Treatment Chamber with Turbulent Flow for Liquid Food Pasteurization

Rai Naveed Arshad, Zolkafle.Buntat, Ali M.Dastgheib, Mohd Hafizi Ahmad, Kaleem U. Babar

***Abstract:** The pulsed electric field (PEF) is a suitable technological option for pasteurization but the laminar flow inside the treatment chamber is a reason for treatment inhomogeneity in most of the treatment chambers. This work was performed to measure the efficiency of PEF treatment of the liquid food by using the helical sterilization chamber. The helical shape shows significant advantages during the flow of fruit juices by disrupting the laminar flow inside the treatment zone. Thus, it provides a uniform electric field to the whole treated sample with little temperature rise and longer exposure time. The effectiveness of the chamber was determined experimentally and simulated using COMSOL Multiphysics. Three different lengths of the chamber at 30 kV/cm were used to sterilize the liquid samples of pineapple, mango, and coconut milk. The treated samples were assessed by monitoring the chemical changes and log reduction. Helical chamber length of 30 cm exhibited inactivation effects of 7.5, 5.7, and 5.55- log_{10} CFU/mL for the treated samples of mango, pineapple, and coconut milk, respectively. This study provides new insight into industrial set up with multiple helical chambers in a continuous flow.*

***Index Terms**: Keywords: Non-Thermal Pasteurization, Pulse Electric Field, Shelf Life, Electrodes, Sterilization Chamber, Microbial Growth Reduction.*

I. INTRODUCTION

Applying an electric field to living cell results in a modification in the permeability of the cell membrane. This process, known as electroporation, can be either reversible or non-reversible. The theory of electroporation has been reviewed in the literature [1], [2]. A critical amount of potential builds positive and negative charges on two ends of the cell membrane, affecting compression of the cell [3]. The compression results in the thickness of the membrane decreasing and becoming permeable to its surrounding medium, which causes the cell membrane to break down [4], [5]. Reversible processes are used in drug-delivery applications while non-reversible electroporation is useful for treatment or extraction applications. Table 1 demonstrates the various applications of

electroporation and can be seen that there are different biological effects induced by PEF. The factors of the PEF system influence the efficacy so the experimental setup are likewise different. However, it's essentially required to build a system that covers a wide range of applications. [6] has showed the requirement of different electric field characteristics in various applications of electroporation.

Microorganisms impact the consumable nature of fluid nourishment and represent an immediate risk to human wellbeing. Therefore, sterilization is a vital system in liquid food preservation. The process of warming up the liquid food for sterilization was initiated a hundred years ago. In thermal treatment of liquid food, heat produces alterations to the flavor and taste as well as results in a nutrient loss. The PEF technology acts as a non-thermal process to partially inactivate microorganisms in liquid foods with a least adverse effect on the physical characteristics of the treated food [7], [8]. The utilization of PEF in liquid food sterilization turns out to be increasingly well known after reported first time by the German engineer, Heinz Doevenspeck [9]. Multiple research groups have involved in extensive research on PEF pasteurization where a food sample is placed in an insulated treatment zone surrounded by two electrodes connected to a high power pulse modulator to provide a sufficient electric field to the sample placed in the treatment chamber and achieve membrane electroporation [10]. A properly designed sterilization chamber is essential to bring about much powerful PEF to kill or weaken the microorganisms in the juices [11], [12].

The efficiency of the microbial inactivation is also determined by the treatment chambers [13]. Changing the design of the treatment chamber can either reshape the insulator [14] or electrode design or addition of an insulator material or a metallic grid into the flow shape designs [15]. The flow rate is an interdependent parameter in the PEF processing and plays a vital role in it. Meneses, Jaeger [16] studied the shape of the treatment zone and flow rate of the liquid food using a continuous co-linear PEF system. Laminar flow is a reason for treatment inhomogeneity in most of the treatment chambers because a turbulent flow is possible only with a higher flow rate. In order to accommodate the laminar flow, a power modulator is required with high power, as well as a higher frequency, to deliver the needed quantity of energy per volume. The helical chamber was also the motivation due to the flow geometry because the curvature of the helical treatment zone produces turbulent flow of sample irrespective of its viscosity at a low flow rate [17]. Furthermore, it provides a longer exposure time with the low-temperature rise. In the configuration of electrodes; parallel configuration of electrodes produces a field improvement problem at the edges and co-linear electrodes overestimated the actual electric field strength inside the treatment zone [18], [19]. Thus, the

Revised Manuscript Received on December 22, 2018.
Rai Naveed Arshad, IVAT, Universiti Teknologi Malaysia, Johor, Malaysia, rainaveed@yahoo.co.uk
Zolkafle.Buntat, IVAT, Universiti Teknologi Malaysia, Johor, Malaysia, zolkafle@fke.utm.my
Ali M.Dastgheib, Islamic Azad University, Marvdasht Branch, Iran, ali_m_dastgheib@yahoo.com
Mohd Hafizi Ahmad, IVAT, Universiti Teknologi Malaysia, Johor, Malaysia, mohdhafizi@utm.my
Kaleem U. Babar, Department of Applied Physics, Federal Urdu University, Islamabad, Pakistan, kaamikhankm@gmail.com.

combination of coaxial electrodes with helical treatment zone provided a uniform pulsed electric field to the whole sample without a dielectric breakdown by upgrading the flow patterns of the treated sample.

In this study, the uniformity of the electric field distribution was confirmed by using COMSOL. The experimental work was carried out to identify the optimum length of the helical sterilization chamber. The effectiveness of the chamber was verified by the chemical and biological analysis of liquid food samples from pineapple, mango, and coconut milk. The experiments were repeated three times and noted that 30 cm length of helical sterilization chamber promised the higher characteristics of fruit juices with a temperature rise of the only 3^{o}C (<10%) that is comparably lower than the earlier designs [20], [21].

II. EXPERIMENTAL SETUP

The helical sterilization chamber was a combination of coaxial electrodes and a helical treatment zone. The treatment zone was made by a Pyrex glass tube with an inner diameter of 8 mm and 1 mm wall thickness arranged in a helical shape. The 8 mm inner diameter of the treatment zone allowed the fruit juice to flow easily. A hollow stainless-steel cylindrical electrode with a diameter of 4.5 cm was placed inside the helical treatment zone. This stainless-steel electrode was used as a medium for applying high voltage pulses to generate a pulsed electric field in the treatment region. As a ground electrode, an aluminum sheet was wrapped around the outer side of the helical glass.

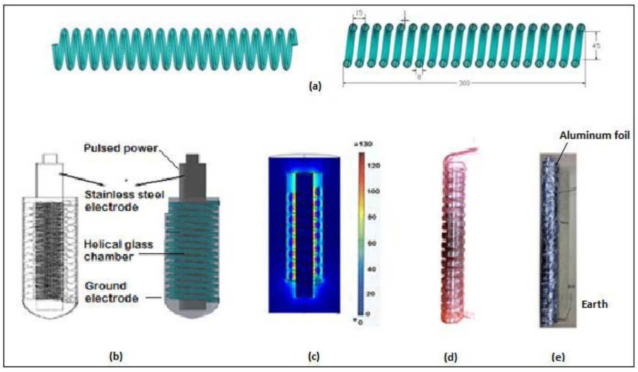

Fig. 1. (a) Drawing of helical treatment zone in mm dimensions (b) SOLIDWORK model (c) COMSOL simulation result (d) helical treatment zone (e) helical sterilization chamber

Fig. 1.a shows all the dimensions of the helical treatment zone with its cross-sectional view. Before developing the sterilization chamber; a simulation study was carried out using COMSOL Multiphysics software to confirm the sufficient and uniform electric field in the treatment zone. Fig. 1 shows the development phases of the helical sterilization chamber. Fig. 1.b is the SOLIDWORK model of the helical chamber that was used in COMSOL Multiphysics to measure the PEF, as shown in Fig. 1.c. The simulation of the helical sterilization chamber by using COMSOL software in 3D mode showed the uniform electric field strength to all parts of the sterilization chamber. The developed helical treatment zone is shown in Fig. 1.d and Fig. 1.e is the whole picture of the helical sterilization chamber. Three lengths (20 cm, 30 cm, and 50 cm) of sterilization chamber were fabricated to study the effects of length. Each test sample was treated for 5 minutes in a batch mode with the residence time of 40 sec.

$$E = \frac{V}{r\ln\left({}^{R2}/_{R1}\right)} \tag{1}$$

From this equation, an applied pulse voltage was calculated for different electric fields. Here, 'r' is the location inside the treatment zone at which the electric field is calculated while R1 and R2 are the radius of the internal and external electrode, respectively. Thus it is clear from the equation 1 that an applied voltage of 30kV was required to achieve a peak value of 30kV/cm at the center of the treatment zone, i.e. r =5cm in equation 1.

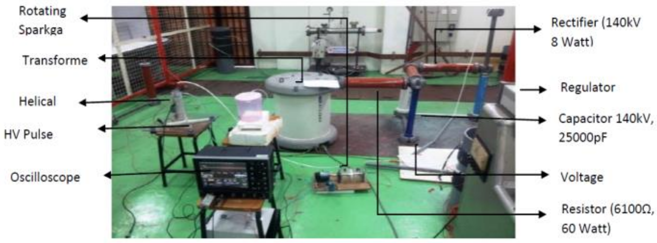

Fig. 2. Experimental setup used for static PEF treatment

This process is carried out by the pulse-forming network, power switches, power supply that capable to charge the capacitor up to required voltages, capacitors, sterilization chambers and resistors (2Ω-10 MΩ). For this project, a pulsed high voltage system developed at the IVAT, Universiti Teknologi Malaysia; was used to analyze the PEF, as shown below Fig. 2. It is composed of a high voltage supply (high voltage AC transformer model Haefely PZT 100-0.1 & voltage regulator model Kosijaya K-5051), a coaxial Blumlein lines pulse forming system to generate exponential decay pulse, a rotating spark gap as a switching medium, Tektronix probe model P6015A to measure the voltage waveforms across the test cell, and the digital oscilloscope to record the generated pulses. Blumlein lines are classical generators and used commonly in electroporation. A purely resistive load 200 Ω is required as a load resistor in the double Blumlein pulse generator set up for matching purposes. Hence, the mixing of distilled water and copper sulfate was used as the water resistor of 200 Ω. The experimental test began with the temperature at 25- 26 °C and humidity of 54-56 %. Fig. 3 shows the Blumlein generator and applied voltage waveform.

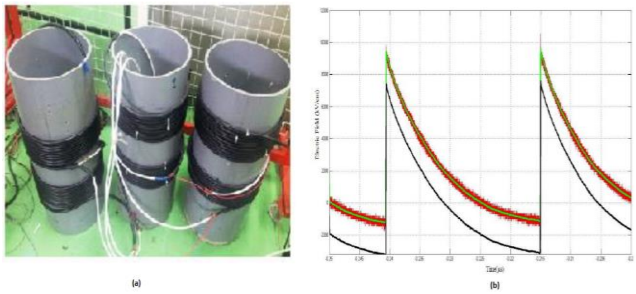

Fig. 3. Generator and corresponding output pulse. (a) coaxial-Blumlein generator (b)Applied Voltage and Electric field waveform

Published By:
Blue Eyes Intelligence Engineering & Sciences Publication

The winding of the stacked- Blumlein generator was used in this research is shown in Fig. 3.a. The black exponential decay waveform in this Fig. 3.b is the applied to the sterilization chamber and the green waveform is the electric field captured by the attenuator probe. Exponential decay pulses are slightly efficient and cheaper than the rest of the pulses used for microorganism degradation [22], [23].

III. RESULTS AND DISCUSSION

The following sections discuss the effectiveness of the helical sterilization chamber by comparing the results of treated, non-treated, and fresh samples of coconut milk, pineapple, and mango juice. All the juice samples were produced in a controlled clean environment. The fruit pulps and solid particles were separated by passing the fruit juices through paper filters (MN6151/4) to avoid unexpected electric field discharge during the PEF treatment [24]. In contrast with pineapple and mango juices, the sample of coconut milk was used without filtering. Treated and non-treated samples were stored under the same environmental conditions for eight days to allow the growth of natural contaminants [11], [25]. After storage of eight days; the physical condition of treated and untreated samples with sterilization chamber lengths of 20 cm, 30 cm, and 50 cm separately is shown in Fig. 4.

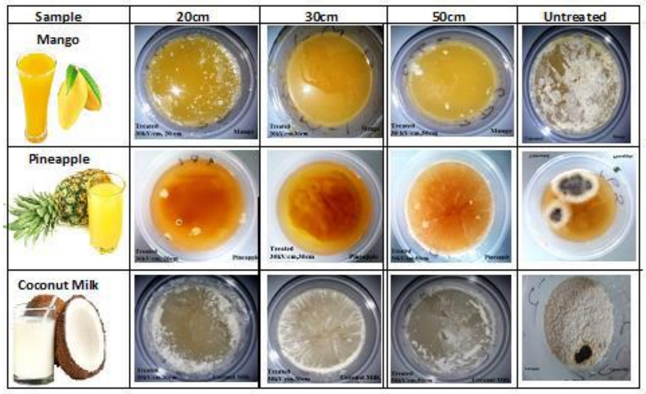

Fig. 4. After storage of eight days; visual comparison of untreated and treated samples with three sterilization lengths at 30kV/cm

As this proposed method illustrated, there was no direct contact between the electrode surface and the liquid samples, which was targeted to avoid temperature rise during the PEF processing. During the treatment procedure; the proposed configuration did not require any cooling system. The temperature of the juice samples before and after PEF processing is shown in Fig. 5. After applying the PEF; there was a 3.3 °C increase in temperature of treated samples, which was sufficiently lower than the previous designs. The temperature was also measured before and after with the help of a thermocouple. For the final analysis; the changes in the chemical and bioscience parameters of the treated and untreated sample are compared with the fresh samples.

A. Analysis of Chemical Parameters

This experimental research has shown the effect different length of the sterilization chamber (10, 20 and 30cm) onto the three types of tropical fruit juices. After storage of seven days; the treated samples were analyzed by YSI device (ProDSS Digital, USA) and spectrophotometer for the chemical and bioscience analysis. Later on, all the recorded data were compared to the findings of the previous research. It helped to validate and determine the effect of length of the newly designed sterilization chamber on the quality of the tropical fruit juices. This section describes the results of the chemical analysis (conductivity, pH, ºBrix, and viscosity) of the treated, untreated, and fresh samples. These chemical parameters are reviewed with regard to distinct sterilization chamber lengths and various electric fields. Chemical assessment device model YSI was used to measure the chemical parameters [26].

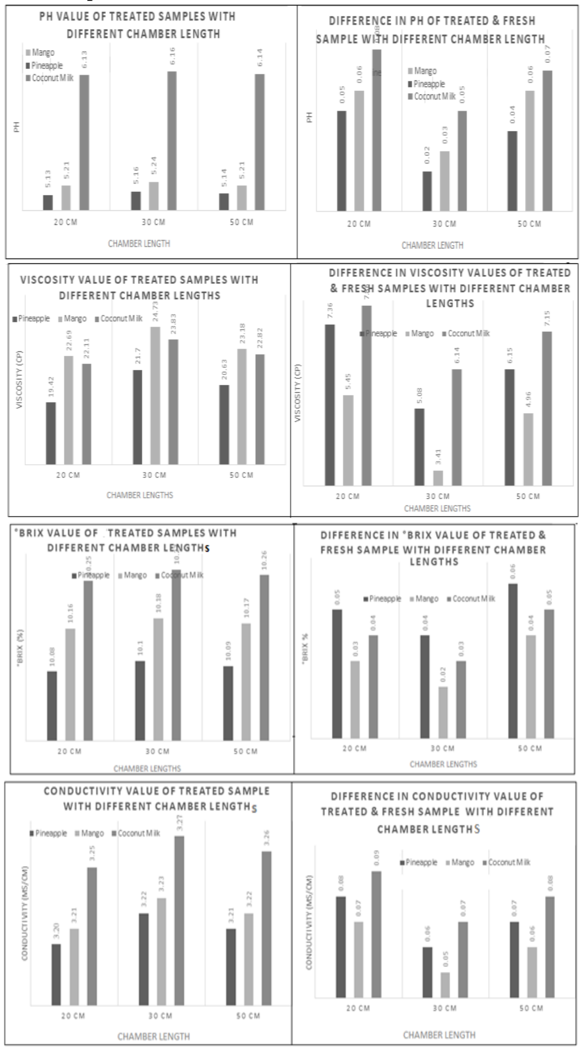

Fig. 5. Effects of pH, Brix, Viscosity, and conductivity of the treated sample with sterilization chamber lengths (20 cm, 30 cm, & 50 cm) at 30 kV/cm

Fig. 5 shows a significant increase in all the four measuring parameters (conductivity, ph, Brix, and viscosity) of the treated fruit juices when the chamber length is increased from 20 cm to 30 cm. However, further increase the chamber length from 30 cm to 50 cm has caused all these measured parameters of the treated sample to reduce slightly. This is in contrast with the initial expectation that the longer chamber length, treatment time for the juice samples increases, therefore, the more effective it is to kill the bacteria. This unpredictable result is due to the creation of bubbles which caused the spark inside the fruit juice samples. Hence, 50 cm shows little effectiveness in killing or preventing the growth of the microorganisms and bacteria in the fruit juice samples. Table II shows the change in chemical parameters of treated samples with helical sterilization chamber of 30 cm at 30 kV/cm and compares the findings in comparison to the results quoted by earlier researchers. The helical chamber is established more suitable for sterilization as compared to the previous studies conducted by Krishnaveni, Subhashini [27] and Khanal [28].

Table I: The difference of chemical parameters between treated liquid and fresh

Food juice	Treatment Conditions	Conductivity (mS/cm)	pH	°Brix (%)	Viscosity (cP)	Reference
Coconut Milk	SC=30 cm , E=30kV/cm	0.07	0.05	0.03	6.14	Current research
Mango	SC=30 cm, E=30kV/cm	0.05	0.03	0.02	3.14	Current research
Pineapple	SC=30 cm, E=30kV/cm	0.06	0.02	0.04	5.08	Current research
Sugarcane juice	30 kV cm−1, 150 pulses		1.71	0.5		Krishnaveni, Subhashini [27]
Skim milk		0.18	0.02	0.13	0.03	Khanal [28]
Apple	40 kV/cm, 100 pulses	0.14	0.03	-0.1		Moonesan and Jayaram [29]

B. Analysis of Microbial Inactivation

Bioscience test by a spectrophotometer is one of the most popular methods for detection of microbial growth rate in fruit juices. A T60 UV spectrophotometer (PG Instruments UK) was used to note the bacterial culture growth in the sample of treated, untreated and freshly squeezed juices. Samples were incubated for 30 min and their optical spectra were recorded [30].

Table II: Log reduction of treated juices with different lengths

Electric field	Mango	Pineapple	Coconut milk
20 cm	5.2	4.2	4.72
30 cm	7.5	5.7	5.55
50 cm	6.4	5	5.05

According to Table II, a chamber with a length of 30 cm shows the highest performance in hindering microbial growth. With the PEF of 30 kV/cm, it attains the LR of 7.5, 5.7, and 5.55-log_{10} CFU/mL for the treated samples of mango, pineapple, and coconut milk, respectively, for this experimental test process.

IV. CONCLUSION

In this study, the optimization of the sterilization chamber lengths successfully improves the performance of the PEF processing. The proposed sterilization chamber is capable to effectively kill the bacteria in tropical fruit juice samples as it applies uniform electric field strengths to whole treated sample due to turbulence flow and provides a longer residence time as compared to other designs.

REFERENCES

1. Weaver JC, Chizmadzhev YA. Theory of electroporation: a review. Bioelectrochemistry and bioenergetics. 1996;41(2):135-60.
2. Castro AJ, BARBOSA-CÁNOVAS GV, Swanson BG. Microbial inactivation of foods by pulsed electric fields. Journal of Food Processing and Preservation. 1993;17(1):47-73.
3. Zimmermann U. Electrical breakdown, electropermeabilization and electrofusion. Reviews of Physiology, Biochemistry and Pharmacology, Volume 105: Springer; 1986. p. 175-256.
4. Sale A, Hamilton W. Effects of high electric fields on microorganisms: I. Killing of bacteria and yeasts. Biochimica et Biophysica Acta (BBA)-General Subjects. 1967;148(3):781-8.
5. Knorr D, Geulen M, Grahl T, Sitzmann W. Food application of high electric field pulses. Trends in food science & technology. 1994;5(3):71-5.
6. Reberšek M, Miklavčič D. Advantages and disadvantages of different concepts of electroporation pulse generation. Automatika: časopis za automatiku, mjerenje, elektroniku, računarstvo i komunikacije. 2011;52(1):12-9.
7. McAuley CM, Singh TK, Haro-Maza JF, Williams R, Buckow R. Microbiological and physicochemical stability of raw, pasteurised or pulsed electric field-treated milk. Innovative Food Science & Emerging Technologies. 2016;38:365-73.
8. Ramaswamy R, Ramachandran RP, editors. Electric field analysis of different compact electrodes for pulsed electric field applications in liquid food. Power Modulator and High Voltage Conference (IPMHVC), 2016 IEEE International; 2016: IEEE.
9. Sitzmann W, Vorobiev E, Lebovka N. Applications of electricity and specifically pulsed electric fields in food processing: Historical backgrounds. Innovative Food Science & Emerging Technologies. 2016;37:302-11.
10. Mohamed ME, Eissa AHA. Pulsed electric fields for food processing technology. Structure and function of food engineering: InTech; 2012.
11. El-Hag AH, Jayaram SH, Griffiths MW. Inactivation of naturally grown microorganisms in orange juice using pulsed electric fields. IEEE transactions on plasma science. 2006;34(4):1412-5.
12. Ohshima T, Tanino T, Kameda T, Harashima H. Engineering of operation condition in milk pasteurization with PEF treatment. Food Control. 2016;68:297-302.
13. Masood H, Diao Y, Cullen PJ, Lee NA, Trujillo FJ. A comparative study on the performance of three treatment chamber designs for radio frequency electric field processing. Computers & Chemical Engineering. 2018;108:206-16.
14. Van den Bosch H. Chamber design and process conditions for pulsed electric field treatment of food. Food preservation by pulsed electric fields. 2007:70-93.
15. Jaeger H, Meneses N, Knorr D. Impact of PEF treatment inhomogeneity such as electric field distribution, flow characteristics and temperature effects on the inactivation of E. coli and milk alkaline phosphatase. Innovative food science & emerging technologies. 2009;10(4):470-80.
16. Meneses N, Jaeger H, Moritz J, Knorr D. Impact of insulator shape, flow rate and electrical parameters on inactivation of E. coli using a continuous co-linear PEF system. Innovative food science & emerging technologies. 2011;12(1):6-12.
17. Islek AA. The impact of swirl in turbulent pipe flow: Georgia Institute of Technology; 2004.
18. Buckow R, Semrau J, Sui Q, Wan J, Knoerzer K. Numerical evaluation of lactoperoxidase inactivation during continuous pulsed electric field processing. Biotechnology progress. 2012;28(5):1363-75.

Published By:
Blue Eyes Intelligence Engineering & Sciences Publication

19. Bermaki H, Ziane M, Semmak A, Bellebna Y, Belhassaini H, Tilmatine A. EXPERIMENTAL ANALYSIS OF MONOAXIAL AND BIAXIAL PULSED ELECTRIC FIELD TREATMENT CHAMBERS FOR FOOD PROCESSING. CARPATHIAN JOURNAL OF FOOD SCIENCE AND TECHNOLOGY. 2017;9(1):43-50.
20. Bi X, Liu F, Rao L, Li J, Liu B, Liao X, et al. Effects of electric field strength and pulse rise time on physicochemical and sensory properties of apple juice by pulsed electric field. Innovative Food Science & Emerging Technologies. 2013;17:85-92.
21. Baba K, Kajiwara T, Watanabe S, Katsuki S, Sasahara R, Inoue K. Low-Temperature Pasteurization of Liquid Whole Egg using Intense Pulsed Electric Fields. Electronics and Communications in Japan. 2017.
22. Elserougi A, Ahmed S, Massoud A. High-voltage pulse generator based on capacitor-diode voltage multiplier centrally fed from dc-dc boost converter. 2016.
23. Elgenedy MA, Darwish A, Ahmed S, Williams BW. A modular multilevel generic pulse-waveform generator for pulsed electric field applications. IEEE Transactions on Plasma Science. 2017;45(9):2527-35.
24. Ikhu-Omoregbe D. Effect of solid particles on the thermal conductivity of mango juice in a shear flow field. International Journal of Food Properties. 2009;12(4):885-95.
25. EVRENDILEK GA, Dantzer W, Streaker C, Ratanatriwong P, Zhang Q. SHELF-LIFE EVALUATIONS OF LIQUID FOODS TREATED BY PILOT PLANT PULSED ELECTRIC FIELD SYSTEM. Journal of food processing and preservation. 2001;25(4):283-97.
26. Barbosa-Cánovas GV, Zhang QH. Pulsed electric fields in food processing: fundamental aspects and applications: CRC Press; 2010.
27. Krishnaveni S, Subhashini R, Rajini V. Inactivation of bacteria suspended in water by using high frequency unipolar pulse voltage. Journal of Food Process Engineering. 2017;40(6).
28. Khanal D. Non-thermal processing of skim milk: Impact on microbial reduction, physico-chemical properties and quality of Brie type cheese 2014.
29. Moonesan MS, Jayaram SH. Effect of Pulsewidth on Medium Temperature Rise and Microbial Inactivation Under Pulsed Electric Field Food Treatment. IEEE Transactions on Industry Applications. 2013;49(4):1767-72.
30. Rukchon C, Nopwinyuwong A, Trevanich S, Jinkarn T, Suppakul P. Development of a food spoilage indicator for monitoring freshness of skinless chicken breast. Talanta. 2014;130:547-54.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication