BIO Web of Conferences **142**, 01016 (2024) https://doi.org/10.1051/bioconf/202414201016
ISAEB 2024

Use of High-Voltage Pulsed Electric Fields for the Preservation of Fresh Foods

Nan Li, Yongrui Wang and Han Yang*

Institute of Systems Engineering, Academy of Military Sciencest, Beijing 100141, China

Abstract. Today, China's productivity is steadily growing, and the output of agricultural and sideline products is also increasing. There is an increasing need for the preservation of fresh foods such as vegetables that are not consumed immediately after harvest or sale. Electric field technology, as a new method of preservation, features the advantages of extending the shelf life, being sustainable, pollution-free, and consuming less energy. Compared to traditional preservation methods, it better meets modern demands for healthy, green food. This article evaluates the effects of high-voltage pulsed electric field treatment on the preservation of fresh milk and carrot juice through experimental verification. The study found that within the range of output voltages from 20kV to 30kV, output frequencies from 100Hz to 200Hz, and treatment times from 1 minute to 2 minutes, the factor that most significantly affects the high-voltage pulse electric field sterilization and preservation effect is the output frequency, while the impact of the output voltage is not significant. Based on the results, the paper discusses the potential applications and future prospects of electric field technology in the field of food preservation, providing suggestions and directions for future research and application.

1 Introduction

Food preservation is a key aspect of the modern food industry. It involves using various methods and technologies to extend the edible shelf life of food, maintain its nutrition and flavor, and ensure food safety[1]. As living standards improve, consumers have higher demands for the freshness and quality of food. Effective preservation techniques can meet these demands by maintaining the freshness and nutritional value of food[2]. Throughout the entire supply chain from production to sale, preservation technology is crucial for ensuring food safety and quality. Good preservation measures can reduce losses, lower costs, and improve efficiency[3].

High-Voltage Pulsed Electric Fields (HPEF) is a non-thermal food processing technology that uses short bursts of high voltage pulses to treat food, achieving sterilization and preservation effects. These electric fields typically feature high voltage and low frequency. By applying these pulse electric fields to the target material, it can effectively kill microorganisms, extend food shelf life, or improve certain properties of the material, while maintaining the color, aroma, taste, and nutritional components of the food as much as possible[4]. A typical HPEF system includes a HPEF generator, treatment chamber, pump, cooling coils, container, and monitoring system. These components work together to effectively process the food, with industrial HPEF generation voltages generally set between 20kV/cm and 30kV/cm.

Studies have shown that pulse width and frequency significantly affect temperature rise, which in turn impacts the inactivation of microorganisms. For instance, Moonesan and others used a high-voltage square pulse generator to study the effects of pulse width and frequency on temperature rise while keeping electric field strength and energy constant[5]. Therefore, blindly increasing pulse width and frequency to enhance preservation effects is not advisable. Generally, frequencies are set between 100Hz and 200Hz, and pulse widths can vary from a few nanoseconds to several milliseconds depending on the study.

The duration of the pulses also significantly impacts the effectiveness of bacterial inactivation. For example, Beveridge and others found that for pulse durations of 1, 2, 3, and 4 microseconds, unipolar pulses were more effective than bipolar pulses at 1-2 microseconds. However, as the pulse duration increased to about 3 microseconds, there was no significant difference between the two, and longer pulses showed that bipolar pulses were superior to unipolar pulses[6]. Thus, when deploying in industrial settings, the pulse processing time can be set between 1.5 minutes and 4.5 minutes, depending on the desired effect.

Although HPEF is a non-thermal processing technique, in some cases, it may still need to be performed at higher temperatures to achieve desired effects or other purposes, such as Wu Xinhui's study on the storage energy and loss changes in four fruits and vegetables treated with HPEF at temperatures ranging from 25°C to 90°C[7].

* Corresponding author: 2248449089@qq.com

Therefore, high-voltage pulsed electric field technology, as a preservation method applied to the storage of food products, holds significant importance. This paper focuses on this background to study the application of high-voltage pulsed electric fields for preserving fresh foods.

2 Assessment of Preservation Effectiveness

Due to the unique advantages of high-voltage pulsed electric fields in liquid foods, this paper selects two representative liquid foods to verify the sterilization and preservation effects of high-voltage pulsed electric fields, namely fresh carrot juice and fresh milk. The pulse equipment has an input voltage of 220V and 50Hz, with output voltages set at 20kV, 25kV, and 30kV, and output frequencies set at 100Hz, 150Hz, and 200Hz. The treatment time were set to 1 minute, 1.5 minutes, and 2 minutes. The experimental setup, as shown in Fig. 1, uses a high-voltage pulsed electric field sterilization device from Changzhou Lanno Optoelectronics Technology Co., Ltd., which allows for setting output voltages and frequencies.

Fig. 1. electric field generator.

The samples were raw milk purchased from local dairy farmers and fresh carrots picked from the vegetable garden in the early morning, with experiments beginning immediately.

First, the same batch of milk was divided into nine large portions, each then subdivided into two smaller portions of approximately 1000ml each, evenly distributed into ten reagent bottles. One small portion was placed in an electric field generator for sterilization and then sealed and stored in a refrigerator at 0-5°C, while the other small portion was stored directly in the refrigerator at 0-5°C without electric field treatment. The same batch of carrot juice was also divided into nine large portions and treated in the same manner as the milk, with each portion stored in the corresponding location. Microbial residuals in the milk and carrot juice were recorded on the 1st, 2nd, 3rd, 4th, and 5th days.

Before the experiment, the initial microbial counts of the raw milk and raw carrot juice were measured using the microbial plate count method. The daily averages of microbial residuals were calculated and recorded for samples treated in different ways. The relationship between microbial residuals and days, when the output frequency was set at 150Hz, the treatment time at 1.5 minutes, and the output voltages at 20kV, 25kV, and 30kV, is shown in Tables 1, 2 and 3.

Table 1. The correlation between microbial residue over time (in days) at an output voltage of 20 kV.

measure time (day)	process materials ($\times 10^6$cfu/ml)			
	Milk processed	Milk unprocessed	Carrot processed	Carrot unprocessed
1	0.312	0.944	3.64	7.51
2	0.460	1.531	4.17	9.45
3	0.597	2.214	6.03	11.48
4	0.722	3.133	8.26	13.40
5	0.891	4.159	9.67	15.23

Table 2. The correlation between microbial residue over time (in days) at an output voltage of 25 kV.

measure time (day)	process materials ($\times 10^6$cfu/ml)			
	Milk processed	Milk unprocessed	Carrot processed	Carrot unprocessed
1	0.214	0.944	2.97	7.51
2	0.326	1.531	3.54	9.45
3	0.483	2.214	5.25	11.48
4	0.625	3.133	7.32	13.40
5	0.798	4.159	8.59	15.23

Table 3. The correlation between microbial residue over time (in days) at an output voltage of 30 kV.

measure time (day)	process materials ($\times 10^6$cfu/ml)			
	Milk processed	Milk unprocessed	Carrot processed	Carrot unprocessed
1	0.194	0.944	2.51	7.51
2	0.227	1.531	3.12	9.45
3	0.323	2.214	4.76	11.48
4	0.511	3.133	6.72	13.40
5	0.630	4.159	7.94	15.23

From Table 1, it can be observed that the growth rate of microbial populations in milk and carrot juice sterilized by pulsed electric fields is lower compared to those that were untreated. Additionally, according to relevant food safety standards, raw milk is no longer suitable for consumption when its microbial count per milliliter exceeds a certain limit, and the same applies to fruit and vegetable juices. Typically, the refrigeration shelf life of fresh milk and vegetable juices is about 1-3 days. From Tables 2 and 3, it is evident that the safe consumption period for both types of food extends by more than three days after electric field treatment, with a slowed growth rate of microbial populations. Moreover, with the same output frequency and treatment duration, increasing the output voltage from 20kV to 30kV enhances the sterilization and preservation effects.

When the output voltage is set at 25kV and the treatment time at 1.5 minutes, with output frequencies of 100Hz, 150Hz, and 200Hz, the relationship between microbial residuals and days is shown in Tables 4, 5 and 6.

Table 4. The correlation between microbial residue over time (in days) at an output frequency of 100 Hz.

measure time (day)	process materials $(\times 10^6 cfu/ml)$			
	Milk processed	Milk unprocessed	Carrot processed	Carrot unprocessed
1	0.365	0.944	3.76	7.51
2	0.449	1.531	4.62	9.45
3	0.591	2.214	6.67	11.48
4	0.711	3.133	8.44	13.40
5	0.876	4.159	9.84	15.23

Table 5. The correlation between microbial residue over time (in days) at an output frequency of 150 Hz.

measure time (day)	process materials $(\times 10^6 cfu/ml)$			
	Milk processed	Milk unprocessed	Carrot processed	Carrot unprocessed
1	0.359	0.944	3.57	7.51
2	0.460	1.531	4.49	9.45
3	0.587	2.214	6.29	11.48
4	0.703	3.133	8.39	13.40
5	0.864	4.159	9.76	15.23

Table 6. The correlation between microbial residue over time (in days) at an output frequency of 200 Hz.

measure time (day)	process materials $(\times 10^6 cfu/ml)$			
	Milk processed	Milk unprocessed	Carrot processed	Carrot unprocessed
1	0.327	0.944	3.26	7.51
2	0.435	1.531	4.11	9.45
3	0.576	2.214	6.06	11.48
4	0.699	3.133	8.17	13.40
5	0.856	4.159	9.54	15.23

From Tables 4, 5 and 6, it can be found that after the electric field treatment, with the same output voltage and treatment time, and within the output frequency range of 100Hz to 200Hz, the sterilization and preservation effects on the two types of food improve as the frequency increases.

When it was determined that the output voltage was 25kV, the output frequency was 150Hz, and the treatment times were 1 minute, 1.5 minutes, and 2 minutes, the relationship between microbial residue and days was shown in Tables 7, 8 and 9.

Table 7. The correlation between microbial residue over time (in days) when the processing time is 1 minute.

measure time (day)	process materials $(\times 10^6 cfu/ml)$			
	Milk processed	Milk unprocessed	Carrot processed	Carrot unprocessed
1	0.383	0.944	3.76	7.51
2	0.432	1.531	4.64	9.45
3	0.584	2.214	6.15	11.48
4	0.670	3.133	8.85	13.40
5	0.804	4.159	11.15	15.23

Table 8. The correlation between microbial residue over time (in days) when the processing time is 1.5 minutes.

measure time (day)	process materials $(\times 10^6 cfu/ml)$			
	Milk processed	Milk unprocessed	Carrot processed	Carrot unprocessed
1	0.296	0.944	3.19	7.51
2	0.375	1.531	4.16	9.45
3	0.431	2.214	5.96	11.48
4	0.583	3.133	8.24	13.40
5	0.764	4.159	9.79	15.23

Table 9. The correlation between microbial residue over time (in days) when the processing time is 2 minutes.

measure time (day)	process materials $(\times 10^6 cfu/ml)$			
	Milk processed	Milk unprocessed	Carrot processed	Carrot unprocessed
1	0.246	0.944	2.87	7.51
2	0.306	1.531	3.68	9.45
3	0.360	2.214	4.99	11.48
4	0.486	3.133	6.67	13.40
5	0.633	4.159	8.79	15.23

From Tables 7, 8 and 9, it can be seen that under the same output voltage and frequency conditions, increasing the treatment time for food enhances the sterilizing effect of the electric field and correspondingly extends the food's preservation time. A synthesis of the nine tables reveals that among the three variables, treatment time has the greatest impact on the efficacy of electric field sterilization at the scale of minutes, followed by output voltage at the scale of kV, and finally, output frequency at the scale of 10Hz has the least impact on the sterilizing effect. Therefore, within the experimental range demonstrated, the larger these three variables are, the better the sterilizing and preservation effect on the food, provided that the original flavor of the food is not damaged.

Consequently, in order to obtain the most suitable sterilization conditions for the two types of food, and to study the factors that have the greatest impact on the sterilization effect, output voltage, output frequency, and treatment time were taken as factors at three levels. The residual colony rate on the first day and the growth rate by the fifth day were used as indicators. An orthogonal experiment was conducted according to the orthogonal test table L9 (3^3), as shown in Table 10.

Table 10. Orthogonal experimental table.

Trial Number	Output Voltage (kV)	Output Frequency (Hz)	Processing Time (min)
1	20	100	1.0
2	20	150	1.5
3	20	200	2.0
4	25	100	1.5
5	25	150	2.0
6	25	200	1.0
7	30	100	2.0
8	30	150	1.0
9	30	200	1.5

The residual colony rate is the proportion of the remaining number of colonies after electric field treatment compared to the initial value of colonies. The colony growth rate is the proportion of the increase in the number of remaining colonies on the fifth day compared to the number of remaining colonies on the first day after electric field treatment.

Table 11. Orthogonal experiments conducted on milk.

Trial Number	Colony Survival Rate	Growth Rate
1	0.410	2.970
2	0.330	2.855
3	0.250	2.600
4	0.387	2.400
5	0.261	2.573
6	0.233	2.375
7	0.345	2.147
8	0.252	2.126
9	0.211	2.007

Table 12. Orthogonal experiments conducted on carrot juice

Trial Number	Colony Survival Rate	Growth Rate
1	0.503	2.934
2	0.485	2.657
3	0.452	2.677
4	0.475	2.734
5	0.382	3.062
6	0.376	2.841
7	0.365	2.465
8	0.342	2.424
9	0.334	2.395

Plot the two sets of data as line graphs, as shown in Figs. 2 and 3.

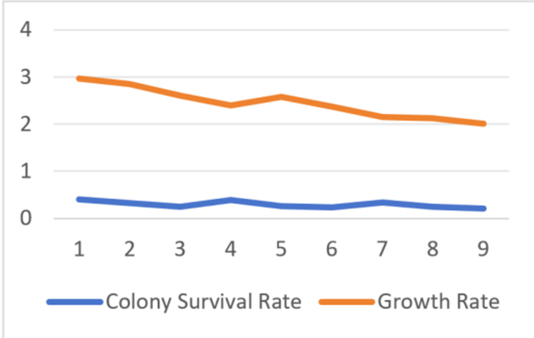

Fig. 2. Orthogonal experiments conducted on milk.

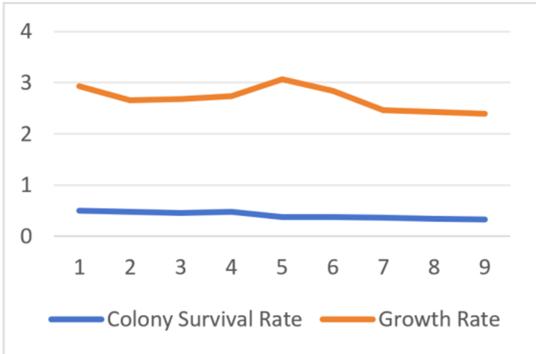

Fig. 3. Orthogonal experiments conducted on carrot juice.

Table 13. F-values for the three factors.

Factor name	Output Voltage	Output Frequency	Processing Time
F-values	0.217	5.14	1.31

The data were processed using MATLAB to calculate the between-group variance and within-group variance for each factor. ANOVA was used to test the F-value (the ratio of between-group variance to within-group variance). A higher F-value indicates a greater impact on the results. The results are shown in Table 13.

From Tables 10-13, it can be concluded that within the range of 20-30 kV, the F-value for output voltage is relatively small. Therefore, the effect of different output voltages within this range on the Colony Survival Rate and Growth Rate is not significant. Although different output voltages do affect the sterilization effectiveness, this effect is not strongly reflected in the overall data. Additionally, during the calculations, it was found that the within-group variance is quite large, indicating considerable variability in Output Voltage at the same voltage level, which may be due to experimental errors or other uncontrolled factors. On the other hand, within the range of 100 Hz-200 Hz, the F-value for output frequency is relatively high, showing a significant impact on the Colony Survival Rate and Growth Rate. Therefore, output frequency within this range has a substantial effect on the sterilization and preservation results. The impact of treatment time is moderate.

3 Conclusion

Through the analysis under single-factor conditions, the effects of output voltage and frequency of High Pulsed Electric Field (HPEF) on its sterilization performance were studied. With the increase in output voltage and frequency, the sterilization and preservation effects of the electric field significantly improved. Compared to traditional thermal processing, HPEF treatment usually requires lower energy consumption. It can largely maintain the original flavor, color, and nutritional components of food. In addition, compared to pasteurization, HPEF requires a lower temperature, and the duration of the electric pulses is usually in the microseconds to milliseconds range, making the entire process very rapid. For subsequent specific food sterilization treatments, a broader range of orthogonal experiments on parameters such as output voltage and frequency of the electric field can be conducted to determine the most suitable treatment conditions, and these can be used as standards to promote the preservation processing of HPEF in this food area.

Although successful applications have been achieved in laboratories and small-scale production, due to the relatively high cost of purchasing and maintaining HPEF equipment, expanding this technology to large-scale industrial production still faces technical and economic challenges. How to achieve lighter and more economical solutions will be one of the future directions for HPEF technology development. Meanwhile, for consumers, there might be a need for time to accept the safety and effectiveness of this new food processing technology.

References

1. Zhu Hongli, Yang Binbin, Zhang Xiuqi, et al(2006). Analysis on the status quo and development of fruit and vegetable fresh-keeping processing.J.food science,(10):596-600.
2. Li J R. Research progress of fresh food preservation technology(2010).J. Chinese Journal of Food Science,10(03):1-12.
3. Han Mei GUI, Zhou Yingtang(2007). Several Key problems and Countermeasures of safe supply of fresh agricultural products.J. Anhui Agricultural Sciences,(12):3686-3689+3696.
4. Wang, Q., Li, Y., Sun, D. W., & Zhu, Z(2018). Enhancing Food Processing by Pulsed and High Voltage Electric Fields: Principles and Applications. Critical Reviews in Food Science and Nutrition, 58(13), 2285–2298.
5. M. S. Moonesan and S. H. Jayaram (2013), "Effect of Pulsewidth on Medium Temperature Rise and Microbial Inactivation Under Pulsed Electric Field Food Treatment," in IEEE Transactions on Industry Applications, vol. 49, no. 4, pp. 1767-1772, July-Aug.
6. J. R. Beveridge, S. J. MacGregor, J. G. Anderson and R. A. Fouracre(2005), "The influence of pulse duration on the inactivation of bacteria using monopolar and bipolar profile pulsed electric fields," in IEEE Transactions on Plasma Science, vol. 33, no. 4, pp. 1287-1293, Aug.
7. Wu Xin-Hui, GUO Yu-Ming, FENG Hui-min (2016). Effect of high-voltage pulsed electric field pretreatment on dynamic viscoelastic properties of fruits and vegetables. J. Transactions of the Chinese Society of Agricultural Engineering, 32(18):247-254.