JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Commercial Scale Pulsed Electric Field Processing of Tomato Juice

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Effects of commercial scale pulsed electric field (PEF) processing on the quality of tomato juice were studied and compared with those of thermal processing. Tomato juice was prepared by hot break at 88 °C for 2 min or by cold break at 68 °C for 2 min and then thermally processed at 92 °C for 90 s or PEF processed at 40 kV/cm for 57 μs. Thermally processed, PEF processed, and unprocessed control juices were packed into 50 mL sterilized polypropylene tubes in a sanitary glovebox and stored at 4 °C for 112 days. Both thermally and PEF processed juices showed microbial shelf life at 4 °C for 112 days. The lipoxygenase activities of thermally and PEF processed juices were 0 and 47%, respectively. PEF processed juice retained more ascorbic acid than thermally processed juice at 4 °C for 42 days ($p < 0.05$). No significant differences were observed in the concentration of lycopene, °Brix, pH, or viscosity between thermally and PEF processed juices during the storage ($p > 0.05$). Sensory evaluations indicated that flavor and overall acceptability of PEF processed juice were preferred to those of thermally processed juice ($p < 0.05$).

KEYWORDS: Pulsed electric field; thermal processing; tomato juice; shelf life; ascorbic acid

INTRODUCTION

Tomatoes are the second-most consumed vegetable around the world (*1*). Most tomatoes are consumed as processed products such as tomato juice, paste, puree, ketchup, sauce, and canned tomatoes (*2*). Processed tomato products are important sources of minerals and vitamins in diets (*3*). Flavor, color, taste, and nutritional value are considered to be the major quality attributes of foods and influence the consumer's choice. Thermal processing is the most common method to extend the shelf life of tomato juice by inactivating microorganisms and enzymes. However, thermal processing can lower the sensory and nutritional qualities of foods (*4*). Therefore, alternative juice processing methods were sought for tomato industries to produce higher quality tomato juice.

Pulsed electric field (PEF) processing is being extensively studied as a nonthermal food preservation method (*5*). PEF processing is very effective for the pasteurization of juices due to their high acidity and low protein concentration. The high acidity of juices retards the growth of bacteria and the germination of bacterial spores (*6*). A shielding layer of PEF may be formed on the surface of electrodes when charged molecules including proteins migrate to the surface of electrodes and monopolar pulses are successively applied (*7*). The low protein content and use of bipolar pulses may not cause the formation of the shielding layer.

Laboratory or pilot plant scale PEF processing was successfully conducted and has increased the shelf life of juice products, minimizing the loss of flavor, color, and nutrients of juice products (*8*−*10*). However, no research was done with commercial scale PEF processing. No information is available about the effects of PEF on the lipoxygenase activity, lycopene, ascorbic acid, physical properties, and sensory properties of tomato juice. The objectives of this research were (1) to study the effects of commercial scale PEF processing on the inactivation of endogenous microorganisms in tomato juice, (2) to investigate the effects of commercial scale PEF processing on the quality of tomato juice, and (3) to compare the quality of PEF processed orange juice with that of thermally processed tomato juice during storage at 4 °C for 112 days.

MATERIALS AND METHODS

Tomatoes. Roma-type Midwest tomatoes (H9423) were supplied by Hirzel Canning Co. and Farms (Toledo, OH) throughout the year 2001 tomato season. Tomatoes were processed within 5 h after harvesting.

Preparation of Tomato Juice. A total of 1100 kg of fresh tomatoes was used to prepare tomato juice. Fresh raw tomatoes were washed in a soak tank with air agitation and then washed again with 150 psi sprayed water while being conveyed on a roller conveyor. Tomatoes were sorted and chopped by a mill (model D, The W. J. Fitzpatrick Co., Chicago, IL) equipped with a 1.91 cm screen. The chopped tomatoes were heated in a tubular heat exchanger (H2187C type, Specialty Brass Co., Kenosha, WI) for 2 min at 88 °C for hot break and at 68 °C for cold break. Hot break tomato juice was used for all studies except the study of lipoxygenase activity. Hot break tomato juice did not possess enough lipoxygenase activity to be used for that

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10.1021/jf0260444 CCC: $25.00
Published on Web 04/16/2003

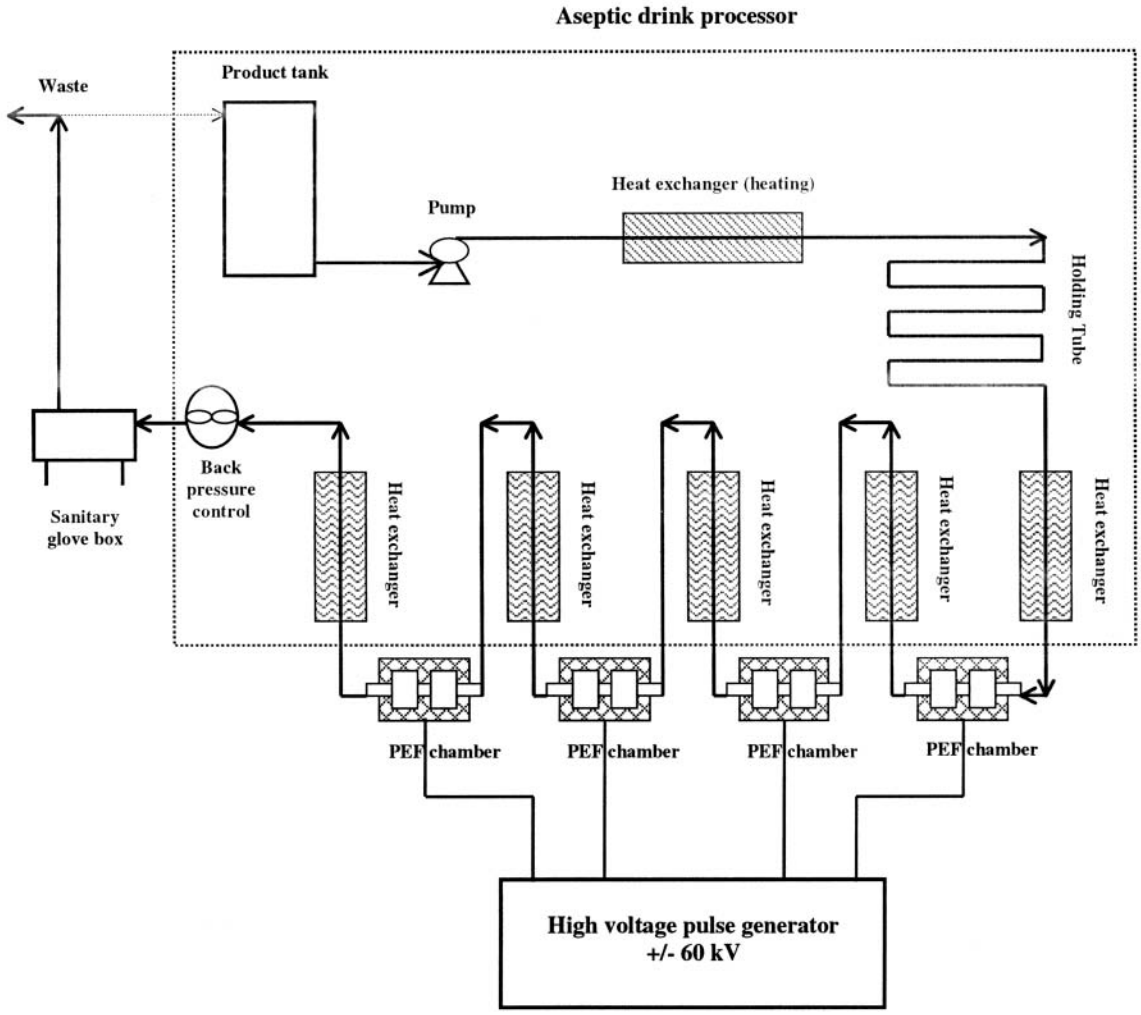

Figure 1. Flowchart of OSU-6 commercial scale PEF processing system.

study. Tomato juice was prepared by a screw-type extractor (CJE-360-D28, Chisholm-Ryder Co., Niagara Falls, NY) with a screen of 1.27 cm diameter.

PEF Processing System. The OSU-6 commercial scale PEF processing system is illustrated in **Figure 1**. The OSU-6 commercial scale PEF processing system consisted of an aseptic drink processor (TetraPak, General-Guisan, Switzerland), a high-voltage pulse generator (Diversified Technology, Inc., Bedford, MA), and co-field tubular PEF chambers (The Ohio State University, Columbus, OH). The aseptic drink processor monitored and controlled production rates, temperatures, and pressures during PEF processing. The high-voltage pulse generator provided bipolar squared waveform pulses. Pulses were monitored with a high-voltage probe (attenuation factor = 10000:1, VD-60, Northstar, Albuquerque, NM), current monitors (attenuation factor = 100:1, model 110, Pearson, Palo Alto, CA), and oscilloscopes (TDS-210, Tektronix, Beaverton, OR). Each co-field tubular PEF chamber consisted of two boron carbite tubular electrodes and a tubular insulator body made of ceramic (*11*). The inner diameter of the cylindrical processing zone was 0.808 cm, and the distance between the electrodes was 1.270 cm. Six PEF chambers were connected electrically in parallel and in series for fluid flow. The peak current through each PEF chamber was 75 A.

Thermally Processed, PEF Processed, and Control Tomato Juices. The production rate was 500 L/h for all thermally processed, PEF processed, and control tomato juices. Juice processing was performed in the following order: sterilization-in-place (SIP), thermal processing, PEF processing, control collection, and clean-in-place (CIP).

For thermal processing, tomato juice was held at 92 °C for 90 s in a holding tube and then cooled to 25 °C by the heat exchanger following the holding tube (**Figure 1**). PEF remained off throughout thermal processing. The cooled tomato juice was packaged inside a sanitary glovebox (**Figure 1**). The processing mode was switched from thermal to PEF after 10 min of filling thermally processed tomato juice.

PEF processing conditions were an electric field strength of 40 kV/cm, a pulse duration time of 2 μs, and a total PEF treatment time of 57 μs. The number of PEF treatment chambers was six. Tomato juice was pumped to the PEF chambers without thermal processing. The inlet temperature of juice to each set of two PEF chambers was maintained at 45 °C by the heat exchangers at the upstream of each set of PEF chambers (**Figure 1**). The temperature change per a pair of PEF treatment chamber was 8 °C. PEF processed tomato juice was cooled to 25 °C prior to packaging inside the sanitary glovebox. After 10 min of filling PEF processed juice, PEF was turned off in preparation for control collection.

For control tomato juice, tomato juice was passed through the system without thermal or PEF processing and packaged inside the sanitary glovebox.

Packaging and Storage. Thermally processed, PEF processed, and control juices were packaged into the 50 mL sterilized polypropylene tubes (Corning, Acton, MA) inside a sanitary glovebox filling unit (The Ohio State University, Columbus, OH). The glovebox was prepared by following the procedure described in ref *12*. The glovebox consisted of a gastight stainless steel box with a glass window, a pair of gloves, a double-door transfer tunnel, a germicidal UV lamp (Cole Parmer, Vernon Hills, IL), and a HEPA air filter (Fisher Scientific, Pittsburgh, PA). The glovebox was sanitized by spraying and swabbing 35% hydrogen peroxide and lighting germicidal UV at 254 nm with an intensity of 76 μW/cm^2. The HEPA air filter with 0.3 μm pore size and a 1600 cm^2 filtration area was installed to supply positive pressure with bacteria-free air inside the glovebox. Each polypropylene tube

with juice sample was covered with aluminum foil to prevent the exposure of tomato juice to light. Packaged juices were stored at 4 °C.

Microbial Inactivation Study. The purpose of the microbial inactivation study was to examine how many of microorganisms of tomato juice could be inactivated by thermal processing or commercial scale PEF processing. A high microbial load was required in tomato juice for microbial inactivation study. Hot break tomato juice was incubated for 3 days at 22 °C to obtain $\sim 1.0 \times 10^6$ colony-forming units (CFU)/mL of microorganisms before thermal or PEF processing. The total aerobic plate count and the yeast and mold count were 1.0×10^6 and 7.9×10^5 CFU/mL, respectively, after the incubation.

Plate count agar (PCA) and acidified potato dextrose agar (PDA) were used to enumerate the total aerobic plate and the yeast and mold plate, respectively, in thermally processed, PEF processed, and control tomato juices. PCA, PDA, and peptone water were purchased from Difco (Detroit, MI). PDA was acidified with 10% tartaric acid (Sigma-Aldrich, St. Louis, MO). Tomato juice was diluted with 0.1% sterile peptone water and plated by a spiral autoplater (model 3000, Spiral Biotech Inc., Bethesda, MD). Two samples per processing were randomly chosen at each sampling day. Two aliquots were obtained from each sample. Each aliquot was diluted 10^{-1}, 10^{-2}, 10^{-3}, and 10^{-4}. Two plates per dilution were made. PCA plates were incubated at 30 °C for 48 h. PDA plates were incubated at 22 °C for 5 days.

Shelf-Life Study. Hot break or cold break juice was cooled to 45 °C and thermally processed or PEF processed without incubation. Cold break juice was used only for the study of lipoxygenase activity. Thermally processed, PEF processed, and control tomato juices were packaged and stored at 4 °C. The shelf-life study was conducted for 112 days.

Microbial Stability. Hot break juice without incubation was thermally processed or PEF processed for the shelf-life study. The initial total aerobic plate count and yeast and mold count of tomato juice before thermal or PEF processing were 20 and 10 CFU/mL est., respectively. The microbial stability was determined by using the same method as described for the microbial inactivation study.

Lipoxygenase Activity. Lipoxygenase activity was measured according to the methods of Ben-Aziz et al. (*13*) and Tangwongchai et al. (*14*). Cold break tomato juice of 50 g was homogenized with 100 mL of 0.1 M phosphate buffer (pH 6.5), containing 1 mM EDTA and 0.1% (w/v) Triton X-100. The homogenate was filtered through a double layer of cheesecloth and centrifuged at 20000*g* for 40 min at 5 °C. The enzyme solution was prepared by diluting 0.5 mL of supernatant with 1.0 mL of 0.1 M phosphate buffer (pH 6.5). A substrate solution containing linoleic acid (2.5×10^{-3} M) and Tween 20 (0.2%) was prepared according to the method of Ben-Aziz et al. (*16*). The substrate solution was diluted to 2.5×10^{-5} M with 0.2 M phosphate buffer (pH 6.5). The enzyme solution of 0.1 mL was pipetted into the cuvette containing 2.4 mL of the substrate solution at zero time. The absorbance was measured at 234 nm for 3 min at a 15 s interval using a Spectronic Genesys 5 spectrometer (Milton Roy, Rochester, NY) at 22 °C. The rate of the reaction was automatically computed from the linear portion of the curve. One unit of lipoxygenase activity was defined as a change of 0.001 unit of absorbance per minute and milliliter of enzyme solution.

Lycopene Analysis. A hexane extract was obtained by using the method of Chandler and Schwartz (*15*) with some modifications. Tomato juice of 5.0 g was homogenized in 50 mL of methanol (Fisher Scientific, Pittsburgh, PA) with 1.0 g of calcium bicarbonate (Sigma-Aldrich, St. Louis, MO) and 3.0 g of Celite (Sigma-Aldrich). The homogenate was successively extracted with a 50 mL mixture of 1:1 acetone/hexane (v/v; Fisher Scientific) and vacuum-filtered through Whatman no. 1 and 42 papers (Whatman International Ltd., Maidstone, U.K.). The filtrant was combined in a separatory funnel. Distilled water was added into the separatory funnel to induce the separation of the hexane layer.

The lycopene in the hexane extract was analyzed by a high-performance liquid chromatography (HPLC, series 1100, Hewlett-Packard, Palo Alto, CA). A reversed phase C18 column (201TP54, Vydac, Holland, MI), a guard column packed with C18 stationary phase (Vydac), a diode array detector (HP 1100 DAD, Wilmington, DE), and an autosampler were used for all separations. The separation was performed at 1.0 mL/min using a linear gradient of 32−53% methyl *tert*-butyl ether (Fisher Scientific) in methanol for 60 min. HPLC solvents were of certified HPLC grades. The lycopene in tomato juice was quantified from the HPLC profile by using the lycopene standard from tomatoes (Sigma-Aldrich).

Ascorbic Acid Analysis. The concentration of ascorbic acid in the tomato juice was measured following the procedure described in ref *16* using an HPLC system (Hewlett-Packard, 1050 series, Wilmington, DE).

Particle Size Distributions. The particle size of tomato juice was analyzed by a Mastersizer (Malvern Instruments, Inc., Worcs, U.K.). Tomato juice of 10 mL was diluted with 500 mL of distilled water and circulated in the Mastersizer at 2000 rpm. A computer equipped with Mastersizer Micropulus 2.15 (Malvern Instruments, Inc.) recorded distributions of the particle size of tomato juice.

The $D[4, 3]$, $D[3, 2]$, $D(v, 0.1)$, $D(v, 0.5)$, and $D(v, 0.9)$ were reported. The $D[4, 3]$, $D[3, 2]$, and $D(v, 0.5)$ were used for the comparison of particles sizes of thermally processed, PEF processed, and control tomato juices. $D[4, 3]$ is the volume moment mean of particles and defined as the following equation, where d is the diameter of one unit.

$$D[4, 3] = \sum d^4 / \sum d^3$$

$D[3, 2]$ is the surface area moment mean of particles and determined as

$$D[3, 2] = \sum d^3 / \sum d^2$$

$D[4, 3]$ and $D[3, 2]$ are used to measure particles on the basis of volume and surface area, respectively. $D(v, 0.1)$ is the size of particle for which 10% of the sample is below this size. $D(v, 0.5)$ is the median of the particle size distribution on the basis of volume. $D(v, 0.9)$ gives a size of particle for which 90% of the sample is below this size (*17*).

°Brix and pH. The °Brix of tomato juice was measured using a hand-held refractometer (Fisher, Pittsburgh, PA). The pH of tomato juice was measured using a pH meter (370, Orion, Beverly, MA) at 22 °C.

Viscosity. The viscosity of tomato juice was measured by using a Brookfield viscometer (LVDVII+, Brookfield Engineering Laboratories, Inc., Stoughton, MA) with a UL adapter. Viscosity was determined at 22 °C and 4 rpm with 16 mL of juice placed in the UL adapter.

Sensory Evaluation. Thermally processed and PEF processed juices, stored at 4 °C for 1 week, were used for the sensory evaluation. One week was needed for Silliker Laboratories (Columbus, OH) to confirm the absence of pathogen microorganisms, *Salmonella* spp., *Listeria monocytogenes*, and *Escherichia coli* O157:H7, in both thermally processed and PEF processed juices. A 30-member panel participated in the sensory tests. The panelists consisted of graduate students in the Department of Food Science and Technology at The Ohio State University and members of the food industry. Twenty-eight of 30 panelists were trained for a sensory test at least once before. Each panelist had consumed tomato products at least four times a week. The panelists were asked to rate the preference of appearance, color, texture, flavor, and overall acceptability by marking on a horizontal line corresponding to the amount of the perceived stimulus. The sensory evaluation was done by paired comparison. A hedonic scale of 1−9 was used for each attribute. The higher number represents higher preference of attributes. Thermally processed and PEF processed juices were served in randomly numbered plastic cups on a tray with a cup of water and a piece of nonsalted cracker at the beginning of the evaluation.

Statistical Analysis. Analysis of variance and Tukey's multiple-comparisons method at the 5% significance level were performed for the determination of significant differences among thermally processed, PEF processed, and control tomato juices. All of the analyses were duplicated. Minitab 13.31 (Minitab, Inc., State College, PA) was used for all statistical analyses.

RESULTS AND DISCUSSION

Effects of Thermal Processing and PEF Processing on Microbial Inactivation. The total aerobic plate count and the

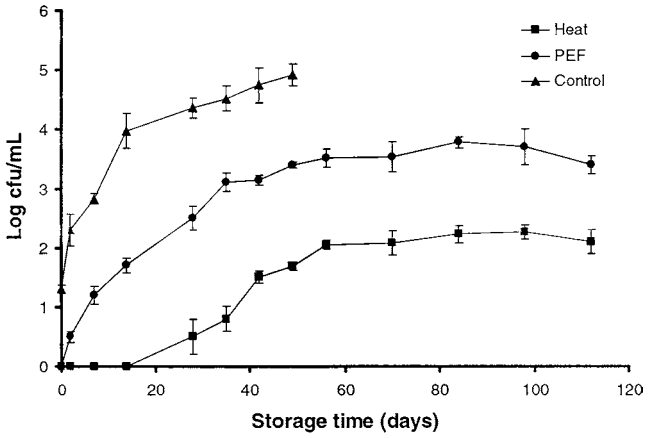

Figure 2. Effects of thermal processing and PEF processing on the total aerobic plate counts of tomato juice during storage at 4 °C for 112 days.

yeast and mold count in tomato juice incubated at 22 °C for 3 days were 1.0×10^6 and 7.9×10^5 CFU/mL, respectively. Both total aerobic plate count and the yeast and mold count were reduced to <10 CFU/mL (est) after either thermal or PEF processing. Thermal processing and commercial scale PEF processing reduced endogenous microorganisms of tomato juice by 6 logs.

Successful inactivation of yeasts including *Saccharomyces cerevisiae* and *Zygosaccharomyces bailii* by PEF was reported (*18*−*20*). Microscopic examination indicated that the major microorganism in control tomato juice was yeast. Yeasts and molds are the major spoilage microorganisms in juice products due to their survival and growth at low-pH environments and use of sugars and vitamins in juices (*21*). Yeasts are more tolerant to high temperature than bacteria (*22*). The temperature of tomato juice increased from 45 to 53 °C and maintained at 53 °C for 5 s during the PEF processing. To investigate the effect of thermal treatment at 53 °C for 5 s on the yeast and mold counts of the tomato juice incubated at 22 °C for 3 days, the incubated tomato juice was only thermally processed at 53 °C for 5 s and plated on PDA. The numbers of yeasts and molds on PDA before and after the thermal processing at 53 °C for 5 s were 7.9×10^5 and 6.3×10^5 CFU/mL, respectively, and were not significantly different from each other ($p > 0.05$). The temperature increase from 45 to 53 °C and the holding at 53 °C for 5 s do not cause the 5.9 log reduction of yeasts and molds. Therefore, the inactivation of yeasts and molds was due to PEF. Commercial scale PEF processing was effective for the inactivation of endogenous microorganisms in tomato juice.

Effects of Thermal Processing and PEF Processing on the Microbial Stability during Storage. Effects of thermal processing and PEF processing on the total aerobic plate counts and the yeast and mold counts of tomato juice during storage at 4 °C for 112 days are shown in **Figures 2** and **3**, respectively. The initial total aerobic plate count of the control hot break juice at 0 days was 10 CFU/mL (est). Both PEF and thermally processed juices had <10 CFU/mL (est) aerobic microorganisms at 0 day. The number of total aerobic microorganisms in thermally processed juice was <100 CFU/mL during the storage at 4 °C. The number of total aerobic microorganisms of PEF processed juice was $<1.0 \times 10^4$ CFU/mL during storage at 4 °C for 112 days, whereas that of control juice reached 1.0×10^5 CFU/mL at 4 °C after 49 days. Control juice was not sampled after 49 days due to the gas formation by multiplied microorganisms. The initial yeast and mold count of control hot break juice at 0 day was 20 CFU/mL. The yeast and mold counts of thermally processed juice were <10 CFU/mL and

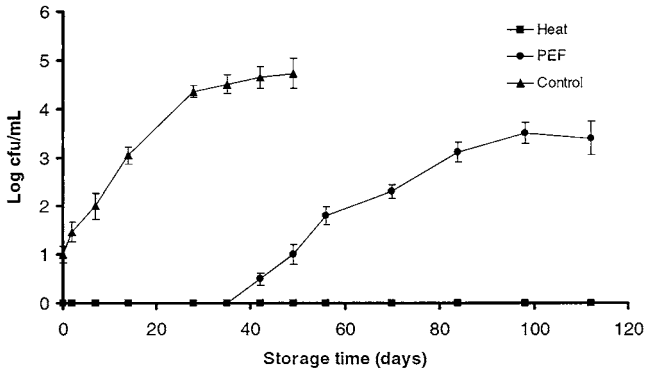

Figure 3. Effects of thermal processing and PEF processing on the yeast and mold counts of tomato juice during storage at 4 °C for 112 days.

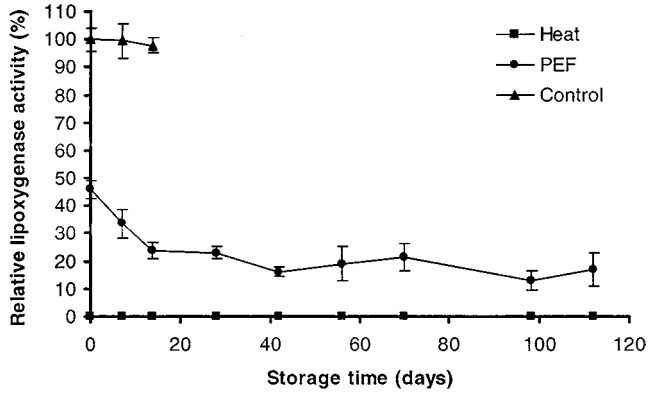

Figure 4. Effects of thermal processing and PEF processing on the lipoxygenase activity of tomato juice during storage at 4 °C for 112 days. Lipoxygenase activity of the thermally processed tomato juice was under the detection limit.

those of PEF processed juice were $<1.0 \times 10^4$ CFU/mL during storage at 4 °C for 112 days.

The higher rate of microbial growth in PEF processed juice than in thermally processed juice during storage may be due to the relatively lower inactivation of the spores by PEF and the germination of the surviving spores during storage. Spores of *Bacillus* and ascospores of molds and yeasts were detected from the PEF processed tomato juice by a microscopic examination. Most studies reported that PEF does not efficiently inactivate bacterial spores (*23*, *24*). Little or no effect of PEF on the inactivation of mold ascospores, including *Byssoclamys nivea* ascospores and *Neosartorya fischeri* ascospores in tomato juice, was also reported (*6*, *23*). A higher number of spores of *Bacillus* and ascospores of molds and yeasts probably survived in PEF processed juice than in thermally processed juice so that there was more growth of microorganisms in PEF processed juice than in thermally processed juice. PEF processing can be effective for microbial inactivation, extending the shelf life of foods, but not for complete disintegration of microorganisms including spores (*23*).

Effects of Thermal Processing and PEF Processing on Lipoxygenase Activity. Effects of thermal processing and PEF processing on the lipoxygenase activity of tomato juice during storage at 4 °C for 112 days are illustrated in **Figure 4**. Lipoxygenase activity was not detected in thermally processed juice throughout the storage at 4 °C for 112 days. Commercial scale PEF processing inactivated 54% of the lipoxygenase in the cold break juice. The reduced lipoxygenase activity in PEF processed juice decreased further during the storage at 4 °C.

Table 1. Effects of Thermal Processing and PEF Processing on the Concentration of Lycopene of Tomato Juice during Storage at 4 °C for 112 Days[a]

storage time (days)	concn of lycopene (mg/100 g)		
	thermally processed tomato juice	PEF processed tomato juice	control tomato juice
0	11.91 ± 0.29a	11.92 ± 0.35a	12.14 ± 0.28a
7	8.42 ± 0.47a	9.55 ± 0.48b	9.75 ± 0.50b
14	8.41 ± 0.51a	8.85 ± 0.49a	9.44 ± 0.52a
28	6.86 ± 0.28a	7.60 ± 0.30b	8.09 ± 0.38b
35	5.86 ± 0.55a	6.60 ± 0.47a	6.95 ± 0.56a
42	5.78 ± 0.31a	6.21 ± 0.25a	6.21 ± 0.28a
49	5.58 ± 0.50a	6.03 ± 0.41a	ND
56	5.50 ± 0.24a	5.80 ± 0.42a	ND
70	5.15 ± 0.37a	5.61 ± 0.31a	ND
84	4.65 ± 0.52a	5.66 ± 0.51a	ND
112	4.08 ± 0.25a	5.73 ± 0.27b	ND

[a] Values are mean ± SD from duplicates of four measurements; different letters in the same row indicate significant differences ($p < 0.05$). ND: not determined.

The lipoxygenase in tomato juice was irreversibly inactivated by thermal or PEF processing.

Most desirable fresh flavor compounds in tomatoes including hexanal, *cis*-3-hexenal, *trans*-2-hexenal, hexanol, *trans*-2-hexenol, and *cis*-3-hexenol are generated from unsaturated fatty acids such as linoleic and linolenic acid (*25*). Lipoxygenase plays an important role in the formation of the flavor compounds through the oxidation of unsaturated fatty acids (*26*). PEF processed tomato juice may possess a fresher flavor than thermally processed juice due to the activity of the residual lipoxygenase.

Conformational changes of enzymes are suggested as the mechanism of enzyme inactivation by PEF; however, further research is required (*23*, *27*). PEF does not inactivate enzymes to the extent of thermal processing.

Effects of Thermal Processing and PEF Processing on the Concentration of Lycopene. Effects of thermal processing and PEF processing on the concentration of lycopene in the tomato juice during storage at 4 °C for 112 days are shown in **Table 1**. The concentrations of lycopene in thermally processed and PEF processed juices decreased from 11.9 to 4.08 mg/100 g and from 11.9 to 5.7 mg/100 g, respectively, after 112 days at 4 °C. The concentration in control juice decreased from 12.8 to 6.2 mg/100 g after 42 days. There was no significant difference in the concentration of lycopene among thermally processed, PEF processed, and control juices during storage ($p > 0.05$). The concentration of lycopene decreased as storage time increased regardless of processing methods.

The concentration of lycopene did not change significantly after thermal or PEF processing ($p > 0.05$). Lycopene is chemically more stable than other pigments of plant or animal origin such as chlorophyll, anthocyanin, hemoglobin, and myoglobin (*2*). Lycopene in tomato products is resistant to degradation including thermally induced trans−cis isomerization reactions (*28*). It was proposed that tocopherols, ascorbic acid, and phenolic antioxidants help to stabilize lycopene during processing (*29*).

The main cause of carotenoid degradation in foods is oxidation (*3*). Oxygen in the headspace of the sampling tube would cause the oxidation of lycopene in tomato juice. The losses of lycopene in thermally processed, PEF processed, and control tomato juices for 7 days were most significant throughout the storage ($p < 0.05$). This may be due to the high oxygen availability in the headspace of the sampling tubes during the early storage period. Rodriguez-Amaya (*30*) found that the stability of carotenoids of foods depends on oxygen availability and packaging conditions.

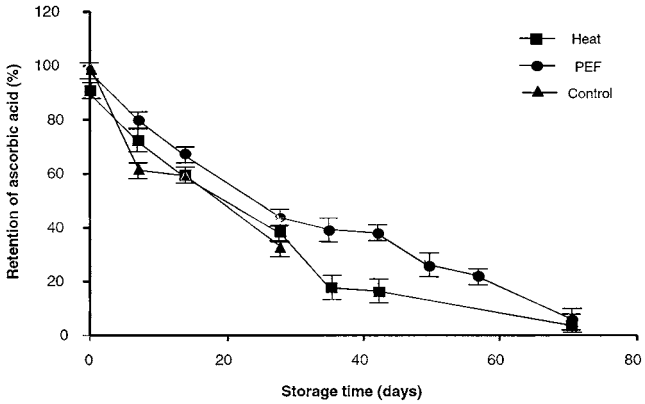

Figure 5. Effects of thermal processing and PEF processing on the retention of ascorbic acid of tomato juice during storage at 4 °C for 70 days.

Effects of Thermal Processing and PEF Processing on the Retention of Ascorbic Acid. The effects of thermal processing and PEF processing on the concentration of ascorbic acid during the storage at 4 °C for 112 days are illustrated in **Figure 5**. Ascorbic acid decreased 10% after thermal processing ($p < 0.05$) but did not decrease significantly after PEF processing ($p > 0.05$). The concentration of ascorbic acid in tomato juice decreased as the storage time increased regardless of processing methods. However, a higher retention of ascorbic acid in PEF processed juice than in thermally processed juice was observed during storage until 42 days ($p < 0.05$).

Thermal processing in the manufacture of vegetable juices caused a noticeable loss of ascorbic acid (*31*). Heat generated during thermal processing initiates and accelerates chemical reactions in foods (*32*). Ascorbic acid is a heat sensitive nutrient (*33*). The higher retention of ascorbic acid of PEF processed juice than of thermally processed juice might be due to the low processing temperature of PEF processing.

The difference between the concentrations of ascorbic acid of thermally processed juice and PEF processed juice decreased as storage time increased, and no difference was observed after 70 days ($p > 0.05$). The oxygen in the headspace of the package and the oxygen permeated through the package are considered to limit the shelf life of food products (*4*, *34*). The minimization of oxygen in the headspace of the package and of oxygen permeation through the package is essential to obtain minimal oxidative degradations of ascorbic acid, flavor, and color (*35*). The high concentration of ascorbic acid of PEF processed juice during early storage time can be extended over time by selecting proper juice packaging materials such as poly(ethylene terephthalate) (PET) (*36*) and methods such as nitrogen flushing into packages (*37*).

Effects of Thermal Processing and PEF Processing on the Particle Size Distribution, °Brix, pH, and Viscosity. Effects of thermal processing and PEF processing on the particle size distribution of tomato juice are shown in **Table 2**. A particle size distribution is a particle parameter as a function of the particle size such as volume and surface area (*38*). $D[4, 3]$ and $D[3, 2]$ are means of particles on the basis of volume and surface area, respectively (19.5). $D[4, 3]$ and $D[3, 2]$ of PEF processed tomato juice were significantly smaller than those of thermally processed and control juices ($p < 0.05$). Yeom and others (*10*) found that orange juice processed by a pilot plant scale PEF system at 35 kV/cm for 59 μs contained significantly smaller particle size than orange juice thermally processed at 94.6 °C

Table 2. Effects of Thermal Processing and PEF Processing on the Particle Size Distribution of Tomato Juice

	D[4, 3]			*D*[3, 2]			*D*(v, 0.1)			*D*(v, 0.5)			*D*(v, 0.9)		
	heat[a]	PEF[a]	control[a]	heat	PEF	control	heat	PEF	control	heat	PEF	control	heat	PEF	control
av[b] (μm)	281.11a	273.32b	277.06c	123.70a	115.33b	119.43c	126.81a	120.26b	122.78c	284.84a	276.38b	280.71b	445.72a	437.93b	441.69a
SD[c] (μm)	2.24	1.75	1.46	1.84	1.40	2.06	1.38	0.98	1.18	2.43	2.75	1.58	2.66	2.06	1.39

[a] Heat = thermally processed tomato juice; PEF = PEF processed tomato juice; control = control tomato juice. [b] Average of four replicates. Different letters indicate significant differences ($p < 0.05$). [c] Standard deviations.

for 30 s. Miki and Akatsu (*39*) reported that the preparation methods of tomato products such as homogenization and ultrasonication markedly influenced the particle size distributions of the products. They found that tomato products showed uniform dispersion of lycopene when their particle sizes are small.

D(v, 0.5) is the median of the particle size distribution on the basis of volume (*17*). *D*(v, 0.5) values of thermally processed, PEF processed, and control tomato juices were higher than *D*[4, 3] values (**Table 2**). This indicates that the particle size distributions on the basis of volume were left-skewed.

D(v, 0.5) values of PEF processed and control juices were not significantly different ($p > 0.05$), whereas the *D*[4, 3] value of PEF processed juice was significantly smaller than that of control juice. The actual particle size of tomato juice might be not changed by PEF processing. It is likely there was change in the volume of particles. Coagulated substances in pulp might be separated by PEF processing, resulting in a significant change in the volume but an insignificant change in the actual particle size.

Thermally processed juice had the largest particle size distribution in all measurements ($p < 0.05$). The colloidal materials in juice products are usually coagulated by heating and settle out readily (*40*). The larger particle size of thermally processed juice compared with PEF processed and control juices may be due to the coagulation of colloidal materials in tomato juice.

The °Brix values for thermally processed tomato juice and PEF processed tomato juices were 5.20 ± 0.10 and 5.14 ± 0.13, respectively, during storage at 4 °C for 112 days. There was no significant difference in the °Brix between thermally processed and PEF processed juices ($p > 0.05$). However, the °Brix of control juice decreased from 5.20 to 4.64 during storage for 49 days. This significant decrease ($p < 0.05$) in the °Brix of control juice during storage may be due to the high growth of microorganisms and their consumption of soluble solids.

The pH values of thermally processed, PEF processed, and control juices were 4.27 ± 0.06, 4.30 ± 0.05, and 4.33 ± 0.07, respectively, during storage at 4 °C for 112 days. There was no significant change in pH in thermally processed, PEF processed, and control juices during storage ($p > 0.05$). No significant change ($p > 0.05$) in the °Brix and pH of thermally processed and PEF processed juices during storage for 112 days may be related to the effective inactivation of spoilage microorganisms by thermal processing and PEF processing.

The viscosity of the control juice was 381 ± 42 mPa·s. The viscosity of tomato juice was not significantly changed after either thermal or PEF processing ($p > 0.05$). This may be due to the effective inactivation of pectic enzymes such as pectin-galacturonase (PG) and pectin methylesterase (PME) by the hot break. The hot break might sufficiently inactivate pectic enzymes. Pectic enzymes depolymerize pectin molecules in tomato pulp or serum and cause a decrease in the viscosity of tomato products (*3*, *41*). The interaction between pectins and proteins, which forms a reversible electrostatic complex, is also an important contributor to the viscosity of tomato juice (*3*). The maximum pectin−protein interaction occurs at pH 4.0−4.5, within which all thermally processed, PEF processed, and control juices ranged during the storage.

Effects of Thermal Processing and PEF Processing on Sensory Quality. There were significant differences in flavor and overall acceptability between thermally processed and PEF processed juices ($p < 0.05$). The panel scores for flavor were 4.7 for thermally processed juice and 6.2 for PEF processed juice. The panel scores for overall acceptability were 4.8 for thermally processed juice and 6.2 for PEF processed juice. A higher number indicates a higher preference. The flavor and overall acceptability of PEF processed tomato juice were preferred to those of thermally processed juice.

Thermal processing strongly changes the sensory property of tomato products, including fresh tomato flavors (*42*). The higher flavor intensity of PEF processed juice compared with thermally processed juice may be related to the higher activity of lipoxygenase of PEF processed tomato juice (**Figure 4**). The lipoxygenase forms hexanal, *cis*-3-hexenal, *trans*-2-hexenal, hexanol, *trans*-2-hexenol, and *cis*-3-hexenol, which are responsible for the fresh flavor of tomato juice (*25*). Freshness is likely to be determined by consumers with their perceptions (*43*), and flavor is an important element in consumers' perceptions of the freshness of juice products. The overall acceptability of tomato juice may be mainly determined by freshness. The higher ranking of PEF processed juice in flavor intensity and overall acceptability compared with thermally processed juice may be associated with the higher freshness of PEF processed tomato juice compared with thermally processed juice.

ACKNOWLEDGMENT

We thank Dr. F. Ozadali (Hirzel Canning Co. and Farms) for supplying fresh tomatoes. We thank Dr. S. Schwartz, B. Keller, and J. Lee for technical support. We acknowledge Dr. H. Wang, S. K. Min, S. N. Rao, and R. Caldwell for the preparation of tomato juice and the operation of the PEF system.

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Received for review October 17, 2002. Revised manuscript received March 11, 2003. Accepted March 25, 2003. We acknowledge the DoD Dual Use Science and Technology Program for funding this research.

JF0260444