	56	0.58[e]	0.81[d]	6.83[b]	2.31[a]	35.08[a]	55.85[a]	256.53[a]	3.36[b]
8	31	56	0.58[e]	0.81[d]	6.83[b]	2.31[a]	35.08[a]	55.85[a]	256.53[a]	3.36[b]
9	31	24	0.5[g]	0.81[d]	6.83[b]	2.31[a]	34.67[a]	54.7[ab]	256.53[a]	4.55[a]
10	31	56	0.58[e]	0.81[d]	6.83[b]	2.31[a]	35.08[a]	55.85[a]	256.53[a]	3.36[b]
11	50	24	0.48[h]	0.84[b]	6.82[bc]	2.31[a]	33.94[c]	52.93[c]	256.46[a]	4.32[a]
12	31	56	0.58[e]	0.81[d]	6.83[b]	2.31[a]	35.08[a]	55.85[a]	256.53[a]	3.36[b]
13	31	88	0.66[b]	0.83[bc]	6.82[bc]	2.32[a]	34.66[c]	54.31[ab]	255.99[a]	2.17[c]

Abbreviations (TA = titratable acidity; AA = ascorbic acid; DPPH = antioxidant activity; TP = total phenolic content; TVC = total viable count)

CNTJP samples. This increase in acidity may be ascribed to spread of intracellular components owing to thermal treatment.

The linear regression model for the total soluble solids (Brix) and quadratic regression models for pH and titratable acidity of the dried lime juice are listed in Table 2. The results indicated that the model of the total soluble solids (Brix) and titratable acidity were significant, whereas the model was not significant for the pH response. The coefficients of determination (R^2) of quadratic regression models of titratable acidity and total soluble solids (Brix) were .88 and .54, respectively. Similarly, the values of the adjusted R^2 of titratable acidity and the total soluble solids (Brix) were .81 and .45, respectively, which were close to the R^2 values. Consequently, the results confirmed that a good relationship was found between the experimental and the predicted values. The lack-of-fit test was used to measure the failure of the model to show the data at points that are not inserted in the regression (Wang et al., 2013). As summarized in Table 2, lack-of-fit was not significant

TABLE 2 Summary of the statistical analysis and the regression coefficients of the tested models[a]

Source	Electrical conductivity (S/m)	Physicochemical properties: pH	Physicochemical properties: TA	Physicochemical properties: Brix	Phytochemical compounds with antioxidant capacity: TP	Phytochemical compounds with antioxidant capacity: AA	Phytochemical compounds with antioxidant capacity: DPPH	Microbial quality: TVC
p Value of the model	.0001	.57	.003	.0188	.9702	.0177	.0046	.0102
Intercept	0.47	2.34	0.83	6.86	257.8	34.67	45.97	5.83
X_1	−1.10	−1.77	−1.34	−7.02	−0.06	−0.010	0.369	−0.012
X_2	2.53	−2.87	1.53	−2.08	−9.65	0.021	0.155	−0.037
X_1X_2	–	4.11	−2.88	–	9.87	7.89	−4.65	–
X_1^2	–	2.05	3.92	–	5.04	−5.77	−5.58	–
X_2^2	–	2.36	8.92	–	−2.62	−4.13	−1.32	–
R^2	.9565	.36	.88	.54	.101	.8119	.8747	.60
Adj R^2	.9478	−.08	.81	.45	−.53	.6776	.7852	.52
F-value of the model	109.97	0.82	11.25	6.07	0.16	6.04	9.77	7.51
Lack of fit	0.1056	0.83	0.13	0.5882	0.7252	0.4236	0.3418	0.682

Abbreviations (TA = titratable acidity; AA = ascorbic acid; DPPH = antioxidant activity; TP = total phenolic content; TVC = total viable count)
[a]Columns with missing X_1X_2, X_1^2, and X_2^2 values are linear regression models, whereas other columns are quadratic regression models.

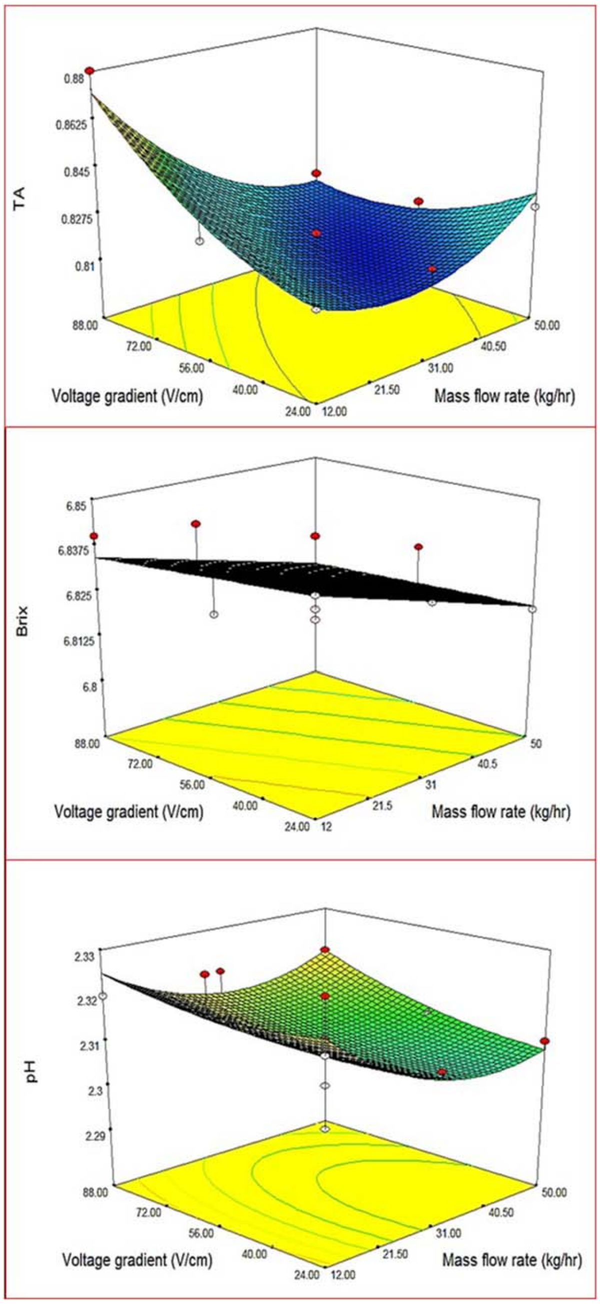

FIGURE 3 Response surface plot showing the effect of flow rate (kg/hr) and voltage gradient (V/cm) on titratable acidity (TA), total soluble solids (Brix), and pH

for titratable acidity, total soluble solids (Brix), or pH. All these results indicated that the model was satisfactory within the applied range of independent variables for predicting the titratable acidity and the total soluble solids (Brix), whereas the model was not suitable for predicting the pH values (Table 2). Response surface models using three-dimensional (3D) surface plots were applied to estimate the optimum conditions for independent and dependent variables (Altemimi, Watson, Choudhary, Dasari, & Lightfoot, 2016). The effects of flow rate and voltage gradient and interactions for predicting titratable acidity, total soluble solids (Brix), and pH are shown in Figure 3. The optimized conditions to maximize titratable acidity, total soluble solids, and pH were at a flow rate of 28.24 kg/hr and a voltage gradient of 82.38 V/cm.

3.2 | Effects of CNTJP application on phytochemical compounds with antioxidant capacity of dried lime juice

The TP, AA, and the antioxidant activity (DPPH) are summarized in Table 1. Total phenolic content of CNTJP samples was found to be between 255.22 and 257.12 mg/g Gallic acid, whereas the TP of the control and thermal treatment samples were 250.6 and 150.81 mg/g Gallic acid, respectively. In brief, TP was for CNTJP was significantly ($p < 0.05$) higher than both the control and the thermal treatment samples. This result indicated that using lower processing temperature is suitable for juice extraction (Evrendilek et al., 2012). The results also showed a statistically significant difference ($p > .05$) between AA values of CNTJP samples and both the control sample and the thermal treatment, with CNTJP being higher than thermal treatment. Ascorbic acid values of dried lime juice of CNTJP samples were between 33.94 and 35.08 mg/100 mL sample (Table 1), whereas AA values of the control and thermal treatment samples were 35.64 and 29.21 mg/100 mL sample, respectively. This result concurred with those of Demırdöven (2009) and Vieira, Teixeira, and Silva (2000) who showed that EFs with alternating current had the capability of obtaining higher TP and AA values for carrot juices compared to thermal treatment. 1,1-Diphenyl 2-picrylhydrazyl of CNTJP samples was found to be between 51.97 and 55.85%, whereas the antioxidant activity values of the control and thermal treatment samples were 25.5 and 19.11%, respectively. The increase in antioxidant activity values of CNTJP samples was statistically significant ($p < .05$) compared to the control and thermal treatment samples. This result was in agreement with Yıldız, İcier, Demırdöven, and Baysal (2009), who found that moderate electric treatment released higher antioxidant activity values for sour cherry juices.

Analysis of variance (ANOVA) was used to analyze the adequacy of the CCD developed model and the significance of the related factors for TP, AA, and DPPH (Table 2). The regression models for AA and DPPH were significant ($F = 6.04$, $p = .0177$ and $F = 9.77$, $p = .0046$, respectively). The lack of fit was not significant for AA nor DPPH ($F = 6.04$, $p = .4236$ and $F = 9.77$, $p = .3418$, respectively), indicating that the model was adequate for predicting both the values. For AA and DPPH, R^2 values were .82 (adj $R^2 = .68$) and .87 (adj $R^2 = .79$), respectively, indicating a good relationship between the predicted and the observed values (Ballard, Mallikarjunan, Zhou, & O'keefe, 2010). In contrast, the model was not significant to predict the TP (Table 2).

Three-dimensional plots of surface responses were generated by altering two variables within the experimental range and keeping the third variable constant at the central level (Figure 4). Total phenolic content, AA, and DPPH increased when the mass flow rate increased in the range of 12–28.24 kg/hr and the voltage gradient increased in the range of 24–82.38 V/cm. All values of TP, AA, and DPPH decreased above 28.24 kg/hr and 82.38 V/cm. The highest recovery for TP, AA, and DPPH values occurred at lower mass flow rate and

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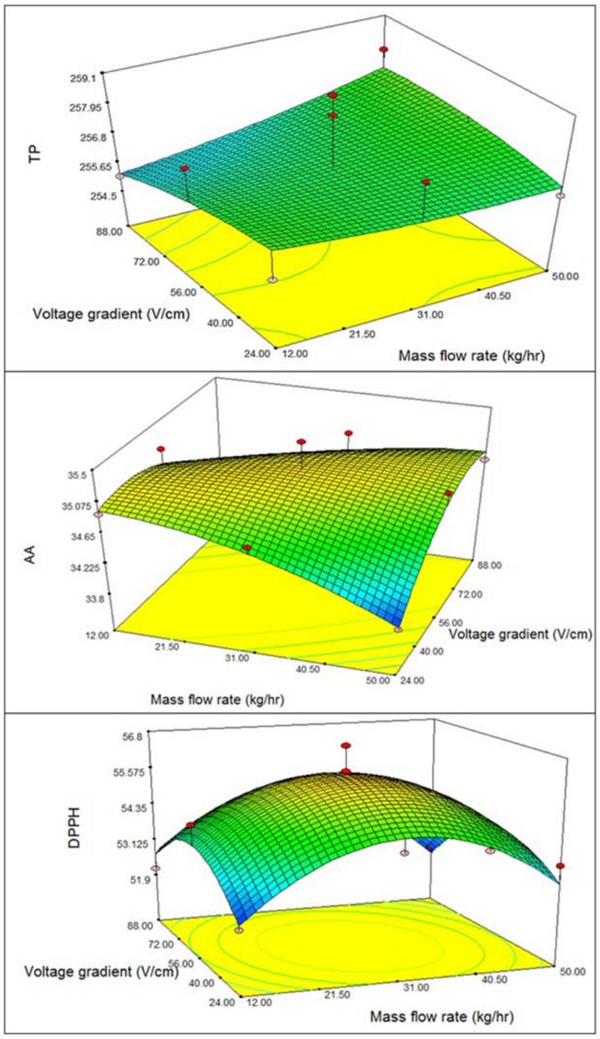

FIGURE 4 Response surface plot showing the effect of flow rate (kg/hr) and voltage grad (V/cm) on total phenol (TP), ascorbic acid (AA), and antioxidant activity (DPPH)

lower voltage gradients. This result was in agreement with Baysal, Demirdöven, and Rayman (2011) and Demirdöven (2009), who found that the antioxidant capacities of pomegranate juice and grape juice mostly decreased as the voltage gradient increased.

3.3 | Effects of CNTJP application on the microbial quality of dried lime juice

Coliform bacteria, yeast, and mold did not grow in any of the control, CNTJP, or thermal-treated samples (Table 1). However, the TVC of CNTJP samples varied between 1.93 and 4.79 (Log_{10} CFU/mL), whereas the TVC of the control and thermal-treated samples were 5.99 and 3.82 (Log_{10} CFU/mL), respectively. There was a significant difference ($p < .05$) between CNTJP samples and both the control and the thermal-treated samples. Table 2 summarizes the results of the significant ($p = .01$) linear model for TVC yielding an R^2 of .60 (adj $R^2 = .52$), which indicates that this model was an acceptable fit. Figure 5 shows the 3D response surface for TVC. Total viable count of CNTJP samples was reduced with an increase in the mass flow rate in the range of 12–28.24 kg/hr and an increase in the voltage gradient from 24 to 82.38 V/cm. The highest reduction of the TVC of CNTJP samples occurred when mass flow rate was 28.24 kg/hr and voltage gradient was 82.38 V/cm. The reduction in the microbial load could be ascribed to the combined physical and chemical mechanisms which led to thinning of microbial cell membranes during moderate electric treatment. This result was in agreement with Evrendilek et al. (2000), who succeeded to inactivate and reduce *Escherichia coli* O157:H7 in apple juice by using EF. Matsuki, Ishikawa, Imai, and Yamaguchi (2008) announced that electroporation can occur by using low electrical field (75 V/cm).

3.4 | Electrical conductivity

Based on the electrical conductivity (Table 1), the first-order model (linear) was used for the analysis. Table 2 summarizes the ANOVA for fitting the linear model to experimental electrical conductivity. The voltage gradient and mass flow rate had a highly significant ($p < .01$) effect on the electrical conductivity. Also, the lack of fit was not significant ($F = 3.87$, $p > .05$) for the response surface model, indicating a good fit and the model explained nearly all of the variation of the data ($R^2 = .96$, adj. $R^2 = .95$). The following first-order equation was used to predict the electrical conductivity (σ) of dried lime juice.

$$\sigma = +0.47406 - 1.10439 X_1 \times 10^{-3} + 2.53125 X_2 \times 10^{-3} \quad (6)$$

where X_1 is the mass flow rate and X_2 is the voltage gradient.

Figure 6 shows the response surface for electrical conductivity. Electrical conductivity increased as voltage gradient rose for all mass flow rates owing to increased current with increased voltage gradient (Figure 7). Many researchers have studied the effect of voltage gradients on electrical conductivity. Castro, Teixeira, Salengke, Sastry, and Vicente (2003) showed that the electrical conductivity for fresh strawberries and strawberry jelly increased as voltage gradients increased. The electrical conductivity of orange and apple juice at 15 °C was 0.35 and 0.17 S/m, respectively (Amiali, Ngadi, Raghavan, & Nguyen, 2006). Icier and Ilicali (2004) found that the effect of the voltage gradient on electrical conductivity was not significant only between 20–40 V/cm for apple juice and 20–30 and 50–60 V/cm for sour cherry. Also, they reported that the range of the electrical conductivity values for fruits juices was 0.1–1.6 S/m. Machado et al. (2010) mentioned that the

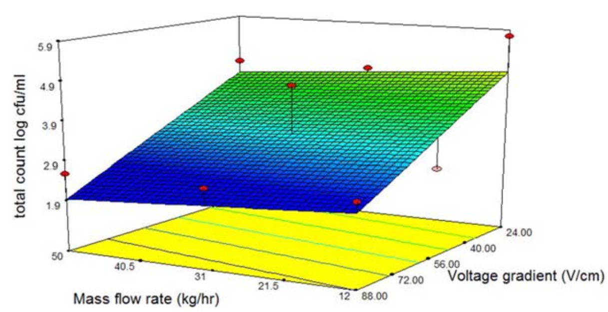

FIGURE 5 Response surface plot illustrating the effect of flow rate (kg/hr) and voltage grad (V/cm) on the total viable count in CNTJP dried lime juice samples

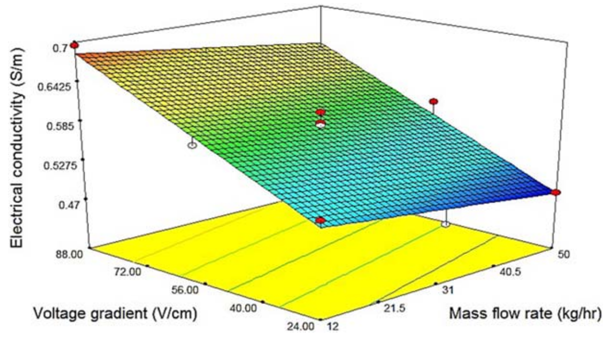

FIGURE 6 Response surface plot illustrating the effect of flow rate (kg/hr) and voltage grad (V/cm) on the electrical conductivity in CNTJP dried lime juice samples

electrical conductivity was changed with the electrical gradient and the electrical conductivity reached 0.04, 0.05, and 0.045 mS/cm when the electrical gradients were 50, 160, and 280 V/cm, respectively. Also, they concluded that moderate electrical field can be classified as a non-thermal treatment. Electrical conductivity increased linearly with increased temperature, and the electrical conductivity of lemon juice was strongly dependent on temperature (Darvishi, Hosainpour, Nargesi, Khoshtaghaza, & Torang, 2011).

In contrast, the electrical conductivity decreased as the mass flow rate increased at all voltage gradients. Probably, because of increasing velocity of juice and reduced exposure time to EF which led to reduced electrical current passing through the juice and reduced ion movement. The average electrical current was decreased from 0.28 to 0.25 A as the mass flow rate increased from 12 to 50 V/cm (Figure 7). Abdulsattar (2014) had a similar result of decreased electrical conductivity with increased mass flow rate at all voltage gradients when processing milk. The highest value of electrical conductivity was 0.68 S/cm at a mass flow rate of 12 kg/hr and voltage gradient of 88 V/cm. At the optimum conditions of 28.24 kg/hr mass flow rate and 82.38 V/cm voltage gradient, the highest electrical conductivity was 0.65 S/m. Machado et al. (2010) stated that the inactivation of the microorganisms occurs owing to the electrical conductivity during treatment by electrical field. The results showed that the increase of the voltage gradient and decrease of the mass flow rate led to increase of electrical conductivity for dried lime juice.

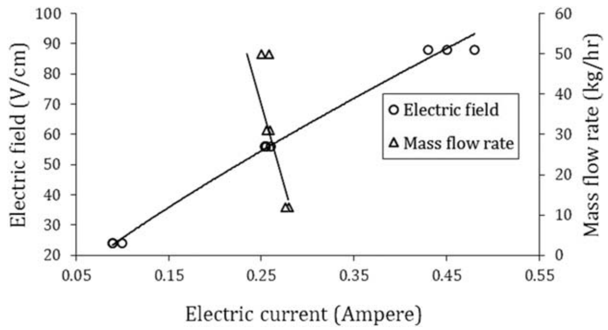

FIGURE 7 The relationship among the electric field, mass flow rate, and alternating electric current

4 | CONCLUSIONS

This is the first report for dried (black) lime juice processing using EF with an alternating current. In this study, the effects of EF using voltage gradients (X_1) from 24 to 88 V/cm and mass flow rates (X_2) of 12–50 kg/hr on quality of lime juice were investigated. Thermal treatment in water bath at 90 °C for 15 min was also used to compare with the efficiency of the EF method at optimized conditions. We found that EF with alternating current had the capability of obtaining higher TP, AA, and DPPH values compared to thermal treatment. There was no significant difference ($p > .05$) between CNTJP treatment and both the thermal treatment and the control samples regarding total soluble solids and pH. However, the titration acidity value of dried juices in thermal treatment was significantly higher ($p < .05$) compared to the control and CNTJP samples. The highest reduction of the TVC of CNTJP samples was at the optimum conditions of 28.24 kg/hr mass flow rate and 82.38 V/cm voltage gradient. In conclusion, CNTJP using EF with alternating current can be used to improve the quality of dried (black) lime juice.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interests.

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