



Article

Postharvest Preservation of Thai Mango var. Chok-Anan by the Combination of Pulsed Electric Field and Chemical Pickling

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Abstract: Mango is one of the most favorable tropical fruits grown and consumed in several parts of the world. However, there is overproduction during the ripening stage. In this situation, appropriate techniques are needed to utilize the abundant supply. Pickling is one of the oldest and most successful methods for preserving mango. In this study, mango pickles were prepared by using chemical pickling assisted with pulsed electric field (PEF). The physicochemical and textural properties of mango pickles prepared with PEF at 30 and 50 °Brix were studied in comparison with the conventional pickling process. The water loss, solids gain, and diffusion efficiency were increased by twofold when PEF was applied in pickling Thai mango variety Chok-anan. This process also reduced the moisture content and water activity. The PEF-assisted pickling process caused changes in lightness (L^*) and redness (a^*) values. The textural properties of the mango pickles produced by the PEF-assisted pickling process were also changed. In addition, the PEF-assisted pickling process caused a 20% increase in beta-carotene content and a 47% decrease in ascorbic acid content. The microstructure of the mango was more disintegrated on the surface after PEF than that from the conventional pickling process.



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Keywords: preservation; Thai mango; pickling process; pulsed electric field; decrease excess supply

1. Introduction

Mangifera indica, commonly known as mango, is a perennial fruit crop and one of the most commercialized fruits in several countries [1]. It is rich in several bioactive components with antioxidant and anti-inflammatory activity such as carotenoids, ascorbic acid, and phenolic compounds [2]. Mango fruits are harvested at a mature green stage, ripen within 6–10 days, and take 15 days to become overripe and spoiled [3], at which point they cannot be consumed and must be eliminated. Because of its diverse nature and vast growing area, mango suffers from a large supply during the ripening seasons, which leads to a decrease in the price and abundance of unsold fruit [4]. In addition, postharvest waste occurs in producing countries due to insufficient handling, transport, and storage. Therefore, to make mangoes more commercially valuable by prolonging their shelf life, various techniques are used, namely, ozone, electrolyzed water, ultraviolet radiation, ultrasound, high pressure [5], and coating with edible polymers [6]. However, these methods use more pieces of equipment and technology, which might not be suitable for farmers. There are several types of preserved mango products such as canned slices in syrup, juice, nectar, jam, chutney, and dehydrated mango [7]. However, these preserving processes are conducted at the ripening stage. One of the methods used to minimize loss is utilizing green fruit for making pickles [8]. Pickling is simply a preservation method and is an attractive process in an effort to produce all-natural and minimally processed foods [9]. In addition, pickles could be consumed as a side dish and act as appetizers and digestive agents [10]. A traditional method for fruit, vegetable, meat, and egg preservation

is pickling [11]. Pickling can be divided into two main categories: chemical pickling and fermentation [12]. In chemical pickling, the food product is placed in an edible solution, such as brine, vinegar, alcohol, sugar, or oil, to kill microorganisms, while fermentation involves microorganisms to produce a preservation agent [12]. In Thailand, ma-muang chae-im (sweet pickled mango) is a traditional preserved product [13]. Mango pickling is a sequential immersion process carried out by immersing mango pulp in a sugar solution [13]. Generally, sweet pickled mango is first immersed in a weaker sugar solution (30 °Brix) and then shifted to a 50 °Brix sugar solution [14]. Thus, during the immersion process there is mass transfer of the sugar solution and mango pulp [13]. However, the pickling process is ineffective for mass transfer, time-consuming, and difficult to control [15].

Several different innovative methods have been applied to increase the mass transfer from solutions into foods during the pickling process, such as pulse pressure [15,16] and pulsed electric field (PEF) [17]. PEF is a technique for pretreating fruits and vegetables, and it is widely applied in various food processing methods [18]. Although it has been well explored in several research studies that used PEF pretreatment in the dehydration of fruits such as kiwifruit [19], strawberries [20], mango [21], apple [22–25], and goji berry [26], there is a lack of research on the transfer of the chemical solution into pickled food by PEF; only Li et al. [17] applied PEF treatment to lotus root (*Nelumbo nucifera* Gaertn.) before the pickling process.

The PEF pickling of mango has not been thoroughly studied. Thus, in this study, we aim to utilize Thai-made PEF machines to assist the mango pickling process. Chok-anan mango is the most frequently used variety for producing preserved mango. This is because of their attractive color, flavor, taste, and nutritional properties [27]. This study's aim was to analyze the effectiveness of a PEE-assisted pickling process with 30 and 50 °Brix sucrose solutions on the moisture content, water activity, color, pH, beta-carotene content, ascorbic acid content, hardness, toughness, water loss, and solids gain of Chok-anan mango pickle. Moreover, the structure of the fresh and pickled mango tissues was evaluated at the microscale using a scanning electron microscope (SEM).

2. Materials and Methods

2.1. Mango Fruit and Sucrose Solutions Preparations

Mature green mango fruits (*Mangifera indica*; Chok-anan variety) were purchased from local farms in Chiang Mai, Thailand. The mangoes were washed with water, peeled with a knife, and sliced to separate the pulp and seeds. The sliced pulp was cut into 5 × 20 × 45 mm (height × width × length) rectangular-shaped pieces with a weight of 10 ± 1 g. A sucrose solution (30 and 50 °Brix) was prepared by mixing a commercial sugar (Mitrphol, Dan Chang, Thailand) with distilled water.

2.2. PEF Equipment

The PEF prototype was designed and built at the Research Unit of Applied Electric Field in Engineering (RUEE) Laboratory at Rajamangala University of Technology Lanna, Chiang Mai, Thailand (Figure 1a). This Thai-developed machine has a potential similar to that of PEF machines built in other countries [28]. The system consists of a control system, a treatment chamber, a spark gap, a 0–380 Vac variac, transformers with single-phase high voltage (33 kV), a 40 kV 2 A diode, a 40 kΩ charging resistor, and a 2 μF 40 kV pulse capacitor (Figure 1b).

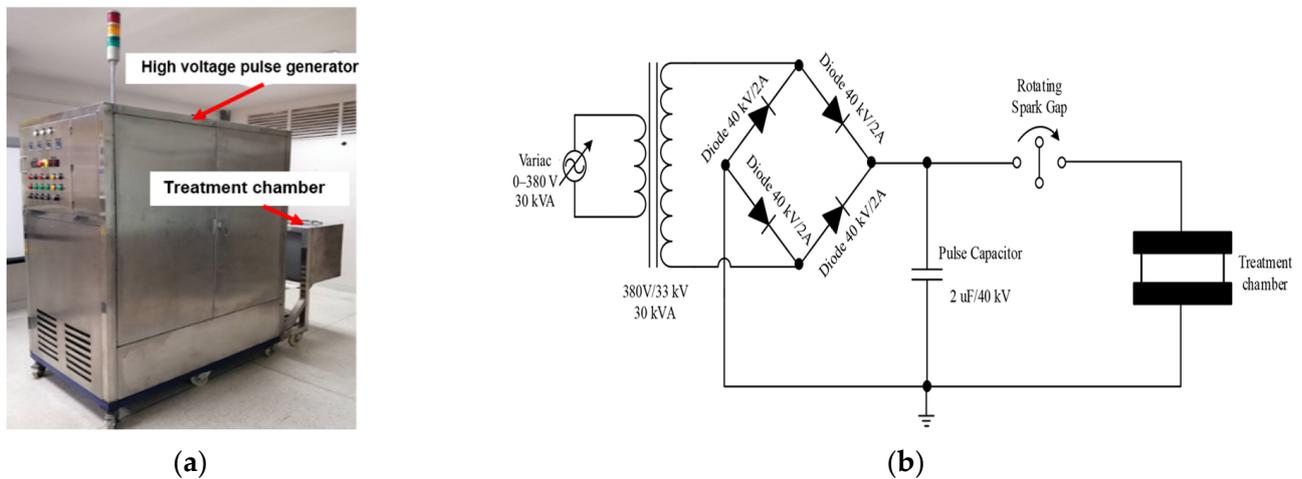


Figure 1. Thai PEF machine prototype (a) and PEF diagram (b) used in this study.

2.3. PEF-Assisted Pickling Process

The PEF-assisted pickling process was conducted by immersing 30 pieces of mango in 1 L of the sucrose solution and then putting the mixture into a 5 L PEF chamber (40 mm height \times 450 mm width \times 375 mm length). The experiment was set up by applying 500 pulses at a field strength intensity of 3 kV/cm and a frequency of 1 Hz. The average specific energy input under these conditions was 180.0 kJ/kg. The PEF chamber was maintained at ambient temperature. After the PEF process, the samples were left to pickle at ambient temperature for 24 h before analysis [14].

2.4. Conventional Pickling Process

Conventional mango pickling was conducted according to Uthairungsri et al. [14]. Briefly, 30 mango cubes were immersed in 1 L of the sucrose solution (30 °Brix and 50 °Brix) for 24 h.

2.5. Water Loss, Solids Gain, and Effective Diffusivity

The water loss (WL), solids gain (SG), and diffusion efficiency (DE) were evaluated by using Equations (1)–(3), respectively [19].

$$WL \text{ (g/g)} = \frac{(W_0 - M_0) - (W_t - M_t)}{M_0} \quad (1)$$

$$SG \text{ (g/g)} = \frac{M_t - M_0}{M_0} \quad (2)$$

$$DE = \frac{WL}{SG} \quad (3)$$

where:

W_0 = initial weight of the fresh mango (g)

W_t = weight of the sample after a time t of preservation (g)

M_0 = dry mass of the sample before preservation (g)

M_t = dry mass of the sample after a time t of preservation (g)

2.6. Physicochemical Analysis

2.6.1. Moisture Content, Water Activity, and pH

Following the AOAC method, an oven technique at 105 °C was used to estimate the moisture content of the mango samples until a constant weight was maintained [29]. The AquaLab Water Activity Meter (Decagon, Pullman, WA, USA) was used to determine the

water activity. A pH meter (Mettler Toledo, Columbus, OH, USA) was used to measure the pH value. All of the experiments were measured in triplicate.

2.6.2. Surface Color of the Mango

The surface color of the mango was evaluated in an $L^* a^* b^*$ system by a HunterLab chromameter (MiniScan EZ, Reston, VA, USA) [30]. The results were recorded in triplicate. The total color change (ΔE) and browning index (BI) were calculated using Equations (4)–(6), respectively.

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (4)$$

$$BI = \frac{100 \times (x - 0.31)}{0.17} \quad (5)$$

$$\text{where, } x = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \quad (6)$$

2.6.3. Beta-Carotene Content

The beta-carotene content of the mango was evaluated by high-performance liquid chromatography (HPLC) [31]. A mortar and pestle were used to ground the samples (0.1 g). Next, 1.5 mL of 95% n-hexane consisting of 0.75 mL of ethanol, and 0.75 mL of acetone was added to the samples. The samples were transferred to a centrifuge tube along with 5 mL of water. Centrifugation was performed for 10 min at 3000 rpm and 25 °C. An aliquot (5 mL) was taken and added to a new tube where it was combined with 5 mL of 95% n-hexane. The sample was filtered through a 0.2 μm syringe filter (ALWSCI corporation, Zhejiang, China) before the final sample (20 μL) was injected into an HPLC system (Agilent Technologies, Santa Clara, CA, USA) containing a C_{18} reverse-phase column (Waters C_{18} , 250 \times 4.6 mm, 5 μm particle size) and a photodiode array detector. Methanol and methyl-tert-butyl ether were used for the gradient elution at a detection wavelength of 470 nm and a flow rate of 1.0 mL/min. The measurement was done in triplicate. The beta-carotene content was calculated using a commercial standard.

2.6.4. Ascorbic Acid Content

The ascorbic acid content of the mango was measured according to the method of the National Bureau of Agricultural Commodity and Food Standards [32]. The mangoes (2.5 g) were ground and mixed with 3% m-phosphoric acid in a 100 mL volumetric flask. The mixtures were vigorously shaken for 2 min and then sonicated in an ultrasound bath for 5 min. An aliquot was then filtered through a 0.2 μm filter (CNW, China). The sample (20 μL) was injected into the HPLC system, and the optical density was measured at 248 nm using a UV detector at a flow rate of 0.5 mL/min. A mixture of 3 mM of potassium dihydrogen phosphate in 0.35% (v/v) o-phosphoric acid was used as the mobile phase. The ascorbic acid content was measured in triplicate.

2.7. Texture Analysis

The hardness and toughness of the mango samples were measured with a texture analyzer (TA-XT plus, Stable Micro Systems, Surrey, UK) equipped with a stainless-steel probe of 5 mm in diameter. The pre-test, test, and post-test speeds were 1.5, 1.5, and 100 mm/s, respectively. The tests were done in ten replications.

2.8. Electrical Conductivity Disintegration Index (Z)

Immediately after the PEF, the electrical conductivity of the samples was measured using a conductometer (TDS&EC meter, Zhejiang, China). The electrical conductivity

disintegration index (Z) evaluated the degree of tissue damage (Z) [33], as presented in Equation (7).

$$Z = \frac{(\sigma - \sigma_i)}{(\sigma_d - \sigma_i)} \quad (7)$$

where σ is the measured electric conductivity value (S/m), and the subscripts i and d refer to the conductivity of the initial mango (fresh) and completely damaged tissues, respectively.

2.9. Surface Morphology

The surface morphology of the fresh mango, conventionally pickled mango, and PEF-assisted pickled mango was examined using an SEM (PrimaTM E, Thermo Scientific, Waltham, MA, USA). The samples were cleansed of the pickling agent by rinsing with water and then cut into 1 × 1 cm pieces. The cut mango was placed on SEM stubs using double-faced tape and a photograph taken at an excitation voltage of 5 kV using image processing software (PentaFETTM precision, X-act, Oxford Instruments, Abingdon, UK).

2.10. Statistical Analysis

The experimental values are expressed as the average and standard deviation (S.D.). Post hoc testing was completed using Duncan's multiple range test, SPSS version 17.0 (IBM, Armonk, NY, USA). ANOVA was used for the significance analysis. A significant difference is indicated by $p < 0.05$.

3. Results and Discussion

3.1. Effect of PEF-Assisted Pickling Process on Water Loss, Solids Gain, and Diffusion Efficiency

The variations of WL, SG, and DE due to the conventional and PEF-assisted pickling processes with 30 °Brix and 50 °Brix sucrose solutions were compared (Figure 2a–c). The results show that WL (Figure 2a) and SG (Figure 2b) depended on the process conditions.

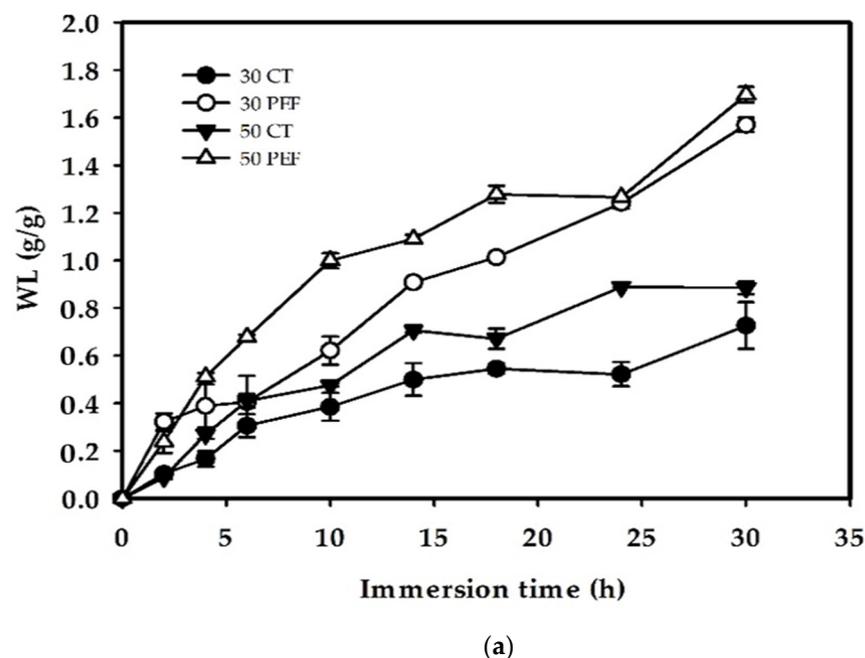
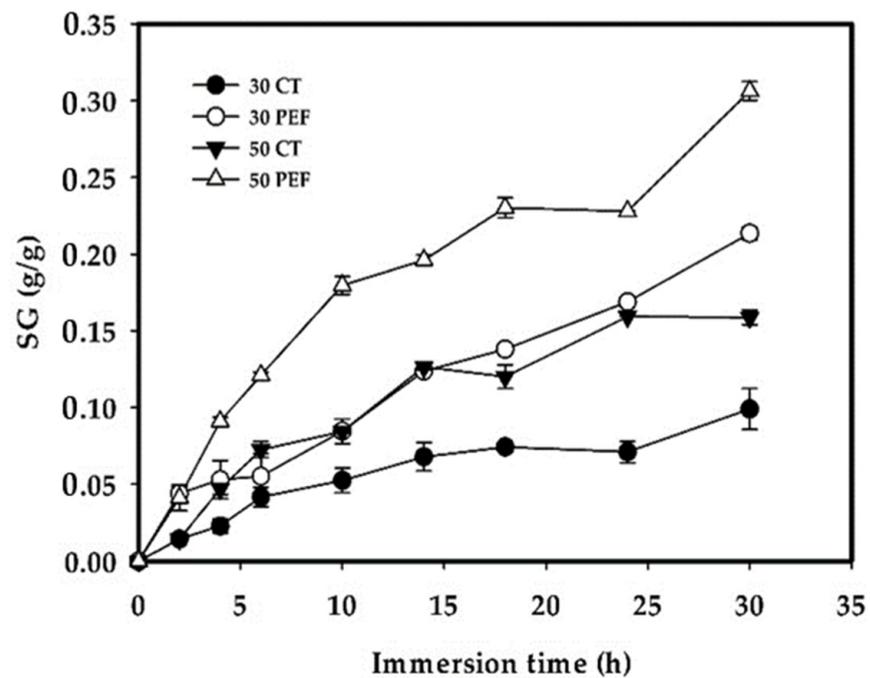
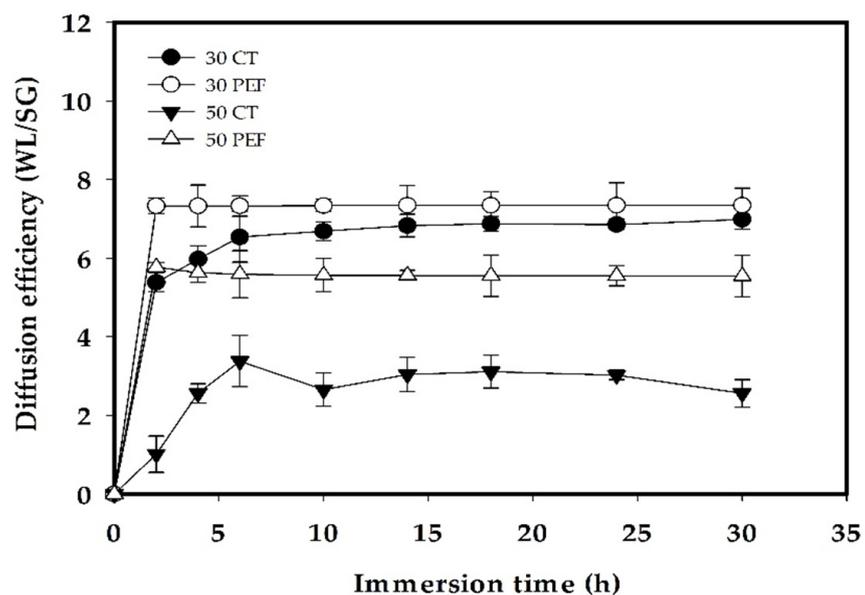


Figure 2. Cont.



(b)



(c)

Figure 2. Time course of the mango pickles: (a) water loss (WL) and (b) solids gain (SG), and (c) diffusion efficiency (DE) for conventional pickling at 30 °Brix (●) and 50 °Brix (▼), and PEF-assisted pickling at 30 °Brix (○) and 50 °Brix (△).

An increase in the WL and SG values resulted from the increase in immersion time. WL is a significant factor of the mass transfer that presents the osmotic efficiency [34]. The increase in osmotic pressure gradients presented a greater WL in the mango immersed in a higher concentration of sucrose (50 °Brix). A longer pickling process contributed to a greater WL. This was due to the combined action of different mass transport mechanisms such as hydrodynamics and osmo-diffusion [19]. The water from the sugar layer defused into the pickling solution, causing the sugar layer thickness and viscosity to increase and in turn increasing SG [24]. There were differences in the values of these parameters between

the 30 °Brix and 50 °Brix sucrose solutions, and they were slightly higher than those for the conventionally pickled samples. It seems that the use of the PEF-assisted pickling process was more potent in increasing WL and SG values: by 2.15 and 2.10 times for the 30 °Brix solution and by 1.93 and 1.94 times for the 50 °Brix solution, respectively, at the end of the pickling process. The 30 °Brix sugar solution gave a lower process driving force, which may have caused a greater number of cell layers to be affected by the diffusion solution, causing the membranes to be denatured, allowing diffusion through a wider area in the mango, and promoting WL and SG values [35].

The DE ratio was used to investigate the relation between the transfer of solids (SG) into the tissue and the removal of water (WL) from the objects [36]. A high efficiency was attributed to a higher value of WL/SG (Figure 2c). The conventionally pickled mango showed a lower diffusion ratio and took a longer time to reach an equilibrium state, while the PEF-assisted pickling process could effectively shorten this phenomenon by increasing cell membrane permeability, which agrees with Li et al. [17]. For the PEF-assisted process, the mango pickled in the 30 °Brix sucrose solution had a higher WL/SG ratio (7.35) than the mango pickled in the 50 °Brix sucrose solution (5.25). The efficiency of electroporation can explain this phenomenon, due to factors such as the size of the pores formed [36]. In addition, a low concentration presents a greater diffusivity of the substances [37]. However, it seems that the PEF-assisted pickling of mango at 50 °Brix could increase the diffusion rate by 2.16 times, which was more than that for the mango pickled in the 30 °Brix solution (1.05 times).

The different structural effects induced by PEF can explain this behavior. [36]. Mass transfer action was accelerated by diffusion coupled with the action of hydrodynamic mechanisms [35]. Li et al. [17] suggested that different mass transfer outcomes during the pickling process result from the PEF-enhanced permeability of the membrane.

3.2. Effect of the PEF-Assisted Pickling Process on Moisture Content, Water Activity, and pH

The variations in the moisture content, water activity, and pH due to the conventional and PEF-assisted pickling processes with 30 and 50 °Brix sucrose solutions were compared at the end of the process (Table 1). The initial moisture content of fresh mango was $84.63 \pm 0.54\%$, and the water activity was 0.990 ± 0.001 . A decrease in moisture content and water activity after the pickling process was observed. The use of PEF significantly reduced the moisture content of both the 30 °Brix- and 50 °Brix-pickled mango. However, it was found that the 50 °Brix-pickled mango had a greater change in moisture content than that pickled in the 30 °Brix sugar solution. The moisture content of the 30 °Brix-pickled mango was reduced by 20%, while that of the 50 °Brix-pickled mango was reduced by 30%, which was two times higher than that of the conventionally pickled mango. PEF causes electroporation and enhances the moisture transfer rate [38]. The water activity for the PEF-assisted pickling process with 30 and 50 °Brix sucrose solutions was reduced by 0.006 and 0.008, respectively, in comparison with the conventional process. It seems that the PEF-assisted pickling process with the 50 °Brix sucrose solution reduced water activity most effectively. This is the result of the high sucrose gain during the pickling process, which is correlated with the SG results (Figure 1b).

The pickling conditions did not result in a significant ($p < 0.05$) difference in the pH values of the mango pulp. However, a decrease in the pH value from 4.77 to 3.80 was shown for the PEF coupled with the 30 °Brix sugar solution and from 3.34 to 3.32 for the PEF coupled with the 50 °Brix solution. This might be due to enzyme activity during the pickling process and the attribution of native acid lixiviation during the application of PEF [39].

Table 1. Moisture content, water activity, and pH for the conventional and PEF-assisted pickling processes with 30 °Brix and 50 °Brix sucrose solutions (processing time = 24 h) ¹.

Conditions	Parameters			
	Moisture (%)	Water Activity	pH (Pulp) ^{ns3}	pH (Solution)
Fresh mango	84.63 ± 0.54 ^{a2}	0.990 ± 0.001 ^a	3.01 ± 0.01	-
Conventional pickling				
30 °Brix	80.94 ± 0.49 ^b	0.964 ± 0.002 ^b	3.05 ± 0.04	4.77 ± 0.10 ^a
50 °Brix	68.41 ± 0.01 ^c	0.977 ± 0.001 ^b	3.21 ± 1.66	3.34 ± 0.21 ^c
PEF-assisted pickling				
30 °Brix	71.16 ± 0.21 ^c	0.958 ± 0.000 ^c	3.03 ± 0.34	3.80 ± 0.05 ^b
50 °Brix	61.54 ± 0.03 ^d	0.969 ± 0.007 ^b	3.10 ± 0.19	3.32 ± 0.01 ^c

¹ The values are expressed as the mean ± standard variation ($n = 3$). ² Duncan's multiple range test shows that a–d within the same column are statistically different at $p < 0.05$. ³ ns is a non-significant difference ($p > 0.05$).

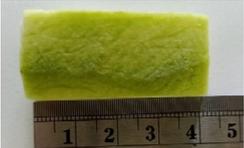
3.3. Effect of the PEF-Assisted Pickling Process on Appearance and Color

The appearances of the fresh mango, conventional pickled mango, and PEF-assisted pickled mango are represented in Table 2. Color analysis showed that the application of PEF caused increased redness. A brighter product is represented by a higher L^* value. Red to green and yellow to blue colors are represented by positive and negative a^* and b^* values, respectively. In this study, the application of PEF coupled with the pickling process tended to increase the brightness (L^*) and redness (a^*) of the products. However, the b^* and ΔE parameters for PEF coupled with the pickling process did not change in comparison with the conventional process. The increase in L^* is associated with the transparency gained due to the air loss in the pores by the impregnation of the solution [40], while the higher a^* value of the PEF-assisted pickled mango resulted from the enzymatic browning reaction occurring during the PEF treatment [36]. Our results also confirmed that melanoidin formation and a Maillard reaction occurred in the conventional process, which presented an increase in BI from 70.05 ± 1.55 to 94.34 ± 14.54 for the 30 °Brix solution and 84.77 ± 13.99 for the 50 °Brix solution, while the use of PEF coupled with the pickling process exhibited a non-significant difference ($p < 0.05$) of the BI values of 66.98 ± 2.37 and 75.12 ± 0.76 for the 30 °Brix and 50 °Brix solutions, respectively. This result was consistent with that of Cserhalmi et al. [41], who showed that the use of PEF inhibited a non-enzymatic browning reaction for grapefruit, lemon, orange, and tangerine.

3.4. Effect of PEF-Assisted Pickling Process on Texture Properties

The changes in the hardness and toughness of the conventionally pickled mango and PEF-assisted pickled mango are shown in Table 3. The hardness and toughness of the fresh mango were 51.27 ± 0.98 N and 189.13 ± 45.48 mJ/m³, respectively. In this study, it was found that osmotic treatment significantly decreased hardness and toughness in both the conventionally pickled mango and PEF-assisted pickled mango, the hardness being reduced by 43.39–65.23% and the toughness by 62.75–88.54%. Diffusion leads to a decrease in the firmness and hardness of plant tissues. This is brought about through plasmolysis, vacuole compartment shrinkage, the dissolution of plant cells' middle lamella, and changes in the structure and size of the outer pericarp's cell wall [42]. The reduction in hardness and toughness by PEF coupled with the pickling process was probably due to the creation of pores and the rupture of the internal structure, resulting in increased softening of the plant tissues [17].

Table 2. Appearance and color values of fresh, conventionally pickled, and PEF-pickled mangoes at the 30 °Brix and 50 °Brix solutions ¹.

	Fresh Mango	Conventional Pickling		PEF-Assisted Pickling	
		30 °Brix	50 °Brix	30 °Brix	50 °Brix
Appearance					
Top surface					
1: 0.5 cm					
- Side surface					
L^*	54.63 ± 2.08 ^{ab2}	52.27 ± 1.84 ^b	55.55 ± 1.58 ^{ab}	58.29 ± 3.40 ^{ab}	55.41 ± 2.50 ^{ab}
a^*	-3.14 ± 0.25 ^d	-0.77 ± 0.06 ^b	-1.13 ± 0.05 ^c	1.95 ± 0.02 ^a	2.09 ± 0.14 ^a
b^*	29.81 ± 1.41 ^b	33.65 ± 4.52 ^a	33.43 ± 4.60 ^a	28.43 ± 0.93 ^b	29.41 ± 1.53 ^b
ΔE ^{ns3}	0	5.83 ± 2.66	5.51 ± 2.58	7.03 ± 1.64	5.92 ± 0.51
BI	70.05 ± 1.55 ^{bc}	94.34 ± 14.54 ^a	84.77 ± 13.99 ^{ab}	66.98 ± 2.37 ^c	75.12 ± 0.76 ^{bc}

¹ The values are expressed as the mean ± standard variation ($n = 3$).² Duncan's multiple range test shows that a–d within the same column are statistically different at $p < 0.05$. ³ ns is non-significant difference ($p > 0.05$).

Table 3. Texture properties for the conventional and PEF-assisted pickling processes with 30 °Brix and 50 °Brix sucrose solutions (processing time = 24 h) ¹.

Conditions	Texture Properties	
	Hardness (N)	Toughness (mJ/m ³)
Fresh mango	51.27 ± 0.98 ^{b2}	189.13 ± 45.48 ^a
Conventional pickling		
30 °Brix	38.03 ± 3.71 ^c	98.67 ± 8.12 ^c
50 °Brix	63.80 ± 0.07 ^b	136.98 ± 13.26 ^b
PEF-assisted pickling		
30 °Brix	23.36 ± 1.93 ^d	30.36 ± 4.82 ^d
50 °Brix	72.65 ± 1.98 ^a	114.82 ± 1.19 ^c

¹ The values are expressed as the mean ± standard variation ($n = 10$).² Duncan's multiple range test shows that a–d within the same column are statistically different at $p < 0.05$.

3.5. Effect of the PEF-Assisted Pickling Process on Beta-Carotene and Ascorbic Acid Content

The PEF processing significantly affected the contents of beta-carotene (Figure 3a) and ascorbic acid (Figure 3b) in the mango pickled with both 30 and 50 °Brix sugar solutions. Moreover, the concentration of beta-carotene increased by 20% with PEF processing compared with that of the fresh and conventionally pickled mangoes. The increase in beta-carotene was due to the leakage of chloroplasts from the broken cells along the cell surface during the PEF process [43]. Bot et al. [43] suggested that PEF can induce modification not only to cell membranes but also in carotenoid–protein conformation. Ascorbic acid and vitamin C are major antioxidants in foods and vegetables. In this study, the ascorbic acid

content of the fresh mango was 44.14 mg/100 g. Under the conventional pickling process, the ascorbic acid content was increased to 61.31 and 58.50 mg/100 g for the 30 °Brix sucrose solutions, respectively. However, the concentration of ascorbic acid in the mango subjected to PEF processing decreased by 26% compared to that in the fresh mango and by 47% compared to that of the conventionally pickled mango. The loss of ascorbic acid after PEF processing was due to faster leaching into the osmotic solution [19]. In addition, PEF also attacks the hydroxyl group, which belongs to the second carbon atom of ascorbic acid, to complete the conversion of the configuration [44]. Vitamin C oxidation catalyzed by ascorbate oxidase may also be inactivated by PEF. [45]. The change in ascorbic acid might be due to oxidation and other chemical reactions with decreased antioxidant activity [41]. However, this might be replaced with the increase in beta-carotene, which also exhibited antioxidant activity as well [46].

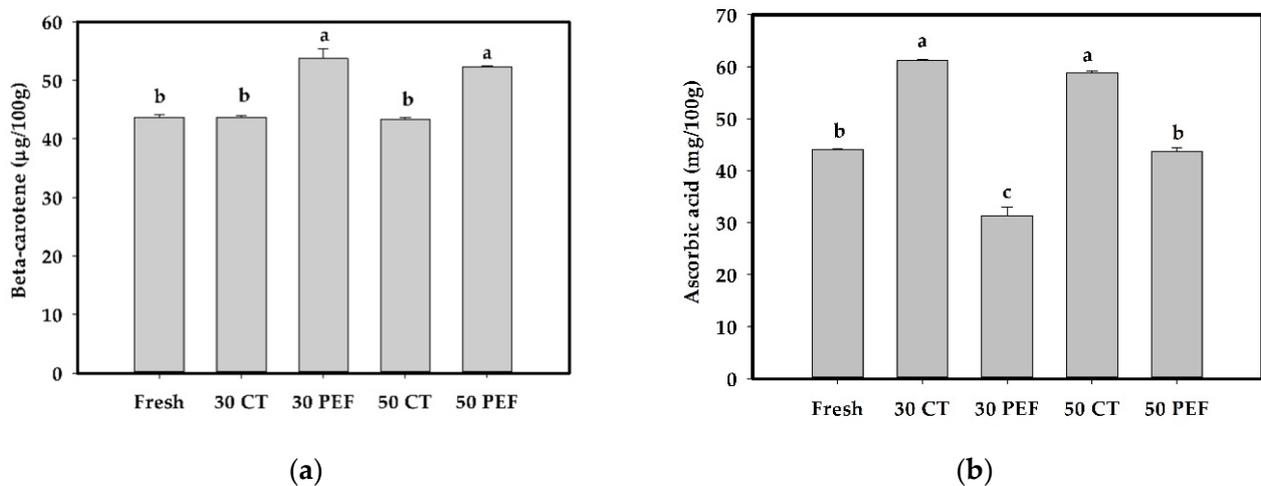


Figure 3. Beta-carotene (a) and ascorbic acid content (b) of the mango pickled with 30 °Brix and 50 °Brix sugar solutions after the PEF-assisted pickling process at 3 kV/cm, 1 Hz, and 500 pulses in comparison with that of the conventionally pickled mango and fresh mango. The values are expressed as the mean \pm standard variation ($n = 3$). Duncan's multiple range test shows that a–c within the same figure are statistically different at $p < 0.05$.

3.6. Effect of the PEF-Assisted Pickling Process on Microstructure and Cell Disintegration (Z)

The changes in the mango tissue structure are presented in Figure 4. A high degree of cell disintegration (Z) was found for the PEF-assisted pickling process at 30 °Brix ($Z = 0.65$). The use of PEF caused changes in the microstructure of the mango on both surface sides (top and side; yellow arrows). In the case of the top surface, the cavities were much larger than those on the side surface. However, they were smaller than those of the conventionally pickled mango and fresh mango. The change in the tissue structure was caused by the electroporation of PEF, which strengthened the electric field (cat-ions and an-ions) on the surface of the mango. The formation of pores around the cell membranes results from the destruction of tissue [45]. Electro-osmotic movement in the solution towards and through the membrane still persists, and the potential difference is preserved even though the concentration polarization is reduced and the later diffusion on the side surface is rapidly depleted. Because divalent ions have a higher sorption efficiency, they will interact with the membrane ion-exchange groups [46].

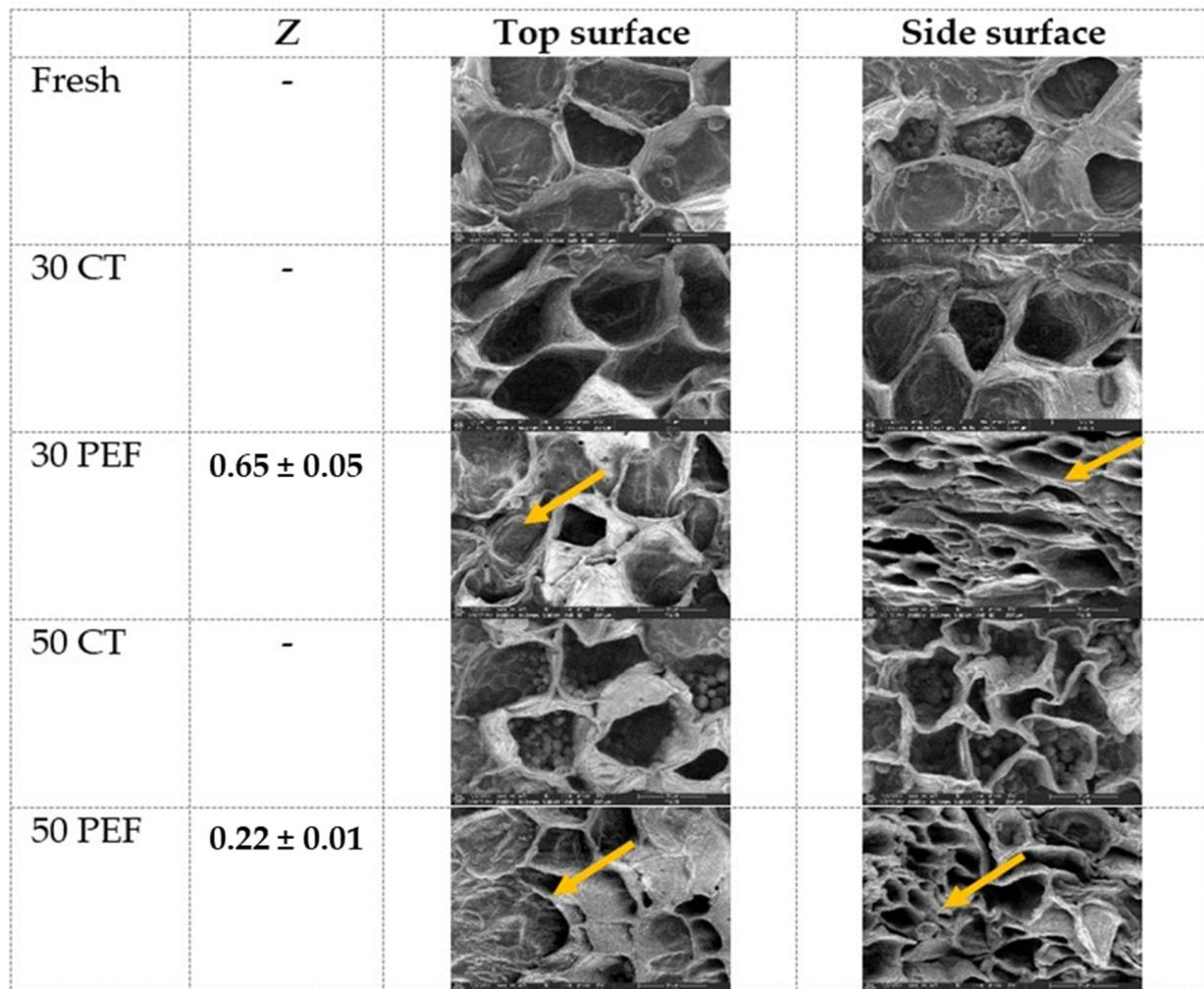


Figure 4. SEM images of the top and side surfaces of the fresh mango, conventionally pickled mango, and PEF-assisted pickled mango in both the 30 °Brix and 50 °Brix sucrose solutions ($\times 2000$). Yellow arrows show the disintegrated cell area.

4. Conclusions

The application of a Thai-built PEF system coupled with a pickling process on Thai mango variety Chok-anan is effective for increasing mass transfer and reducing moisture content and water activity. The PEF-assisted pickling process favored mass transfer regardless of the sucrose solution concentration (30 °Brix or 50 °Brix), without changes in the pH. The PEF-assisted pickling process caused undesirable changes in the redness (a^*) and lightness (L^*) values and a desirable loss of hardness and toughness. The PEF-assisted pickling process also caused changes in the beta-carotene and ascorbic acid contents as well as in the microstructure. These results might provide useful information for farmers or small and medium business operations to use the developed PEF machine in the pickling process in order to reduce the pickling time and costs because the machine is easy to handle and repair. In addition, the price of this developed PEF machine is significantly lower than those of imported PEF machines.

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