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# Effect of batch infrared extraction pasteurizer (BIREP)-based processing on the quality preservation of dried lime juice

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## Abstract

Infrared irradiation is an alternative method for the thermal processing of foods. Lime is one of the citrus fruits and considered beneficial for human health. Dried lime juice is common in the Middle Eastern region and alternatives are desired to the conventional resistance heating method for the elimination of undesirable microorganisms. A batch infrared extraction pasteurizer (BIREP) was developed to test both infrared and conventional heating methods. Dried lime juice was treated in the BIREP using combinations of temperature (60, 75, and 90°C) and power output (350, 525, and 700 W) from infrared bulbs using a central composite design. Samples were subsequently analyzed for dependent variables of ascorbic acid content, total phenolic content, antioxidant activity, pectin methylesterase, hydroxymethyl, total plate counts, lightness, redness, and yellowness. Each combination of temperature and power was also quantified for specific infrared energy consumption, energy efficiency, and productivity. BIREP temperature and power settings were optimized for all dependent variables. The resulting optimized settings were used to process another set of dried lime juice samples. These samples were compared to control (untreated) and conventional heating samples. Sensory (appearance, aroma, taste, and overall acceptability) evaluation was conducted by a panel of humans. Infrared processing was superior to conventional processing and equivalent to control samples in all four sensory tests. The results indicated strong potential for infrared processing as a superior alternative to conventional heating for the preservation of dried lime juice.

## Practical applications

Infrared heating offers a safe alternative to conventional resistance heating that equals or improves the consumer-desired characteristics compared to fresh dried lime juice and provides a marked improvement over conventional heating. This may allow infrared processed juice to warrant a price premium over conventional thermal processing. Since dried lime producers typically thermally process their juice using the batch method, they can switch to infrared heating to improve the quality of their processed juice and promote the resulting benefits. Cost-benefit studies would be appropriate for dried lime juice processers to evaluate the conversion of thermal processing to infrared heating to take advantage of the superior product.

  

## 1 | INTRODUCTION

Lime along with orange and tangerine are citrus fruits, which are grown and widely spread all over the world (Velu, Cheong Yew, Zaman, & Abu Bakar, 2019). Lime is a fruit crop belonging to the Rutaceae family and is considered an essential source of ascorbic acid, and frequently used to strengthen a weak immune system for patients (Rahman, Jahan, & Mim, 2019; Raza, Shehzad, Baloach, & Ikram, 2019). The tropical and subtropical regions create the most suitable conditions for growing citrus fruits and ecologic factors such as water, heat, and drought are considered the only factors limiting growth (Iqbal, Khera, Hanif, Ayub, & Al-Sadi, 2020). Citrus is globally one of the most broadly cultivated fruits which have been used for human consumption with exceptional flavor, sour taste, and appealing color (Inthuja, Mahendran, & Jemziya, 2019).

Consumer demand for healthy, fresh, and nutritious food products has continuously increased in recent years, particularly those healthy beverages, which possess functional ingredients (Nazir et al., 2019). Lime juice consists of bioactive compounds such as alkaloids, phenolics, terpenoids, saponins, tannins, carotenoids, and flavonoids (Inthuja et al., 2019; Li, Wu, Wang, Yu, & Yang, 2019). Some studies reported a significant role for citrus fruit juice to work as antimicrobial agents to inhibit and prevent either foodborne pathogens or spoilage bacteria. In addition, citrus juice with low pH can act as a natural microbial substance (Velu et al., 2019).

Currently, thermal processing is one of the most popular and common pasteurization methods in food industries due to its ability to inhibit microbial growth and inactivate enzymes in fruit and vegetable juices (Xiang et al., 2019). Innovative approaches of thermal processing such as microwave pasteurization (Mendes-Oliveira, Deering, San Martin-Gonzalez, & Campanella, 2020), ultra-high temperature (UHT) sterilization (Alves Filho et al., 2020), high-temperature short-time (HTST) pasteurization (Komora et al., 2020), ohmic heating (Hardinasinta, Salengke, Juaedi, & Mursalim, 2019; Mannozzi et al., 2019), and infrared (IR) heating (Aboud, Altemimi, Al-Hilphy, Yi-Chen, & Cacciola, 2019; Aghajanzadeh, Kashaninejad, & Ziaiifar, 2016) have been applied to extend the shelf life of food and improve the quality of food products.

IR radiation is one of the electromagnetic spectra and the wavelength range of IR radiation is between 0.5 and 100 μm (Aghajanzadeh, Kashaninejad, et al., 2016). IR heating applications in food processing include food drying (Yao, Fan, & Duan, 2020), inactivation of enzymes (Jeevitha, Hebbar, & Raghavarao, 2016), peeling of fruits and vegetables (Vidyarthi et al., 2019), inactivation of microorganisms (Watson, Kamble, Shanks, Khan, & El Darra, 2020), roasting (Bagheri, Kashaninejad, Ziaiifar, & Aalami, 2019), cooking (Ogundele & Kayitesi, 2019), and blanching (Wu, Guo, Wang, Pan, & Ma, 2018). IR possesses a lot of advantages compared to conventional thermal heating such as uniform heating, deep penetration, significant energy saving, less heating time, and decreased rate of food degradation thereby improving the quality of food preservation (Krishnamurthy et al., 2008).

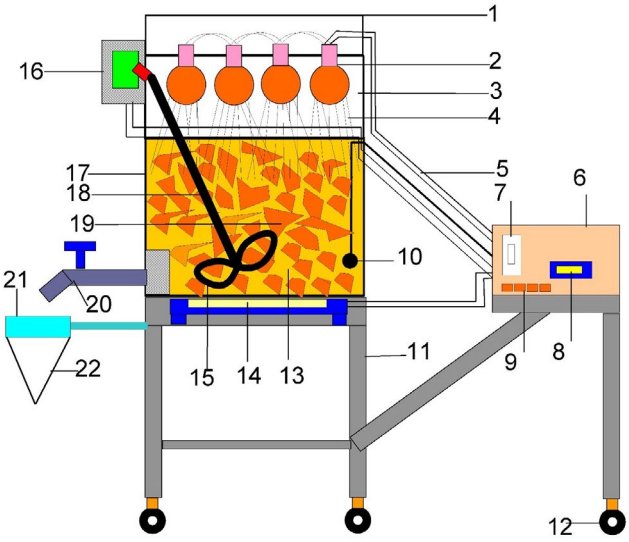


**FIGURE 1** Schematic diagram of batch infrared extraction pasteurizer (BIREP) consisting of: (1) External cover; (2) infrared lamps; (3) internal cover; (4) infrared radiation; (5) wires; (6) control panel; (7) switch; (8) digital temperature gauge; (9) operation switches; (10) thermocouple; (11) chassis; (12) tire; (13) water; (14) electric heater; (15) mixer; (16) electric motor; (17) reservoir; (18) shaft; (19) pieces of dried Basrah lemon; (20) tap; (21) screen; and (22) funnel

However, the application of IR heating on the quality of black dried lime (BDL) juice has not been previously reported. Therefore, the aim of this study was to investigate the effect of IR heating on the physicochemical properties of phytochemical compounds with antioxidant capacity and microbial content of dried lime juice.

## 2 | MATERIALS AND METHODS

### 2.1 | Sample preparation

Black limes (BL; *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. Basrah key limes (500 g) were crushed to obtain a fine powder and then passed through a 40-mesh sieve to remove seeds, impurities, and particles. Water and sugar (10 L and 1,550 g, respectively) were mixed with the Basrah key lime powder and poured into the reservoir of a juice pasteurizer (Figure 1). The required temperature was set using the control panel. After that, the machine was turned on by delivering the power to the infrared lamps which emit heat radiation into the mixture for heating. The mixer was stirred smoothly inside the mixture to distribute the heat uniformly. After heating was completed, the valve was opened to allow the juice to exit the tank and move to the funnel for filtering. In contrast, the traditional method was applied using the electric heater only until the mixture reached the appropriate temperature and was filtered through the funnel. The juice was kept at 4°C until the experiments were performed.

## 2.2 | Key lime juice extraction pasteurizer

A batch infrared extraction pasteurizer (BIREP) (Figure 1) was designed and constructed in our food engineering laboratory (Department of Food Science, College of Agriculture, University of Basrah, Basrah, Iraq). The device consisted of a basin height of 25 cm and a diameter of 35 cm made of stainless steel, and was equipped with a mixer of 50 watts rotating at a speed of 2.2 revolutions per minute for the purpose of homogeneity of heat transfer in all parts of the juice mixture. The tank at the bottom contained a manual valve that controlled the exit of juice. The BIREP was equipped with both IR and resistance electrical heating sources for the comparison of the two heating methods. The IR source was four IR lamps (Philips Company, South Korea) that operated at a wavelength of 6 μm. The lamps were 175 watts. The lamps were positioned 2 cm from the surface of the mixture. The conventional heating source was a 1,000 W Chinese-made electric heater to reach 90°C for 15 min. Exiting juice was filtered through a 25 μm screen and attached to a plastic funnel by a stainless steel clamp. Other parts of the device were the chassis and console.

## 2.3 | Physicochemical analysis

### 2.3.1 | pH and total soluble solids (Brix)

The pH of the pasteurized juice was measured at 25°C after 10 ml was poured into a beaker and stirred. The beaker of juice was allowed to cool further to room temperature and total soluble solids were estimated using a refractometer (Bellingham, England). The refractometer prism was cleaned with distilled water before and after measurements. A table of conversion factors was used to report the Brix value.

### 2.3.2 | Titratable acidity

A slightly modified titration method (Bhat, Kamaruddin, Min-Tze, & Karim, 2011) was used to determine titratable acidity. A 10 ml of pasteurized juice sample was poured into a beaker and 200 ml of distilled water was added and gently stirred. A solution of 0.1 N sodium hydroxide was prepared and tinted pink with phenolphthalein (3–5 drops) with a pH of 8.2 ± 0.1. The acidity was expressed as a percent of citric acid content and calculated as follows.

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

### 2.3.3 | Ascorbic acid (AA) content

The AA content of the pasteurized juice was measured using a slightly modified iodine titration method (Jafari, Jabari, Dehnad, & Shahidi, 2017; Kashyap & Gautam, 2012). The iodine solution started with 200 ml of distilled water in a beaker, into which 0.268 g of potassium iodate ($KIO_3$) and 5 g of potassium iodide (KI) were dissolved. Then 30 ml of 3 M sulfuric acid was added along with sufficient distilled water to achieve a final volume of 500 ml. A fresh starch solution 1% (w/v) was prepared as an indicator. To measure AA, 20 ml of juice in a beaker was diluted with 150 ml of distilled water, followed by 10 drops of starch solution. The iodine titration solution was added to the diluted juice until the starch-iodine complex turned the juice solution to a clear dark blue color. The following equation was used to determine the AA content.

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

### 2.3.4 | Total phenolic content

The Folin–Ciocalteu method (Slinkard & Singleton, 1977) with some minor changes (Aadil et al., 2015) was used to determine the total phenolic (TP) content of pasteurized juice. A solution consisting of 0.5 ml of juice, 1 ml of freshly prepared 10% (w/v) Folin–Ciocalteu reagent, and 2 ml of 20% (w/v) sodium carbonate was vigorously agitated for 6 min and stored for 60 min, without light, at 30°C. Based on a spectrophotometer (Jenway, Model 6,305, United Kingdom), the mixture absorbance was measured at 760 nm. Gallic acid was used to develop a calibration curve and TP was expressed as mg of Gallic acid equivalent per g of sample.

### 2.3.5 | Antioxidant activity

The 1,1-diphenyl 2-picrylhydrazyl (DPPH) method (Sánchez-Moreno, Larrauri, & Saura-Calixto, 1998) with some modifications (Klimczak, Małecka, Szlachta, & Gliszczyńska-Świgło, 2007) was used to determine the antioxidant activity of the juice. The DPPH solution consisted of 25 mg of DPPH radical dissolved in 50% v/v methanol, with a vortex used for gentle mixing. Pasteurized juice (0.1 ml) was added to 3.9 ml of the freshly prepared DPPH solution, mixed, and stored in the dark for 25 min at room temperature (Altemimi, Ali, Al-Hilphy, Lightfoot, & Watson, 2018). The 517 nm wavelength absorbance measured with the spectrophotometer was used to calculate antioxidant activity based on the DPPH radical scavenging activity using the following formula.

$$\text{Antioxidant activity } (\%) = \left[A_c - A_J / A_c\right] \times 100 \quad (3)$$

where $A_c$ is the absorbance of the control and $A_j$ is the absorbance of the juice sample.

## 2.4 | Pectin methylesterase (PME)

PME was determined in juice samples according to the method described by Kimball (1999). In the first step, a liter of pectin-salt solution (1%) was prepared by mixing 10 g of pectin and 15.3 g of NaCl into

distilled water. The second step was to prepare a solution of NaOH (2 N) and (0.05 N). Then, 10 ml of BDL juice was transferred to a 100 beaker, with 40 ml of pectin-salt solution (1%) added to the beaker and mixed using a magnetic stirring bar. The 100 ml beaker containing the solution was placed inside a 250 ml beaker of water. Both beakers were placed on a magnetic stirrer at 30°C and kept until the temperature inside the beaker reached 30°C using a thermometer. Drops of NaOH (2 N) were added to the 100 ml beaker, while continuously stirring until the pH reached 7. Thereafter, drops of NaOH (0.05 N) were added until the pH was in the 7.6–7.8 range. Finally, 0.1 ml of NaOH (0.05 N) was added and the timer was switched on to record the time for the solution to regain the same pH within the 7.6–7.8 range. The enzyme activity of PME was calculated according to the equation below:

$$\text{PME (unit/ml)} = \frac{\text{NaOH (0.05N)} \times 0.1\text{ml NaOH (0.05N)}}{10\text{ml of sample} \times \text{time (minute)}} \quad (4)$$

## 2.5 | Hydroxymethylfurfural (HMF)

The methods mentioned by Cohen, Birk, Mannheim, and Saguy (1998) were used for the following assays. Ethyl alcohol (5 ml of 95%) was added to 5 ml of juice sample and centrifuged for 15 min at 1,000 *g*. Supernatant (2 ml) was introduced into a 10 ml screw-cap tube to determine the HMF content. Acids of 2 ml of 0.025 M thiobarbituric acid (TBA; Carlo Erba, Italy) and 2 ml of 12% w/w trichloroacetic acid (TCA; Sigma, Germany) were added to the tube and mixed thoroughly. The absorbance at 443 nm was measured after the tubes were in a 40 ± 0.5°C water bath for 50 min and subsequently cooled with tap water. The HMF concentration was quantified with a calibration curve (Aldrich, Germany).

## 2.6 | Microbiological analysis

A sterilized test tube was prepared with 9 ml of peptone water solution and 1 ml of pasteurized juice was added and mixed thoroughly for a serial dilution ($10^{-1}$ to $10^{-3}$) to measure total plate counts, coliform bacteria, yeast, and mold. Each of the different juice dilutions (1 ml) was placed on nutrient agar plates. The plates were then incubated for 24–28 hr at 35°C before measuring the total count of bacteria. For coliform bacteria, MacConkey agar was substituted for nutrient agar. An incubation period of 24–48 hr at 37°C was used for the Petri dishes. Similarly, yeast and mold counts were estimated using potato dextrose agar, with a 3-day incubation at 37°C. The results were expressed as log colony forming units (CFU/ml) of juice. The microbiological analysis was repeated three times for each treatment and the mean was reported (Keyser, Műller, Cilliers, Nel, & Gouws, 2008).

## 2.7 | Determination of color

The color of the juice was determined by image processing. Images were captured by a 6-megapixel digital camera (Android & PC Endoscope, type-C, China) in the appropriate light. ImageJ software was used to analyze the images and the mean values of color parameters were converted to standard values as follows according to Yam and Papadakis (2004):

$$L^* = \frac{L}{255} \times 100 \quad (5)$$

$$a^* = \frac{240a}{255} - 120 \quad (6)$$

$$b^* = \frac{240b}{255} - 120 \quad (7)$$

where $L$ is the lightness, $a$ is the redness/greenness, $b$ is the yellowness/blueness, and $L^*$, $a^*$ and $b^*$ are corrected values.

## 2.8 | Specific IR energy consumption and energy efficiency

The specific IR energy consumption and energy efficiency were determined with the following equations (Bimbenet, Duquenoy, & Trystram, 2002; Cheaib et al., 2018).

$$\text{SIREC} = \frac{Pt}{m} \quad (8)$$

$$\eta = \frac{Q_0}{P} \times 100 \quad (9)$$

where SIREC is the specific infrared energy consumption (kJ/kg), $P$ is the power (kJ/s), $m$ is the mass of water and key lime, IR is the energy efficiency (%),$Q_0$ is the output power (kJ/s), and $t$ is the time (s).

## 2.9 | Sensory analysis

A sensory evaluation test of juice quality regarding the appearance, aroma, taste, and overall acceptability was carried out according to the method described by Waghray, Gulla, Santhosh Kumar, Praveen Kumar, and Akshay Kumar (2012). Throughout this research, a 10-member trained judging panel (college students and staff) was appointed to assess the efficiency of fresh and manufactured juices. The age range of the judges was 60% (28–41 years) and 40% (43–59 years), whereas the gender distribution was 70% male and 30% female. Water was given to clear the throat during the evaluation of fresh and manufactured juices. The sensory evaluation was given a score from 1 to 4 for determining the appearance, aroma, taste, and overall acceptability.

## 2.10 | Experimental design and statistical methods

The batch infrared pasteurizer (BIREP) parameters (temperature and power) were optimized using response surface methodology (RSM) based on a Box–Behnken design. Two factors (temperature

and power) with three levels (−1, 0, +1) were used. The temperature and power settings were 60, 75, 90°C and 350, 525, 700 W, respectively. The following second-order polynomial model was employed to describe the effect of parameters using Design-Expert version 12 software.

$$Y_i = a_0 + a_1X_1 + a_2X_2 + a_{12}X_1X_2 + a_{11}X_1^2 + a_{22}X_2^2 \quad (10)$$

where $Y$ is the responses, $X_1$ is the temperature, and $X_2$ is Power, $b_o$, $b_1$, $b_2$, $b_{11}$, $b_{22}$, and $b_{12}$ are regression coefficients for intercept, the linear, quadratic, and interaction term, respectively. The significant terms in the models for the responses were determined using analysis of variance (ANOVA; $\alpha = 0.05$).

Once the optimized factors of temperature and power were determined, additional experiments were conducted with the optimized factors. ANOVA ($\alpha = 0.05$) was used to determine any differences among the optimized factors, a control (untreated BDL juice), and conventional resistance heating.

## 3 | RESULTS AND DISCUSSION

### 3.1 | Temperature and power profile

Figure 2 illustrated the temperature curve of key lime juice at different powers. The results showed that the time required to reach 90°C temperature was 440, 280, and 140 min at powers of 350, 525, and 700 W, respectively. The increasing power led to an increase in the heating rate and temperature because of the increasing ion motion in the juice. The conventional resistance heater (1,000 W) required 210 min to heat the key lime juice to 90°C. IR heating at 700 W power was faster than the other IR power settings and conventional resistance heating. An IR system at approximately 615 W would heat the key lime juice to 90°C in about the same time as the 1,000 W resistance heater will reducing power consumption by over 38%. Al-Hilphy, Al-Shatty, and Al-Mtury (2020) stated that the required time to heat fish waste to 60°C temperature using infrared ray with a power of 130 W was 70 min and decreased to 66 min at 250W. The researchers explained the reason for the decreasing time with the increase of the power was increased intensity of the infrared radiation, which increased the movement of vibrating ions.

### 3.2 | Physicochemical content of untreated samples, conventional heating samples, and treated batch infrared extraction pasteurizer (BIREP) samples

The obtained results observed no significant differences of BIREP samples on pH, total soluble solids, and titratable acidity of key lime juice irrespective of the setting for both temperature (°C) and power (W). The pH, total soluble solids, and titratable acidity for the untreated juice were 2.91, 7.94, and 0.78, respectively. The results also showed no significant differences between untreated juice samples and BIREP juice samples and conventional heating samples regarding the pH and total soluble solids. In contrast, the titration acidity of dried juices in thermal treatments was slightly higher significant ($p < .05$) at 1.12 relative to control samples and BIREP juice samples. These results were in agreement with Altemimi et al. (2018) who found that the increase of acidity due to thermal treatment could be ascribed to the distribution of intracellular components. In addition, this result reported that pH, total soluble solids, and titratable acidity of lime juice samples were within the limits of the institute of standards and industrial research of Iran (ISIRI) (2013) and GCC Standardization Organization (GSO) (2018). Furthermore, these results were not in accordance with those observed by Rangel, Carvalho, Fonseca, Soares, and Jesus (2011) obtained for the organic acid lime juice (*Citrus latifolia T.*).

### 3.3 | Effect of BIREP on the ascorbic acid content

Ascorbic acid is an essential element that exhibits antioxidant properties and offers protection against free radicals. AA has been used as a measure of the nutritional content of juices (Khandpur &

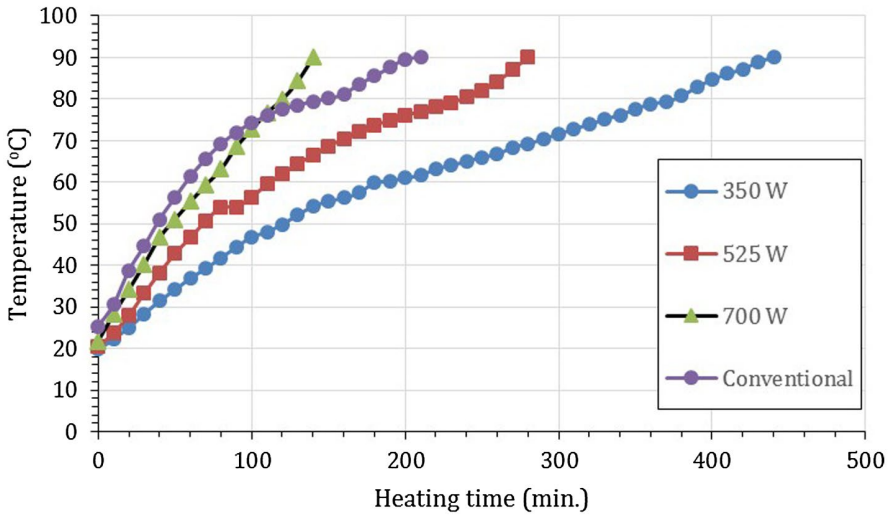


**FIGURE 2** Temperature curves of 350 W, 525 W, and 700 W IR power settings and conventional resistance heater of 1,000 W

Gogate, 2015). AA degradation at various temperatures and power is shown in Table 1. The AA level of the BIREP juice samples varied from 34.86 to 36 (mg/100 ml), while the control and thermal treatment of AA levels were 36.32 and 30.61 (mg/100 ml), respectively. The result of AA also showed significant differences ($p < .05$) between BIREP juice samples and both untreated juice samples (control) and conventional heating samples (Table 2.). The degradation of ascorbic acid using conventional heating was significantly ($p < .05$) different from the control sample. The spectrum of values collected was consistent with the literature (Romero Rodriguez, Vazquez Oderiz, Lopez Hernandez, & Lozano, 1992; USDA, 2001). The infrared heating system allowed higher nutrient preservation and extraction of AA at all temperatures and power relative to other approaches such as conventional heating, thus this result was not in accordance with Vikram, Ramesh, and Prapulla (2005) who reported that the degradation of AA during infrared heating of orange juice samples was higher than the conventional method. Aghajanzadeh, Kashaninejad, et al. (2016) reported that the IR system was more successful in retaining ascorbic acid during dried lime juice production. These findings indicate that AA is more sensitive to reduction with

**TABLE 1** Experimental design and responses of ascorbic acid (AA; mg/100 ml), total phenolic content (TP; mg/g Gallic acid), antioxidant activity (DPPH; %), pectin methylesterase (PME; unit/ml), hydroxymethyl furfural (HMF; mg/L), and total plate counts (TPC; log CFU/ml)

| | Independent variables | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Run | Temperature | Power | AA | TP | DPPH | PME | HMF | TPC |
| 1 | 75 | 525 | 35.11 | 242.09 | 49.85 | 0.00122 | 0.088 | 2.06 |
| 2 | 90 | 350 | 36.00 | 243.41 | 40.87 | 0.00123 | 0.089 | 1.94 |
| 3 | 75 | 525 | 35.89 | 243.84 | 43.97 | 0.00076 | 0.086 | 2.16 |
| 4 | 90 | 525 | 35.83 | 243.24 | 50.13 | 0.00121 | 0.087 | 2.09 |
| 5 | 75 | 700 | 35.76 | 244.04 | 43.00 | 0.00149 | 0.088 | 2.15 |
| 6 | 60 | 350 | 35.81 | 244.10 | 33.33 | 0.00126 | 0.087 | 1.80 |
| 7 | 60 | 700 | 36.00 | 244.41 | 46.64 | 0.00109 | 0.085 | 1.70 |
| 8 | 60 | 525 | 35.00 | 243.41 | 38.36 | 0.00117 | 0.086 | 2.03 |
| 9 | 75 | 525 | 35.69 | 243.41 | 50.13 | 0.00045 | 0.084 | 2.10 |
| 10 | 75 | 525 | 36.00 | 243.41 | 62.05 | 0.00131 | 0.085 | 2.01 |
| 11 | 75 | 525 | 34.86 | 243.34 | 51.11 | 0.00011 | 0.087 | 2.12 |
| 12 | 75 | 350 | 36.00 | 243.41 | 60.50 | 0.00013 | 0.089 | 2.12 |
| 13 | 90 | 700 | 35.58 | 242.87 | 58.54 | 0.00045 | 0.087 | 2.19 |

**TABLE 2** Mean of dependent variables for IR heating under optimized conditions of 62.2°C and 700 W compared with untreated (control) and conventional heating

| Dependent variable | IR optimized* | Control | Conventional |
|---|---|---|---|
| Ascorbic acid (AA) | $35.82 \pm 1.040^{a}$ | $36.32 \pm 1.494^{b}$ | $30.61 \pm 1.200^{c}$ |
| Total phenolic content (TPC) | $244.41 \pm 1.258^{a}$ | $161.32 \pm 1.354^{c}$ | $172.64 \pm 0.873^{b}$ |
| Antioxidant activity (DPPH) | $44.89 \pm 0.763^{a}$ | $24.87 \pm 0.566^{c}$ | $30.14 \pm 0.933^{b}$ |
| Pectin methylesterase (PME) | $0.0012 \pm 0.0003^{c}$ | $0.0120 \pm 0.0003^{a}$ | $0.00220 \pm 0.0002^{b}$ |
| Hydroxymethyl furfural (HMF) | $0.0852 \pm 0.002^{b}$ | $0.079 \pm 0.002^{c}$ | $0.113 \pm 0.003^{a}$ |
| Total plate count (TPC) | $1.83 \pm 0.055^{c}$ | $3.52 \pm 0.094^{a}$ | $2.60 \pm 0.155^{b}$ |
| Lightness ($L^*$) | $73.65 \pm 1.451^{b}$ | $75.45 \pm 1.785^{a}$ | $65.57 \pm 2.051^{c}$ |
| Redness ($a^*$) | $14.1999 \pm 0.573^{b}$ | $16.93 \pm 0.231^{a}$ | $12.45 \pm 0.541^{c}$ |
| Yellowness ($b^*$) | $37.524 \pm 1.054^{b}$ | $39.56 \pm 1.112^{a}$ | $33.57 \pm 0.984^{c}$ |
| Specific energy consumption (SEC) | $278.84 \pm 4.890^{b}$ | NA** | $834.87 \pm 6.093^{a}$ |
| Energy efficiency | $56.1852 \pm 1.067^{a}$ | NA** | $47.89 \pm 0.995^{b}$ |
| Productivity | $6.25071 \pm 0.351^{a}$ | NA** | $5.16 \pm 0.0438^{b}$ |

*Means in the same row with the same superscript letter are not significantly different.

**Energy and productivity calculations do not apply (NA) to control, as no heating was applied.

conventional processing conditions (Darvishi, Mohammadi, Fadavi, Saba, & Behroozi-Khazaei, 2019; El-Ishaq & Obirinakem, 2015; Saberi et al., 2019).

The optimal conditions of BIREP parameters by implementing a polynomial method of second-order and multiple regression were used to obtain the regression coefficient of independent variables (Table 3). The adequacy of the resulting model of central composite design (CCD) was evaluated using ANOVA. The statistical analysis revealed that the proposed model was adequate ($R^2 = 0.4$) and lack of fit was not significant for the AA content. The positive linear effect of BIREP temperature ($X_1$) and power ($X_2$) was significant for AA. Also, the interaction ($X_1X_2$) and quadratic effect of BIREP temperature ($X_1^2$) on the ascorbic acid content were observed to be significant. However, the quadratic power ($X_2^2$) was not significant for the AA content.

The ascorbic acid content increased when the temperature increased in the range of 60–90°C and the power increased in the range of 350–700 W (Figure 3). All values of AA decreased above 62.2°C at 700 W. The highest recovery for AA values occurred at lower temperature and highest power. This result concurred with the finding of Aghajanzadeh, Kashaninejad, et al. (2016) who observed that the content of ascorbic acid was significantly decreased ($p < .05$) as the temperature increased using IR heating.

## 3.4 | Effect of BIREP on the total phenolic content and antioxidant activity

The range of TP and DPPH of BIREP samples was 242.09–244.41 mg/g Gallic acid and 33.33%–62.05%, respectively. In

**TABLE 3** Regression coefficients, $R^2$, and $p$ values of the model for six dependent variables for BIREP juice samples

| Regression coefficient | AA | TP | DPPH | PME | HMF | TPC |
|---|---|---|---|---|---|---|
| $b_0$ | 34.92974 | 246.8794 | −1298.44 | 0.00604 | 0.0851 | −6.13448 |
| $b_1$ | 0.080385 | −0.01221 | 0.372 | −0.000185 | 0.0000556 | 0.145 |
| $b_2$ | −0.00981 | −0.0087 | 2.08 | 0.00000706 | 0.00000476 | 0.0213 |
| $b_1b_2$ | −0.0000591 | 0.000081 | −0.0601 | −0.00000006 | – | −0.000258 |
| $b_{12}$ | −0.000288 | 0.000187 | −0.251 | 0.00000139 | – | −0.000557 |
| $b_{22}$ | 0.0000131 | 0.0000144 | 0.000182 | 0.00000001 | – | −0.0000255 |
| $b_1b_{22}$ | 0.00000105 | −0.00000018 | 0.000419 | – | – | −0.00000028 |
| $b_{12}b_2$ | −0.00000283 | −0.00000163 | −0.00000223 | – | – | −0.00001186 |
| $R^2$ | 0.40 | 0.56 | 0.80 | 0.65 | 0.35 | 0.75 |
| $p$ value of the model | 0.638 | 0.034 | 0.125 | 0.023 | 0.174 | 0.032 |
| $p$ value of lack of fit | 0.756 | 0.874 | 0.9742 | 0.331 | 0.688 | 0.077 |

*Note:* Abbreviations: AA = ascorbic acid; DPPH = antioxidant activity; HMF = hydroxymethyl furfural; PME = pectin methylesterase; TP = total phenolic content; TPC = total plate counts.
Subscripts: 1 = temperature, 2 = power.

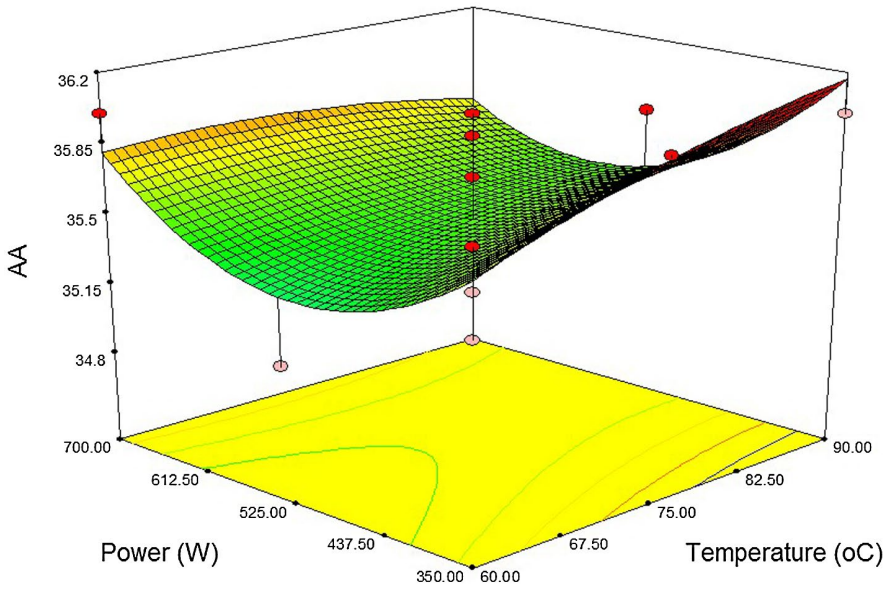


**FIGURE 3** Response surface for ascorbic acid (AA; mg/100 ml) of BIREP juice samples as a function of temperature (°C) and power (W)

contrast, the TP and DPPH of the control and thermal treatment samples were 161.32 mg/g Gallic acid, 24.87% and 172.64 mg/g Gallic acid, 30.14%, respectively (Table 2). The maximum TP of 244.34 mg/g Gallic acid and DPPH of 44.89% was achieved using BIREP at 62.2°C and 700 W. In addition, the obtained results exhibited that both TP and DPPH values for BIREP were significantly ($p < .05$) higher than both control and conventional heating treatment. This finding was in agreement with those reported by Igual, García-Martínez, Camacho, and Martínez-Navarrete (2010) and La Cava and Sgroppo (2019), indicating the significant effects of heat on the phenolic contents in different fruit juices.

The results of the regression analysis are summarized in Table 3. The model $p$ values showed that TP was significant ($p < .05$), whereas the model for DPPH was not significant. The $R^2$ values for TB and DPPH were 0.56 and 0.8, respectively. The small coefficient of variation (CV) values of 0.23 and 12.2, respectively for TP and DPPH, indicated strong reliability and negligible model variation. The predicted residual error sum of squares (PRESS) in Table 3 indicates that the model used can predict the independent variable very well. The performance of the model used often represented the comparatively low importance of acceptable precision. These values displayed a good signal-to-noise ratio. The signal-to-noise ratio greater than 4 is optimal for acceptable precision (Rahmawati, Saputra, Sahim, & Priyanto, 2019). It was concluded that the model could be used to optimize and navigate the research design.

Response surface plots were generated for TP (Figure 4) and DPPH (Figure 5). TP and DPPH improved as the temperature increased from 60 to 62.2°C and the power increased from 350 to 700 W, respectively. All TP and DPPH values were decreased above 62.2°C and 700 W. At lower temperature and higher power, the highest recovery for TP and DPPH values was achieved. However, Azad, Piao, Park, and Cho (2018) reported that the antioxidant

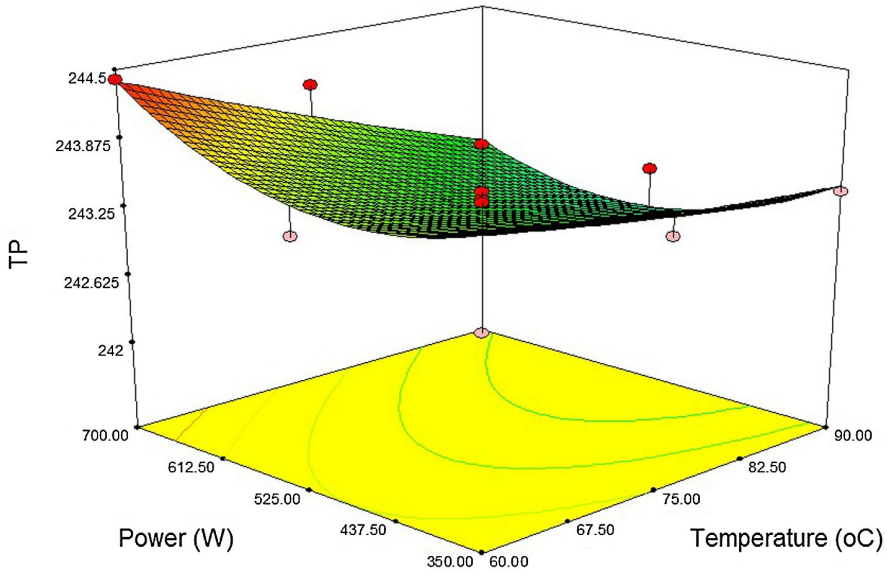


**FIGURE 4** Response surface for total phenolic compound (TP; mg/g Gallic acid) of BIREP juice samples as a function of temperature (°C) and power (W)

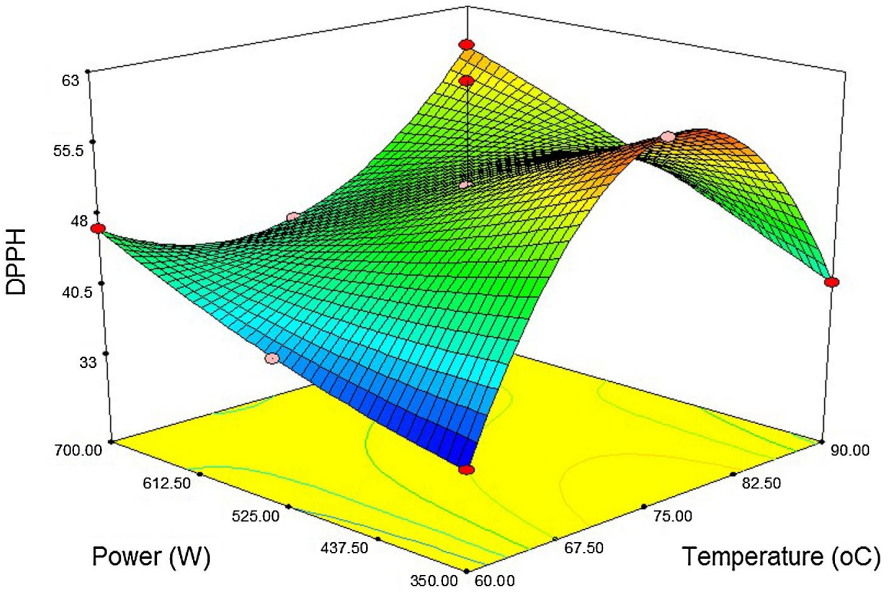


**FIGURE 5** Response surface for antioxidant activity (DPPH; %) of BIREP juice samples as a function of temperature (°C) and power (W)

activity of Angelica gigas Nakai extracts was two times higher (79%) using IR treatment at 220°C compared to control (37%). This result was in agreement with El KantarRajha, Maroun, and Louka (2020) who illustrated that infrared treatment had the ability to improve the polyphenol diffusivities and increase the inhibition percentage of the free radical DPPH.

### 3.5 | Influence of BIREP on PME and HMF contents

The PME and HMF of the control and conventional samples were 0.0120 unit/ml, 0.079 mg/L and 0.00220 unit/ml, 0.113 mg/L, respectively (Table 2). The range of PME and HMF of all BIREP samples was found to be between 0.00011–0.00149 unit/ml and 0.084–0.089 mg/L, respectively. The result of PME also showed significant differences ($p < .05$) between BIREP juice samples and untreated juice samples (control), whereas there were no significant differences between BIREP juice samples and conventional heating samples. Moreover, the activity of PME using conventional heating was significantly ($p < .05$) lower compared to the control sample. These results were not in agreement with Aghajanzadeh, Kashaninejad, et al. (2016) who reported that the PME activity of lime juice was less than 0.0001 using IR heating or thermal processing. These differences could be firstly ascribed to using high power of 1,500 W by Aghajanzadeh, Kashaninejad, et al. (2016), which significantly reduced PME activity at 90°C. Second, the presence of heat resistance fraction of PME Aghajanzadeh, Ziaiifar, Kashaninejad, Maghsoudlou, and Esmailzadeh (2016) and some researchers found isoforms of PME, which had considerably higher thermal resistance (De Sio, Palmieri, Servillo, Giovane, & Castaldo, 2001). The maximum PME of $0.0012 \pm 0.0003$ unit/ml was obtained using BIREP at 62.2°C and 700 W.

There were statistically significant variations between HMF contents of the BIREP samples and conventional heating, whereas there was no significant difference ($p < .05$) between BIREP juice samples and untreated juice samples (control) immediately after the treatments. The increase in the HMF content of BIREP juice was 8.6%, compared to the control. This observation was not in accordance with Hebbar, Nandini, Lakshmi, and Subramanian (2003) who reported that infrared heating caused an increase of 220% of the HMF content of honey. Similar results were obtained by Sabanci, Cevik, Cokgezme, Yildiz, and Icier (2019), where thermally produced fruit juice concentrates had higher HMF contents. The linear regression model for HMF and quadratic regression models for PME of BIREP samples are listed in Table 3. The results indicated that the model of HMF was not significant, whereas the model was significant for PME. The coefficient R-square for HMF and PME and were observed to be 0.35 to 0.65, respectively. The lack-of-fit method was used to assess the inability of the model to display results at points not used in the regression (Wang et al., 2013). Table 3 illustrates that the lack-of-fit was not significant for HMF and PME. These findings suggested that the model was adequate within the set of independent variables used to predict HMF and PME. The optimum conditions for independent (temperature and power) and dependent variables were estimated by applying the response surface models using three-dimensional (3D) surface plots. The effects of temperature and power and interactions for predicting HMF (Figure 6) and PME (Figure 7) were shown. The optimized results of HMF content were 0.0852 mg/L using BIREP at 62.2°C and 700 W (Table 2). The optimized conditions to minimize HMF and PME were at a temperature of 62.2°C and a power of 700 W.

### 3.6 | Effect of BIREP on the microbial activity of lime juice

Results revealed that neither coliform bacteria nor yeast and mold were grown in the BIREP treated samples, conventional heating

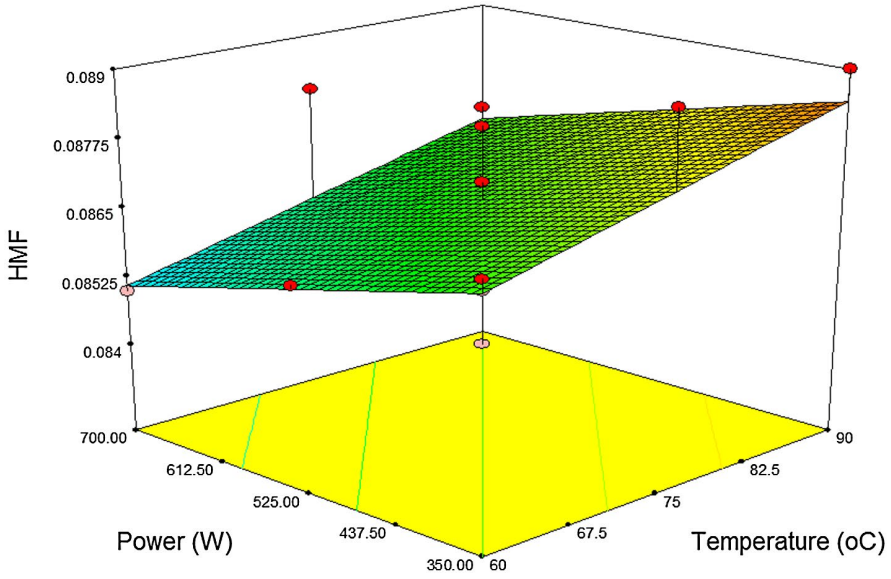


**FIGURE 6** Response surface for hydroxymethylfurfural (HMF; mg/L) of BIREP juice samples as a function of temperature (°C) and power (W)

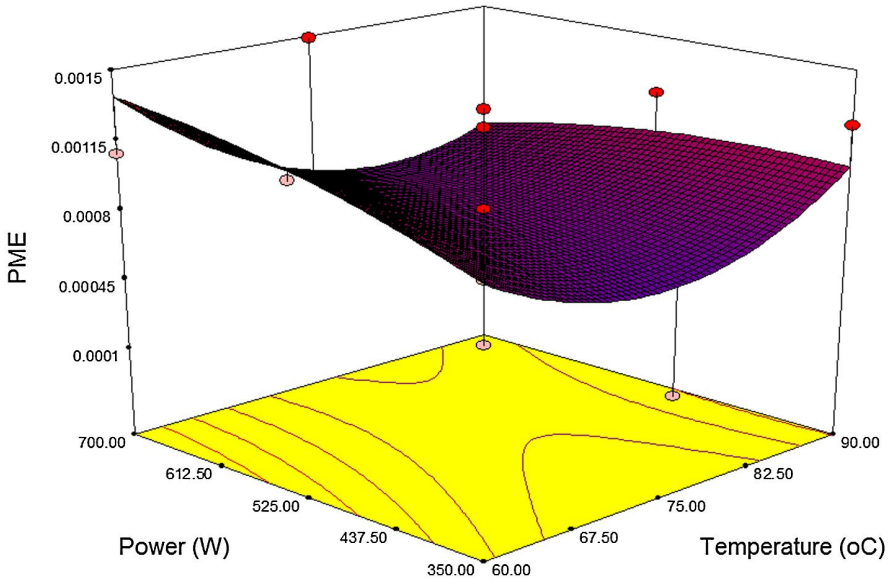


**FIGURE 7** Response surface for pectin methylesterase (PME; unit/ml) of BIREP juice samples as a function of temperature (°C) and power (W)

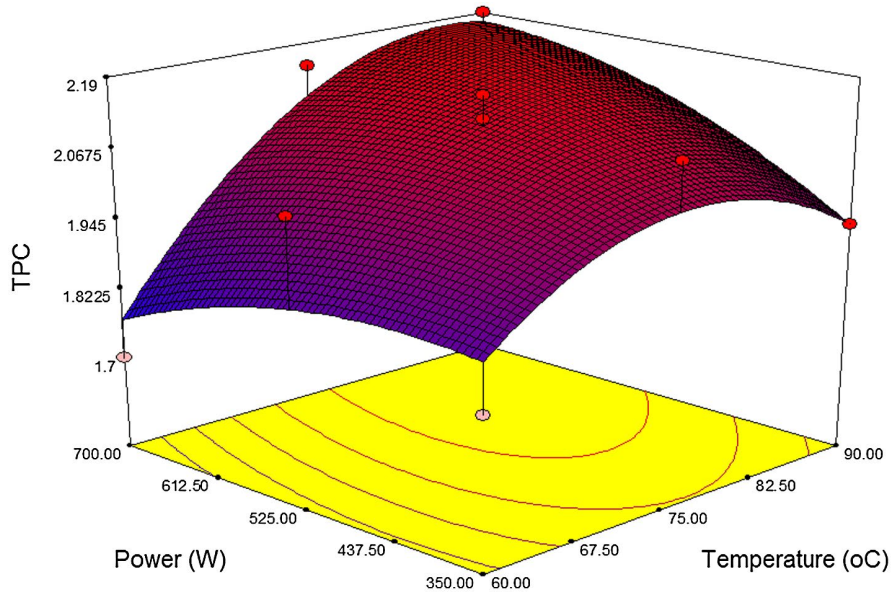


**FIGURE 8** Response surface for total plate counts (TPC; log CFU/ml) of BIREP juice samples as a function of temperature (°C) and power (W)

samples, or untreated juice samples (control). The obtained data in the present study were contrary to the result of Divyashree, Jamuna, and Brabahavanthis (2013) who identified *Aspergillus and Penicillium* in the three varieties of fresh lime juice. The dried lime juice was also enumerated for its total viable plate counts (TPC) as shown in Table 1.

The TPC of BIREP samples were found to be between 1.70 and 2.16 (log CFU/ml) for all used combinations of temperatures and power, while TPC of the control and thermal-treated samples were 3.52 and 2.60 (log CFU/ml), respectively (Table 2). Optimized BIREP juice samples had significantly ($p < .05$) lower TPC than control samples and conventional heating samples. Furthermore, TPC of dried lime juice in conventional thermal treatments were significantly ($p < .05$) lower than control samples. Similar results were reported by Rastogi (2012a) and Ramaswamy, Krishnamurthy, and Jun (2012) who reported the lethal effects of IR treatments in pasteurizing vegetative bacterial cells effectively compared to thermal conductive heating. In addition, Sawai, Sagara, Hashimoto, Igarashi, and Shimizu (2003) also suggested that far-infrared heating could rapidly reduce bacterial infection rates. The summarized ANOVA findings of the significant regression model are described in Table 3 for TPC of BIREP samples with an $R^2$ of 0.75 (adjusted $R^2 = 0.57$), suggesting that this model was an appropriate fit.

Figure 8 displays the 3D response surface for optimizing the parameters. The TPC of BIREP samples were decreased with an increase in the temperature within a range of 60–62.2°C and an increased power from 350 to 700 W. The highest reduction of the TPC of BIREP samples occurred when the temperature was 62.2°C and power was 700 W. The IR energy was absorbed by both microorganism and food components, resulting in potential inactivation of microorganisms (Krishnamurthy, Tewari, Irudayaraj, & Demirci, 2010; Rastogi, 2012b).

## 3.7 | Color characteristics

### 3.7.1 | Effect of BIREP on the $L^*$ value of lime juice

Table 4 revealed that $L^*$ values (lightness) changed with different runs of treatments (power and temperature). The highest $L^*$ value was 79.6078 at a power of 350 W and temperature of 75°C, with the lowest value of 61.9608 at 525 W power and 75°C temperature. The decreasing $L^*$ value because of increasing power indicated increased heating energy on the product. As to the effect of temperature on the $L^*$ value, the results showed that the $L^*$ value decreased from 78.6275 at a temperature of 75°C to 64.5098 at a temperature of 90°C at a constant power of 525 W. The decrease in $L^*$ value may be attributed to the increase in temperature that led to accelerated non-enzymatic reactions between acid and sugar which reduced the lightness. Al-Shatty, Al–Hilphy, A. R.S., and Al–Mtury, A. A.A. (2019) found that increasing infrared power led to no significant decrease in the $L^*$ values of fish oil. For the control and thermal treatment samples, $L^*$ value reached 75.45 and 65.57 respectively. Moreover, the differences between the control and thermal treatment in $L^*$ values were significant ($p < .05$) as shown in Table 2. The regression model and lack of fit did not have a significant effect on the $L^*$ value as shown in Table 5.

Figure 9 showed the three-dimensional plot of the response surface for $L^*$ value as a function of power and temperature. The results indicated that the $L^*$ value was reduced as the power and

**TABLE 4** Experimental design and the responses of color parameters ($L^*$, $a^*$, $b^*$), SIREC (kJ/kg), energy efficiency (%), and productivity (L/hr)

| Run | Power (W) | Temperature (°C) | $L^*$ | $a^*$ | $b^*$ | SIREC | Energy efficiency | Productivity |
|---|---|---|---|---|---|---|---|---|
| 1 | 525 | 75 | 75.8824 | 16.0941 | 54.5882 | 444.40 | 47.1272 | 3.52941 |
| 2 | 350 | 90 | 78.6275 | 5.64706 | 57.8824 | 766.80 | 34.2493 | 1.36364 |
| 3 | 525 | 75 | 61.9608 | 16.1941 | 56.9412 | 444.40 | 47.1272 | 3.52941 |
| 4 | 525 | 90 | 64.5098 | 27.2941 | 59.7647 | 731.95 | 35.8802 | 2.14286 |
| 5 | 700 | 75 | 72.9412 | 7.35294 | 49.4118 | 487.97 | 42.9194 | 4.28571 |
| 6 | 350 | 60 | 70.1961 | 15.5294 | 57.4118 | 348.55 | 44.9481 | 3.00 |
| 7 | 700 | 60 | 71.5686 | 16.4706 | 36.7059 | 278.84 | 56.1852 | 7.50 |
| 8 | 525 | 60 | 77.6471 | 0.941176 | 48.9412 | 365.98 | 42.8077 | 4.28571 |
| 9 | 525 | 75 | 73.3333 | 16.4706 | 58.8235 | 470.54 | 44.509 | 3.33333 |
| 10 | 525 | 75 | 70.3922 | 16.2412 | 55.5294 | 499.56 | 41.9237 | 3.07397 |
| 11 | 525 | 75 | 74.3137 | 16.322 | 56.9412 | 429.50 | 48.7622 | 3.65186 |
| 12 | 350 | 75 | 79.6078 | 0.941176 | 48.9412 | 575.10 | 36.4165 | 1.81818 |
| 13 | 700 | 90 | 67.8431 | 13.6471 | 53.1765 | 487.97 | 53.8203 | 4.28571 |

*Note.:* $L^*$ is the lightness, $a^*$ is the redness, $b^*$ is the yellowness, SIREC is the specific infrared energy consumption.

**TABLE 5** Regression coefficients, $R^2$, and $p$ values of the model for six dependent variables (Physical characteristics) for BIREP juice samples

| Source | $L^*$ | $a^*$ | $b^*$ | SIREC (kJ/kg) | Efficiency (%) | Productivity (L/hr) |
|---|---|---|---|---|---|---|
| $b_0$ | 41.7 | 789 | 5,850 | −907.14 | 42.4 | 4.41 |
| $b_1$ | 0.514 | −13.3 | −14.2404 | 21.49 | −0.222 | −0.0777 |
| $b_2$ | 0.0715 | −2.74 | −1.07415 | 1.07 | 0.0355 | 0.00942 |
| $b_1 b_2$ | 0.00116 | 0.04.17 | 0.0293 | −0.0199 | – | – |
| $b_1^2$ | 0.264196 | 0.0266 | 0.0873 | – | – | – |
| $b_2^2$ | 0.005112 | 0.00244 | 0.000019 | – | – | – |
| $b_1 b_2^2$ | 0.002627 | −0.000024 | −0.000167 | – | – | – |
| $b_1^2 b_2$ | 0.018890 | −0.000035 | −0.093773 | – | – | – |
| $R^2$ | 0.2732 | 0.8762 | 0.9506 | 0.8979 | 0.5832 | 0.8871 |
| $p$ value of the model | 0.3886 | 0.0465 | 0.0054 | <0.0001 | 0.0126 | < 0.0001 |
| $p$ value of lack of Fit | 0.6019 | < 0.0001 | 0.0893 | 0.0648 | 0.0914 | 0.0238 |

*Note:* $L^*$ is the lightness, $a^*$ is the redness, $b^*$ is the yellowness, SIREC is the specific energy consumption. Subscripts: 1 = temperature, 2 = power.

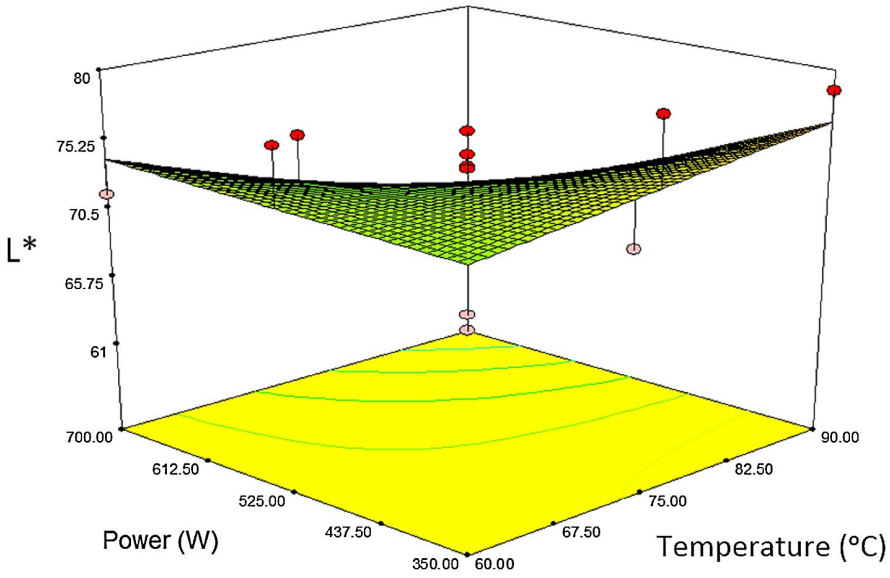


**FIGURE 9** Response surface for $L^*$ of BIREP juice samples as a function of temperature (°C) and power (W)

temperature increased. The minimum $L^*$ value was 62 at a power of 350 W and temperature of 60°C. The decreasing $L^*$ value with power and temperature increase was due to the increased IR exposure time to reach the desired temperature because of the power was lowest and the effect of infrared radiation stays long time on the product which causes darkness of color. In contrast, $L^*$ value was increased as both of power and temperature increased because of processing time is reduced and led to reduce the effect of infrared radiation on the color. The optimized result of the $L^*$ value content was 73.65 using BIREP at 62.2°C and 700 W (Table 2). There were statistically significant variations between 73.65 of the BIREP samples and conventional heating (65.57) because the infrared led to heat juice via the vibration of water molecular but in the case of thermal treatment, the juice heat via conduction which cause overheating at the wall of container led to decrease in the $L^*$ value. As well as, there was a significant difference ($p < .05$) between BIREP juice samples and untreated juice samples (control) immediately after the treatments because the heat did not use in the control.

### 3.7.2 | Effect of BIREP on the $a^*$ value of lime juice

For $a^*$ value (redness), the results in Table 4 illustrated that the lowest $a^*$ value of 0.941176 was at a power of 525 W and temperature of 60°C, and the highest $a^*$ value was 27.2941 at a power of 525 W and temperature of 90°C. This is because of the color of key lime trends to red color and temperature led to increase extraction of dye from it. The results disclosed that the $a^*$ value changed with power and at a power of 350, 525, and 700 W at 60°C was 15.5294, 0.941176, and 16.4706, respectively. For the control and thermal treatment samples, $a^*$ value reached 16.93 and 12.45 respectively. Moreover, the differences between the control and thermal treatment in $a^*$ values were significant ($p < .05$) as shown in Table 2.

The reduced cubic model and lack of fit have a significant effect ($p < .05$) on the $a^*$ value as shown in Table 5. On the other hand, there are no significant effect of interaction between power and temperature, squared temperature and interaction between squared temperature and power on $a^*$ value. The results in Figure 10 showed the response surface for $a^*$ of BIRP juice samples as a function of temperature (°C) and power (W). The results illustrated that the $a^*$ value generally increased with temperature and power until 525 W. The power of 525 W and temperature of 90°C gave the highest $a^*$ value. The redness increased at these conditions because the temperature increased the non-enzymatic reactions and the IR radiation increased the color due to the longer exposure time to achieve the highest temperature at the medium power setting. The lowest $a^*$ value was at a power of 525 W and temperature of 60°C due to low temperature. The optimized result of $a^*$ value was 14.199 using BIREP at 62.2°C and 700 W (Table 2). There were statistically significant variations between 14.199 of the BIREP samples and conventional heating (12.45) because the volumetric heating by infrared led to homogenize heat juice with very little effect on the $a^*$ value, but in the case of thermal treatment, the increasing heating intensity of juice and the heating distribution was not homogenized and led to a decrease in the $a^*$ value. As well as, there was a significant difference ($p < .05$) between BIREP juice samples and untreated juice samples (control) immediately after the treatments because the heat did not use in the control.

### 3.7.3 | Effect of BIREP on the $b^*$ value of lime juice

As for the $b^*$ value (yellowness), the results in Table 4 clarified that the $b^*$ value was affected by the power and temperature. The $b^*$ value ranged between 36.7059 at power of 700 W and temperature of 60°C to 59.7647 at power of 525 W and temperature of 90°C. A key lime beverage tends to yellowness because $b^*$ values have positive signs. The $b^*$ value increased from 48.9412 at a power of 525 W and temperature of 60°C to 59.7647 at a power of 525 W and temperature of 90°C. For the control and thermal treatment samples, $b^*$ value reached 39.56 and 33.57, respectively.

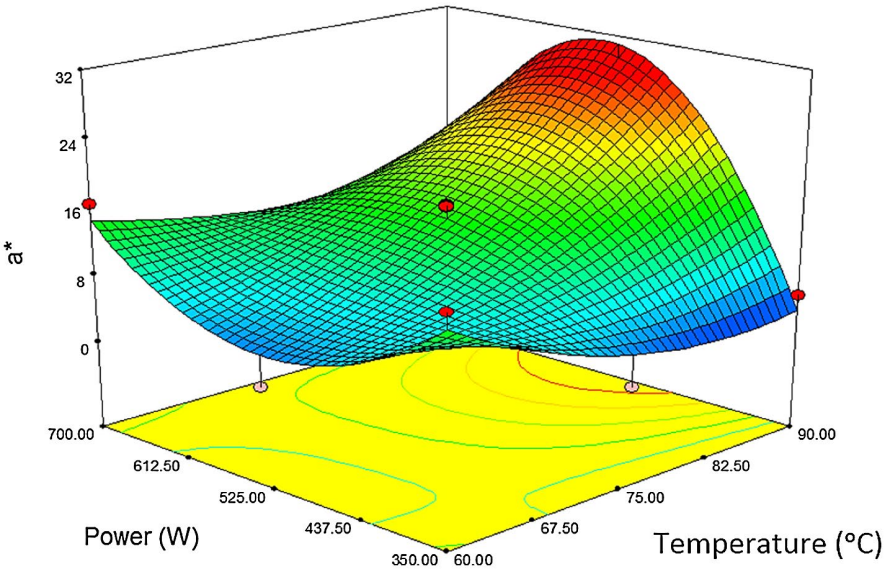


**FIGURE 10** Response surface for $a^*$ of BIREP juice samples as a function of temperature (°C) and power (W)

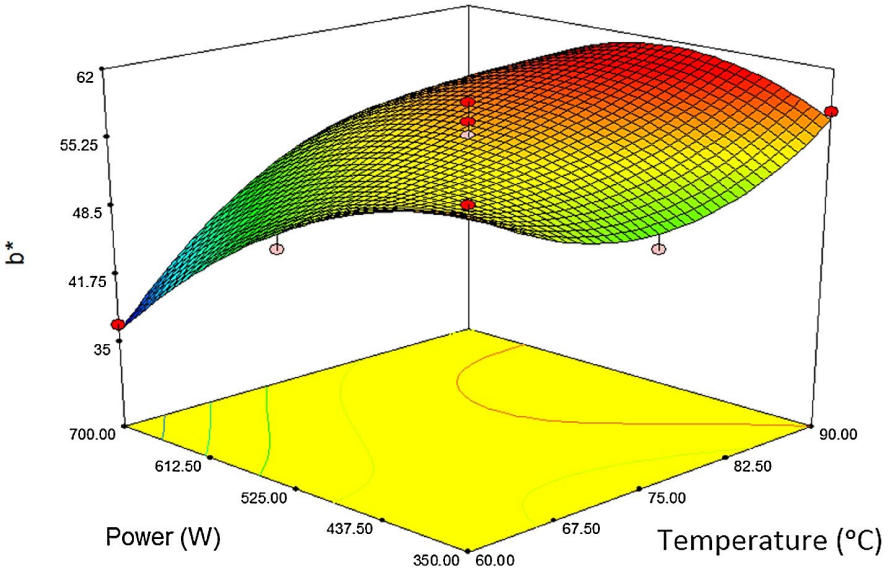


**FIGURE 11** Response surface for $b^*$ of BIREP juice samples as a function of temperature (°C) and power (W)

Moreover, the differences between the control and thermal treatment in $a^*$ values were significant ($p < .05$) as shown in Table 2. Table 5 shows that the reduced cubic mode had a significant effect on the $b^*$ value, but lack of fit was not significant. According to the statistical parameters, the reduced cubic mode can be used to predict the $b^*$ value of key lime.

Figure 11 illustrated the three-dimensional plot of the response surface of $b^*$ value as a function of power and temperature. The results showed that the highest $b^*$ value was 61 at a power of 525 W and temperature of 90°C. The lowest $b^*$ value was 36 at a power of 700 W and temperature of 60°C. The $b^*$ value increased as the temperature increased and power until 525 W and after that $b^*$ value decreased. Increased power beyond 525 W had a negative effect on the $b^*$ value because the intensity of IR caused overheating and caused the color to be darker and reduced the yellowness. Al-Mtury (2019) found that the $b^*$ value of fish oil extracted by infrared was insignificantly increased with power and insignificantly decreased with temperature. Vikram et al. (2005) stated that the lowest degradation of orange juice color was at a temperature of 90°C compared with temperatures of 50°C, 60°C, and 75°C. The optimized result of the $b^*$ value was 37.524 using BIREP at 62.2°C and 700 W (Table 2). There were statistically significant variations between 37.524 of the BIREP samples and conventional heating (33.57) because of the increase in heating intensity by conventional heating. As well as, there was a significant difference ($p < .05$) between BIREP juice samples and untreated juice samples (control) immediately after the treatments because the heat did not use in the control.

## 3.8 | Specific IR energy consumption (SIREC) by BIREP

In relation to specific energy consumption, the results in Table 4 revealed that at a power of 350 W, SIREC increased as the temperature

increased, with temperatures of 60, 75, and 90°C having SIREC values of 348.55, 575.10, and 766.80 kJ/kg, respectively. Energy consumption increased with temperature. SIREC decreased as the power increased because of the decreased time to heat the mixture of key lime and water. At 90°C, SIREC decreased from 766.80 kJ/kg at a power of 350 W to 487.97 kJ/kg at a power of 700 W. For the thermal treatment samples, specific energy consumption reached 39.56 as shown in Table 2. Table 5 illustrates that the 2FI Model had a significant effect ($p < .05$) on the SIREC. Moreover, the lack of fit was not significant. According to the results of statistical analysis, the linear model was adequate to predict the SIREC.

Figure 12 shows the 3D plot of the response surface of SIREC as a function of power and temperature. The results disclosed that the increase in temperature and decrease in power led to an increase of SIREC because of the increase in the heating time with reduced power, as well as increase the differences of temperature between the initial and final product. The highest SIREC was 777.49 kJ/kg at a power of 350 W and temperature of 90°C. Moreover, the lowest SIREC was 301.15 kJ/kg at a power of 700 W and temperature of 60.0°C. The effect of temperature was higher than power on changing the SIREC. SIREC was minimized by increased power and decreased temperature. The optimized result of SIREC was 278.84 using BIREP at 62.2°C and 700 W (Table 2). There were statistically significant variations between 278.84 of the BIREP samples and conventional heating (834.87) because the heating rate of juice using infrared was faster than the conventional heating which led to reduce the required time to arrive the specific temperature.

## 3.9 | Energy efficiency of BIREP

It can be noticed from Table 4 that the energy efficiency generally increased with the increase in power. For example, when power was 350, 525, and 700 W at 90°C, the energy efficiency reached 34.2493%, 35.8802%, and 53.8203% respectively. This may be due to the increased heating rate with higher power and reduced time required to heat key lime and water to a desired temperature. Moreover, the energy efficiency declined with an increase in temperature. The energy efficiency decreases from 56.1852% at 60°C to 53.8203% at 90°C temperature at a constant power of 700 W. This is because of increasing heat loss with temperature. Brown, Farrelly, O'Shaughnessy, and Robinson (2016) stated that the energy efficiency of the electric IR element reached 40% and 50% using an electric input power of 200 and 600 W, respectively. Xie, Dong, Chen, Jiang, and Yao (2016) disclosed that the maximum energy efficiency for deicing was 55.9% using IR. Singh (1994) mentioned that the energy use efficiency reached 38.5% and 38.9% for drying potatoes and carrots with IR. For the thermal treatment samples, energy efficiency reached 47.89 as shown in Table 2. It can be seen from Table 5 that the linear model has a significant effect ($p < .05$) on the energy efficiency, but the lack of fit was not significant. According to the results of statistical analysis, the linear model was adequate to predict the productivity.

Figure 13 illustrated the response surface for the energy efficiency of BIREP juice samples as a function of temperature (°C) and power (W). The results revealed that the increasing temperature and reducing power led to decreased energy efficiency, with a minimum value of 34%. The maximum value of energy efficiency was 55.5% at a power of 700 W and temperature of 60°C. The lower power settings did not compensate for the longer heating time required to reach the desired temperature. The optimized result of energy efficiency was 56.18 using BIREP at 62.2°C and 700 W (Table 2). There were statistically significant variations between 56.18 of the BIREP samples and conventional heating (47.89) because the BIREP needs lower input power than the conventional heating.

## 3.10 | Productivity of BIREP

It can be seen from Table 4 that the power of 700 W at 60° had the highest productivity of 7.50 L/hr. Increased power reduced the

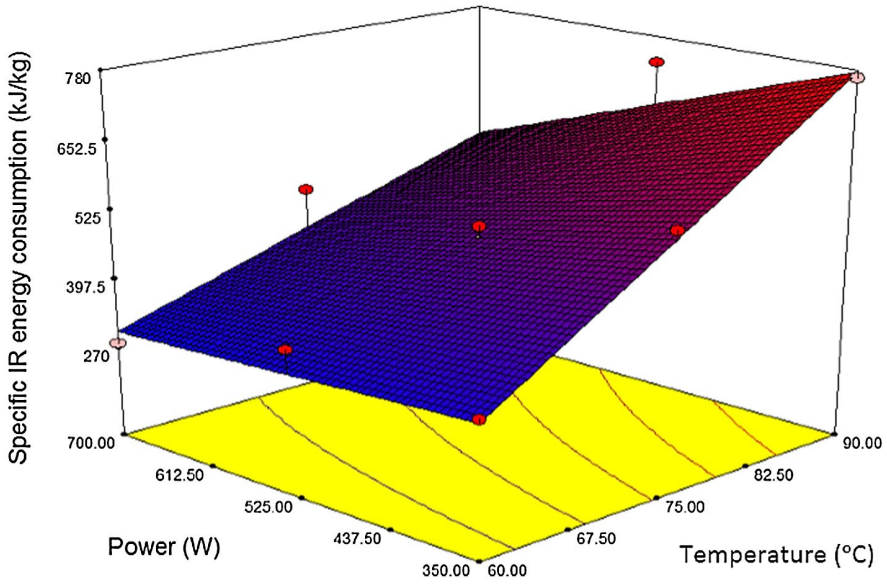


**FIGURE 12** Response surface for SEC (kJ/kg) of BIREP juice samples as a function of temperature (°C) and power (W)

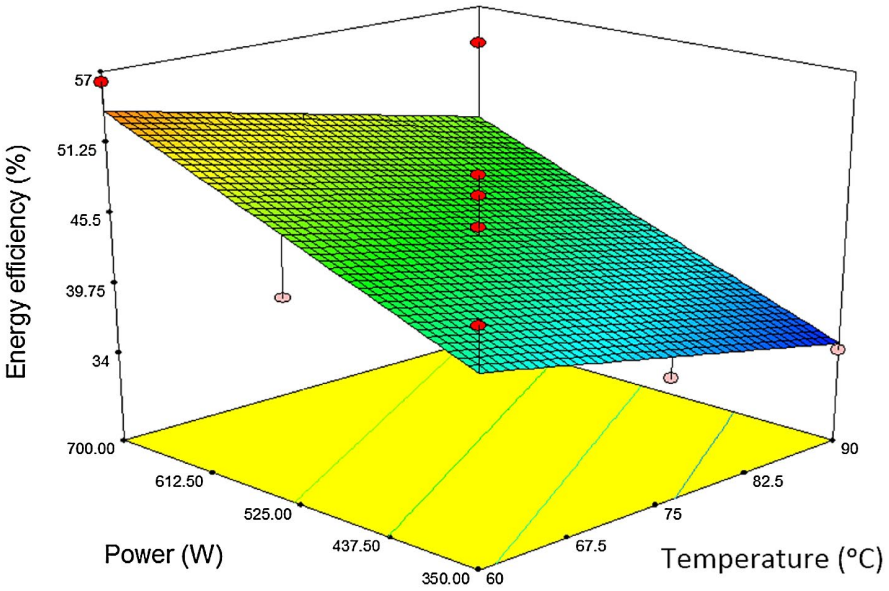


**FIGURE 13** Response surface for energy efficiency (%) of BIREP juice samples as a function of temperature (°C) and power (W)

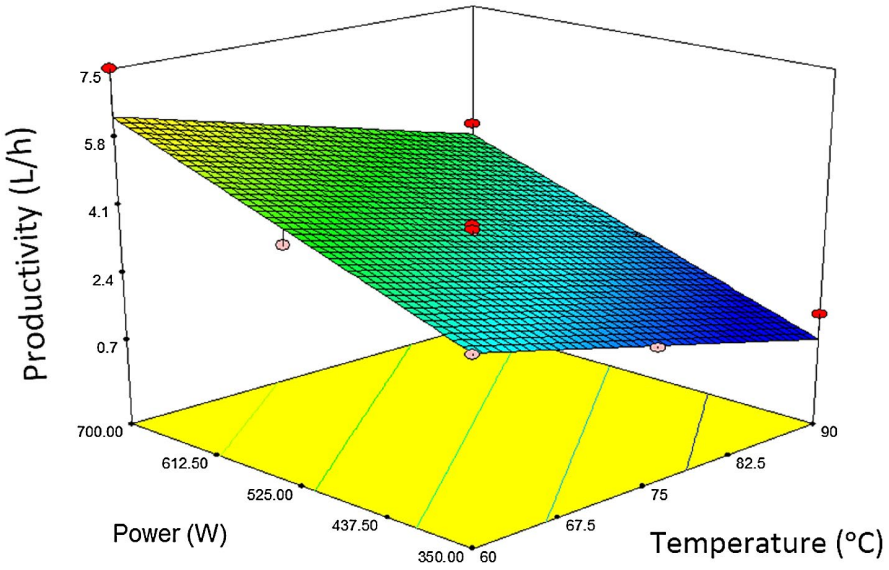


**FIGURE 14** Response surface for productivity (L/hr) of BIREP juice as a function of temperature (°C) and power (W)

required time to reach the desired temperature and lower power and temperature increased productivity. The lowest productivity was 1.36364 L/hr at a power of 350 W and temperature of 90°C. This was due to the increased time to achieve a temperature of 90°C at the lower power. For the thermal treatment samples, productivity reached 5.16 as shown in Table 2. Table 5 shows that the linear model and the lack of fit had a significant effect on the productivity. According to the results of statistical analysis, the linear model was adequate to predict the productivity. Figure 14 illustrates the response surface of the productivity in the 3D plot with power and temperature. The results revealed that the increasing power and decreasing temperature led to an increase in productivity. This is due to increased heating rate with power which led to reduce processing time and lower temperatures reduced time. The highest productivity was 6.20 L/hr at power of 700 W and temperature of 60°C, and the lowest productivity was 0.70 L/hr by using power of 350 W and temperature of 90°C. The results disclosed that the effect of power on the productivity was higher than the temperature. The optimized result of productivity was 6.25 L/hr using BIREP at 62.2°C and 700 W (Table 2). There were statistically significant variations between 6.250 of the BIREP samples and conventional heating (5.16) because the heating rate using the BIREP was higher than the conventional heating. Moreover, the required time for heating by the BIREP was higher.

### 3.11 | Sensory evaluation of processed and fresh dried key lime juice

Table 6 summarizes the results of sensory evaluation for untreated juice samples (control), BIREP juice samples under optimized conditions (temperature at 62.2°C and power at 700 W), and conventional heating samples. The panelists could distinguish between untreated juice samples (control) and conventional heating samples ($p < .05$) regarding the aroma and taste attributes. In contrast, results for sensory evaluation showed no significant differences between

**TABLE 6** Sensory evaluation scores of untreated juice samples (control), BIREP juice samples, and conventional heating samples

| Sample | Appearance | Aroma | Taste | Overall acceptability |
|---|---|---|---|---|
| Untreated juice (control) | $4.16 \pm 0.254^{ab}$ | $4.00 \pm 0.476^{a}$ | $3.68 \pm 0.458^{a}$ | $3.72 \pm 0.753^{ab}$ |
| Conventional heating | $3.87 \pm 0.590^{a}$ | $3.53 \pm 0.649^{b}$ | $3.20 \pm 0.573^{b}$ | $3.27 \pm 0.754^{a}$ |
| BIREP juice | $4.30 \pm 0.394^{b}$ | $4.18 \pm 0.364^{a}$ | $3.92 \pm 0.441^{a}$ | $4.08 \pm 0.509^{b}$ |

*Note:* Means + *SD* are an average of 10 replicates. The same superscript letters (a, b, c) within the same column indicate means were not significantly different.

untreated juice samples (control) and conventional heating samples regarding the appearance and overall acceptability attributes. In addition, the panelists actually could not distinguish between BIREP juice samples (control) and conventional heating samples among all tested attributes. The favorable results obtained in the sensory test confirmed that the control and BIREP juices appeared similar to each other regarding the appearance, aroma, taste, and overall acceptability attributes. This result of the sensory evaluation was consistent with Rawson et al. (2011) and (Alothman, Bhat, & Karim, 2009) who reported that the infrared irradiation of food products may cause minimal modification in the flavor, color, nutrients, taste, and other quality attributes.

## 4 | CONCLUSIONS

A batch infrared extraction pasteurizer (BIREP) with conventional resistance heating capability was used to process dried lime juice at temperatures of 60, 75, and 90°C and infrared power levels of 350, 525, and 700 W using a central composite design. Models for each dependent variable were used to obtain a single temperature (62.2°C) and power setting (700 W) to optimize the output of all dependent variables. Samples from infrared heating at the optimized temperature and power were found to be significantly better than both control (untreated) and conventional resistance heating for ascorbic acid, total phenolic content, antioxidant activity (DPPH), pectin methylesterase, total plate count, lightness, redness, and yellowness. For the remaining variable of hydroxymethylfurfural there was no significant difference between infrared and control treatments, but infrared heating was significantly better than conventional heating. Infrared was significantly superior to conventional heating based on the measures of specific energy consumption, energy efficiency, and productivity.

Sensory evaluation results found that infrared heating was superior to conventional heating for appearance, aroma, taste, and overall acceptability, while equivalent to fresh untreated juice in the same categories. Infrared heating did not have the negatives that consumers typically associate with conventional heat treated lime juice compared to fresh untreated juice.

For dried lime juice submitted to thermal processing for preservation, infrared heating is preferable to conventional resistance heating, in physicochemical properties, appearance, and sensory perception. When comparing infrared heating to control, all physicochemical properties, except for HMG, were significantly improved with infrared heating.

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## CONFLICTS OF INTEREST

The authors have declared no conflicts of interest for this article.

## AUTHOR CONTRIBUTIONS

Salam A. Aboud, Ammar B. Altemimi, Asaad R. S. Al-Hilphy, and Dennis G. Watson all participated in the design and drafting of this manuscript.

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