Design and Electro-Thermal Evaluation of a Solar PV-Integrated Ohmic Heating System for Kiwi Juice Pasteurization

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Abstract

A factorial design experiment was used to evaluate the electrothermal performance of an ohmic heater using photovoltaic energy for pasteurization of kiwi juice. The ohmic heater was designed to run in controlled conditions using solar cells connected to a hybrid inverter with a lithium-ion battery unit for stable electrical power supply. To achieve this, an acrylic heating chamber covered with transparent cover sheets was fabricated and equipped with stainless-steel electrodes. The fresh kiwi juice was processed at six levels of applied voltage; 30, 45, 60, 75, 90 and 105 V with processing times of 30-105 seconds. Electrothermal performance was evaluated in terms of changes in temperature, current, pH, electrical conductivity, and total dissolved solids which were measured and statistically analyzed. Increase in applied voltage and processing time led to high significance ($P \leq 0.01$) in temperature rise, current intensity, EC and TDS. The highest temperature and current attained were 66.7oC and 2.20 A respectively. There was also a great increase in EC from 4252 to 5510 µS/cm and TDS from 2141 to 2472 ppm. However, pH changed slightly within the range 3.70-3.80. The observed changes might have been associated with ion movement in juice and/or changes in permeability of cell membranes during ohmic heating.

Keywords: Solar, System, Fruit, Pasteurization, p^H.

Introduction

Renewable energy technologies have become increasingly important in agricultural and food-processing applications because of rising global energy demand and environmental concerns associated with fossil fuel consumption [1]. Among renewable energy sources, solar photovoltaic systems have gained considerable attention because of their environmental sustainability, low operating cost, and suitability for off-grid areas [2]. Iraq possesses high solar radiation intensity during most months of the year, making photovoltaic systems highly suitable

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for decentralized industrial and agricultural operations [1].

In general, traditional thermal pasteurization of fruits often causes undesirable changes in the nutritional composition, taste, color, and other physicochemical properties of the products [3]. The application of conventional heating systems is often associated with non-uniformity in the process of heat transfer and the formation of fouling on the walls of heat exchangers [4].

One of the most promising advanced thermal processing methods applied in food technology is ohmic heating (OH). In OH technology, the electric current goes through the heated materials directly, thus causing volumetric heat generation because of electrical resistance [6]. This method can ensure even distribution of heat energy inside the treated material, which makes it possible to significantly reduce thermal gradients [7].

Fruit juices can be easily heated ohmically owing to their natural content of various electrolytes and organic acids responsible for their high level of conductivity [8]. Generally, the electrical conductivity of liquids heated ohmically grows along with the growth of temperature due to an increase in the mobility of ions and the decrease of viscosity [9]. Moreover, moderate electric field can lead to the induction of electroporation and, consequently, an increase in cell membrane permeability [10].

Kiwi fruit (Actinidia deliciosa) is well known for its high biological value that is determined by the high content of vitamin C, antioxidants, minerals, dietary fiber, and other bioactive compounds [11]. On the contrary, kiwi juice is not resistant to conventional thermal pasteurization, and it is characterized by a number of undesirable qualities caused by the negative effect of heating [12]. Thus, OH can be a good replacement for the classical pasteurization of the product in order to preserve its quality.

A number of different operational parameters influence the effectiveness of OH systems [13]. Voltage fluctuations may lead to non-uniform heating and electrochemical reactions, especially in acidic products such as fruit juices [14]. Consequently, integrating OH systems with photovoltaic energy sources and hybrid MPPT-controlled inverters may improve operational stability and provide sustainable processing solutions in areas with unstable electrical infrastructure.

The Aims of the present study was to design and evaluate a solar PV-integrated ohmic heating system and investigate the effects of voltage gradient and treatment time on temperature development, current intensity, pH stability, electrical conductivity, and total dissolved solids of kiwi juice.

Material and Methods

2.1 Solar Power System

The ohmic heating unit was powered using a photovoltaic energy system consisting of LONGi 520 W monocrystalline solar panels connected to an Axpert VM IV 4000 W hybrid inverter equipped with Maximum Power Point Tracking (MPPT) technology [2]. Electrical energy was stored using a CHISAGE lithium-ion battery system (25.6 V, 314 Ah, 8.03 kWh) to ensure stable electrical output during operation.

2.2. Ohmic Heating Reactor

The reactor tank was designed using clear acrylic with an overall volume of 400 ml. Two electrodes made from stainless steel (SS316) were placed in the reactor tank maintaining a constant electrode separation distance of 8.5 cm. SS316 electrodes were chosen due to their high resistance to corrosion under acidic conditions [14].

2.3 Experimental System Layout

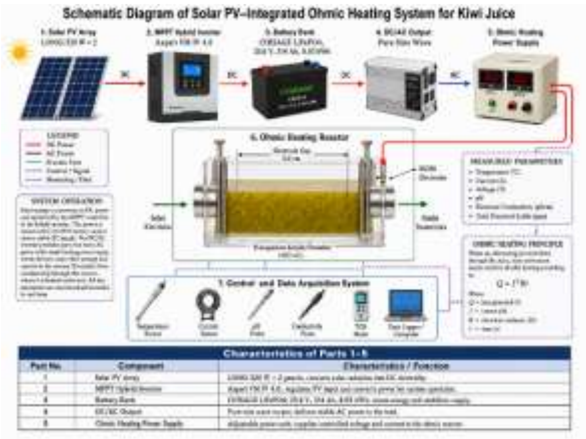

Figure 1. Schematic diagram of the solar PV-integrated ohmic heating system used for kiwi juice pasteurization.

The system design included solar panels, hybrid inverter, lithium battery array, ohmic heating power source, reactor chamber made from acrylic, and data acquisition system. The monitoring equipment involved sensors for temperature, voltage, current intensity, pH, electrical conductivity, and total dissolved solids.

2.4 Kiwi Juice Preparation

Ripe kiwi fruit samples were washed, de-peeled, mashed, and strained to get homogenous kiwi juices. Four hundred milliliters of kiwi juice was added to the reactor chamber during each experiment [11].

2.5 Experimental Procedure

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Six voltage levels (30, 45, 60, 75, 90, and 105 V) were applied during ohmic treatment. Measurements of current intensity, temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS) were recorded during treatment periods ranging from 30 to 105 s [15].

2.6 Statistical Analysis

The experiment was conducted using a factorial arrangement within a completely randomized design (CRD). Data were analyzed statistically using SAS software, and means were compared using Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$.

3. Results and Discussion

3.1 Temperature Development During Ohmic Heating

The temperature behavior of kiwi juice during ohmic treatment is presented in Table 1. Significant increases $(P|0.01)$ in temperature were observed with increasing voltage gradient and treatment duration. The highest temperature $(66.7^{\circ}C)$was obtained at 105 V after 105 s of treatment, whereas the lowest temperature remained at $22.4^{\circ}C$in the control treatment.

The rapid temperature increase may be attributed to volumetric heat generation resulting from electrical resistance inside the conductive juice matrix [5 and 16].

The developed photovoltaic-powered system maintained stable electrical output during treatment, contributing to homogeneous heat generation and consistent thermal behavior throughout processing, this result agree with [17].

3.2 Current Intensity

Current intensity increased significantly with increasing voltage gradient and treatment duration (Table 2). The highest current value (2.20 A) was observed at 105 V.

The increase in current intensity reflects the reduction in electrical resistance caused by elevated temperatures and improved ionic mobility inside the juice medium [9]. Similar conductivity-current relationships during ohmic processing were reported by Doan et al. [5].

3.3 pH Stability

The pH values remained relatively stable during ohmic treatment, ranging from 3.70 to 3.80 (Table 3). The limited changes indicate that the stainless steel electrodes maintained electrochemical stability during processing [14].

From other hand, rapid volumetric heating and shorter exposure times may have contributed to preserving juice acidity and minimizing chemical degradation reactions, and that agree with [3].

3.4 Electrical Conductivity (EC)

Electrical conductivity increased significantly during ohmic treatment, reaching 5510 µS/cm at the highest voltage level (Table 4).

The increase in EC is mainly associated with enhanced ionic mobility at elevated temperatures and reduced viscosity inside the juice matrix [8]. Electroporation effects may also have contributed to intracellular electrolyte release during treatment [10]. Similar findings were reported by Kaur and Sharma [18].

3.5 Total Dissolved Solids (TDS)

TDS values increased gradually during processing, reaching 2472 ppm at 105 V (Table 5).

The increase in TDS may be associated with mineral release and increased solute diffusion caused by electroporation effects during ohmic treatment [10 and 19].

Table 1. Effect of voltage and treatment time on temperature (°C)

Voltage means	5	4	3	2	1	0	Time (s)
24.58 F	26.7 V	25.9 W	25.0 Z	24.2 A*	23.3 C*	22.4 D*	30
26.23 E	29.4 Q	28.5 R	27.3 T	25.8 X	24.0 B*	22.4 D*	45
29.62 D	36.1 K	34.0 M	31.6 N	28.4 S	25.2 Y	22.4 D*	60
34.32 C	46.5 F	41.9 H	36.8 J	31.5 O	26.8 U	22.4 D*	75
39.80 B	58.3 C	51.0 D	43.2 G	35.4 L	28.5 R	22.4 D*	90
44.62 A	66.7 A	58.6 B	49.7 E	39.8 I	30.5 P	22.4 D*	105

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Voltage means	5	4	3	2	1	0	Time (s)
	43.95 A	39.98 B	35.60 C	30.85 D	26.38 E	22.40 F	Time means

Legend: Temperature values represent the thermal response of kiwi juice during ohmic heating treatment. Means followed by different letters within the same row or column differ significantly according to Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$.

Table 2. Effect of voltage and treatment time on current intensity (A)

Voltage means	5	4	3	2	1	0	Time (s)
0.82 F	1.10 T	1.03 V	1.00 W	0.96 X	0.80 Z	0.00 A*	30
0.92 E	1.20 P	1.17 R	1.12 S	1.05 U	0.95 Y	0.00 A*	45
1.04 D	1.40 L	1.35 M	1.28 O	1.18 Q	1.05 U	0.00 A*	60
1.20 C	1.60 H	1.55 I	1.48 J	1.35 M	1.20 P	0.00 A*	75
1.38 B	1.90 D	1.82 E	1.70 G	1.55 I	1.30 N	0.00 A*	90
1.58 A	2.20 A	2.10 B	1.95 C	1.75 F	1.45 K	0.00 A*	105

Means followed by different letters within the same row or column differ significantly according to Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$.

Table 3. Effect of voltage and treatment time on pH values

Voltage means	5	4	3	2	1	0	Time (s)
3.745 C	3.760 E	3.760 E	3.750 FG	3.740 HI	3.730 JK	3.730 JK	30
3.770 A	3.800 A	3.790 B	3.780 C	3.770 D	3.750 FG	3.730 JK	45
3.749 B	3.760 E	3.760 E	3.755	3.750	3.740	3.730	60

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Voltage means	5	4	3	2	1	0	Time (s)
			EF	FG	HI	JK	
3.734 D	3.730 JK	3.732 JK	3.735 IJ	3.740 HI	3.735 IJ	3.730 JK	75
3.713 E	3.700 M	3.700 M	3.705 M	3.715 L	3.725 K	3.730 JK	90
3.745 C	3.750 FG	3.755 EF	3.750 FG	3.745 GH	3.740 HI	3.730 JK	105
	3.750 A	3.750 A	3.746 B	3.743 B	3.737 C	3.730 D	Time means

Means followed by different letters within the same row or column differ significantly according to Duncan's Multiple Range Test (DMRT) at $P \leq 0.0$

Table 4. Effect of voltage and treatment time on electrical conductivity (µS/cm)

Voltage means	5	4	3	2	1	0	Time (s)
4352.00 F	4452 T	4412 W	4372 Y	4332 A*	4292 C*	4252 D*	30
4412.83 E	4547 O	4505 Q	4458 S	4395 X	4320 B*	4252 D*	45
4444.17 D	4591 L	4540 P	4495 R	4432 U	4355 Z	4252 D*	60
4653.67 C	5075 E	4890 H	4720 J	4565 N	4420 V	4252 D*	75
4777.83 B	5225 C	5080 D	4905 G	4700 K	4505 Q	4252 D*	90

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Voltage means	5	4	3	2	1	0	Time (s)
4916.17 A	5510 A	5280 B	5050 F	4825 I	4580 M	4252 D*	105
	4900.00 A	4784.50 B	4666.67 C	4541.50 D	4412.00 E	4252.00 F	Time means

Means followed by different letters within the same row or column differ significantly according to Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$

Table 5. Effect of voltage and treatment time on TDS values (ppm)

Voltage means	5	4	3	2	1	0	Time (s)
2143.50 F	2146 Y	2145 Z	2144 A*	2143 B*	2142 C*	2141 D*	30
2199.67 E	2241 N	2228 P	2215 S	2198 U	2175 X	2141 D*	45
2225.67 D	2290 J	2270 L	2245 M	2220 R	2188 W	2141 D*	60
2252.83 C	2341 G	2315 H	2285 K	2240 O	2195 V	2141 D*	75
2307.50 B	2449 B	2405 D	2350 F	2290 J	2210 T	2141 D*	90
2328.00 A	2472 A	2435 C	2385 E	2310 I	2225 Q	2141 D*	105
	2323.17 A	2299.67 B	2270.67 C	2233.50 D	2189.17 E	2141.00 F	Time means

Means followed by different letters within the same row or column differ significantly according to Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$

Conclusion

According to the obtained results, the solar-powered ohmic heating system is a robust and sustainable technology for kiwi juice pasteurization. The 105V gradient successfully raised the temperature to 66.7°C within the 5-minute

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interval. The increase in PPM provides quantitative proof of electroporation-induced mineral release. The use of high-efficiency inverters and lithium storage provides the necessary stability for precision food processing, aligning with global green energy goals.

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