



Effect of relative humidity on the inactivation of foodborne pathogens by corona discharge plasma jet (CDPJ)

Chaeyoung Kim, Taehoon Lee, Pradeep Puligundla, Chulkyoon Mok*

Department of Food Science & Biotechnology, Gachon University, 1342 Seongnam-daero, Sujeong-gu, Seongnam-si, Gyeonggi-do, 13120, Republic of Korea

ARTICLE INFO

Keywords:

Corona discharge plasma
Humidity
Foodborne pathogen
Inactivation
Plasma species

ABSTRACT

In this study, we compared the bactericidal activities of corona discharge plasma jet (CDPJ) at different relative humidities (RHs) against *Escherichia coli* O157:H7, *Salmonella typhimurium*, and *Staphylococcus aureus*. CDPJs were produced at 41–62% RH range. The levels of CO, NO, and NO₂ species were increased from 62 to 69 ppm, 271 to 311 ppm, and 15 to 26 ppm, respectively, with increasing RH from 41 to 51%. Thereafter, between 51 and 62% RH, their concentrations were decreased. The inactivation effect of CDPJ on the bacteria at different RHs followed the same trend as the plasma species production. Exposure (300 s) to CDPJ produced at 51% RH had resulted in a decrease of *E. coli* O157:H7, *S. typhimurium*, and *S. aureus* counts by 4.01, 3.65, and 3.31 log, respectively. The inactivation patterns exhibited better fit to a Weibulltail model. The first decimal reduction times (δ values) were decreased with rise in RH from 41 to 51%. The inactivation effect was increased with increasing concentrations of CO, NO and NO₂ species. In addition, correlation analysis between individual plasma species and inactivation effect indicated that the concentration of NO_x species had the greatest effect on the inactivation.

1. Introduction

Foodborne pathogens have received increasing attention not only from food safety authorities but also from consumers since they pose serious challenges to public health and food safety worldwide (Gao et al., 2019). For instance, in the year 2011, an outbreak of infection with Shiga-toxin-producing *Escherichia coli* O104:H4 resulted in 3816 illnesses (including 54 deaths) in Germany. In addition, the infection was spread to 15 more countries by people who had traveled to northern Germany during that period (Frank et al., 2011).

Escherichia coli O157:H7 is one of the major foodborne pathogens, known to cause hemolytic uremic syndrome and hemorrhagic colitis in humans (Zhao, Doyle, Shere, & Garber, 1995). *E. coli* O157:H7 has the capability to secrete Shiga-like toxins and has a low infectious dose; and it has been linked to various outbreaks (Gao et al., 2019). Therefore, its decontamination has received much attention. *Staphylococcus aureus* has been reported to be the most common foodborne pathogen by the Centers for Disease Control and Prevention (Dewey-Mattia, Manikonda, Hall, Wise, & Crowe, 2018). In underdeveloped and industrial countries, *Salmonella* has been shown to be one of the major foodborne pathogens, accounting for 93.8 million cases of illnesses (including 155,000 deaths) per year (Eng et al., 2015; Oh & Park, 2017).

Conventionally, thermal processing technologies have been

extensively used to ensure food safety and extended shelf-life. However, thermal-based methods are known to contribute to undesirable changes in sensory quality and food matrix (Bhavya & Hebbar, 2019). Therefore, researchers have increasingly focused on the development of non-thermal alternative technologies, such as pulsed electrical fields (PEF), ultraviolet (UV) decontamination, high hydrostatic pressure (HHP), high-intensity pulsed light, high-power ultrasound, pulsed white light, high-intensity laser, high-voltage arc discharge, oscillating magnetic fields, streamer plasma, etc., in order to meet consumer demand for fresh-like food products with superior organoleptic quality and an acceptable shelf-life (Devlieghere, Vermeiren, & Debevere, 2004).

Different types of non-thermal plasmas have been used for the decontamination of foodborne pathogens in various food products (Misra, Tiwari, Raghavarao, & Cullen, 2011). Corona discharge is one among different approaches for non-thermal plasma generation at atmospheric pressure; and these discharges in air exhibit a strong bactericidal effect (Kim, Puligundla, & Mok, 2015; Puligundla, Kim, & Mok, 2018). Humidity can influence the microbicidal effect of a plasma, especially in the case of atmospheric pressure plasmas operated in humid ambient air, and humidity has been shown to play an important role in plasma chemical processes (Fridman, 2008; Winter et al., 2013). Dissociation of water molecules may lead to a variety of subsequent plasma chemical reactions and products formed thereby (e.g., hydrogen peroxide (H₂O₂),

* Corresponding author.

E-mail address: mokck@gachon.ac.kr (C. Mok).

<https://doi.org/10.1016/j.lwt.2020.109379>

Received 16 December 2019; Received in revised form 2 April 2020; Accepted 5 April 2020

Available online 09 April 2020

0023-6438/ © 2020 Elsevier Ltd. All rights reserved.

atomic oxygen (O) and hydroxyl (OH)) can be potent to generate oxidative stress in biological samples (Winter et al., 2013). In an earlier study, an increased inactivation of *Aspergillus niger* conidiospores was observed following treatment with a cascaded dielectric barrier discharge at a high relative gas humidity (70%) in comparison with inactivation at a low humidity (0%) (Muranyi, Wunderlich, & Heise, 2008). In another study, critical role of relative humidity of gaseous atmosphere in a plasma (resistive barrier discharge) treatment chamber on the decontamination of *Salmonella enteritidis* and *Salmonella typhimurium* on shell eggs has been shown (Ragni et al., 2010). For *S. enteritidis*, maximal reductions of 2.5 and 4.5 log CFU/eggshell were obtained following treatment (90 min) at relative humidities of 35% and 65%, respectively. In the present study, the bactericidal effects of corona discharge plasma jet (CDPJ) against selective foodborne pathogens under different relative humidities were investigated.

2. Materials and methods

2.1. Microorganisms

Standard cultures of *Escherichia coli* O157:H7 NCTC 12079, *Salmonella enteritidis* KCCM12021, and *Staphylococcus aureus* ATCC 14458 were procured from Korean Culture Center of Microorganisms (KCCM, Seoul, Korea). The pathogens were cultured at 37 °C for 24 h using tryptic soy broth (BD Company, Le Pont de Claix, France) prior to use in plasma treatment experiments. The counts of these bacteria after 24 h culture were in the range of 8.26–9.18 log CFU/mL.

2.2. Corona discharge plasma jet (CDPJ)

CDPJ was generated at atmospheric pressure conditions using a custom-made apparatus (Plasma Life Co. Ltd., Incheon, Korea). The plasma generator was powered by a high voltage (20 kV DC output voltage) power source, with an input current of 1.5 A and a frequency of 58 kHz, as described in our previous reports (Kim et al., 2015; Lee, Puligundla, & Mok, 2017). Streamer-type corona discharge in air was observed between tungsten electrodes under high voltages. In order to create plasma jet, a centrifugal air blower (Ventur Tekniska, Goteborg, Sweden) was used at a rotational (impeller) speed of 3312 rpm. Air velocity at the tip of the electrodes was 2.5 m/s.

2.3. Humidity

In order to maintain different levels of humidity in plasma treatment area, a nebulizer (SN 009141, Philips Respironics, Germany) was used.

2.4. Relative humidity measurement

Relative humidity (RH) change in sample treatment chamber was determined using relative humidity sensors containing digital thermometer (TR-77UI, T&D Co., Matsumoto, Japan).

2.5. Plasma species concentrations

The concentrations of reactive chemical species in CDPJ generated at different relative humidities were determined by a multigas analyzer (Optima 7, MRU Instruments, Inc., Germany). This instrument was optimized to test the concentrations of CO, NO, and NO₂.

2.6. CDPJ treatment

The foodborne pathogenic bacteria were individually inoculated to tryptic soy broth and grown for 24 h at 37 °C. Then, micro-drops of the broth cultures were dispersed separately on slide glasses (10 µL on each slide) and allowed to dry for 1 h in a laminar-flow clean bench at room

temperature (20 ± 2 °C). Thereafter, the pathogen-loaded slides were individually exposed to the CDPJ at different relative humidities (41, 45, 51, 53, 58 and 62% RHs).

2.7. Viable cell count determination

Immediately after CDPJ treatment, each slide glass was washed with saline solution (0.85% NaCl) for 5 times (1 mL/wash) and diluted using normal saline to make a final volume of 10 mL. Later, aliquots (1 mL) of each diluted sample were plated in plate count agar (PCA, BD company) containing Petri plates and incubated at 37 °C for 24 h before colony counting.

2.8. Modeling of inactivation

A first-order kinetic model is commonly used to explain the inactivation patterns of microorganisms upon exposure to lethal agents, as given in Eq. (1)

$$\log \frac{N_0}{N} = \frac{k}{2.303} \cdot t \quad (1a)$$

However, the above equation is valid for log-linear inactivation curves only. Often, microbial survival curves exhibit non-log-linear relationships. Therefore, to analyze non-log-linear survival curves observed following CDPJ treatment, the suitability of the following kinetic models were tested using GINAFIT software (version 1.6, 2012, BioTeC, Leuven, Belgium):

Log-linear model (Bigelow & Esty, 1920):

$$\log_{10} N = \log_{10} N_{10} - \left(\frac{k_{\max} \cdot t}{\ln 10} \right) \quad (2a)$$

Log-linear tail model (Geeraerd, Herremans, & Van Impe, 2000):

$$\log_{10} N = \log_{10} (10^{\log_{10} N_0} - 10^{\log_{10} N_{\text{res}}} \cdot e^{-k_{\max} t} + 10^{\log_{10} N_{\text{res}}}) \quad (3)$$

Weibull model (Mafart, Couvert, Gaillard, & Leguerinel, 2002):

$$\log_{10} N = \log_{10} N_0 - \left(\frac{t}{\delta} \right)^p \quad (4)$$

Weibulltail model (Albert & Mafart, 2005):

$$\log_{10} N = \log_{10} \left[\left(10^{\log_{10} N_0} - 10^{\log_{10} N_{\text{res}}} \right) \times 10^{\left(\frac{-t}{\delta} \right)^p} + 10^{\log_{10} N_{\text{res}}} \right] \quad (5)$$

Where,

N = microbial cell density at time t

N_0 = initial microbial cell density

N_{res} = residual microbial cell density

$k_{\max}$ = first order decrease rate constant (1/min)

p = curve shape factor

δ = initial decimal reduction time (min)

2.9. Statistical analysis

All treatments were performed in triplicate, and results are presented as mean ± standard deviation. Data were statistically analyzed using SAS statistical software package (version 9.2, SAS Institute Inc., Cary, NC, USA). The statistical significance of results was analyzed by one-way analysis of variance (ANOVA), followed by Duncan's multiple range test at $\alpha = 0.05$.

3. Results and discussion

3.1. Plasma species

The concentrations of selective plasma species, namely CO, NO, and

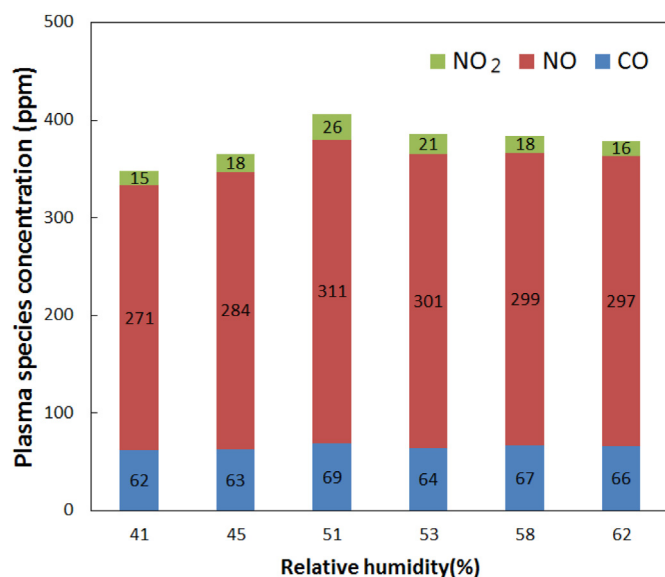


Fig. 1. The concentrations of plasma species at different relative humidities.

NO₂, were progressively increased with increasing relative humidity levels up to 51% (Fig. 1). However, a further increase of humidity up to 62% had negatively impacted the concentrations of all the tested species. The concentrations of CO species were found to range from 62 to 69 ppm at relative humidities of 41 to 62%. Over the same humidity range, the concentrations of NO and NO₂ species in CDPJ were found to range from 271 to 311 ppm and 15 to 26 ppm, respectively.

In a previous study, relative humidity has been shown to be a critical factor in bacterial spore inactivation by a high voltage atmospheric cold plasma (Patil et al., 2014). An investigation into the effect of feed gas humidity on the generation of reactive species in an atmospheric-pressure argon plasma jet revealed a strong dependence of excited plasma species, such as molecular nitrogen, hydroxyl radicals, argon, and atomic oxygen, on feed gas humidity (Winter et al., 2013).

3.2. Pathogen inactivation

The selective pathogens, namely *E. coli* O157:H7, *S. typhimurium*, and *S. aureus*, were inactivated in a time-dependent manner upon CDPJ exposure. Maximum inactivation effect of CDPJ was noted at a relative humidity of 51%; the average levels of inactivation of *E. coli* O157:H7, *S. typhimurium*, and *S. aureus* at this humidity level were 4.01 ± 0.05 log, 3.65 ± 0.10 log, and 3.31 ± 0.13 log following CDPJ treatment for 300 s, respectively (Fig. 2). Relatively low levels of inactivation were observed at a relative humidity of 62% for all the tested pathogens. The highest levels of *E. coli* O157:H7 inactivation (treatment time: 300 s) at relative humidities of 41, 45, 53, 58 and 62% were 3.46 ± 0.08 , 3.44 ± 0.06 , 3.84 ± 0.07 , 3.50 ± 0.04 and 3.45 ± 0.08 log, respectively. The maximum levels of *S. typhimurium* inactivation at 41, 45, 53, 58 and 62% relative humidities were 3.33 ± 0.05 , 3.35 ± 0.07 , 3.51 ± 0.11 , 3.41 ± 0.03 and 3.17 ± 0.11 log, respectively. And, the peak levels of *S. aureus* inactivation at 41, 45, 53, 58 and 62% relative humidities following CDPJ treatment for 300 s were 2.93 ± 0.09 , 3.07 ± 0.17 , 3.07 ± 0.14 , 3.29 ± 0.08 and 3.05 ± 0.01 log, respectively.

Direct exposure of bacterial cells to plasma may result in greater inactivation (Patil et al., 2014). Plasma charged species in coexistence with other species (e.g., OH radicals, ozone, excited molecular, and atomic species), which exert synergistic action, have been reported to play a major role in inactivation (Dobrynin, Fridman, Friedman, & Fridman, 2009; Fridman et al., 2007).

3.3. Kinetic modeling

The suitability of selective models, namely log-linear, log-linear tail, Weibull, and Weibull tail, to explain CDPJ treatment-induced bacterial inactivation at different relative humidities was tested. Among these kinetic models, Weibull tail model was fitted well to the inactivation data and therefore it was regarded as the most suitable model. The suitability was established basing on the values of sum of squared errors (SSE), root mean squared error (RMSE), and coefficient of determination or fit index (R^2). As can be seen from Table 1, relatively low SSE and RMSE values and a high R^2 value for Weibull tail model imply that the model is the best-fitting model compared with others.

The Weibull tail model was used to determine kinetic parameters for *E. coli* O157:H7, *S. typhimurium*, and *S. aureus* inactivations at different humidity levels. As shown in Table 2, relatively low δ -values (time to the first decimal reduction) were observed for *E. coli* O157:H7, *S. typhimurium*, and *S. aureus* inactivations at 51% relative humidity, indicating a superior inactivation rate at this humidity level. The δ -values observed for *E. coli* O157:H7, *S. typhimurium*, and *S. aureus* following CDPJ treatment at 51% relative humidity were 7.27 ± 3.54 , 13.96 ± 2.45 and 21.85 ± 6.68 s, respectively.

The correlation analysis between individual plasma species and the inactivation effect indicated that the concentration of NO_x species (combination of NO and NO₂ species) had significantly higher impact on the inactivation (Table 3).

3.4. Possible mechanism of inactivation

The generation of reactive species is influenced by different parameters such as gas type, applied voltage, treatment time, mode of plasma exposure and including relative humidity (Patil et al., 2014). In humid air, highly oxidizing species such as peroxides, OH, and increased amounts of nitrogen oxides have been shown to play a major role in spore inactivation other than ozone (O₃) (Dorai & Kushner, 2003).

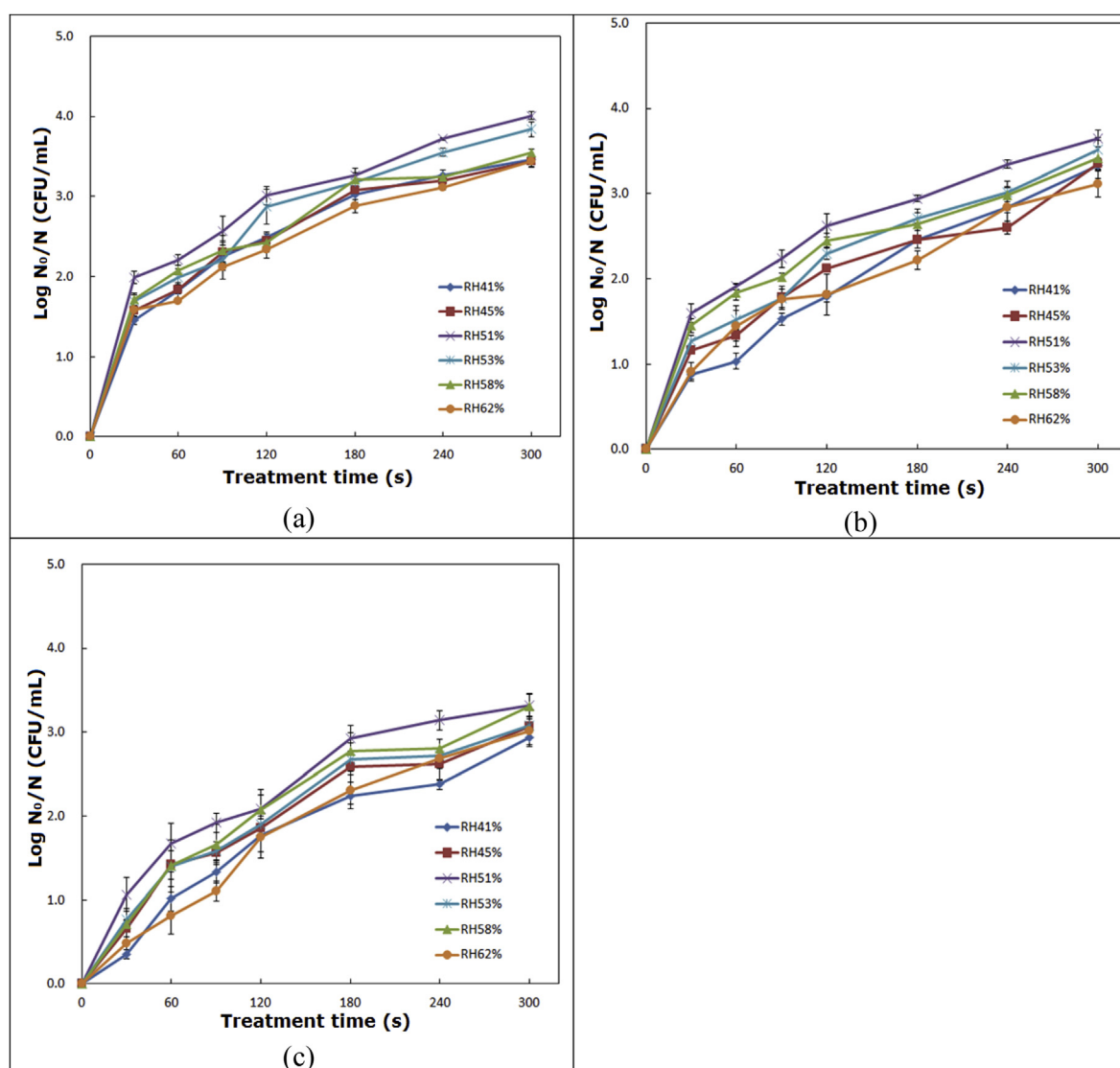
Inside plasma jet, water molecules can be decomposed to generate hydrogen atoms and ·OH radicals.



Under increased levels of humidity, part of H₂O molecules collides with high-energy electrons and form ·OH radicals, resulting in higher inactivation efficiency. An increase of humidity beyond certain level limits the electron density in plasma and quenches activated chemical species (Jie, Yao, Hua, & Qingfa, 2009). With an increase of relative humidity from 35% to 80%, electron density has been shown to decrease in a cold atmospheric plasma jet (Lin, Lyu, Trink, Canady, & Keidar, 2019).

4. Conclusion

The concentrations of the tested plasma species changed with relative humidity during treatment and the highest levels were obtained at 51% relative humidity. As the concentrations of these species increase, the bactericidal power against the foodborne bacteria increased; *E. coli* O157:H7, *S. typhimurium*, and *S. aureus* were decreased maximally by 4.01, 3.65, and 3.31 log, respectively, following CDPJ treatment for 300 s (at relative humidity: 51%). The inactivation patterns exhibited better fit to the Weibull tail model. The correlation analysis between individual plasma species and inactivation effect indicated that the concentration of NO_x species had the greatest effect on the inactivation.



N_0 = initial microbial cell density
 N = microbial cell density at time t

Fig. 2. Inactivation patterns of *E. coli* O157:H7 (a), *S. typhimurium* (b), and *S. aureus* (c) at different relative humidities following CDPJ treatment.

Table 1

Statistical parameter values obtained for different kinetic models used to describe the inactivation of the bacteria by CDPJ treatment.

Model type	SSE	RMSE	R^2 value
Log-linear	0.0528 ± 0.0117	0.2297 ± 0.1142	0.9631 ± 0.0417
Log-linear tail	0.0353 ± 0.0081	0.1878 ± 0.0984	0.9810 ± 0.0279
Weibull	0.0101 ± 0.0031	0.1049 ± 0.0317	0.9894 ± 0.0214
Weibull tail	0.0088 ± 0.0014	0.0938 ± 0.0114	0.9918 ± 0.0094

CRedit authorship contribution statement

Chaeyoung Kim: Methodology, Investigation. **Taecheon Lee:** Methodology, Investigation. **Pradeep Puligundla:** Writing - original draft, Writing - review & editing. **Chulkyoon Mok:** Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Table 2

Relative humidity-dependent changes in first decimal reduction times (δ) obtained (using Weibull tail model) for the inactivation of the foodborne pathogens by CDPJ treatment. (unit: s).

Relative humidity (%)	<i>E. coli</i> O157:H7	<i>S. typhimurium</i>	<i>S. aureus</i>
41	28.01 ± 4.28 ^a	48.84 ± 8.82 ^a	58.16 ± 15.74 ^a
45	20.52 ± 4.37 ^a	28.36 ± 11.41 ^{bc}	41.30 ± 12.62 ^{ab}
51	7.27 ± 3.54 ^c	13.96 ± 2.45 ^d	21.85 ± 6.68 ^b
53	9.59 ± 4.44 ^{bc}	24.18 ± 7.39 ^{bc}	31.34 ± 10.81 ^b
58	14.44 ± 5.12 ^c	31.44 ± 2.12 ^{bc}	35.84 ± 11.42 ^c
62	16.99 ± 5.75 ^{bc}	36.84 ± 8.88 ^b	49.48 ± 10.48 ^b

Values are given as mean ± SD (n = 3). Distinct letters within the same column indicate significant differences (p < 0.05).

Acknowledgement

This research was supported by a grant (18163MFD025-1) from Ministry of Food and Drug Safety, Korea, in 2018.

Table 3
NOx species-exerted inactivation on the bacteria.

Foodborne pathogen	Regression equation	R ² value
<i>E. coli</i> O157:H7	$\delta = -0.439C_{NOx} + 152.718$	0.9534
<i>S. typhimurium</i>	$\delta = -0.656C_{NOx} + 234.178$	0.8671
<i>S. aureus</i>	$\delta = -0.693C_{NOx} + 255.223$	0.9554

δ : first decimal reduction time (s).

References

- Albert, I., & Mafart, P. (2005). A modified Weibull model for bacterial inactivation. *International Journal of Food Microbiology*, 100(1–3), 197–211. <https://doi.org/10.1016/j.ijfoodmicro.2004.10.016>.
- Bhavya, M. L., & Hebbar, H. U. (2019). Efficacy of blue LED in microbial inactivation: Effect of photosensitization and process parameters. *International Journal of Food Microbiology*, 290, 296–304. <https://doi.org/10.1016/j.ijfoodmicro.2018.10.021>.
- Bigelow, W. D., & Esty, J. R. (1920). The thermal death point in relation to time of typical thermophilic organisms. *The Journal of Infectious Diseases*, 27(6), 602–617. <https://doi.org/10.1093/infdis/27.6.602>.
- Devlieghere, F., Vermeiren, L., & Debevere, J. (2004). New preservation technologies: Possibilities and limitations. *International Dairy Journal*, 14(4), 273–285. <https://doi.org/10.1016/j.idairyj.2003.07.002>.
- Dewey-Mattia, D., Manikonda, K., Hall, A. J., Wise, M. E., & Crowe, S. J. (2018). Surveillance for foodborne disease outbreaks—United States, 2009–2015. *Morbidity and Mortality Weekly Report - Surveillance Summaries*, 67(10), 1–11. <https://doi.org/10.15585/mmwr.ss6710a1>.
- Dobrynin, D., Fridman, G., Friedman, A., & Fridman, A. (2009). Physical and biological mechanisms of direct plasma interaction with living tissue. *New Journal of Physics*, 11(11), 115020. <https://doi.org/10.1088/1367-2630/11/11/115020>.
- Dorai, R., & Kushner, M. J. (2003). A model for plasma modification of polypropylene using atmospheric pressure discharges. *Journal of Physics D: Applied Physics*, 36(6), 666–685. <https://doi.org/10.1088/0022-3727/36/6/309>.
- Eng, S. K., Pusparajah, P., Ab Mutalib, N. S., Ser, H. L., Chan, K. G., & Lee, L. H. (2015). *Salmonella*: A review on pathogenesis, epidemiology and antibiotic resistance. *Frontiers in Life Science*, 8(3), 284–293. <https://doi.org/10.1080/21553769.2015.1051243>.
- Frank, C., Werber, D., Cramer, J. P., Askar, M., Faber, M., an der Heiden, M., et al. (2011). Epidemic profile of Shiga-toxin-producing *Escherichia coli* O104: H4 outbreak in Germany. *New England Journal of Medicine*, 365, 1771–1780. <https://doi.org/10.1056/NEJMoa1106483>.
- Fridman, A. (2008). *Plasma chemistry*. Cambridge: Cambridge University Press.
- Fridman, G., Brooks, A. D., Balasubramanian, M., Fridman, A., Gutsol, A., Vasilets, V. N., et al. (2007). Comparison of direct and indirect effects of non-thermal atmospheric-pressure plasma on bacteria. *Plasma Processes and Polymers*, 4(4), 370–375. <https://doi.org/10.1002/ppap.200600217>.
- Gao, Z., Daliri, E. B. M., Wang, J., Liu, D., Chen, S., Ye, X., et al. (2019). Inhibitory effect of lactic acid bacteria on foodborne pathogens: A review. *Journal of Food Protection*, 82(3), 441–453. <https://doi.org/10.4315/0362-028X.JFP-18-303>.
- Geeraerd, A. H., Herremans, C. H., & Van Impe, J. F. (2000). Structural model requirements to describe microbial inactivation during a mild heat treatment. *International Journal of Food Microbiology*, 59(3), 185–209. [https://doi.org/10.1016/S0168-1605\(00\)00362-7](https://doi.org/10.1016/S0168-1605(00)00362-7).
- Jie, C., Yao, S., Hua, P., & Qingfa, S. (2009). Humidity and oxygen effects on dimethyl sulfide decomposition plasma corona reactor. *Electrostatic precipitation* (pp. 709–712). Berlin, Heidelberg: Springer.
- Kim, J. W., Puligundla, P., & Mok, C. (2015). Microbial decontamination of dried laver using corona discharge plasma jet (CDPJ). *Journal of Food Engineering*, 161, 24–32. <https://doi.org/10.1016/j.jfoodeng.2015.03.034>.
- Lee, T., Puligundla, P., & Mok, C. (2017). Corona discharge plasma jet inactivates food-borne pathogens adsorbed onto packaging material surfaces. *Packaging Technology and Science*, 30(10), 681–690. <https://doi.org/10.1002/pts.2311>.
- Lin, L., Lyu, Y., Trink, B., Canady, J., & Keidar, M. (2019). Cold atmospheric helium plasma jet in humid air environment. *Journal of Applied Physics*, 125, 153301. <https://doi.org/10.1063/1.5086177>.
- Mafart, P., Couvert, O., Gaillard, S., & Leguerinel, I. (2002). On calculating sterility in thermal preservation methods: Application of the Weibull frequency distribution model. *International Journal of Food Microbiology*, 72(1–2), 107–113. [https://doi.org/10.1016/S0168-1605\(01\)00624-9](https://doi.org/10.1016/S0168-1605(01)00624-9).
- Misra, N. N., Tiwari, B. K., Raghavarao, K. S. M. S., & Cullen, P. J. (2011). Nonthermal plasma inactivation of food-borne pathogens. *Food Engineering Reviews*, 3(3–4), 159–170. <https://doi.org/10.1007/s12393-011-9041-9>.
- Muranyi, P., Wunderlich, J., & Heise, M. (2008). Influence of relative gas humidity on the inactivation efficiency of a low temperature gas plasma. *Journal of Applied Microbiology*, 104(6), 1659–1666. <https://doi.org/10.1111/j.1365-2672.2007.03691.x>.
- Oh, J. H., & Park, M. K. (2017). Recent trends in *Salmonella* outbreaks and emerging technology for biocontrol of *Salmonella* using phages in foods: A review. *Journal of Microbiology and Biotechnology*, 27(12), 2075–2088. <https://doi.org/10.4014/jmb.1710.10049>.
- Patil, S., Moiseev, T., Misra, N. N., Cullen, P. J., Mosnier, J. P., Keener, K. M., et al. (2014). Influence of high voltage atmospheric cold plasma process parameters and role of relative humidity on inactivation of *Bacillus atrophaeus* spores inside a sealed package. *Journal of Hospital Infection*, 88(3), 162–169. <https://doi.org/10.1016/j.jhin.2014.08.009>.
- Puligundla, P., Kim, J. W., & Mok, C. (2018). Effect of atmospheric pressure plasma treatment on seed decontamination and sprouting of pak choi (*Brassica rapa* L. subsp. *chinensis* (L.) Hanelt). *Chiang Mai Journal of Science*, 45(7), 2679–2690.
- Ragni, L., Berardinelli, A., Vannini, L., Montanari, C., Sirri, F., Guerzoni, M. E., et al. (2010). Non-thermal atmospheric gas plasma device for surface decontamination of shell eggs. *Journal of Food Engineering*, 100(1), 125–132. <https://doi.org/10.1016/j.jfoodeng.2010.03.036>.
- Winter, J., Wende, K., Masur, K., Iseni, S., Dünbier, M., Hammer, M. U., et al. (2013). Feed gas humidity: A vital parameter affecting a cold atmospheric-pressure plasma jet and plasma-treated human skin cells. *Journal of Physics D: Applied Physics*, 46(29), 295401. <https://doi.org/10.1088/0022-3727/46/29/295401>.
- Zhao, T., Doyle, M. P., Shere, J., & Garber, L. (1995). Prevalence of enterohemorrhagic *Escherichia coli* O157:H7 in a survey of dairy herds. *Applied and Environmental Microbiology*, 61(4), 1290–1293.