PROCESS OPTIMIZATION: ANALYSIS OF SUGARS MOVEMENT IN POTATO STRIPS UNDER DIFFERENT BLANCHING AND PEF TREATMENT

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Master of Professional Studies

by
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ABSTRACT

Objective: understand the effects of different blanching and PEF treatments on extraction of sugars (sucrose, glucose, and fructose), starch, and ions in potato strips. Potato strips (Russet Burbank, 3/8 inch) from different storage duration (4°C, 70 % RH) were treated under different blanching conditions and combined PEF-blanching treatments. It was observed that low temperature long time (LTLT) shows more sugar discharge during blanching process than high temperature short time (HTST). The leaching out of sugar in the whole potato strips was independent of temperature over the range studied but has an direct positive relationship with the blanching duration. PEF treatment led to increased sugar extraction during following blanching process and fructose leached out the most while sucrose the least. The combination of low temperature blanching (50 °C for 10 min) and high temperature blanching (76°C for 30 min) gave better sugar content results than other combinations, but we need more research and analysis to understand the mechanism behind the process.

BIOGRAPHICAL SKETCH

Hao graduated from University of Illinois at Urbana-Champaign and achieved her Bachelor of Chemistry in 2019. She joined the Abbaspourrad Research Group in August 2019 for her Professional master's degree in food science Department. Hao possesses strong ability to carry out academic research. She is conducting research on optimizing the Pulsed Electric Field (PEF) treatment and blanching process to improve the food quality of Frozen French Fries. This novel approach to being able to compare the leach out of different sugars content under different processing conditions and combine the overall results to conclude the optimal parameters. Hao eagerly accepted this challenge even though she did not have much experience in the field. She has done an amazing job at developing new methodology including moisture content analysis and combined sugar and starch extraction from potatoes. Hao run into several challenges during her method development such as unclear separation between extracted sugars and starch which would bring about incorrect results. However, she consistently and independently came up with novel solutions to make the method work.

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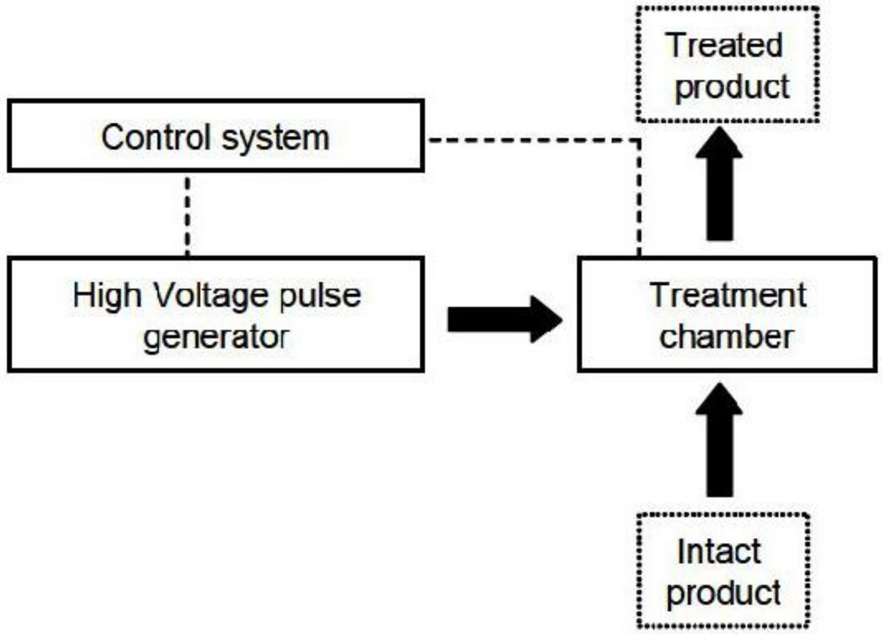
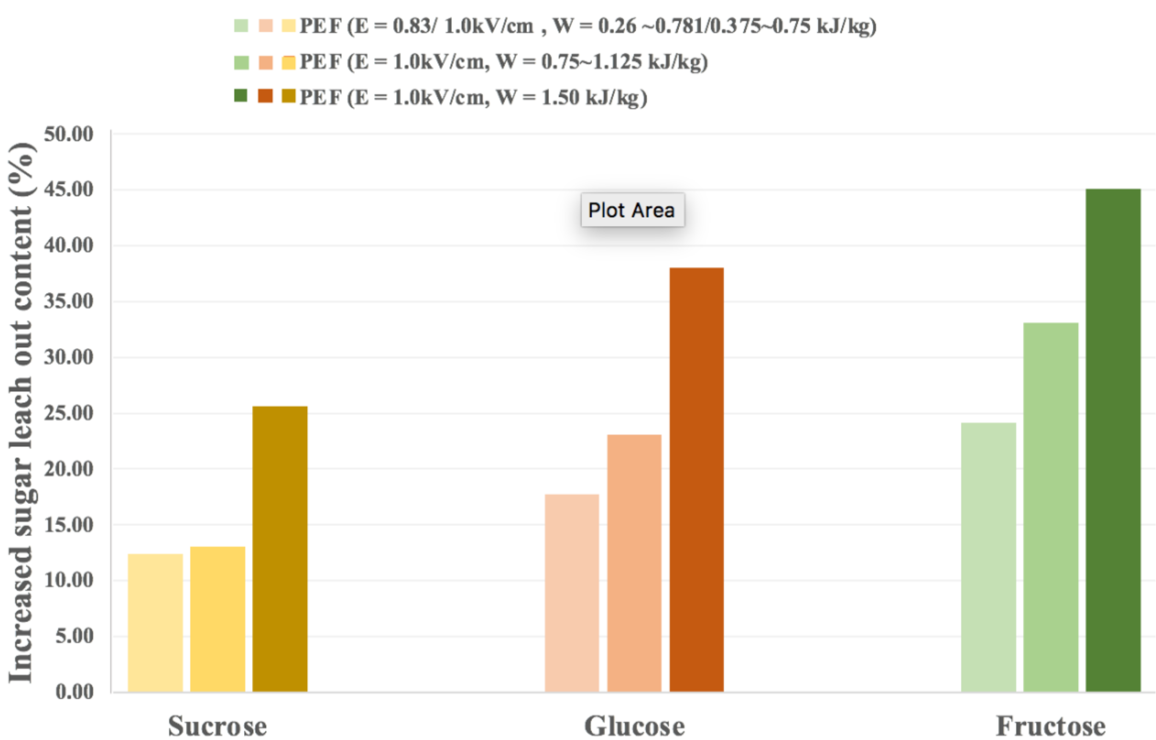


Fig. 1. Schematic diagram of PEF system and treatment chamber.



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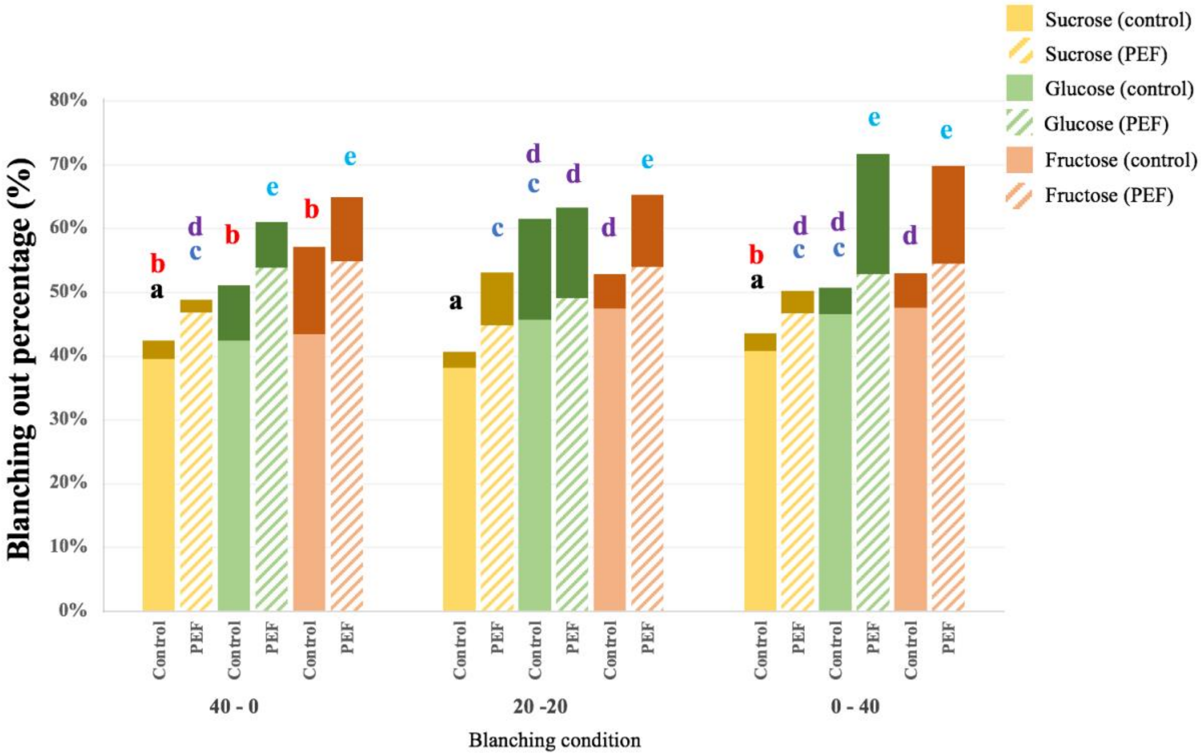

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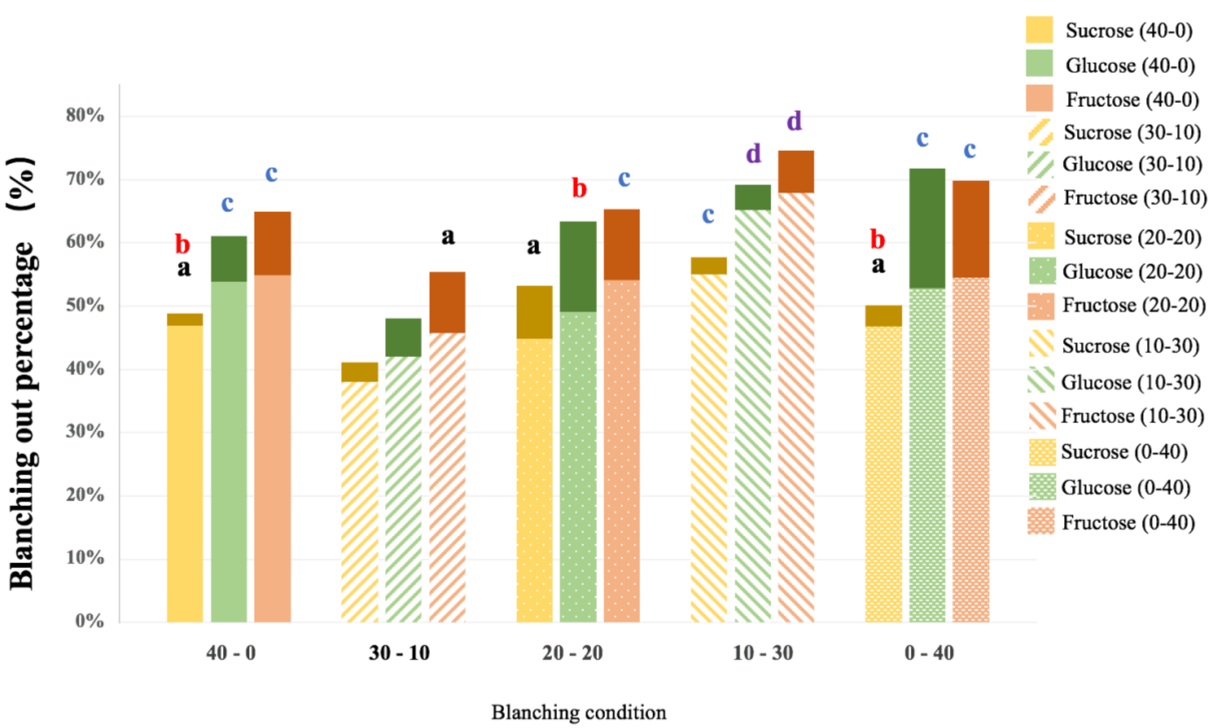

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Time of storage (w)	Blanching condition	Sucrose	Glucose	Fructose
3	Control	0.38 ± 0.02	0.22 ± 0.015	0.23 ± 0.06
	76 °C 12 min	0.36 ± 0.03^{a}	0.20 ± 0.02^{d}	0.20 ± 0.01^{g}
	80 °C 12 min	0.36 ± 0.02^{a}	0.19 ± 0.07^{d}	0.21 ± 0.04^{g}
5	Control	0.40 ± 0.09	0.24 ± 0.04	0.29 ± 0.03
	76 °C 12 min	0.38 ± 0.07^{b}	0.20 ± 0.02^{e}	0.27 ± 0.05^{h}
	80 °C 12 min	0.38 ± 0.11^{b}	0.20 ± 0.01^{e}	0.27 ± 0.02^{h}
7	Control	0.55 ± 0.09	0.24 ± 0.10	0.33 ± 0.09
	76 °C 12 min	0.53 ± 0.17^{c}	0.21 ± 0.08^{f}	0.31 ± 0.06^{i}
	80 °C 12 min	0.53 ± 0.19^{c}	0.20 ± 0.06^{f}	0.31 ± 0.09^{i}

$^{a\text{-}i}$Means within columns with different superscript letters differ; $P < 0.05$.

*Blanched sample sugar content = total sugar content – solution sugar content.

*Sugar concentration were showed as percentage in FW (fresh weight).

Table 2. Sugar content left in raw and blanched potato strips in terms of sucrose, glucose and fructose to observe sugar elimination differences between low temperature long time (LTLT) and high temperature short time (HTST) blanching conditions[1].

Time of storage (w)	Blanching condition	Sucrose	Glucose	Fructose
16	Control	1.46 ± 0.27	2.16 ± 1.04	3.79 ± 0.45
	76 °C 12 min	0.96 ± 0.19	1.56 ± 0.99	2.41 ± 0.53
	85 °C 5 min	1.15 ± 0.06	1.91 ± 0.95	2.89 ± 0.64

[1]Results are presented as mean ± SD.

*Blanched sample sugar content = total sugar content – solution sugar content.

*Sugar concentration were showed as percentage in FW (fresh weight).

[1]Results are presented as mean ± SD.

Table 3. Sugar leaching out percentage in terms of sucrose, glucose and fructose of potato tubers to observe sugar elimination differences between different blanching conditions[1]

Time of storage (w)	Blanching condition	Sucrose	Glucose	Fructose
12	85 °C 12 min	32.75 ± 2.75	27.59 ± 2.29^{g}	17.93 ± 6.37^{o}
	76 °C 12 min	25.96 ± 4.12	27.85 ± 2.52^{g}	16.98 ± 3.85^{o}
	80 °C 8 min	22.12 ± 7.82	23.41 ± 2.12	7.07 ± 2.79
	76 °C 5 min	19.51 ± 1.99^{a}	19.27 ± 4.99^{h}	11.95 ± 5.47^{p}
	85 °C 5 min	18.51 ± 3.27^{a}	17.57 ± 4.32^{h}	10.53 ± 2.06^{p}
13	85 °C 12 min	38.12 ± 10.50^{b}	37.40 ± 3.42^{i}	34.64 ± 2.59^{q}
	76 °C 12 min	41.85 ± 11.42^{b}	34.44 ± 5.79^{i}	33.72 ± 3.03^{q}
	80 °C 8 min	26.30 ± 0.84	26.47 ± 0.84	21.06 ± 1.26^{r}
	76 °C 5 min	18.44 ± 5.67^{c}	18.42 ± 2.39^{j}	19.20 ± 3.04^{r}
	85 °C 5 min	22.11 ± 6.98^{c}	16.06 ± 1.12^{j}	21.25 ± 2.61^{r}
14	85 °C 12 min	24.70 ± 4.73	27.10 ± 2.21^{k}	27.22 ± 5.82^{s}
	76 °C 12 min	31.98 ± 1.33	31.35 ± 7.33^{k}	30.75 ± 4.04^{s}
	80 °C 8 min	19.55 ± 8.01^{d}	19.55 ± 2.78	17.98 ± 6.68
	76 °C 5 min	11.88 ± 2.27^{d}	14.41 ± 8.80^{l}	14.84 ± 8.58^{t}
	85 °C 5 min	14.14 ± 6.68	16.68 ± 1.48^{l}	13.77 ± 3.88^{t}
18	85 °C 12 min	57.63 ± 10.43^{e}	49.94 ± 17.75^{m}	50.97 ± 11.21^{u}
	76 °C 12 min	53.07 ± 12.59^{e}	47.01 ± 12.47^{m}	51.67 ± 13.55^{u}
	80 °C 8 min	36.57 ± 5.60	34.55 ± 7.12	33.20 ± 5.64
	76 °C 5 min	22.96 ± 12.96^{f}	24.31 ± 10.09^{n}	23.34 ± 7.07
	85 °C 5 min	28.61 ± 4.88^{f}	29.36 ± 9.81^{n}	26.09 ± 7.52

$^{a-u}$Means within columns with different superscript letters differ; $P < 0.05$.

*Extracted sugar % were calculated by raw potato sugar concentration divided by leaching out sugar concentration

*Blanched sample sugar content = total sugar content – solution sugar content

[1]Results are presented as mean ± SD

Table 4. Average and SD of sucrose, glucose and fructose contents (% of FW) in raw potato samples from 18 weeks storage

	Sucrose	Glucose	fructose
Average	2.18%	1.97%	2.35%
SD	1.33%	0.77%	0.85%

Table 5. First set of combined PEF and blanching parameters

PEF parameters / Blanching conditions	Pulses	Voltage[kV]	Field strength [kV/cm]	Mass in cell [g]	Energy [J]/ pulse	Energy [J/kg]/ pulse	Specific energy [kJ/kg]
76 °C 12 min 85°C 12 min	5	25.0	0.83	6000	312.5	52.08	0.260
	15	25.0	0.83	6000	312.5	52.08	0.781
	5	30.0	1.00	6000	450	75.00	0.375
	10	30.0	1.00	6000	450	75.00	0.750
	15	30.0	1.00	6000	450	75.00	1.125
	20	30.0	1.00	6000	450	75.00	1.500

Table 6. Combined blanching conditions of different range of low and high blanching temperature

Temperature \ Combination	Control	40 - 0	30 - 10	Control	20 - 20	10 - 30	Control	0 - 40
50 °C	40 min	40 min	30 min	20 min	20 min	10 min	0 min	0 min
76 °C	0 min	0 min	10 min	20 min	20 min	30 min	40 min	40 min

Table 7. Sugar leaching out percentage in terms of sucrose, glucose and fructose of potato strips under different combined PEF and blanching conditions

PEF parameters	Blanching condition	Sucrose	Glucose	Fructose
Control (Blanching)	76 °C 12 min	17.90 ± 2.89[a]	20.12 ± 2.06[e]	14.50 ± 3.18[i]
	85 °C 12 min	18.16 ± 2.39[a]	19.46 ± 8.19[e]	14.38 ± 5.05[i]
PEF + Blanching (E = 0.83 kV/cm, W = 0.260 kJ/kg)	76 °C 12 min	29.82 ± 8.68[b]	29.21 ± 4.70[f]	31.91 ± 2.48[j]
	85 °C 12 min	28.70 ± 9.28[b]	31.77 ± 1.20[f]	29.98 ± 9.29[j]
PEF + Blanching (E = 0.83 kV/cm, W = 0.781 kJ/kg)	76 °C 12 min	30.20 ± 5.26[b]	28.16 ± 9.07[f]	30.18 ± 4.48[j]
	85 °C 12 min	31.39 ± 8.36[b]	31.12 ± 4.70[f]	32.76 ± 3.31[j]
PEF + Blanching (E = 1.0 kV/cm, W = 0.375 kJ/kg)	76 °C 12 min	30.78 ± 9.93[b]	32.96 ± 8.03[f]	31.55 ± 3.00[j]
	85 °C 12 min	30.62 ± 6.82[b]	31.12 ± 12.07[f]	33.50 ± 2.40[j]
PEF + Blanching (E = 1.0 kV/cm, W = 0.750 kJ/kg)	76 °C 12 min	30.86 ± 6.85[b]	30.31 ± 5.42[f]	31.66 ± 3.32[j]
	85 °C 12 min	31.10 ± 2.56[b]	32.06 ± 8.97[f]	33.91 ± 4.72[j]
PEF + Blanching (E = 1.0 kV/cm, W = 1.125 kJ/kg)	76 °C 12 min	35.49 ± 7.89[c]	36.71 ± 4.45[g]	38.66 ± 3.98[k]
	85 °C 12 min	36.10 ± 6.15[c]	38.96 ± 7.99[g]	37.89 ± 5.56[k]
PEF + Blanching (E = 1.0 kV/cm, W = 1.500 kJ/kg)	76 °C 12 min	43.01 ± 7.64[d]	57.69 ± 9.85[h]	59.63 ± 8.27[l]
	85 °C 12 min	44.24 ± 10.59[d]	57.97 ± 6.88[h]	59.46 ± 8.45[l]

[a-k]Means within columns with different superscript letters differ; $P < 0.05$.

*Extracted sugar % were calculated by raw potato sugar concentration divided by leaching out sugar concentration

*Blanched sample sugar content = total sugar content – solution sugar content

[1]Results are presented as mean ± SD

1. Introduction

Russet Burbank is the most widely grown potato cultivar in North America [1]. This cultivar belongs to floury potatoes, which has high specific gravity, low oil absorption, narrow pith, low sugar contents, high starch content and long storability. The Russet Burbank potato does have some weaknesses including late maturity and susceptibility to many diseases [1-3]. Nonetheless, these characteristics make Russet Burbank popular as a major source of baked and mashed potatoes products and French fries.

Nowadays, people have increased awareness and concerns about the influence of food on human health, which has led to a healthier food selection and consumption behavior for consumers [4]. Many epidemiological studies have showed that the consumption of fried and baked foods causes obesity, many cardiovascular diseases related to oil uptake and carcinogenic risk caused by acrylamide formed during product processing [5, 6]. Increasing public awareness of health concerns caused by French fries has led French fry producers to prioritize the improvement of the food quality, nutritional value and shelf-life [7]. Although the variety of cultivar is a key factor influencing the quality of French fries, processing conditions also have a direct effect on the final food quality [8, 9].

In the French fries production process line, blanching is an essential step influencing the desired final product quality [10]. Blanching is a unit operation that comes after cutting and before coating processes. Blanching has been widely employed to achieve the outcome of enzyme inactivation [11], texture modification, oil uptake reduction after frying [12], desirable color, flavor, pathogen and bacterial amount reduction, shelf life extension [13] and nutritional value retention [14] of the final product. More specifically, blanching of potato strips has the main objective of ensuring adequate enzyme inactivation such as peroxidase (POD) [15] and phenolase (development of off-flavors) and polyphenol oxidase (enzymatic browning) [16]. It has been shown blanching can also improve the firmness of cooked potatoes, reducing the negative physical properties and shedding during further processing and preservation [17].

Temperature and time are identified as parameters that significantly affects blanching process efficacy and subsequently the final food quality [18]. Inactivation of enzymes such as POD, phenolase and polyphenol oxidase requires a relatively high temperature, but only for a very short time. Leaching excess sugar, on the other hand, is a relatively slow process that takes place over a wide range of temperatures [19]. When applied to potatoes from different seasons or storage durations, or to potatoes intended for different products, these two factors during blanching process need to be considered carefully.

It is crucial for manufacturers to achieve optimal processing quality of frozen French fries' product by regulating sugar (glucose, sucrose and fructose) content changes during the blanching process. Extracting sugar, especially reducing sugar, out of raw potatoes by blanching determines whether desired uniform color (bright golden yellow, without brown coloring and black spots) of final product can be developed. The Maillard reaction (non-enzymatic browning) between reducing sugar and amino acid would be repressed if the amount of reducing sugar is reduced in the product [6, 15, 20-23]. Storage condition and duration also influence the sugar content in potatoes due to accumulation of reducing sugar from enzymatic sucrose converting during tubers storage [24]. Since sugars, especially reducing sugars, are the limiting factor for color alteration in French fries [25], the concentration of these compounds left in potato strips is the result of as a function of blanching time and temperature. However, there is lack of research on the optimal blanching condition in terms of above aspects.

The concept of natural, fresh and safe food consumption has spawned the concept of "minimum processing," and processing technologies such as new physical fields have become research hotspots in the food industry in the past three decades [26]. In recent years, PEF technology has been widely used in food processing. The impact of PEF on the structure and function of food components and the resulting changes on food quality and safety are the core of basic research on the application of new food processing technology. Researchers have found that PEF can improve the permeability of potato cells and soften the tissues based on the theory of electroporation [27-29]. In addition, PEF pretreatment can decrease reducing sugar content in potato strips, thereby reducing the browning tendency of French fries during frying [30]. PEF has been proven to achieve similar results as traditional potato processing methods, while lowering the energy consumption [31]. However, the effect of different PEF combined with traditional processes (blanching) on sugar diffusion during the process is still unclear.

In this study, we attempt to understand the effect of blanching temperature and time on the extraction of sugars in potato strips from different storage times. Another objective is to explore the effect of combining PEF with blanching pretreatment on the leaching out of sugar content during the manufacturing of French fries. The experiments were performed under a range of temperature-time conditions and different PEF parameters.

2. Materials and Methods

2.1 Plant Materials

Burbank Russet Potato were received from our industry partner. The samples were from the same cultivation and harvest condition. Tubers were stored as received in sieved crates to ensure no accumulation of CO_2. The laboratory cooler was controlled at 4 °C and around 70 % relative humidity.

2.2 Chemicals

Sulfuric acid (98% analytical grade) was from RICCA Chemical Company (Arlington, TX, USA), methanol (99.96% analytical grade) was from Fisher Chemical (Fair Lawn, NJ, USA), sucrose, glucose, and fructose HPLC standards were from Sigma-Aldrich (St. Louis, MO, USA).

2.3 Methods

2.3.1 Blanching process

Tubers were retrieved from storage and handwashed in tap water. They were air dried under ambient temperature (20 °C ± 3) over-night and then were cut into 3/8-inch thickness in strips using French Fry Cutter (New Star Foodservice). To reduce the variable, batches of the strips (50 g each batch) were blanched in 600 ml deionized water in a 1 L beaker which was placed in a thermostatic water bath (VWR International, USA) for a specific time and temperature. The weighed strips were immersed into the beaker immediately when deionized water inside reached the specific temperature and were kept for a specific time. After blanching, the solution was collected, and strips were cooled down and dried until they reach ambient temperature. Blanched strips were stored in the freezer (-20 °C) and solution was stored in the cooler (-4 °C) for further quantification of sugar contents.

2.3.2 PEF process

PEF treatments were performed by using a "PEF-Cellcrack III" system (DIL, German Institute of Food Technologies) in a batch treatment. The schematic diagram of the PEF system is shown in Fig. 1[32]. Due to the preliminary test, the big treatment chamber with a 30 cm distance between electrodes were chosen and the voltage 28 kV and 30 kV resulted in a relative field strength of 0.83 kV/cm and 1 kV/cm were conducted. The number of pulses was varied between 5 to 20 to achieve a total specific energy input between 0.260 to 0.781 kJ/kg and 0.375 to 1.500 kJ/kg relatively. 1000 g ± 20 g of unpeeled whole potatoes were placed in the treatment chamber and filled up with tap water (conductivity 800 - 1200 us/cm) to a final weight of 6000 g. After PEF treatment, the tubers were removed from the chamber and directly passed to combined blanching process. Combined PEF and blanching parameters were determined by literatures, previous experiments and experiences from technicians from ELEA (Table 5 & 6).

2.3.3 Sugar analysis

2.3.3.1 Tuber sample preparation

The raw and blanched potato strips were freeze-dried for 48 h using a freeze dryer model (Labconco, USA) after storing in the freezer (-20 °C) for two days. Then homogenized using a domestic blender and grounding to powder. A mesh (0.8 mm size) was used to make sure the powder contained a particle size of maximum 0.8 mm.

2.3.3.2 Sugar extraction

Double methanol extraction method was adopted and slightly modified for sugar extraction [33]. 0.5 g of sample was added to 4 ml aqueous methanol and stirred with a magnetic stirrer under ambient temperature (~ 20 °C±3) for 20 min. After the first extraction process, methanol was removed from rotary evaporating (Heidolph Instruments, USA) for 5 min (45°C, 400 mmbar). Then we repeated methanol wash and evaporation steps for another round of extraction. Extract residue rotary evaporation was diluted to 10 ml with 10 mM sulfuric acid. We then centrifuged the suspension at 15,000 x g for 10 min to get sugar-contained supernatant and residue [34]. 1ml of supernatant was taken out for sugar content analysis.

2.3.3.3 Sugar characterization method

Sucrose, glucose, and fructose in raw and blanched potato sample or blanching solution were quantified by high performance liquid chromatography refractive index detector (HPLC RI Detectors) analysis as described earlier [33]. Sugar retention was quantified as sugar content in blanched samples or sugar content in raw subtract subtracting sugar content in blanching solution.

2.4 Statistical analysis method

All the tests were carried out in triplicate and the data were presented as the average values ± standard deviation. Multiple-variance analysis was performed using JMP Pro 14.0.0 (2018 SAS Institute Inc.) and Microsoft Excel 16.37 (2020 Microsoft.). The significance was defined as $p < 0.05$.

3. Results and Discussion

3.1 Effect of blanching conditions on the sugar leaching out amount

Table 1 shows the sugar contents comparison between different blanching conditions and different storage duration. In industry, temperature around 76 °C (170 °F) and time about12 min is broadly applied in blanching process especially for 3/8-inch thickness fries. In our experiment, 80 °C, 12 min was chosen for the comparison with 76 °C, 12 min to see whether a 4 °C temperature gap leads to any differences in sugar extraction ability when the blanching duration is held constant. Potato strips (Russet Burbank, 3/8 inch) from different storage duration (4°C, 70 % RH; 3, 5 and 7 weeks) were treated under blanching conditions of 76 °C and 80 °C for 12 min. Five Russet Burbank cultivars were used for each storage condition so in total there were 15 samples were used in this experiment. The averages sugar content of raw samples was from corresponding storage time samples used for blanching. Also, in Table 1, it shows the sucrose content of raw and blanched potato strips from 3, 5- and 7-weeks storage. Sucrose content of raw and blanched potato strips significantly ($P < 0.05$) differed in 3-, 5-weeks and 7-weeks storage results. The same results were also found for glucose and fructose. These results reflected that blanching condition of 76-80 °C, 12 min would bring about the products with similar sugar contents leach out for potato samples stored within first few weeks under low temperature (4 °C). These results are consistent with previous findings that blanching at high temperature of about 70-80 °C for around 10 min appeared to be efficient to extract an important fraction of reducing sugars from the potato strips [35].

Also, as can be seen in Table 1, there was obvious accumulation of sucrose from three to seven weeks storage in raw samples (0.38 to 0.55 % of FW), glucose (0.22 to 0.24 % of FW) and fructose (0.228 to 0.332 % of FW) in the tubers. The largest went to sucrose among these three kinds of sugars. These findings are consistent with the research indicating that sucrose, glucose, and fructose are the major sugars that accumulate at low temperature storage and sucrose increases most rapidly compared to glucose and fructose when potatoes are first exposed to low temperature [36]. Also, sugar contents in Russet Burbank cultivars tended to increase until 15 to 17 weeks [37]. Accordingly, the loss of sucrose, glucose and fructose contents of 7-weeks storage samples were found more than 3- and 5- weeks storage after blanching under 76 °C and 80 °C or 12 min.

Table 2 showed the detailed blanching conditions, each condition used three tubers so there were six tubers were consumed and the average of raw samples was from total 6 tubers. Low-temperature long-time (LTLT), around 55-75 °C for 10-60 min, has been shown to improve the quality of French fries [38]. However, there is also research reporting that higher temperature (i.e., 75-85°C) would be more pronounced than lower temperature on extracting reducing sugar[35]. This experiment was to compare the application of LTLT and HTST blanching conditions. In Table 2, we found that all six samples treated by LTLT (3 samples) and HTST (3 samples) caused significant difference sucrose content left in samples after blanching ($P > 0.05$). Same outcomes can be observed for glucose and fructose. It was also showed that compared to HTST, LTLT showed more sucrose, glucose and fructose leaching out during blanching process. More leaching out means less reducing sugar were retained in strips, which would correspondingly reduce Maillard reaction in following frying process. This result agrees with the findings which stated that LTLT blanching condition can improve overall fries food quality [7, 39]. It was also confirmed that optimal blanching condition range was from 70.8°C to 80.8°C, 14 to 25 min and it depends on the sugar content of the potatoes. Low sugar varieties like Burbank Russet, requires shorter amounts of time [3]. This result also accommodated with research of Mestdagh, De Wilde [35], which showed that 75.9 °C and 8.8 min were the optimal blanching temperature and time that could bring about 41.1 mg/100g extraction of reducing sugars for potatoes stored after 3 months. Similarly, it was observed that LTLT (75 °C, 10 min) blanching treatments was the best procedure for processing French fries [40].

According to results from LTLT and HTST comparison experiment, the temperature range of 76 °C to 85 °C and duration range of 5 min to 12 min would be an appropriate approach to study the influence of blanching temperature and time separately on sugar extraction. The middle blanching condition of 80 °C for 8 min was applied as an intermediate to help the comparison (Table 3). The percentage of extracted sugars were calculated by raw potato sugar concentration divided by leaching out sugar concentration. We used the proportion of extracted sugar to demonstrate instead of sugar concentration remained in blanched potato strips. This is due to the high standard deviation between our samples (Table 4) even they were harvest and stored under exactly the same condition and time. In Table 4, it can be observed that for the same blanching duration (5 min or 12 min), there was no significant difference ($P > 0.05$) of leached out sucrose percentage under different blanching temperature (76 °C and 85 °C) for 13, 14 and 18 weeks storage tubers. In contrast, under same blanching temperature (76 °C or 85 °C), different blanching time (5 min and 12 min) would bring out significantly different ($P < 0.05$) extracted sucrose proportion. Also, in Table 4, glucose and fructose shared the same outcomes. Then it can be concluded from above results that blanching time has greater influence than temperature in the temperature range of 76-85 °C and duration range of 5-12 min. Overall, it was not clear enough for us to conclude whether 76 °C, 12 min or

85 °C, 12 min is the optimal condition to extract the most sucrose and glucose out from potato strips after 12, 13, 14 and 18 weeks storage duration.

As we discussed earlier, combined the results from Table 1, Table 2, Table 3 and Table 4, there was an obvious sugar accumulation during storage. It was found that sugar contents in Russet Burbank cultivars were tend to increase until 15 to 17 weeks and then begin to decrease [37]. And then after 3-month storage period, reducing sugar concentrations would be significantly reduced [25]. Previous research showed that the sweetening under low temperature (4 °C) were induced by several stages: initially decrease in respiration and increase of adenosine triphosphate (ATP); along with the respiration increased during storage tuned on the alternative oxidase, which then led to accumulation of sucrose and reduction of ATP level; invertase then decomposed sucrose to glucose and fructose, thus glucose and fructose contents also were raised up [41]. The possible explanation for this reduction is basically because of the gaps created by contorted and bended cellulose in the aged cell walls. During this process, the cell walls could no longer effectively protect the plasma membrane from disruption from hot water and the permeability of membranes to molecules such as sugars increased [25].

3.2 Effect of combined PEF and blanching pretreatment on the sugar leaching out amount

3.2.1 Effect of different PEF parameters

Blanching is a traditional thermal processing technology widely used in the field of fried potatoes. However, blanching has some disadvantages such as slow heat conduction, long processing time, substantial loss of soluble nutrients, and huge water wastage. The French fries obtained by combining PEF and blanching pretreatment were brighter and golden yellow, and were also softer, and springier and chewier – an overall net improvement in aesthetic appeal and organoleptic profile [42]. The occurring increase in membrane permeabilization by exposure of biological cells to an external electric field positively affects the mass transfer rate [43, 44]. The consequence is that the diffusion of intracellular components in extracellular liquid is increased, while leaving the product matrix relatively unchanged [45]. Post-harvest PEF pretreatment of food raw materials is therefore considered to be a method able to facilitate mass transfer processes and to assist in removing sugars or amino acids that represent the necessary substrates for the Maillard reaction. The above findings may provide useful information to guide effective strategies for the practical application of PEF combined with blanching in the preparation of fried potato foods.

Table 5 shows the detailed PEF parameters and blanching conditions of the first sets of combined PEF and blanching experiment. The leaching our percentage of sucrose, glucose and fructose of different treatments were presented in Table 7. The results under field strength of 0.83 and 1.00 kV/cm lead to similar findings. For all combined conditions, there is no significant difference was observed between 76 or 85 °C, which is similar to our previous results that blanching temperature did not play an important role on sugar diffusion in this temperature range. Besides, compared to control (blanching only) treatment, there was an average increase leaching out of 11.24% sucrose, 10.31% glucose and 17.02% fructose under combined PEF (E = 0.83 kV/cm, 5 and 15 pulses) and blanching treatment 76 or 85 °C for 12 min. The average increase leaching out of 17.25% sucrose, 19.93% glucose and 26.34% fructose were observed under combined PEF (E = 1.00 kV/cm, 5, 10, 15 and 20 pulses) and blanching treatment 76 or 85 °C for 12 min. It can be concluded that there is opportunity to enhance the sugar movement during blanching process applying electrical pulses. In previous literature, PEF treated potato tubers were found performing higher diffusion coefficients of mass transfer [46] and enhanced extractability of reducing sugars (glucose and fructose) and sucrose and consequently, achieved less acrylamide formation and more uniform color [28].

In Fig. 2, the mean of results that are non-significantly different were taken for the comparison between the extraction efficiencies between sucrose, glucose and fructose. Obviously, in all categories (E = 0.83/1.0 kV/cm, W = 0.26 ~ 0.781/0.375 ~ 0.75 kJ/kg; E = 1.0 kV/cm, W = 0.75 ~ 1.125 kJ/kg; E = 1.0 kV/cm, W = 1.5 kJ/kg), sucrose leached out the least while fructose leached out the most. Similarly, researchers found that reduction of the sucrose (28%), glucose (50%) and fructose (55%) content of potato slices achieved after PEF pretreatment (1.5 kV/cm and 20 pulses) and blanching (70 °C for 90 s) in comparison to not PEF treated samples [47]. This is a very important finding because the increased concentration of the carbonyl containing form of fructose would generate faster non-enzymatic browning reactions with fructose than with glucose and require less energy [48], which would further alter the appearance, aroma, flavor and texture of the fries [28]. There are some possible explanations for this phenomenon: i) the molecular weight of sucrose is around 342 g/mol and 180 g/mol for glucose and fructose, thus, the molecular size different might influence the amount of sucrose that could get through the pores during processing, ii) sucrose has 8 hydroxy group in its molecular structure while glucose and fructose have 5, the exposed hydroxy group might form hydrogen bonds or react with other compounds in potato cell structure during process, therefore sucrose might tend to be modified instead of remaining intact, iii) glucose oxidase (GO) is an enzyme that catalyzes the glucose to hydrogen peroxide and D-glucono-δ-lactone [49], and the increased infusion of GO has been found in PEF treated samples [47], which might explain the small difference between glucose and fructose.

The influence of different PEF parameters on extraction of sugars were also investigated. In Table 7, under 25 kV (0.83 kV/cm), specific energy in the range of 0.26~ 0.781 kJ/kg, no significant difference was observed; under 30 kV (1.0 kV/cm), specific energy in the range of 0.375~ 0.75 kJ/kg, no significant difference was observed and in the range of 0.75~ 1.125 kJ/kg, no significant difference was observed. These results could be explained by the findings of [42] that a specific energy input of 0.2 kJ/kg and 0.8 kJ/kg resulted in 43% and 46% cell permeabilization, which are non-significantly different. The energy input of 1.0 kJ/kg lead to an additional significant increase of the cell disintegration index (50%) obtained from impedance measurement, but these results is still not significantly different from the results of 0.8 kJ/kg (46%). The enhanced permeability or cell disintegration index of the PEF treated membrane leads to a reduction in the resistance to mass transfer in cells, therefore the diffusion of small compounds like sugars would also be increased [30]. Summarizing the obtained results, it can be concluded that moderate PEF treatment with sufficiently high electric field strength and low energy input has already reached a plateau of maximum cell disruption, and mass transfer, in our case, sugar extraction, could also follow this pattern. A further increase of the energy input up to 1.5 kJ/kg brought about a significantly higher sugar leaching out percentage, which might explained by the irreversible cell disintegration caused by electrical field [50, 51].

3.2.2 Effect of different combined blanching parameters

Gelatinization temperature of potato starch is between 57~65 °C depends on specific pH and moisture content. During blanching process under high temperature (76~85 °C), starch would be gelatinized partially or totally and would block the channel of pores that generated by electrical field during PEF pre-treatment, therefore making the diffusion of sugars more difficult. At the same time, it was approved that a blanching treatment that combines low temperatures followed by a higher temperature for a short time has been found to be effective in both minimizing texture degradation of vegetables, and in destroying undesirable enzymes [52]. Thus, we designed a set of experiments to which combination of low and high temperature blanching would bring about the most sugar extraction result.

Fig. 3 shows the sugar leaching out percentage results in terms of sucrose, glucose and fructose after 3 different combined PEF and blanching condition treatments and 3 corresponding controls. Fig. 4

showed the sugar leaching out percentage results from different blanching combination process with the same PEF pre-treatment. Similar to previous finding that it's obvious that PEF pretreatment would cause more leaching out of sucrose, glucose and fructose (Fig. 3). Combined with the results from Fig.3 and Fig. 4, we found that among all three kinds of sugars, under the blanching condition of 10-30 (10 min under 50 °C for 10 min and 76 °C for 30 min), sugar leached out the most (55% for sucrose, 65% for glucose and 69% for fructose) while under 30-10 (50 °C for 30 min and 76 °C for 10 min) the least (38% for sucrose, 42 for glucose and 46% for fructose). And 40-0, 20-20 and 0-40 shared the similar results that are not significantly different. It was quite surprising to us since our hypothesis that longer blanching time under lower temperature and shorter blanching time under high temperature would perform better based on the findings from [11, 35, 52, 53]. It was observed that the diffusive coefficient of reducing sugars under 60 °C decreased not dramatically as under 75 °C and 90 °C [52]. To understand the mechanism, more research on the dynamic of starch gelatinization and microstructure of cells during the process.

4. Conclusion

Low temperature–long time blanching was more effective in extracting sugars than high temperature-short time. Extraction of sugars during blanching increased with longer time compared to higher temperature. PEF pretreatment contributed to the increasing of sugar extraction. Enhanced permeability caused by PEF treatment relates to mass transfer in cells, thereby influence the diffusion of sugars. Combined low and high temperature blanching would benefit sugar extraction amount while exact mechanism such as dynamics of starch gelatinization is still unclear to us and need further exploration.

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